Cascaded Use and Sustainable Management of Lithium-ion Batteries in Mobility and Stationary Power

by

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Authors Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The purpose of this thesis is to assess —from a life cycle perspective — the environmental benefits of re-purposing electric vehicle Li-ion batteries to re-use in stationary applications.

The thesis consists of three separate papers arranged in as chapters. The main objectives are threefold: to develop and analyze a parameterized life cycle model of Li-ion battery first use in EV and extended usage to incorporate the re-purposing and re-use in grid storage for a utility application (Chapter 3), to evaluate effective factors on the feasibility of re-purposing used EV Li-ion batteries and the effect of factors on the cumulative energy use and greenhouse gas (GHG) emissions of the re-purposed batteries life cycle (Chapter 4)., and to assess potential environmental impacts of re-purposing and re-using of EV Li-ion batteries into stationary applications from a life cycle perspective and compare with natural gas stationary power generation (Chapter 5).

According to the study, it is found that the magnitude of CO_2 mitigation associated with battery re-use is similar to that of switching from using a conventional vehicle to an electric vehicle, meaning that the GHG benefits of vehicle electrification could be doubled by extending the life of EV batteries, and better using off-peak low-cost clean electricity.

the effects of capacity fade, energy efficiency fade, failure rate, and charge/discharge profile are investigated for Li-ion batteries based on first use in EVs and second-use in ESS. It is estimated that the re-purposed EV battery loses a further 15% of its capacity after its second use in the energy storage system (ESS) over 10 years. As energy efficiency decreases with increased charge/discharge cycles, a capacity fade model is used to approximate the effect of the relationship between cycles and capacity fade over the life of the battery. The performance of the battery in its second use is represented using a model of degradation modes, assuming a 0.01% cell failure rate and a non-symmetric charge/discharge profile. Finally, an accurate modeling of battery performance is used to examine energy savings and GHG emission reduction benefits from using a Li-ion battery first in an EV and then in an ESS connected to the Ontario electrical grid.

A cradle-to-grave life cycle assessment (LCA) of the Li-ion battery pack is conducted and six environmental impact categories are assessed including global warming potential, particulate matter formation, freshwater eutrophication, photochemical oxidant formation potential, metal depletion, and fossil depletion. It is concluded that the manufacturing phase of the Li-ion battery has the main environmental impacts during the life cycle of the battery as concluded from. Utilizing the re-purposed Li-ion battery in contrast with natural gas source in the stationary application powering causes more savings from an environmental standpoint. The assessed environmental impacts highlight the importance of electricity mix used in the processes of the product systems. Finally, the effect of the battery degradation is analyzed through energy efficiency fade effect on the battery performance and it is found that the use phase of the battery in the EV during 8 years is more sensitive to this phenomenon than the re-using of the Li-ion batteries in the stationary application during additional 10 years.

Acknowledgements

This project could not have been achieved without the able assistance and guidance of a number of people. I extend my deep gratitude to my principal supervisor, Dr. Roydon A. Fraser, as well as to the other supervisors of "EV Battery Re-purposing" research group, Dr. Michael Fowler and Dr. Steven B. Young, whose careful guidance and attentive comments through the project were tremendously helpful.

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Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
Introduction

1.1 Background

Technological advances in battery performance combined with the regulatory push for low- and zero-emission vehicles have made widespread electric mobility a growing reality. Commercialization of these systems by major automotive manufacturers is underway, including plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) [1–3]. A major consideration of Electric vehicles (EV)s compared to internal combustion engine (ICE) formats is initial material and energy investment and associated environmental aspects of producing large battery packs that represent a significant investment in resources and materials; however, on a cradle- to-grave life cycle basis, this increased environmental loading at the production stage can be offset because of lower environmental impacts associated with EV use phase compared to fossil–fueled ICE vehicles [4], [5]. This study develops a parameterized life cycle model of Li-ion battery to preliminary analyze of its first use in EV and second use in energy storage systems after re-purposing. EVs powered by lithium ion (Li-ion) batteries provide excellent performance because of their high energy density and advanced gravimetric and volumetric properties [6–8]. Typically, a Li-ion EV battery reaches the end of its useful life in its vehicle use phase when 20% of its initial capacity is lost. This assumption is based on manufacturers' warranties that imply the battery has a useful in-vehicle lifespan of approximately 8 years. Predicting the degradation and state of health (SOH) of Li-ion batteries after their use in EVs and the potential effects on the battery performance into stationary application are number of challenges presented in this thesis. This study investigates the main factors that must be considered to improve the effective application of re-purposed batteries. These factors include the battery's capacity fade, energy efficiency fade, cell failure rate, and charge/discharge profile. The second or "cascaded" use of the battery adds residual value back to the vehicle by allowing the battery to stay in service longer. In other words, by extending the life of the EV battery, the high initial cost of the battery can be distributed among other users [9]. The automotive and power industries can support each other by charging EV batteries with intermittent renewable energy and excess base load nuclear power. Thus the integration of re-purposed EV batteries into the electrical grid can improve energy storage and provide peak power delivery [10]. Energy storage technologies boost the flexibility of grid operations by providing energy buffering capacity and new ways to control the flow of energy [11]. Energy storage systems (ESSs) powered by re-purposed batteries could be a reliable solution for the challenges posed by intermittent renewable energy sources and congested electrical distribution grids [12]. This provision of distributed energy storage is seen as critical to the development of a “smart grid”. Technical challenges involved in the life cycle of batteries in vehicle and re-purposed applications include testing and validation of battery degradation and remaining capacity, testing for failed cells within the pack, new control systems to interface with the battery management system, the safety of the re-purposed pack and battery management strategies to optimize the entire battery life cycle. The technical aspects of battery re-use have been proposed by automakers, governments, and utility companies [13]; however the environmental feasibility of this approach has not been well explored. The environmental and resource investment in the battery can be effectively amortized over a longer lifetime of material use. Environmental benefits can be obtained from re-purposed batteries used to store intermittent low emission renewable energy such as wind and solar used to harmonize supply and demand, or ease electrical grid congestion by providing time of day load electricity leveling in a distributed fashion. Prior studies on the life cycle of EVs indicate that three areas in the vehicle life-cycle are dominant with respect to potential environmental impacts. First is battery manufacturing, including mining and production of metals like cobalt and lithium, which contribute to several impact categories including in particular to local air quality [4], [14–17]. Manufacturing contributes as much as half of the GHGs over the life of an EV; and electronics associated with battery systems may contribute up to half of the acidification impact category [16]. Secondly, the other major area of impact is the EV use phase. Potential impacts are driven by both the quantity of energy used in a vehicle and by the mix of energy sources used to generate electricity supplied by the electric power grid [4], [14], [18]. The environmental performance of EVs is critically dependent on the combination of the vehicle and electricity production impacts as well as key factors such as energy use. Life cycle assessment (LCA) studies on EV storage batteries similarly show that the use phase dominates many of the life cycle impacts [15], [19]. Thirdly, recycling of materials at the end-of-life of the EV, especially the battery, is important in the environmental profile [20], although this is often not considered [4]. The material and resource impacts made in initial production can be partially recovered by accounting for a credit for materials that are recycled.

To complement the studies heretofore conducted and to learn more about the environmental benefits of reusing of EV Li-ion batteries, this thesis assesses a Li-ion battery pack through its entire life cycle including production, electric vehicle use, remanufacturing, and reuse into stationary application.

1.2 Objectives of the thesis

The main objective of this study is to assess the environmental benefits of re-using electric vehicle Li-ion batteries in stationary power applications.

This question was raised from offering of extended lifetime of EV Li-ion batteries in energy ESS after their first use in the mobility. The technical and economic features of battery re-use have been proposed by automakers, governments, and utility companies; however the environmental benefits of this approach has not been well explored. This study considers the environmental feasibility of re-manufacturing and second use of re-purposed EV batteries in the stationary applications from a life cycle perspective. In order to answer this question, a life-cycle assessment (LCA) study is conducted containing Li-ion battery manufacturing, battery first use in the EV, re-manufacturing of batteries, battery re-use in stationary application and end of life.

The specific research aspects in the thesis are as follows:

- Preliminary analysis of the generated CO_2 emissions that might be offset during the second use phase of a vehicle battery pack
- Predict the degradation and state of health of Li-ion batteries after their use in electric vehicles
- Investigate of the main factors that must be considered to improve the effective application of re-purposed batteries including the battery's capacity fade, energy efficiency fade, cell failure rate, and charge/discharge profile
- Determine the energy efficiency fade effect on greenhouse gas (GHG) emissions and energy use of Li-ion batteries during first use in the mobility and second use in the stationary application
- Assess the environmental benefits of re-purposing of used electric vehicle (EV) batteries into stationary applications from a life cycle perspective
- Evaluate the activities that cause the main environmental impacts for re-purposed Li-ion battery performance
- Discuss about the major data gaps and uncertainties.

1.3 Outline of the thesis

The thesis consists of three Papers which are arranged in the separate chapters based on their implementations. In Chapter 1 the background, overall purpose of the thesis, and specific objectives of the papers are defined. Chapter 2 efforts to prepare a general overview of the research conducted in the thesis based on previous studies. Chapter 3 summarizes the results of primary parameterized life cycle model of environmental feasibility to analyze the impacts of possible extension of life of electric vehicle batteries. The results of investigation on the effective factors on EV Li-ion battery re-purposing are summarized in Chapter 4. Chapter 5 continues the analysis of the environmental impacts of re-using of EV Li-ion batteries from a life cycle approach. Finally, Chapter 6 closes the thesis with a presentation of conclusion and discussion on limitations of the research, and recommendations for future research.

CHAPTER 2
Literature Review

2.1. Life Cycle Assessment Methodology

LCA is a method to provide a comprehensive view of impact categories across all stages of the life cycle of a product system from “cradle to grave” [21]. According to Finnveden (2000), LCA is an environmental systems analysis tool applied for valuation of the potential environmental impacts and resources used up during a product’s life cycle including raw material production, manufacturing, use phase and waste management [21], [22]. As shown in Figure 1, LCA involves in the four phases including goal and scope definition, inventory analysis (quantifying flows of resources and environmental releases), impact assessment (collection of impact categories and classification, collection of characterization methods and characterization, and the optional phases of normalization, grouping and weighting), and then interpretation and evaluation the robustness of results [23], [21]. LCA is data intensive and typically is performed with a mix of data sources of variable data quality. Several software packages are available, and a number of national and international databases are widely employed in LCA studies.

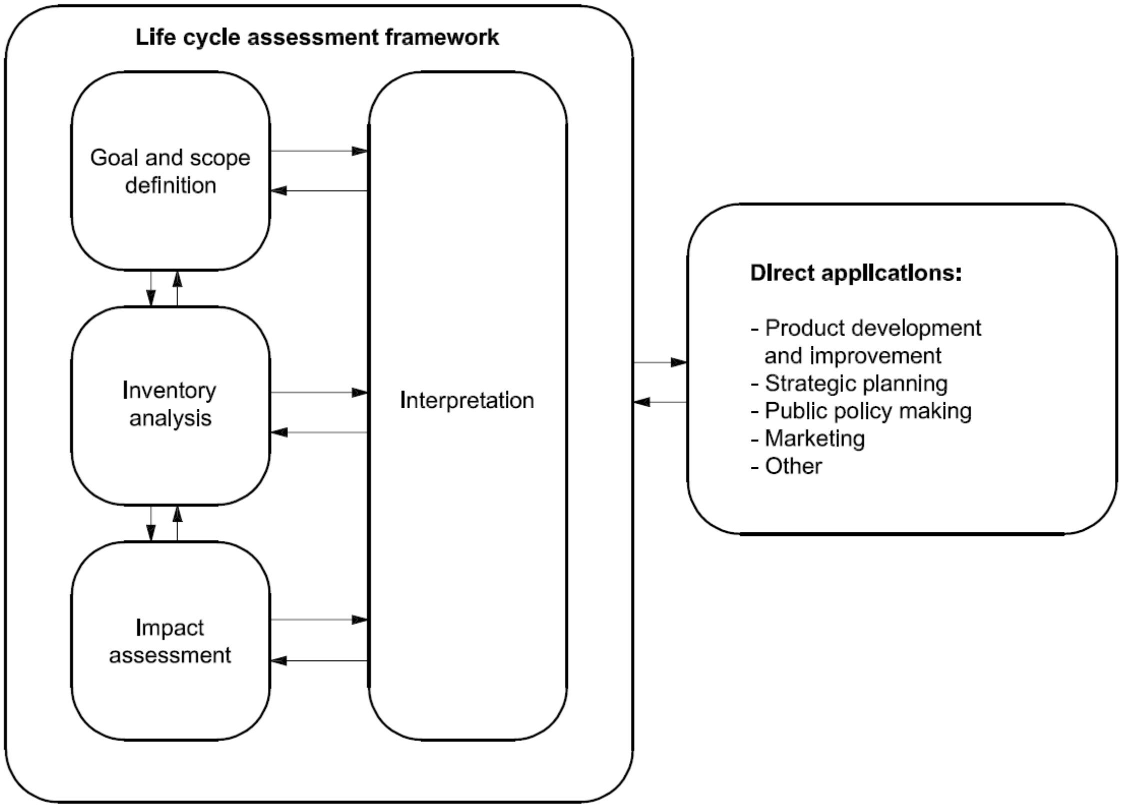


Figure 5: Main phases of life cycle assessment [21]

2.2. Electric Vehicles

Increasing cost of fuels and rising environmental concerns turn research into alternative, cleaner, and more efficient techniques of generating and utilizing energy [24]. A huge amount of energy is consumed in transportation sector and the major source of greenhouse gas (GHG) emissions in Canada, which is more than one third of Canada’s total GHG emissions, is related to this sector [25]. It is estimated that the number of vehicles on the road will approximately be tripled by 2050 [18]. The growing number of users and the finite resources of fossil fuels indicate the importance of the efficient use of resources, the improvement of the fuel economy, and the mitigation of environmental emissions in vehicles [26]. Moreover, by rapidly incremental rate of motorization and industrialization, the environmental and energy challenges will become tense increasingly.

Electrifying the powertrains is a possible answer to support the transportation sector associated with energy and environmental issues, which introduces a new generation of electric vehicles [18]. The technologies of electric and hybrid-electric vehicles are sorted from gasoline hybrid-electric vehicles (HEVs) and PHEVs to fuel-cell electric vehicles (FCEVs), and BEVs. This new generation of technologies— in comparison with the conventional internal combustion engine vehicles (ICEVs) — is possible candidates to help in energy efficiency and emissions reduction. Several studies have assessed the potential benefits of electric-powered vehicles compared to ICEVs and have discussed their fuel-economy potential [1], [2], [27]. EVs supply their power from electric machines to the wheels and by charging the battery packs. If an electric machine typically provides power to the wheels, it is usually called a motor. If an electric machine is used to generate electricity to charge the battery or to operate a motor, it is called a generator [28]. Hybrid electric vehicle includes parallel and series configurations that both of the electric motor and combustion engine can provide power directly to the wheels of the vehicle. These systems can reduce fuel consumption by optimized operation of engine and utilizing effective regenerating braking [28]. Plug-in hybrid recycles the regenerative braking energy to electric storage system instead wasting this energy as heat. Because of the nature of electric motors no energy is consumed when the vehicle is at a stop state. Battery electric vehicles are similar to PHEVs series with this difference that their electricity generator is off- board the vehicle [29]. Fuel-cell electric vehicles supply the electric energy trough hydrogen cells instead chemical batteries. The advantage of the fuel cell is the potential for high energy efficiency and zero tail pipe pollutants [28].

2.3. LCA of electric vehicles

LCA methodology is employed to assess different vehicle technologies from various points in their life cycle. As mentioned above, LCA is a ‘cradle-to-grave’ approach of evaluating technologies by collecting an inventory of applicable inputs and outputs, evaluating the potential environmental impacts associated with defined inputs and outputs, and interpreting the results of inventory and impact phases to support the relevant decision-makings [30]. In a full LCA study a set of broad and diverse environmental impact categories are selected to include energy use, measurement of global and regional air pollutants, and assessment of water pollutant loading [21], [31]. Not easily measured and therefore not well represented in the LCA literature, are other resource use categories, such as water use and biotic/abiotic resource depletion; complex environmental categories such as toxicity to human, terrestrial, and aquatic systems; and impacts resulting from both direct and indirect land-use changes, and associated biodiversity losses. More recently, LCA research has begun to consider social, economic and broader sustainability indicators within the product-oriented LCA framework (see for example, Zamagni et al. 2009 [32]).

Several LCA studies related to different vehicles concerns are purposefully restrained in their consideration of environmental impacts, focusing only on potential GHG emissions as an important and broad based indication of environmental performance [33], [34]. Despite this narrow consideration, GHG performance is a fair metric for the broader assessment of environmental feasibility. Hawkins et al. (2012) highlighted that EV batteries contribute, with great variation and uncertainty, to the non-renewable mineral depletion category, which is a metric with limited scientific meaning that is not widely used in LCA studies [4]. Local air quality, as indicated by photochemical smog potential may be greater for battery production in EVs than for production of ICE vehicles, however this category of emissions for EVs is mostly limited to industrial areas remote from populated centers [14]. Utilization of some minerals such as copper and aluminum that used for electricity conductivity will effect on resource demand and have an impact on resource depletion. The use of lithium and cadmium are significant in battery production [35]. Kleijn et al. (2011) showed that low-carbon electricity technologies such as renewables, nuclear, and carbon capture and storage often requires the application of vast range of metals. However, incremental demand of metals increases mining and processing activities which require huge amount of energy [36]. McManus (2011) indicated that water depletion associated with Li-ion batteries is higher than for comparable lead-acid batteries.

Prior studies on the life cycle of EVs indicate that two areas in the vehicle life-cycle are dominant with respect to potential environmental impacts. First is battery manufacturing, including mining and production of metals like cobalt and lithium, which makes a contribution to several impact categories [4], [14] including in particular to local air quality [14], [16]. The other major area of impact is the EV use phase. Potential impacts are driven by both the quantity of energy used in a vehicle and by the choice of energy sources used to generate electricity supplied by the electric power grid [4], [14], [18]. Helms et al. (2010) showed that the acidification impact category is significant for EVs powered with electricity generated from fossil fuels like coal. Hawkins et al. (2012) assessed a variety of environmental impact categories for conventional and electric vehicles assuming a 150,000 km vehicle lifetime, and based on a European electricity mix. Their results suggest a decrease in GHG emissions by 20% to 24% for EVs in comparison to gasoline ICE vehicles. They suggest that the vehicle lifetime has a great effect on the GHG emissions per distance for EVs, as the emissions intensity production is amortized. The environmental performance of EVs is critically dependent on the combination of the vehicle and electricity production impacts as well as key factors such as energy use. LCA studies on EV storage batteries similarly show that the use phase dominates many of the life cycle impacts [19].

2.4. Li-ion Batteries

The batteries are kind of energy storage devices where-in chemical energy is converted to electrical energy. The batteries are graded based on their energy and power capacities [38]. Different types of batteries are being industrialized that deep cycle ones including Li-ion batteries are proper to be applied in power system application such as electric vehicles and energy storage systems [39]. Li-ion batteries are combined of a cathode of lithiated metal oxide and an anode of graphitic carbon with a layer structure. The electrolyte consists of lithium salts dissolved in organic carbonates. Several studies indicate Li-ion batteries at 80% of their original capacity at the end of life (EOL) within a vehicle can be re-purposed and used in storage, peak-shaving and load-following applications, including electric supply, ancillary services, grid systems, and the integration of renewable energy sources [12], [13]. The long-term reliability of Li-ion batteries is an important characteristic of the technology. In a typical configuration graphite is the choice of negative electrode material because it provides high energy density and stability over a large number of charge cycles [40].

2.5. Battery degradation

Knowledge of battery degradation is considered in designing of durable stationary electrical systems. All batteries experience calendar aging, a gradual decomposition of the electrolyte for a given temperature over the life of the battery simply to basic material degradation [41]. However, the cycling of batteries accelerates their degradation especially if the thermal cycling is not strictly controlled. Battery degradation impacts three distinct performance metrics–capacity fade, power fade, and energy efficiency fade. Capacity fade represents a gradual loss in energy capacity for a given current and it is generally measured in Amp-hours. Capacity fade is predominately caused by the formation of a solid electrolyte interface (SEI) passivation layer at the anode-electrolyte interface due to its consumption of lithium ions [42]. Power fade, measured in watts, is a gradual increase in internal impedance that decreases available power. The SEI also contributes to power fade since the passivation layer at the cathode-electrolyte interface increases resistance to ion transport. Loss of electrode active material can also be caused by fracturing or cracking due to excessive mechanical stresses. As cracks develop, electrical isolation and blocking of insertion sites becomes more extensive and leads to power and capacity fade, consequently

[43], [44]. Energy efficiency fade is the decline of the battery efficiency, which generates from surface layers on anode and cathode [45]. These layers play a barrier role in reactions with electrolyte and cause a growth in cell impedance and reduction in cycling efficiency of the battery [46]. For electric vehicle configurations, both capacity fade and power fade each have two major implications. For capacity fade, the first is that a decrease in useable capacity represents larger state-of-charge (SOC) swings in charge-sustaining operation for a given drive cycle. Secondly, for capacity fade, the battery capacity has a direct correlation to charge-depleting range of the vehicle. Considering power fade, the first implication is that the minimum and maximum high voltage but limits will be achieved at lower battery discharge and charge currents respectively. As a result, the maximum discharge and charge power of the battery is reduced, resulting in less power available during accelerations and less ability to recapture power during regenerative braking. Since the drive cycle and vehicle dynamics determine the required power, the second implication of power fade is a further decrease in useable battery capacity as a given power will require additional current to compensate for a lower terminal battery voltage [42], [45]. Battery degradation is affected by cycling to extreme SOC points, deep depth-of-discharges (DOD), excessive charge rates (i.e. rapid charging), and high temperatures during their operation [47]. Under certain conditions it is feasible to lengthen the battery life to a satisfactory range for PHEV use. For instance by keeping DOD below 60% through avoiding large number of cycles, retaining temperatures below 35°C, fixing average state of charge lower than 60% [48] all contribute to the mitigation of degradation. Therefore, it is important to design an electrical system (either in the vehicle or stationary application) around these important factors to reduce battery degradation and extend the life of the system. Most importantly consumer acceptability of electric vehicle operation will be greatly affected by loss of capacity (i.e. less driving range) or loss of power (i.e. less acceleration or vehicle performance).

Generally a 20% loss in capacity or power will result in a need to battery pack replacement in the vehicle [13], [49], [50].

2.6. Energy storage system

Energy storage refers to the storage of electrical energy through conversion to other forms of energy [51]. Since its foundation in the late 19th century, power grid has operated along one key directive: the constant matching of power supply and demand across the grid [51]. In other words, the energy storage technology affords the required flexibility of the management of today's power grid or what some envision in the future as a ‘smart grid’. As can be seen in Figure 2, traditionally power is generated in centralized locations, and then transmitted through great distances to reach the end users who use electric power to perform various services, such as mechanical work, lighting refrigeration or heating. In order to manage the flow of energy on the grid, grid operators dispatched orders to the generators, informing them of the action required to balance supply with demand. Gradually, grid operators have also engaged in demand management programs, in which power end-users agree to modify their energy consumption pattern as needed.

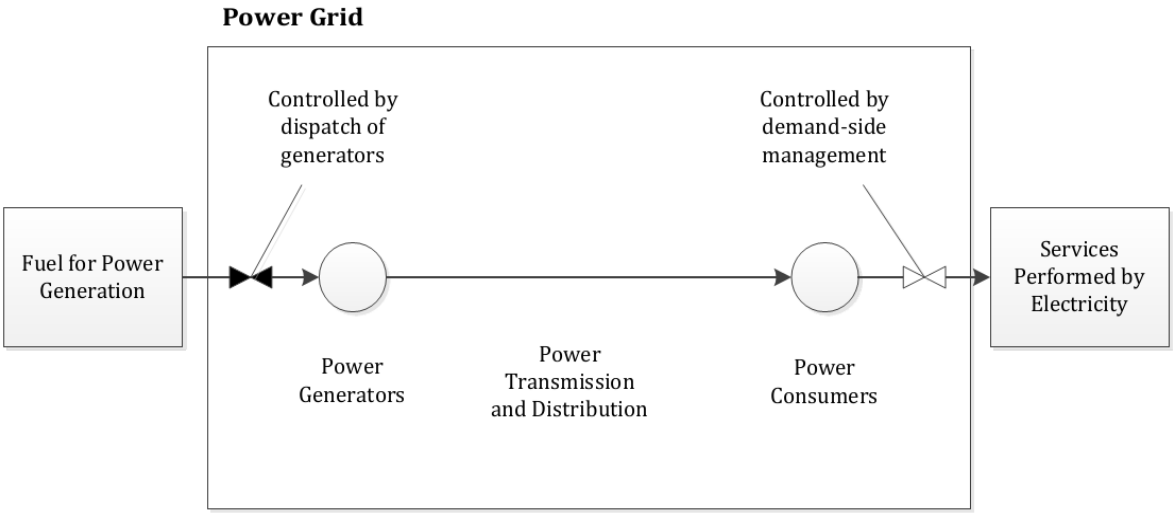


Figure 6: Traditional Paradigm for Power Grid Management

In recent years, new developments in power supply have brought new challenges to power grid management. First, since the 1970s, nuclear power plants have come online and grew to become the dominant base load power supplier in several dominions. In 2011, nuclear power plants supplied 57% of all electricity generated in the Province of Ontario, Canada, for example [52]. In contrast with conventional thermal generators, nuclear generators have limited capability to adjust their power output, for stability of operating nuclear reactors is preferred. Occasionally, this result in surplus base load generation, when the stable output of power from nuclear generators exceeds the demand of power from the grid. Furthermore, collective efforts to decrease global carbon emissions and to hold sustainable energy have resulted in the growth of renewable energy generators such as wind and solar in the supply mix [53]. In Ontario, the Feed-in-Tariff program has contracted 4,600 MW of non-hydro renewable energy projects since its exception in 2009, and is on track to increase these sources to 10,700 MW by 2015 [11]. The inherent intermittency of renewable energy is another cause of concern for grid operators as renewable energy generators cannot be dispatched as are conventional thermal generators. Moreover, the loss in supply flexibility will have a greater impact if renewable energy generators are to gain higher penetration in the grid.

As shown in Figure 3, grid energy storage is a potential solution to address these emerging problems, notably surplus base load generation and increasing intermittency from the deployment of renewable energy generators faced by the electric power supply chain. Energy storage technologies can increase the flexibility of grid operations by providing energy buffering capacity and new ways to control the flow of energy [54].

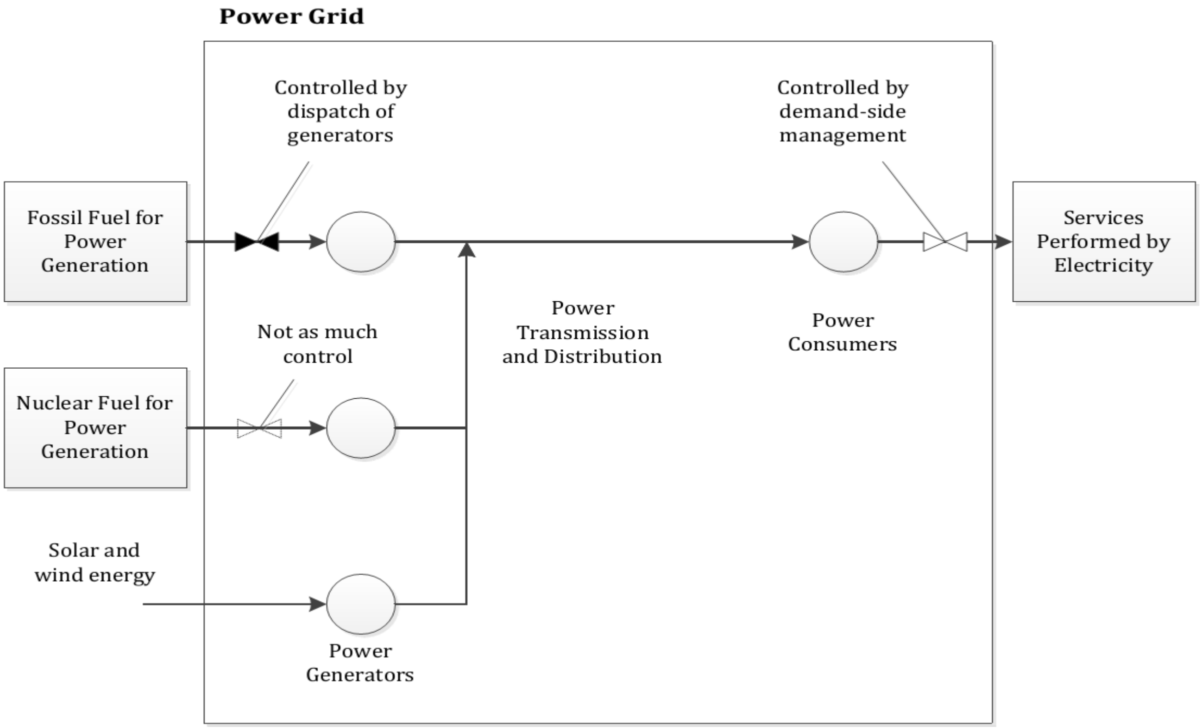


Figure 7: New Paradigm for Power Grid Management with Energy Storage

Specific applications for energy storage technologies depending position within the electric power supply chain: close to the generators, distributed close to the end-users or at critical points of the transmission and distribution network. Each application requires a different parameter profile. Therefore, many energy storage technologies have been proposed and studied. The different technologies differ by the mechanism in which they convert electrical energy to a storable form. The technologies typically proposed for grid energy storage are batteries, compressed air energy storage, pumped hydro energy storage, advanced capacitors, flywheel energy storage, superconducting magnetic energy storage, and energy storage through hydrogen [11], [55–57].

2.7. Battery repurposing

Neubauer and Pesaran [50] noted that the most important impediment for penetration of EVs is the high cost of Li-ion batteries. They showed that re-purposing EV batteries and applying them in a second use can extend their lifetime and contribute to the business case by distributing the high initial cost of batteries to other users. Wood et al. (2011) note that the role of battery lifetime is uncertain in quantifying the cost of EVs and this uncertainty leads to inconsistencies in the results of EV studies. The life cycle costs of EVs are sensitive to the cost of battery replacement and thus depend on the battery's SOC and the ability of the battery management system to minimize battery degradation over time [58]. Energy storage is suggested as one possible second-use application of EV batteries. Usually an EV battery is degraded when it has about 80% of its initial capacity. But it does not mean that the price of retired battery is reduced by 80%. Based on a U.S. Department of Energy study, it is estimated that by 2019 the price of Li-ion batteries will be reduced by almost 70% because of increased production volumes and, at this time, used batteries will be widely available [50]. Moreover, the same study showed that, while second use has a negligible impact on current EVs batteries, a reduction of almost 11% on battery cost through second use would happen by 2015. The prediction of second use life of batteries and their SOH is a challenging issue, which must evaluate 5-10 years after automotive service. The need for further study has been recognized for long-term degradation and detailed analysis of second use applications [50]. Several studies showed that re-purposed batteries could be used in storage applications, including electric supply, ancillary services, grid system, and renewable integration [12], [13], [57]. For instance, intermittent wind could be supported by re-purposed batteries at a potentially low cost [57].

2.8. Recycling

One success in the automotive sector has been the recycling of lead-acid batteries, with an approximate recycling rate of 98% [19]. By applying the physical or chemical or both properties of the battery materials, recycling technologies of Li-ion batteries increase the high grade separation of individual materials of wastes. The chemical processes are the leaching and separation of solved materials while the physical processes include the crushing, sieving, separation with magnet or eddy current and thermal processing [5]. Dewulf et al. (2010) indicated that active cathode material is the most important substance of the Li-ion battery in accordance with environmental risk and contribution to the total mass of battery [59]. Xu et al., 2008 found that recycling processes include the battery shells, aluminum foil, the electrolytes, the cathode and the anode, which majorly cathode materials such as cobalt, nickel, and lithium require to be analyzed. Dewulf et al. (2010) defined two recycling scenarios for Li-ion battery cathode materials. Scenario (A) is based on cobalt and nickel recovered from batteries and scenario (B) is based on virgin cobalt and nickel. It is found that utilization of recycled cobalt and nickel for Li-ion battery cathode material causes a 51% saving in natural resources. Regarding scenario (A), they showed that battery waste contains major constituents 34.1% LiMeO2 cathode, 13.6% graphite anode, 11.4% Cu anode foil, 3.4% Al cathode foil and 13.6% Fe casing which undergoes a smelting process with coke and slag formers in a Umicore facility in Sweden ending in a slag including Al, Si, Ca and Li, and an alloy with Co, Ni, Cu and Fe, and steam [59]. Siret et al. (2009) in an LCA study of Li-ion batteries compared CO_2 emissions and energy use of raw metal extraction with those of recycling of spent Li-ion battery cells. They showed that CO_2 emissions and energy consumption of the recycling option are approximately 70% lower than those of raw material extraction option.[61]. Gaines et al. (2011) calculated lithium requirements in battery packs by 2035 and showed that recycling of lithium significantly reduces virgin material requirements. Moreover, the re-use of batteries in energy storage applications postpones the return of materials for recycling [20].

CHAPTER 3
Environmental feasibility of re-use of electric vehicle batteries

The following section is based on previously published work of “Environmental Feasibility of Re-use of Electric Vehicle Batteries.” *Sustainable Energy Technologies and Assessments* 6 (June): 64–74. doi:10.1016/j.seta.2014.01.006.” by “Ahmadi et.al” and is reproduced by permission from journal of “Sustainable Energy Technologies and Assessments” editorial office. This thesis author specific contribution to this paper is to: “prepare all the graphics and results, prepare the final manuscript and reviewer edits with direction from the project supervisors who are co-authors. This paper is co-authored by Dr. Fowler, Dr. Young, and Dr. Fraser as supervisors. Also, Arthur Yip, an undergraduate student contributed in primary modeling.

3.1. Rationale of research

Due to consumer choice and preference, EV batteries that experience 20% degradation in fade of capacity or power fade they will be considered to be at the end of their useful automotive life and will be removed from service. This represents significant potential for an extension of the battery lifetime and for recovery of economic value as well as associated material and energy investments that can offset initial battery costs. With proper assessment of battery SOH, EV battery packs may be re-purposed for energy storage applications. The technical and economic feasibility of re-purposing EV batteries have been examined and the analyses have shown that the most viable applications for used EV batteries are for peaking power and renewable power integration [63–65]. These applications range from second-to-second to daily charge/discharge cycles. However the energy and environmental case of such cascaded systems has not been researched systematically and several technical challenges are critical. A cascade use for Li-ion systems emerges that optimize technical efficiencies, minimize negative environmental impacts, and maximize value for both producers and consumers of the services provided. There are several technical problems which need to be overcome to realize the environmental feasibility of battery re-purposing. Two of the most relevant problems are as follows:

Li-ion batteries degrade during use in ways that are not easily understood and not well researched at this time. It is currently not possible to make accurate predictions about battery SOH, useful life-expectancy of batteries, or about the possibility remaining power and capacity utility of a particular vehicle battery. The environmental benefits of using Li-ion batteries in vehicles needs to be understood and accurately characterized from a total life-cycle perspective that considers impacts associated with activities of metal and battery production. Moreover, availability of lithium and other critical metals have a potential constraint to scaling the use of electric vehicles.

3.2. Methods

Conceptually, the baseline system starts with extraction of natural resources, mining and processing to battery manufacturing, primary use in the EV, and end-of-life disposal (Fig. 4); however, in the re-purposed system, an additional loop for re-use is added that includes re-purposing and second use for grid storage. A parameterized life cycle model is developed to analyze the impacts of a possible extension of the electric vehicle battery life cycle. Based on previous research, the life cycle model is limited in this study to consider two life cycle stages of the EV: production, which aggregates materials production and manufacturing, and vehicle use, which includes all activities associated with the energy needed to operate the vehicle. For the purposes of this research, other stages of the battery life including disposal are not analyzed, as it is assumed that end-of-life management of the battery is required whether or not the battery is re-used. The re-purposing for second use application extends the life cycle by two additional stages: battery re-purposing and peaking power delivery.

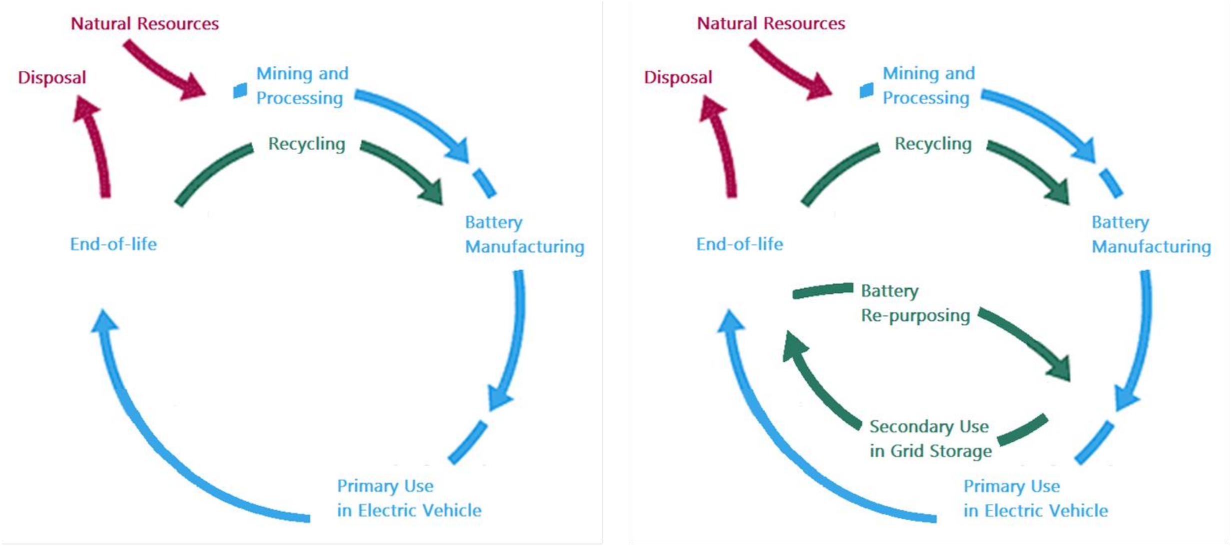


Figure 8. Baseline (left) and a re-purposed (right) scenario for battery packs.

3.3. Scenario definitions

Three paths are described providing a total of five scenarios (Fig. 5). Path 1 describes the baseline scenario in which mobility is provided by an ICE vehicle and peaking power is provided by a natural gas peaking power plant. In path 2 a second scenario of vehicle electrification is presented, with mobility provided by a plug-in hybrid electric vehicle, charged with electricity from the Ontario grid mix (56.5% nuclear, 22.3% hydro, 14.6% natural gas, 2.8% coal, 3% wind, and 0.8% other renewable energy sources), and peaking power still provided in the baseline method of peaking power plants. In path 3, mobility is provided by a PHEV and peaking power is provided by re-purposed vehicle batteries that are charged at an optimal time so that dedicated peaking power plants do not have to be used. Three scenarios for peaking power generation are considered: wind, nuclear, and Ontario grid mix. By comparing the CO2 emission impacts of paths 1, 2, and 3 assessment of the relative environmental feasibility of EV battery re-purposing can be made.

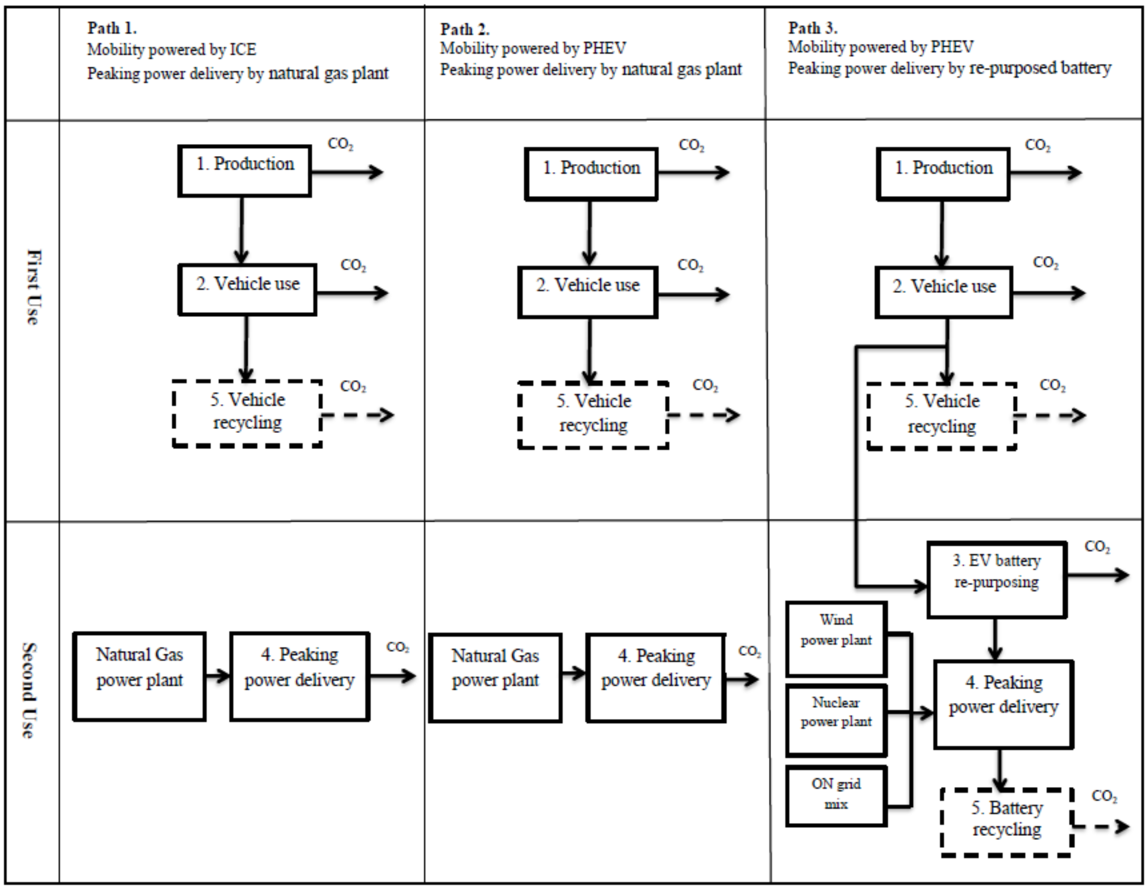


Figure 9. Scenarios defined in the present study for two phases (first use and second use) and three paths. As indicated by dashed boxes, recycling is not included in this analysis.

3.4. Environmental scope

The current study is purposefully restrained in its consideration of environmental impacts, focusing only on potential CO_2 emissions as an important and broad based indication of environmental performance. Despite this narrow consideration, CO_2 emissions performance is a fair metric for the broader assessment of environmental feasibility. In the context of EV and ICE vehicles, the main greenhouse gases (CO_2, CH_4 and N_2O), align strongly with the production of raw materials like metals, and with fossil fuel cycles and combustion including both gasoline and diesel used in ICE systems, and with a significant fraction of electricity generation, used to power batteries in EVs [4]. As such, CO_2 emissions correspond reasonably to several environmental categories other than climate change, including criteria air pollutants which in turn correlate to impact categories for local air quality, acidification and water eutrophication. To a lesser extent, CO_2 emissions performance also corresponds to energy use, as it is fossil resources like coal, crude oil, and natural gas that are significantly used for industrial production of materials, fuels and electricity. Of course, these lists of environmental and resource impact categories are not complete, and this is a limitation of the present study.

3.5. Life cycle definitions and assumptions

The main expected differences are defined between conventional internal combustion engine vehicles and electric vehicles, and between natural gas power plants and using battery charged with nuclear or wind power. A mid-sized American vehicle is selected and the drive-train is assumed to change from ICE to EV. For the ICE, a Chevrolet Cruze with gasoline engine and for the EV a Chevrolet Volt with a 16 kWh battery pack. These are approximately equivalent and comparable [33]. Further parameters are detailed in Table 1. The selection of a 160,000 km vehicle life over eight years is based on auto-manufacturers' warranties. A ten-year lifespan for the stationary application and 7.2 kWh daily discharges are selected as reasonable parameters necessary to support power plant life and justify installation costs. The performance of re-used batteries is considered in detail. The total capacity in the re-purposed pack is calculated assuming 80% of the remaining capacity useable capacity value of a typical pack from a new 16 kWh battery at the time of re-purposing, adjusting for 1% assumed cell failure rate and 95% pack recovery rate. In the re-purposed application a charge/discharge cycle of 20–80% state of charge is assumed, affording an average effective value of 7.2 kWh in useable pack capacity. Battery cells are assumed to be cycled once per day over ten years in their second use. It is assumed that the emissions of re-manufacturing of the spent battery would be half of that required in original battery manufacturing. In further analysis, degradation in battery charge is assumed to occur during the second use: a hypothetical degradation coefficient was applied at each of the first and second use of the battery. Further investigation is underway to characterize this phenomenon.

Table 1. Description of parameters used and associated technical challenges

Stage		**Description**	**Parameters**	**Technical Challenges**	
1	Production	• Materials production: • Battery production • Manufacturing of a vehicle [4], [33]	• ICE: Chevrolet Cruze • EV: Chevrolet Volt (16 kWh $LiFePO_4$ battery [33]	• Selecting an appropriate life time assumption for EVs • Battery size and capacity (uncertainty about future batteries life time and sensitivity parameters) [13]	**Vehicle Use**
2	Vehicle use	• Electricity and gasoline consumed in vehicle • Electricity from coal • Electricity from oil • Electricity from natural gas [33]	• ICE: Gasoline for 160000 km • EV: Gasoline and electricity for 160000 km, Ontario power mix • Utility factor (percentage of kilometres travelled with electric drive) : 67% based on PHEV • Life time: 8 years	• EVs eliminate the tailpipe emissions, but generate emissions during production process (aggregating emissions to determined sources instead of the whole world) [13] • Driving patterns [34]	
3	EV battery re-purposing	• Battery removal • Battery re-manufacturing process [33]	• Approximated as half of manufacturing	• Impact of battery removal • Impact of battery re-purposing process [33] • Approximated as re-manufacturing • Uncertainty related to battery degradation and failure rates • Customers' attitude to batteries retirement (disposal or re-use) [13]	**Stationary Use (Re-use)**
4	Peaking power delivery	• Providing fixed amount of peaking power • From power plant or battery discharge [33]	• Daily discharge of 7.2 kWh of residual battery capacity, after accounting for • 20% battery degradation and 1% failure rate • 80% –>20% depth of discharge • 90% transmission efficiency • 85% battery charge/discharge round-trip efficiency • Life time:10 years	• Selecting appropriate lifetime • Reducing cost • Customer decision on the value of system and capacity [13]	

3.5. Results and discussion

3.5.1. CO_2 emission reductions

Results for the five scenarios are shown in Fig. 6. There is a significant emission reduction associated with the re-use of an EV battery, as shown in path 3 (PHEV with battery re-use) (19 t CO_2e) compared to path 2 (PHEV with natural gas power) (43 t CO_2e), amounting to a total reduction of 56% (24 t CO_2e) over the total eighteen year lifetime. It is interesting to note that path 2–3 delivers a similar magnitude of impact mitigation when switching from using a conventional vehicle to an electric vehicle (path 1 vs. 2) (68 t CO_2e vs. 43 t CO_2e), which is approximately 25 t CO_2e, meaning that the environmental benefits of vehicle electrification could be doubled by re-purposing for second life that captures the value in used EV batteries and in otherwise clean energies such as wind. Results for different life cycle stages for the five scenarios are presented in Fig. 7.

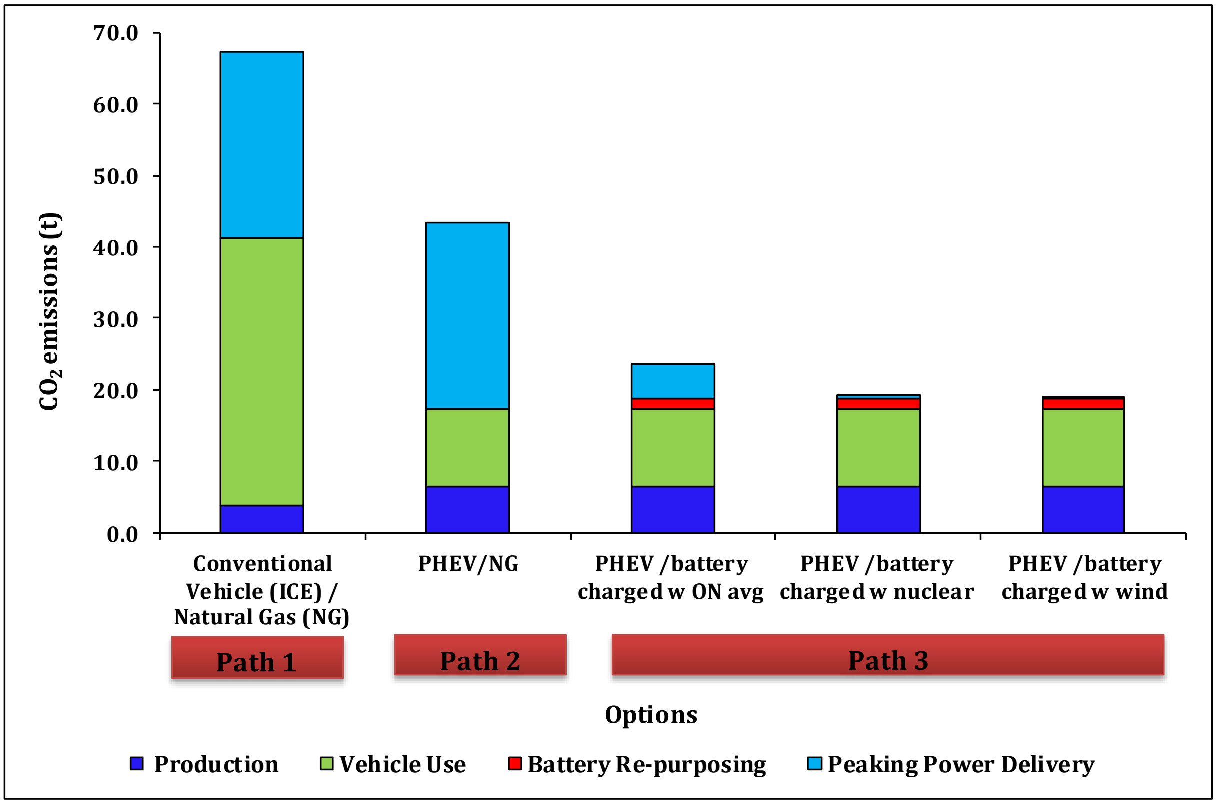


Figure 10: Life cycle CO_2 emissions associated with defined scenarios for paths 1, 2 and 3.

For the vehicle production stage (Fig. 7a), the emissions for the PHEV are 6.6 t. This amount is approximately twice that of conventional vehicles. This is significantly due to the production of batteries [4], [34]. Graphite anode is generated from hard coal which results in a low level of CO_2 emissions in the process. For vehicle use (Fig. 7b), emissions of the conventional vehicle are much higher than the EV (47%), the lower level of emissions of EVs in use phase help compensate for their higher production phase emissions [4].For the battery re-purposing (Fig. 7c), there is no emission in scenarios 1 and 2, whereas the scenarios with battery re-manufacturing require about 1.4 t CO_2. This value is relatively low and does not add greatly to the total impact. For peaking power delivery (Fig. 7d) scenarios 1 and 2 exhibit higher emissions as peaking power is provided by natural gas. In other scenarios where the battery has avoided the need for peaking power plants, emissions are decreased significantly. Scenarios with peaking power generated by renewables (i.e. nuclear or wind), supported by re-purposed batteries, have the lowest level of emissions in this stage. This facility provides an important opportunity to utilize renewable resources.

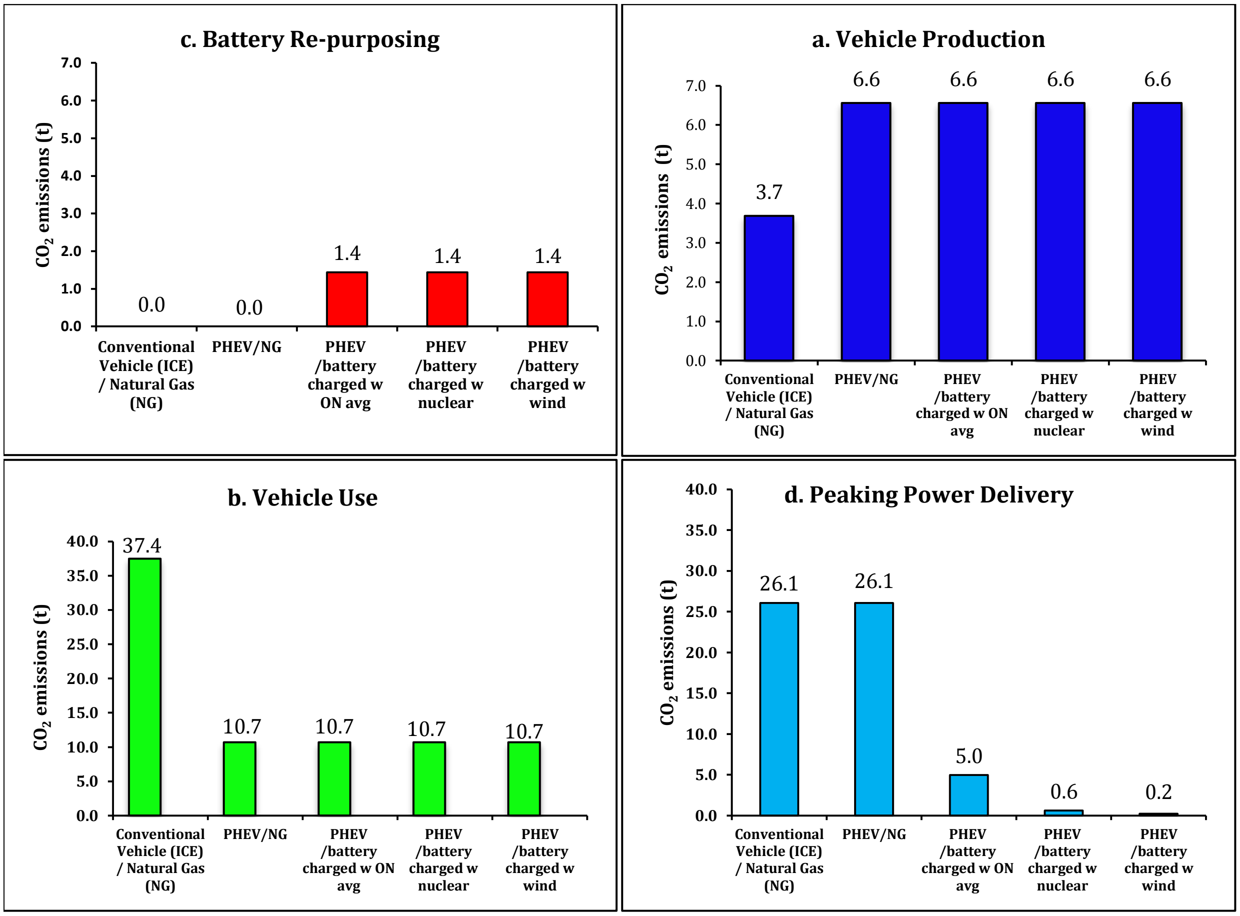


Figure 11: Comparison of CO_2 emissions associated with various stages of battery life cycle.

3.5.2. Role of battery degradation

Capacity fade and power fade are standard performance metrics of the battery in the first use in the vehicle, and the literature has focused on these two degradation measures [40], [66], [67]. However, critical to this research, and confounded with capacity fade is a phenomena that is referred to here as ‘‘energy efficiency fade.’’ Specifically, this refers to the efficiency at which power supplied at an outlet is transferred to the battery thus ‘‘wall-to-battery pack’’, then discharge ‘‘battery pack-to-wall’’, and thus the total round trip efficiency would include losses from the batteries themselves, battery self-discharge, battery management system, pack thermal management system operation, and charge equipment/inverter balance of plant. This builds on Rong and Pedram (2006) who considered battery discharge efficiency in battery design and lifetime estimation [68]. As the battery degrades, the losses associated with battery charging and battery use increase, resulting in energy efficiency fade. There are impacts on the range of the vehicle as the battery degrades, but energy efficiency fade is the difference in ‘‘round-trip efficiency from charging/discharging’’ experienced by the battery pack from new to a degraded state. This is key parameter for stationary power applications and therefore will be an important area for future research. Losses have a significant impact on the ultimate efficiency of the re-purposed pack system, and thus on the economic viability of the proposed stationary system. Energy efficiency fade has less of an impact on the operational satisfaction of vehicle performance as the electricity cost per distance is less significant to the overall customer acceptability. However, energy efficiency fade has significant life cycle impact implications with respect to the amount of emissions and environmental impact associated with the use of the vehicle. This becomes more relevant in the evaluation of second use of batteries as utility energy storage, where capacity, power, and charge and discharge efficiencies are of importance in a stationary application.

The comparison of Fig. 8 to Fig. 9 provides an illustration of how battery degradation influences life-cycle CO_2 emissions associated with batteries over their lifetime. Four main stages are assumed over the eighteen-year lifetime of a battery in two phases: use and re-use. In Fig. 8 efficiency fade is not considered and the emission rate is constant during peaking power delivery phase. The emissions from the production phase are higher for the PHEV than for a conventional vehicle but this is made up before the end of use in the vehicle. In the second use, the battery system operating on clean nuclear power continues to outperform the natural gas peaking power delivery path. The model illustrates the importance of vehicle power-train design and operating parameters on the effectiveness of second use. Fig. 9 develops the model by conceptually adding the phenomenon of ‘‘energy efficiency fade.’’ This is calculated by applying hypothetical coefficients over each use phase of the battery. It is assumed that the coefficient grows and compounds over the Li-ion battery life. Energy efficiency fade results in a decrease of total battery energy efficiency and therefore an increase of emissions over time (Fig. 9), as the battery needs more charging electricity as input and to provide the same discharge output.

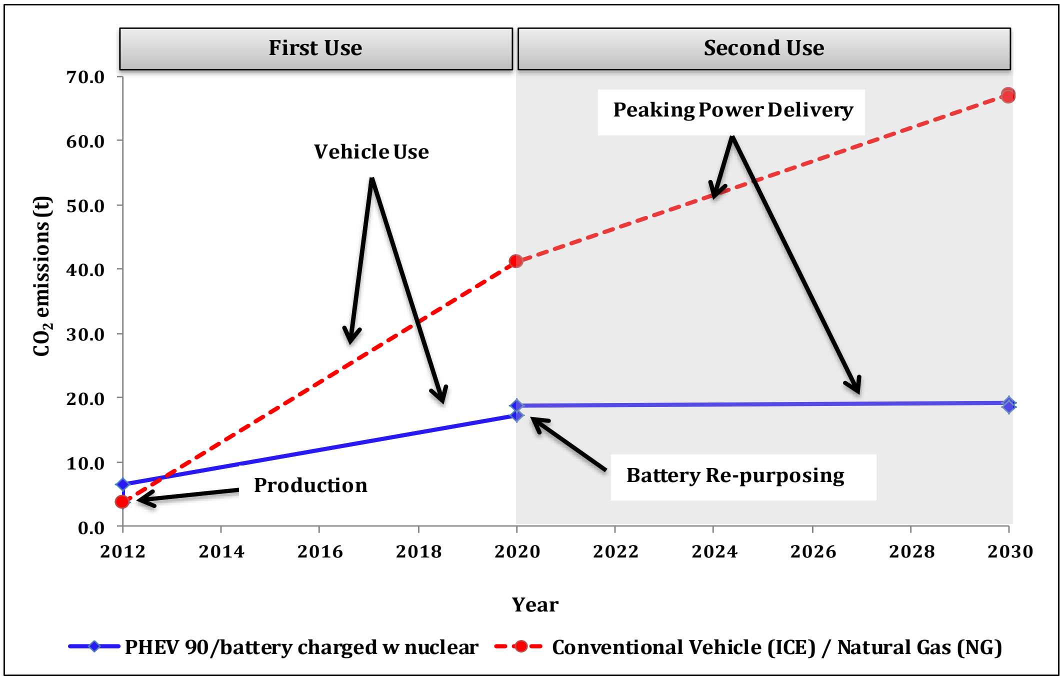


Figure 12: Simulation of CO_2 emissions of battery over its life time; First use in PHEV in comparison with ICE vehicle and second use in peaking power delivery by re-purposed battery in comparison with peaking power delivery by natural gas.

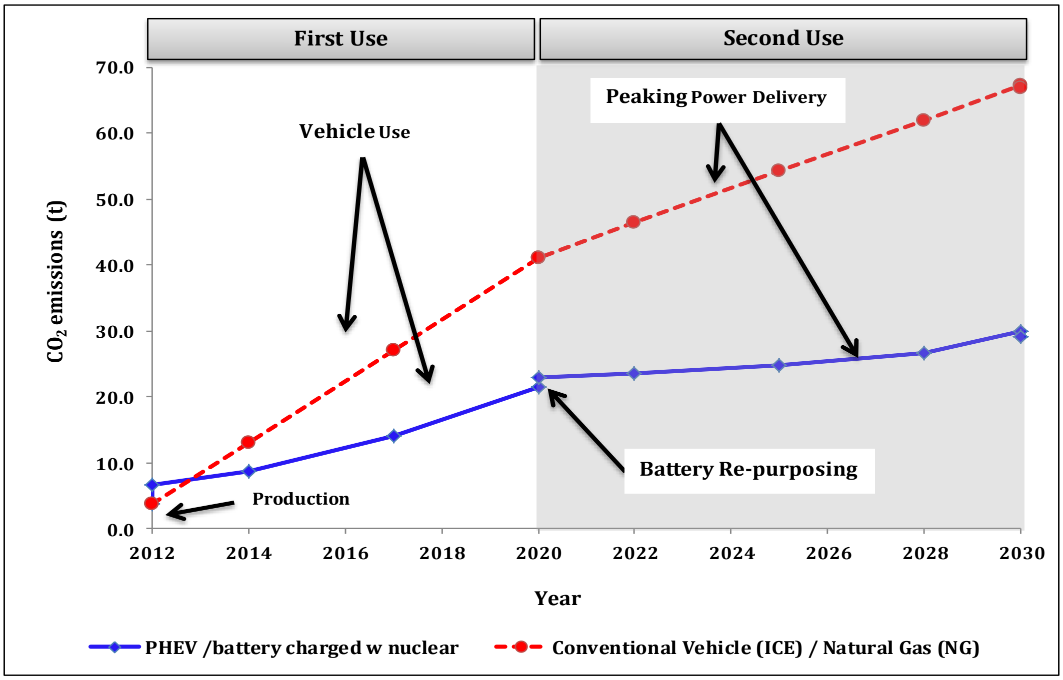


Figure 13: Hypothetical simulation of CO_2 emissions of battery affected by energy efficiency fade over its life time; Firs use in PHEV in comparison with ICE vehicle and second use in peaking power delivery by re-purposed battery in comparison with peaking power delivery by NG

3.5.3. Battery re-purposing challenges

Battery collection at vehicle end-of-life is a challenge in developing second use of re-purposed battery systems (see Table 1). Battery removal poses hazards associated with high voltage safety and handling of liquid coolant. Potentially information obtained from controller area network (CAN) buses would be effective with respect to understanding the lifetime operational history of a battery pack. CAN bus is a vehicle communication standard designed to allow microcontrollers and devices to communicate within a vehicle [69]. With an understanding of the operational history of the battery pack, a recycler will be able to conduct initial classification of the pack with respect to its expected condition. A pack with regular extreme state of charge cycles or extreme temperature events would be expected to have more degradation, and potentially more single cell failures, than a pack that has experienced a less harsh usage. Thus, packs with more extreme stress conditions would naturally require more testing during the re-purposing process. The next step is related to transport the collection and gather them in a central ‘‘re-purposing’’ depot. Then sorting function would need to consider each vehicle’s battery chemistry and different types of cells. Following the sorting, the packs could be disassembled into modules of 10–20 cells. Packs and modules are packaged in sealed containers and cells are likely be welded together with minimal material, which is one of the re-assembly challenges. According to Cready et al. (2003), all the essential constituents for electrical and thermal management of the batteries such as module interconnects, sensor, electronics packs, and fans or coolant channels would be re-used in the re-assembled packs [13]. Then due to examination of suitability of re-purposing, cells would be tested for electrochemical testing, degradation testing, and testing of the integrity of the cooling plates. The re-purposed module would undergo re-assembly of cells and modules into packs, and the installation of a new battery management system suitable for the new second use application and new operational conditions, as well as installation of new communication and overall control systems. If original equipment manufacturers of vehicles were to incorporate the principles of ‘‘design for disassembly’’ or ‘‘design for environment’’ the remanufacturing process could be made much less complex and more efficient [70–72]. Future research should consider the influence of variables such as emissions intensity factors and electricity grid mix, and the trade-off between economic and environmental performance of battery re-use. Planned studies aim to characterize more comprehensive environmental impact categories over extended lifetimes of Li-ion batteries and to develop a more sophisticated technical representation of battery degradation that helps determination of SOH of a battery given a known history of use, operating conditions and vehicle power-train control strategies. Studies inform policy and business regarding strategies for battery management during automotive first use and optimization of second-use applications. Anticipated needs include new technical standards, hazard analysis and safety guidelines, electric grid integration approaches, and design for environment including end-of-life recycling. As a final point, it is noted that by extending the life of an EV battery from eight to eighteen years may raise issues of material resource availability. If implemented on a large scale, additional lithium and other metals would need to mine in order to satisfy demand resulting from a delay in material recycling. This is an interesting consideration for energy sustainability and technology assessment that will be addressed in future analysis.

3.6. Conclusion

A parameterized life cycle model was developed to analyze the impacts of possible extension of life of electric vehicle batteries. The study advances previous research on the economic feasibility of re-purposing of EV batteries to show the potential for significant reduction in environmental impact. Compared to using natural gas fuel for peaking power generation, the model results showed a 56% reduction in life cycle CO_2 emissions by second use of EV batteries, re-purposed for peaking power application using clean electric power. This equates to a similar magnitude of impact mitigation in first use, in the switch from conventional vehicle to electric vehicle. This analysis introduced the concept of energy efficiency fade and provided an initial model of the effect of energy efficiency fade effect on CO_2 emissions over the eight-year vehicle life plus a ten-year second use. Results showed the influence of loss of energy efficiency in the battery on CO_2 emissions. It is suggested that degradation is more severe during first use in the EV than during second use in a more controlled stationary application. This phenomenon presents an important technical challenge in development of re-used battery systems.

CHAPTER 4
Energy Efficiency of Li-ion Battery Packs Re-used in Stationary Power Applications

The following section is based on previously published work “Energy Efficiency of Li-ion Battery Packs Re-used in Stationary Power Applications” *Sustainable Energy Technologies and Assessments*- 10.1016/j.seta.2014.06.006” by “Ahmadi et.al” and is reproduced by permission from journal of “Sustainable Energy Technologies and Assessments” editorial office. This thesis author specific contribution to this paper is to: “conduct the simulations, prepare all the graphics and results, and prepare the final manuscript and reviewer edits with direction from the project supervisors who are co-authors”. This paper is co-authored by Dr. Fowler, Dr. Young, and Dr. Fraser as supervisors. Also, Sean B. Walker, a post-doctoral student and Benjamin Gaffney a MASc. student contributed in edits and primary assessments.

4.1. Theoretical Background

In previous researches it is suggested that re-purposed EV batteries can be used for energy storage applications [13], [73]. In the preceding study by Ahmadi et al. (2014), utilizing a re-purposed Li-ion battery in ESS applications, such as peak shifting, was found to reduce CO_2 emissions by 56%. Building on the previous work, this study is focused on the effect of charge/discharge cycling on capacity and energy efficiency fades over the extended life of the battery.

$LiFePO_4$ is used as the cathode due to its environmental affability, low cost, material availability, and cycling stability [40], [75], [76]. Due to these properties and its potential use in vehicle applications, $LiFePO_4$ is the cathode chemistry analyzed in this study. Moreover, a combination of the graphite anode and the $LiFePO_4$ cathode has been determined to be reliable cell chemistries for ESS applications because of its outstanding cycling stability, energy density, and cost [40], [77], [78].

Several studies show that capacity fade is a common occurrence in EV batteries that is brought about by aging and charge/discharge cycling [6], [66], [67], [77], [79], [80]. Capacity fade is a gradual loss in energy capacity for a given current and is generally measured against Amp-hours (Ah). Capacity fade is predominately caused by the formation of a solid electrolyte interface (SEI) passivation layer at the anode-electrolyte interface due to its consumption of lithium ions [42]. Moreover, surface layers on the anode and cathode play a barrier role in reactions with the electrolyte. This, in turn, causes an increase in cell impedance and a reduction in the charge/discharge cycling efficiency of the battery [46]. These two effect lead to energy efficiency fade, which measures the ability of the fraction of energy that is stored in the battery compared to that delivered to the battery during charging. In an EV, capacity and power fade have significant implications. A reduction in the useable capacity results in larger SOC swings in charge-sustaining operation for a given drive cycle and a shorter driving range. Power fade reduces the maximum discharge and charge power of the battery, resulting in less power available during acceleration and a reduced ability to recapture power during regenerative braking [42], [45].

There are several different types of efficiencies defined for batteries [81] and all decrease over the lifetime of the battery. Energy efficiency is sometimes referred to as "electrical efficiency" and is defined as the ratio of electrical energy that can be removed from the battery to the electrical energy supplied:

$$\eta_{electrical}= \int (VI)_{dis}\, dt \,/ \int (VI)_{chg}\, dt \qquad (4\text{-}1)$$

Where, I_{dis} and I_{chg} refer to the discharge and charge current respectively and V refers to the cell voltage which is the same during discharge and charge.

This efficiency is not a significant concern to vehicle manufacturers but it has important implications in the second use stationary applications of the battery. In practice, the actual energy efficiency observed varies according the usable SOC window, charge and discharge rates, as well as operating temperature.

Note that this is different than “columbic efficiency”, which is defined as the ratio of the discharged capacity to the Ah needed in order to bring the battery to the discharge initial SOC, expressed as follows:

$$\eta_{columbic} = \int I_{dis}\, dt \,/ \int I_{chg}\, dt \qquad (4\text{-}2)$$

Where, I_{dis} and I_{chg} refer to the discharge and charge current respectively and the SOC is the same ate the beginning of discharge and at the end of charge.

Several factors affect the columbic efficiency, such as the charge and discharge current and charging method (constant voltage/power/current). The occurrence of secondary chemical reactions (especially at high SOCs) also significantly reduces the columbic efficiency; i.e. charging at high SOCs is less efficient. Columbic and energy efficiency are related to each other through the voltage efficiency which is defined as the ratio of the average voltage during discharge to the average voltage during charge:

$$\eta_{electrical} = \eta_{coulombic} \times \eta_{voltage} \qquad (4\text{-}3)$$

In previous studies, the $LiFePO_4$/graphite combination was tested to find the capacity fade rate under varying charge rates (C-rates), temperatures, depths of discharge (DOD), SOC, and charge/discharge cycle numbers (i.e. service lifetimes). According to Safari and Delacourt (2011), Li-ion cells aged at 45^0C experience four times the capacity fade of those at 25^0C [82]. Dubarry and Liaw (2009) showed that Li-ion capacity retention changes with different C-rates. Specifically, they illustrated that capacity fade accelerates more quickly with higher C-rates than with lower C-rates [77]. However, Lam and Bauer (2013) conclude that at a moderate room temperature, the discharge C-rate will not have a significant effect on capacity fade, assuming that the rate does not exceed the maximum rating of the cell; the battery management system can keep the battery from over-discharging. They also found that having a high initial SOC and large DOD will cause a high rate of capacity fade and that the large DOD has more impact on capacity fade than does the high initial SOC [66]. In the present study, the results of previous research on the capacity loss of Li-ion cells under different trends of cycling are normalized to create a capacity fade model of Li-ion batteries through their first and second uses in EV and ESS [40], [66], [67], [79], [80], [82–84]. Since previous capacity fade rate experiments for Li-ion cells have been undertaken for a limited number of charge/discharge cycles, the results are extrapolated to practical performance conditions.

In order to be utilized for their second purpose, the spent EV batteries would be repurposed. Re-purposing involves a limited level of disassembly, testing for degradation and failure, packaging the batteries for second use, and adding electrical hardware, control systems, and safety systems to the re-purposed packs. Packs may not be re-used if they exhibit signs of leakage, high internal impedance, or internal short circuits resulting from capacity fading [13]. The failure rate of the spent cells may depend on battery chemistry or extreme stress conditions such as extreme charging/discharging or temperatures. The failure of these cells may be exhibited an inability to perform or if the cell or pack poses an increased risk to human safety Conversely, it has been shown that improving cell design, separator quality and cell construction, makes Li-ion batteries safer [85]. In the second use, safety systems and packaging have to be added to account for potential moisture exposure, fire protection and other risks or hazards that vary from the vehicle use. The battery charge/discharge rate in the vehicle use stage may also contribute to battery failure and effectiveness after its automotive EOL. Moreover, it has been found that capacity fade is related to the inability to fully discharge, and that happens not only during the in-vehicle life, but also during the overall battery calendar life [67]. The charge/discharge profile of the Li-ion battery considered in this study is based on an 8-year life in an EV and a subsequent 10-year life in an ESS after re-purposing.

There are numerous potential applications for second life Li-ion batteries including: 1) transmission support, 2) area regulation, 3) load leveling, 4) renewable energy firming, 5) power reliability, 6) light commercial load following, 7) distributed node telecom backup, and 8) residential load following [13]. These alternatives can be grouped into two contrasting options. Option 1, made up of alternatives (1) through (4), is to create packs for larger applications, such as energy leveling for renewable energy sources such as solar or wind. Option 2, made up of alternatives (5) through (8) is to re-purpose the batteries for peak shaving or load following in smaller applications, such as homes, office buildings and stores. The key differences between these options are the size of the packs needed and the potential market sizes. For example, in Ontario, there are over 3 million semi-detached and detached residential units, as well as 100,000s of commercial settings in which re-purposed EV batteries could be used to store energy bought off-peak. In contrast, there are at most 20 large-scale installations that would be foreseeable for storing energy generated by renewable sources (Table 2).

Table 2. Markets for re-purposed Li-ion Batteries [13], [30], [86]

Market	Number of packs	Market Size	Power	Delivery	Trans. Time	Freq.	$ Saved
Residential	1-2	>3 million	1-10kW	3-4kWh, 10-20kWh	3h	Daily	$5-10/kW/mo
Light Comm.	10-15	10,000-100,000	25-200kW	75-100kWh	3h	Daily	$10-20/kW/mo
Office Building	30-40	100,000s	200-2000kW	<6000kWh	5h	Daily	$180/mo summer
Grocery	30-40	10,000-100,000	400-500kW	500-1000kWh	6h	Daily	$75/mo summer
Stranded Power (Renewables)	900	Uncertain (<10)	1-5MW	1-10MWh	1-10h	10-20/mo	$1000-1500/kW
Transmission Support	1000s	Uncertain (<10)	100MW	1-10MWh	5sec	1/month	$50-$150/kW/yr

From a financial standpoint, the creation of smaller applications in a larger market is a less risky investment, and would harmonize better with EV market penetration rates. In addition to the constraints on new applications caused by financial concerns, it is important to consider the physical size, manufacturing and safety constraints. A key issue when handling Li-ion batteries is the risk of fire and explosion [87], [88]. Thus, as risk is calculated as the product of the probability and severity of an incident, larger applications which call for 100s of batteries create a risk that is greater by orders of magnitude than that of smaller applications [89]. Given these factors, it makes sense to focus on smaller applications. It is also important to consider the grid mix being utilized. Ontario's electricity grid mix is surveyed from 2008-2013 and the grid mix is estimated for the period 2012-2030 [52], [90–95]. The main sources of electricity in Ontario are nuclear power plants, hydro, natural gas, coal, and renewable energy sources such as wind, solar and bio-thermal. Ontario's current policy is to de-carbonize the province's electrical grid through the phase-out of coal facilities by 2014 and the application of a feed-in-tariff (FIT) to promote generation of electricity from renewable sources such as wind and solar [90], [91]. Moreover, the utilization of natural gas-fired power plants will increase to 7% by 2030 and will act as a flexible peak source for the electricity grid. This reduces the carbon footprint because natural gas emits less than half of the carbon dioxide emitted by coal [91]. Nuclear sources, which contribute only 1.26% of Ontario's GHG emissions related to electricity production, reliably supplies almost 53% of the province's power demand by 2014. Nuclear power plants provide much of the base load power, have high electrical output and low GHG emissions, but are less responsive to demand fluctuations. It is predicted that nuclear energy will decrease to 46% of Ontario's power mix by 2030 [52], [90], [91]. Increasing the percentage of renewable energy generation in Ontario results in a high demand for ESS, including re-purposed EV batteries, to provide peak power delivery and load shifting for increased intermittent renewable power sources.

4.2. Methods

In this chapter, CO_2 eq. emissions are used as an indicator of GHG intensity and electricity from the Ontario grid mix is applied to Li-ion battery production, vehicle use, re-purposing and second use during the expected battery lifetime. GHG performance is a fair metric for the broader assessment of environmental feasibility and overall impact from the various power generation sources. GHG emissions can be used to measure environmental categories other than climate change, including criteria air pollutants like particulate matter as well as acid precursors, which in turn correlate to LCA impact categories for local air quality, acidification, water eutrophication, and ozone depletion potential. The environmental impact of battery degradation, including capacity fade, is used to estimate Li-ion battery performance and CO_2 eq. emissions for comparison with previous results. The GHG emission performance of Li-ion batteries in BEVs is contrasted with that of internal combustion engine (ICE) vehicles.

To determine capacity fade of Li-ion batteries through both uses, the cells are assumed to experience one charge/discharge cycle per day through 8 years of EV use (2920 cycles) and 10 years in a subsequent stationary application (3650 cycles). In both uses the average charge rate is 1C in controlled temperature conditions. The change of DOD in the process of cycling is assumed to be negligible and the constant high DOD of 75% is applied in the calculations. It is also assumed that the calculated capacity loss is generated only from cycling and that other degradation factors are negligible. Based on collected data from previous studies, the majority of the experimental results on battery cycling are limited to durations of approximately one year. The present model considers a trend of generalized capacity loss discerned from detailed examination of previous studies [6], [66], [79], [82–84], [96] and extrapolation to the 18-year cascaded use lifetime of the Li-ion battery. In the second use application the capacity fade may not be significant if the battery pack is cycled with very low power demands and small SOC swings. However, this study assumes the worst-case scenario with respect to capacity fade. In this paper, capacity fade is based on Ah-processed as a measure of time, the number of charge/discharge cycles, nominal cell capacity, DOD, and charge/discharge cycle rate.

4.3. Results

The capacity fade percentage of the Li-ion battery versus Ah-processed is simulated in the EV and in the ESS based on data from previous studies. Unique relationships define the three periods of capacity fade apparent during the battery's life. As discussed in section 3, the relationship between capacity fade and Ah-processed is determined by extrapolating previous studies to the 18-year cascaded use lifetime of the Li-ion battery. During the first 300-350 charge/discharge cycles (the first year of service in the EV), capacity fade follows an exponential trend, resulting in an 8% loss in capacity. For an EV with a battery warranty of 160,000 km this initial fade occurs over the first 20,000 km of driving (Figure 10).

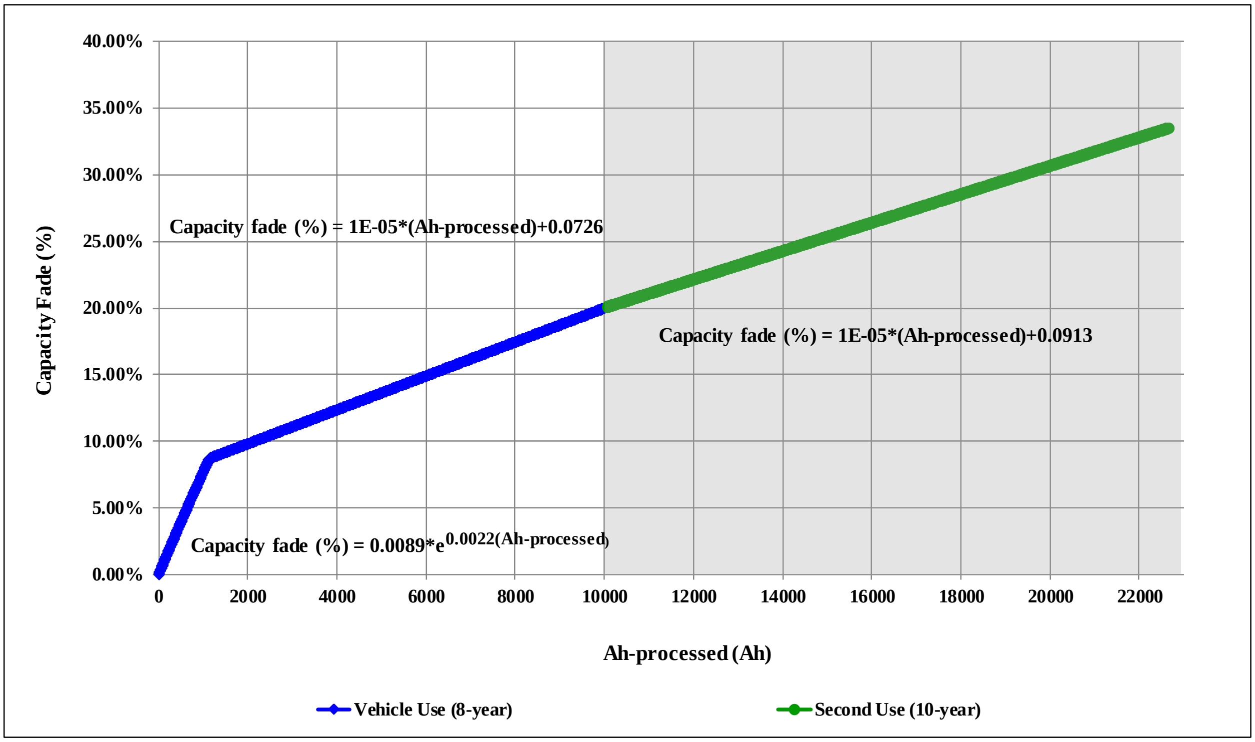


Figure 14: Predicted model of capacity fade based on Ah-processed over battery lifetime in EV use and second use in a stationary application (assumes no failure rate).

In the next period of battery use, the capacity fade continues to increase, but now in a linear fashion. According to previous studies, as illustrated in Figure 10, it is assumed that an EOL Li-ion EV battery possesses approximately 80% of its initial capacity and they assume 80% of energy efficiency. Thus, in the second period of fade, the model shows capacity loss increasing according to a constant coefficient over the remaining driving lifetime of the battery, to a point where the battery degrades to 80% of its original capacity and reaches the end of its warranty. With 80% of its initial capacity remaining after use in the EV, the battery moves on to a second use for a set life of 10 years, during which another period of linear capacity fade is predicted at a lower rate of degradation.

As illustrated by the green line in Figure 10, battery capacity loss in the second use increases linearly with a positive constant coefficient which is estimated to be approximately 10^{-3}%, irrespective of failure rate. During the 10-year stationary application of the used battery, the total capacity fade is 15%, which is a smaller amount than during vehicle use. This is justified because the stationary application is presumed to have a less strenuous cycling pattern and does not include degrading factors such as regenerative braking. Although some studies have indicated limited degradation during less stressful stationary applications, it is assumed the second use experiences some degradation. The battery already is in a degraded state, resulting in further loss of capacity and some material degradation modes.

The estimated slopes for each of the three parts of the simulated capacity fade curve are subject to uncertainty, due to the lack of data points and environmental differences between the laboratory experiments; therefore, a Monte Carlo risk analysis is conducted. The results depict the limitation of capacity changes with 99% certainty. The fluctuation of the first section of the capacity curve could be around 1.30%, while for the second and third sections this number increases to approximately 2.15%. This clarifies the sensitivity of the slopes of the second and third sections of the curve (Figure 11).

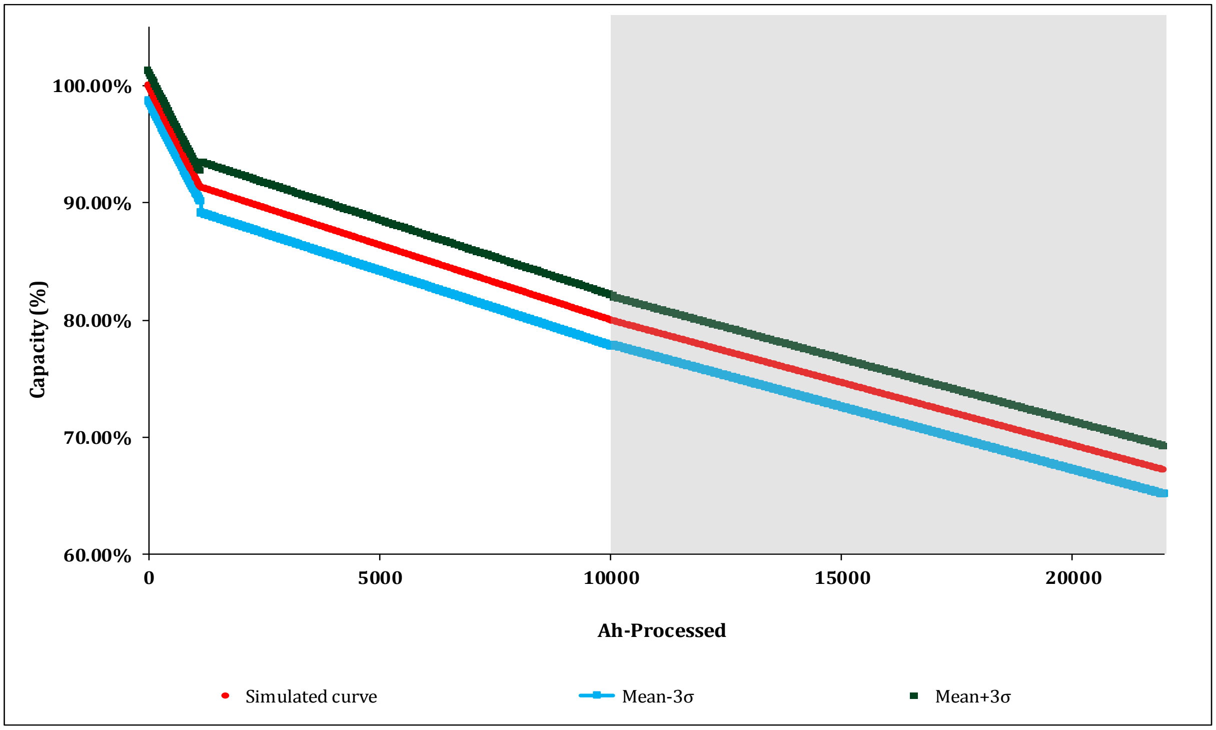


Figure 11: Risk analysis of Li-ion battery capacity changes during first use in electric vehicle and second use in a stationary application based on Monte Carlo method.

4.4. Discussion

A combination of capacity fade, irreversible loss occurring in the first charge/discharge cycle, cycling performance, and energy efficiency are the main factors affecting the performance of the Li-ion battery through its life and which inform the battery's design [97]. According to previous studies, the charge/discharge profile of a cell shows coordinated variations with the cell capacity changes [98–100]. In this study, it is estimated that the energy efficiency of a Li-ion battery may present the same type of fade through its uses in an EV and an ESS. Thus, the energy efficiency fade of a Li-ion battery in an EV may display a combination of exponential and linear trends whereas a linear trend is likely during the 10-year stationary application. However, future research is needed to empirically examine the patterns of energy efficiency fade of re-purposed batteries.

Battery degradation is affected by cycling to deep discharge SOC levels, high charge and discharge rates, and high temperatures during operation. However, capacity and power fade are of less importance during the second use because the packs can be configured for low-power draws and oversized to accommodate the energy storage requirements.

In this study, the capacity fade is correlated with energy efficiency fade, and energy efficiency has a direct impact on the economics of the second-use application. In the re-purposed battery application in the ESS, energy efficiency refers to the efficiency at which power supplied from an outlet is transferred to the battery thus “wall-to-battery pack”, and then discharged “battery pack-to-wall”. Thus the total round-trip efficiency includes losses from the batteries themselves, battery self-discharge, battery management system, pack thermal management system operation, and charge equipment/inverter balance of the plant [68]. Losses associated with charging and discharging the pack lead to lower round-trip energy efficiency. These energy losses reduce the economic viability of the application. Moreover, the losses in energy efficiency mean that more energy is lost in use, resulting in increased emissions from the power generation needed to charge the battery packs.

Not all material degradation modes contribute to energy efficiency fade (which is directly related to increased resistance), so the assumption of a direct correlation of capacity fade to energy efficiency fade needs to be further explored in the future. However, due to the lack of research on energy efficiency fade at this present time in the literature, the authors posit a direct correlation between energy efficiency fade and capacity fade. This is a reasonable assumption since both fade mechanisms principally involve increased resistances within the cell.

4.4.1. Failure Rate

It is expected that a number of individual cells in a battery pack fail during use in an EV. This failure rate influences the effectiveness of the battery re-purposing process. Based on previous studies, there is data for the estimated failure rate of Li-ion battery packs after long-term cycling. It is hypothetically assumed that the Li-ion battery pack presents no failure rate after the battery is removed from the EV.

This assumption is based on the reference scenario that the battery pack experiences insignificant stress conditions and the failure rate does not affect the battery capacity fade. Sensitivity analyses are undertaken to make a reasonable estimation about whether the Li-ion battery failure rate during use in an EV will have environmental impacts in the second use. Three more scenarios are assumed which are related to mild, average, and severe stress conditions of driving cycles (Table 3).

Table 3. Summary of reference scenario and sensitivity analysis on the Li-ion battery failure rate

Scenarios	Percentage of failure rate	Effect of failure rate on the capacity fade rate during the battery second use
Reference scenario	0.00%	Capacity fade (%) = 19.8783%-33.31034%
Mild cycling conditions	0.0001%	Capacity fade (%) = 19.8784%-33.31036%
Average cycling conditions	0.001%	Capacity fade (%) = 19.8785%-33.31053%
Severe cycling conditions	0.01%	Capacity fade (%) = 19.8803%-33.31233%

It is considered that a battery pack with regular extreme SOC cycles or temperature events is expected to have more degradation and potentially more single-cell failures, thus reducing the performance of the re-purposed battery in its second use. Moreover, cell failures during the battery’s vehicle use before EOL are also plausible. The impact of the failure rate due to stress conditions on the capacity fade is small even in severe cycling conditions. In the defined scenarios, the effect of cell failure on capacity is approximately 0.002%, which is insignificant when compared with the capacity fade during the long charge/discharge cycling of the battery’s second use. However, this suggests the failure rate of long-term charge/discharge cycling of Li-ion batteries needs additional analysis and use history to provide more reliable results. It is assumed that during the re-purposing process there are technical means by which the failed cells can be by-passed in the system either through the battery management system or via some physical modification to the pack.

4.4.2. GHG Emissions

GHG emissions generated from the Ontario grid mix are modeled for a Li-ion battery pack throughout an EV lifetime and a stationary application. It is assumed that the battery pack is produced and installed in the EV in 2012 and will be used in the EV until 2020. In 2020, the used battery will be re-purposed in a stationary ESS until 2030. Throughout this time, the Ontario grid mix is the source of electricity for charging the battery and the emitted CO_2 eq. is thus affected by Ontario's energy management. The CO_2 eq. emissions per kWh of electricity used by the Li-ion battery during its first and second use are based on typical drive cycles and recharging the battery pack from the aggregate mix of Ontario's power generation [52], [93], [101]. As illustrated by the blue line, the Li-ion battery pack generates higher GHG emissions during the 8-year application in the BEV in comparison with the 10-year stationary application (Figure 12).

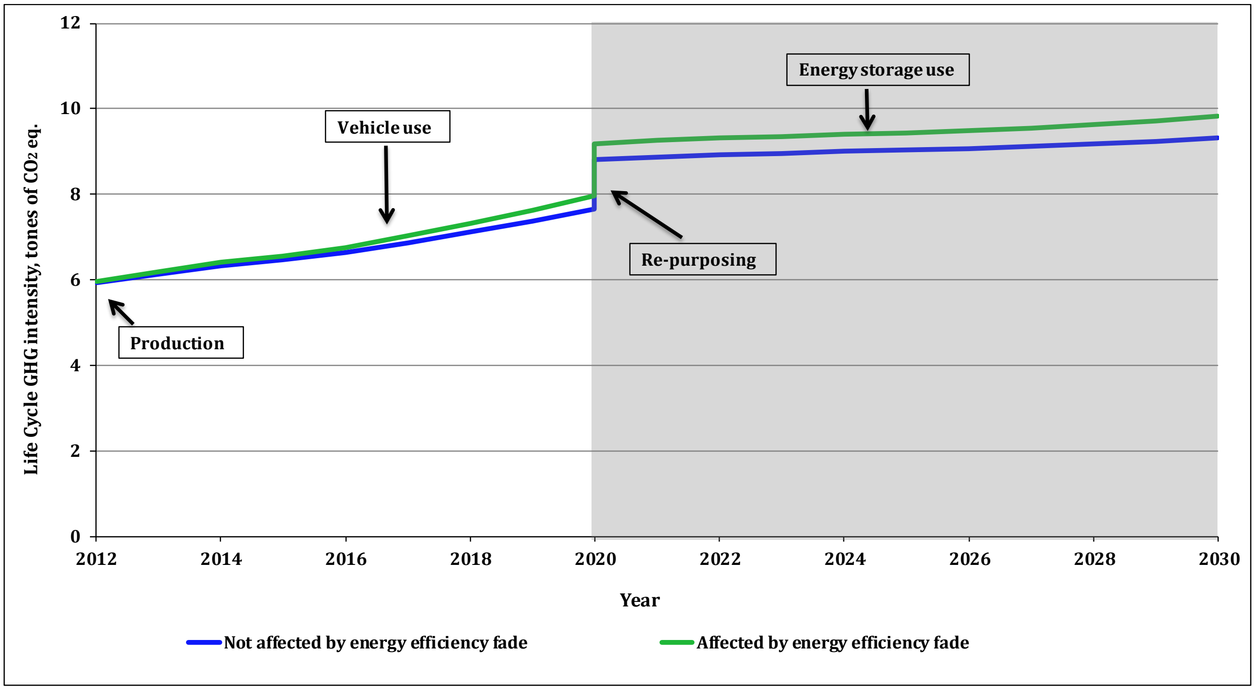


Figure 12: Comparison of life-cycle GHG intensity of Li-ion battery during its first use in the BEV and second use with and without assuming energy efficiency fade effect based on Ontario grid mix of power.

Thus, the emissions during vehicle use increase by 2t, which is approximately 2 times larger than the re-purposed battery's emissions during a longer time of application. The green line shows the GHG emissions associated with EV batteries affected by the energy efficiency phenomenon. The rates from the energy efficiency fade model (based on the correlation with capacity fade) have been applied to the 8-year phase of the battery in a BEV and to the 10-year second use phase of the battery. The effect of energy efficiency fade results in further emissions, as illustrated by the upward movement of the curves in Figure 12. However, the extent and type of emissions growth is different in the first and second use. The GHG emissions of the first years of the battery's vehicle application are slightly higher than the rest of the years, which is due to the energy efficiency fade trend. However, the re-purposed battery during the 10-year life has constantly growing CO_2 eq. emissions at a rate greater than in the first use. To clarify, it is assumed that the vehicles are charged from the Ontario mix of power generation, but that in the second use the battery pack will be charged with off-peak renewable power and low-GHG off-peak excess nuclear power, and the discharged power from the pack will be used to displace peaking power from natural gas power plants (Figure 13).

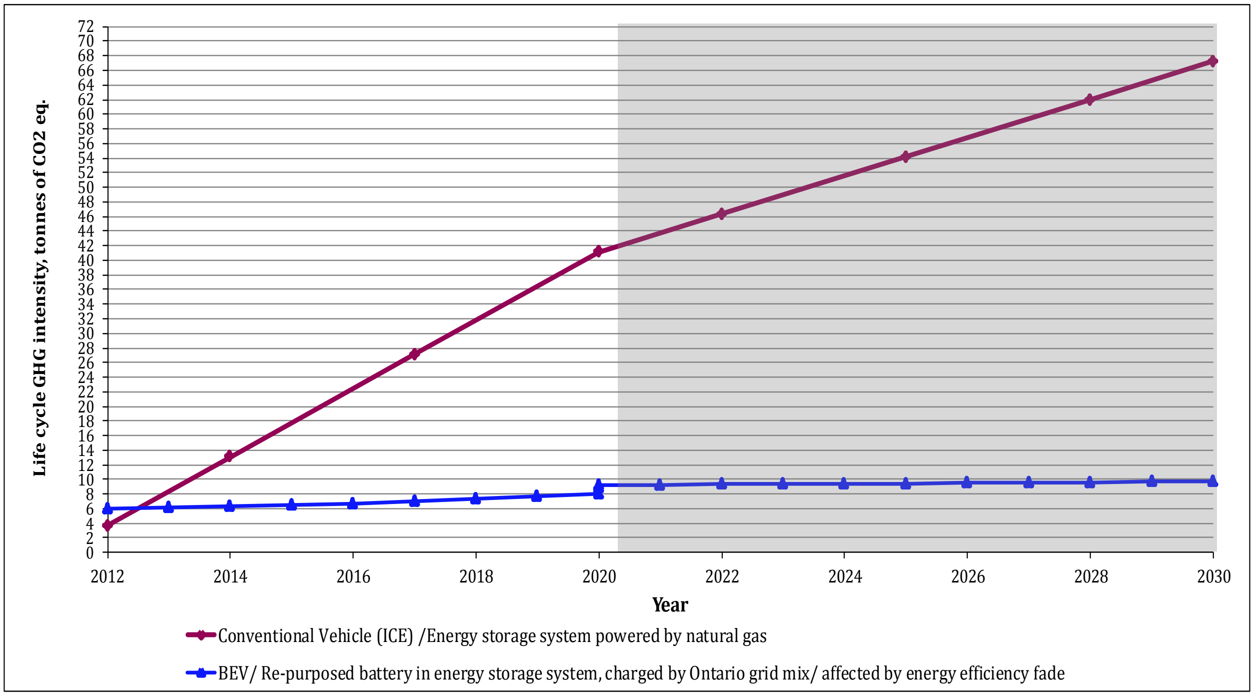


Figure 13: Simulation of GHG emissions of battery affected by energy efficiency fade over its life time; First use in BEV in comparison with ICE vehicle and second use in peaking power delivery by re-purposed battery in comparison with peaking power delivery by natural gas.

In contrast with conventional vehicles and stationary applications powered by natural gas, the GHG emissions of EVs and peaking power delivery by repurposed batteries is fairly minor and the difference in emissions between the first and second use is negligible.

4.4.3. Energy Use

The energy use of the Li-ion battery packs is the next environmental impact investigated. Since the BEV is charged with electricity from Ontario's electrical grid, changes to the province's electric grid mix have an effect on the fluctuation of energy usage and GHGs of applications such as EVs. The number of used Li-ion batteries from EVs by 2030 and their useable capacity to apply in the second use has been estimated [102], [103]. Using these estimates an improved energy use model can be created. In order to improve this energy model of the expected battery packs, the number of kWh of electricity which a BEV consumes per driven km is applied to determine first-use energy consumption. Likewise, an aggregate of delivered power for the collected applications in Table 2 is applied to measure the repurposed battery's energy consumption. A total number of re-purposed battery packs are assumed for this analysis. The average daily discharging time needed is estimated at three hours for residential and light commercial loads based on the Ontario electrical grid. Figure 14 shows the trend of electricity consumption of the Li-ion battery over its life in first and second use. Energy consumption in the stationary application of the re-purposed battery is lower than in the EV application, as shown by the gradual slope of the third part of the plot. However, the effect of energy efficiency fade of the amount of energy used by the batteries is more significant than that of vehicle use. Thus applying re-purposed batteries for ESS saves energy and re-purposed EV batteries can provide reliable backup power for these systems.

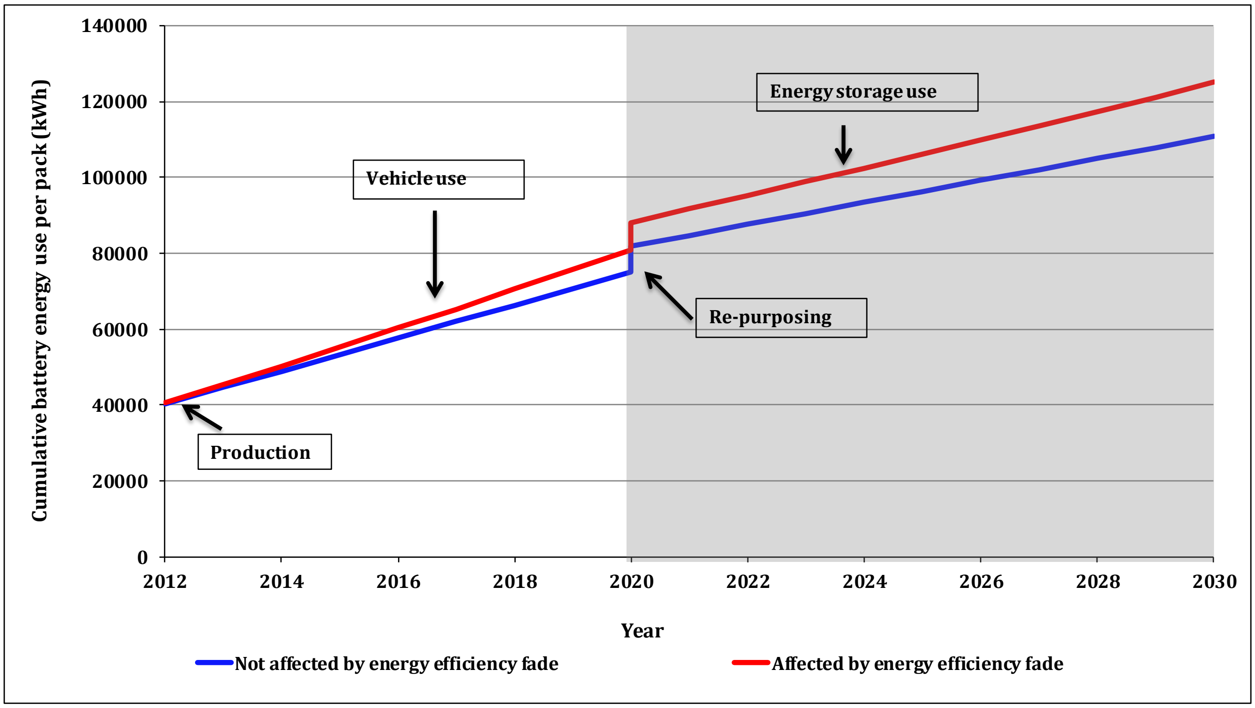


Figure 14: Comparing model of energy use of Li-ion battery during its first use in the BEV and the second use with and without energy efficiency fade effect

In Figure 14, a model of the energy usage of a Li-ion battery is applied to compare the effect of energy efficiency fade and the difference between energy use trends with and without this phenomenon. A failure rate of 0.01% is applied in the re-purposing phase of the battery life and it is assumed that the batteries experience harsh stress conditions during driving cycles. The capacity loss effect on the energy efficiency and subsequently on the energy use trend is similar to its effect on the amount of GHG emissions and causes the increase in emissions. In other words, energy efficiency fade results in higher electricity consumption and consequently greater use of energy sources such as nuclear, hydro, natural gas, and renewables.

As mentioned above, the loss of energy efficiency has the same effect on energy consumption in both the first and second use. It can be concluded that the loss of energy efficiency in the battery causes the lower ‘round trip’ efficiency in the second use, so more electricity is needed to charge the battery back and less energy is effectively discharged. As a result, the re-purposed battery that is affected by capacity fade and the associated energy efficiency fade requires more energy input to provide the same energy output. In this case it is assumed that the round trip efficiency is constant and equal to the efficiency of a full-capacity battery. A sensitivity analysis is carried out to investigate the effect of changes of round trip efficiency in different levels of battery capacity. Decreasing the battery capacity has a direct effect on lessening the round trip efficiency, meaning the battery consumes more energy to be charged and less energy can be efficiently discharged (Figure 15).

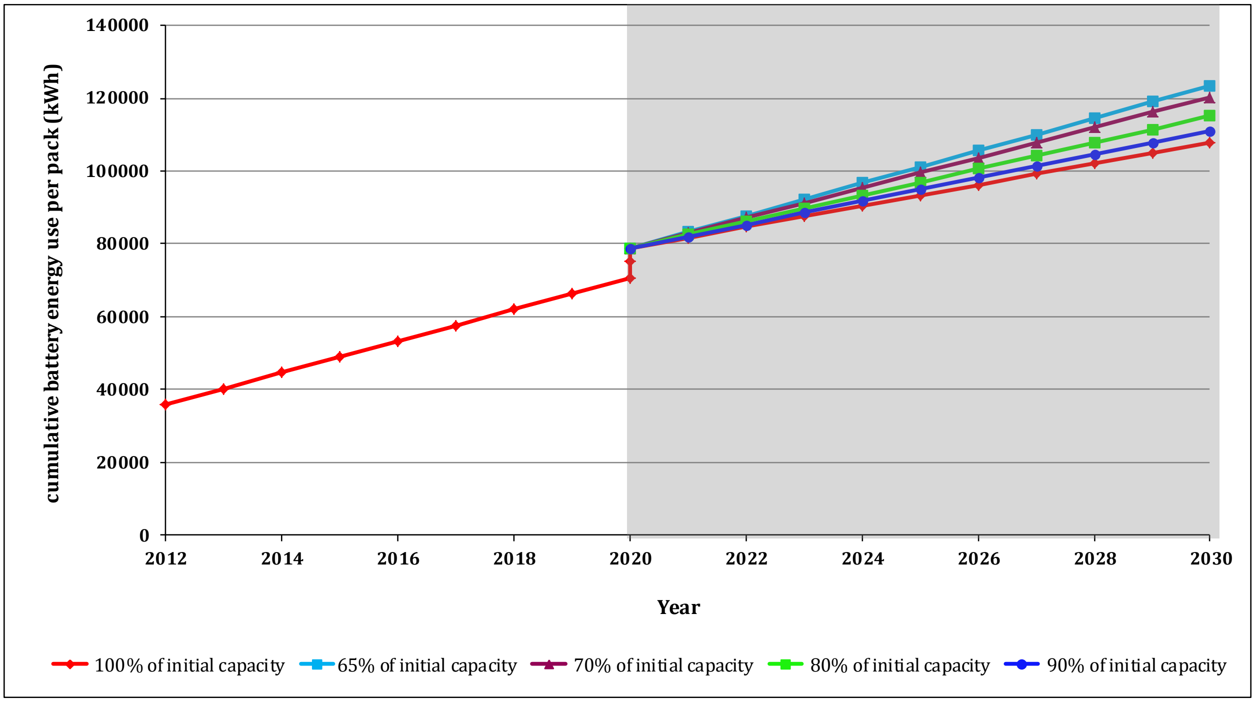


Figure 15: Sensitivity analysis for the round trip efficiency of the battery in different levels of battery capacity

4.5. Conclusion

Using a number of experimental studies of the capacity fade of EV Li-ion battery cells with a limited number of charge/discharge cycles, a simulated capacity fade model is presented for a battery used first for 8 years in a vehicle and then 10 years in an ESS. The model assumes that the Li-ion battery cycles at constant temperature, C-rate, DOD, and SOC and that the capacity fade results from charge/discharge cycling alone. According to the model, the cells' capacity fade follows an exponential trend during the first year of the driving cycle after which it follows a linear trend. Further, after being repurposed and used in an ESS, the battery capacity continues to fade more swiftly resulting in a further 15% loss. It is presumed that energy efficiency fade follows a similar trend during the expected life of the battery lifetime. The failure rate effect, an area of future research, is modeled using a sensitivity analysis which showed it scarcely affects capacity fade. The energy efficiency fade effects the GHG emissions and energy use of Li-ion batteries energy efficiency by increasing CO_2 emissions and electricity usage during both phases of the battery’s extended life. Capacity fade and energy efficiency fade, two effective factors on battery reuse should be considered during life cycle analyses due to their direct environmental impacts. As such this work has demonstrated the importance of considering the impact of energy efficiency fade which has not be a significant concern in automotive applications but is critical in the second use as it directly impacts the environmental and economic viability of energy load shifting arbitrage applications.

CHAPTER 5

Life Cycle assessment of Li-ion Battery in Mobility and Stationary Power Application

Life Cycle Assessment

To systematically assess the environmental impacts of a product the whole life cycle needs to be investigated. For this the method known as life cycle assessment (LCA) is employed in the present study. LCA is a method to provide a comprehensive view of impact categories across all stages of the life cycle of a product system from “cradle to grave” [21]. LCA is an environmental systems analysis tool applied for evaluation of the potential environmental impacts and resources used up during a product’s life cycle, including raw material production, manufacturing, use phase and waste management [21], [22].

LCA involves four phases of goal and scope definition, life cycle inventory analysis (LCI) including quantifying flows of resources and environmental releases, life cycle impact assessment (LCIA) including selection of impact categories and classification, characterization methods and characterization, and then interpretation and evaluation the robustness of results [21], [23]. LCA is data intensive and normally is performed with a mix of data sources of variable data quality.

5.1. Goal and Scope of Study

5.1.1. Goal of Study

The main objective of this study is to assess the potential environmental costs and benefits of re-purposing and re-using of electric vehicle (EV) Li-ion batteries into an energy storage system (ESS).

This question is addressed by offering of an extended lifetime of EV Li-ion batteries in ESS after their first use in an EV providing mobility. Technical and economic features of battery re-use have been proposed by automakers, governments, and utility companies; however the environmental benefits of repurposed EV batteries has not been well explored. This study considers to the environmental feasibility of re-manufacturing and “second use” of re-purposed EV batteries to deliver power into the energy storage systems. The LCA study is conducted to assess the Li-ion battery during its life cycle, including battery manufacturing, battery use in the EV, re-manufacturing and re-use of the battery in energy storage system ESS.

5.1.2. Intended Application

This study aims to support is to gather comprehensive information about environmental concerns of the re-purposed Li-ion battery technology re-used in the ESS to help decision-makers in the field of power generation and energy storage systems to improve the future strategies and policies. It is targeted that the results of this study would be supportive for making decision about re-purposing of used batteries after their end of life (EOL) in the EVs and utilizing them in the stationary applications. Moreover, the knowledge and structure of this LCA study could be applicable for battery production companies and automakers in their decisions about future electric mobility.

5.1.3. Intended Audience

Battery powered electric vehicles recently have attracted major vehicle manufactures attention to be part of their product lines [9], [104]. Technological advances in battery performance and cost combined with the regulatory push for low- and zero-emission vehicles have made widespread electric mobility a growing reality. Commercialization of these systems by major automotive manufacturers is underway across all continents, including plug-in hybrid electric vehicles (PHEV) and BEVs [1–3]. Adding a second use of the used EV batteries may assist EV owners in recovering some of their initial costs of vehicle purchase, reclaiming a portion of the purchase price of the battery. This technical approach has been proposed by automakers, governments, and utility companies [13]. The results of environmental assessment of the re-purposed Li-ion battery systems and their application in the energy storage systems would be considerable for vehicle manufacturers, EV owners, energy provider organizations and government, to attend them in the future decisions and strategies.

5.2. Scope of the Study

According to ISO 14044 [23], the scope of an LCA study should define the studied product system, the function of the product system, the functional unit, allocation procedures, type of impacts and LCIA methodology, interpretation, data requirements, data quality requirements, limitations and assumptions.

5.2.1. Product System

The product system of this study is a Li-ion battery pack used in two applications to deliver power, first in EV and second in ESS. The product system is a Li-ion battery pack with cell chemistry of LiFePO4/ graphite. As shown in Figure 16, Bettez et al. (2011) depicted the applied procedure to model the battery pack of preferred power and energy density [15]. As can been seen at the first step the mass of the non-cell components (a,b) are presented and then, the share of the cell is represented by electrochemically active materials which are selected based on the preferred total energy density and the properties of the materials (c). Lastly, the selected mass ratio of positive and negative electrodes (d) is shown, which their reversible charge capacities are equal.

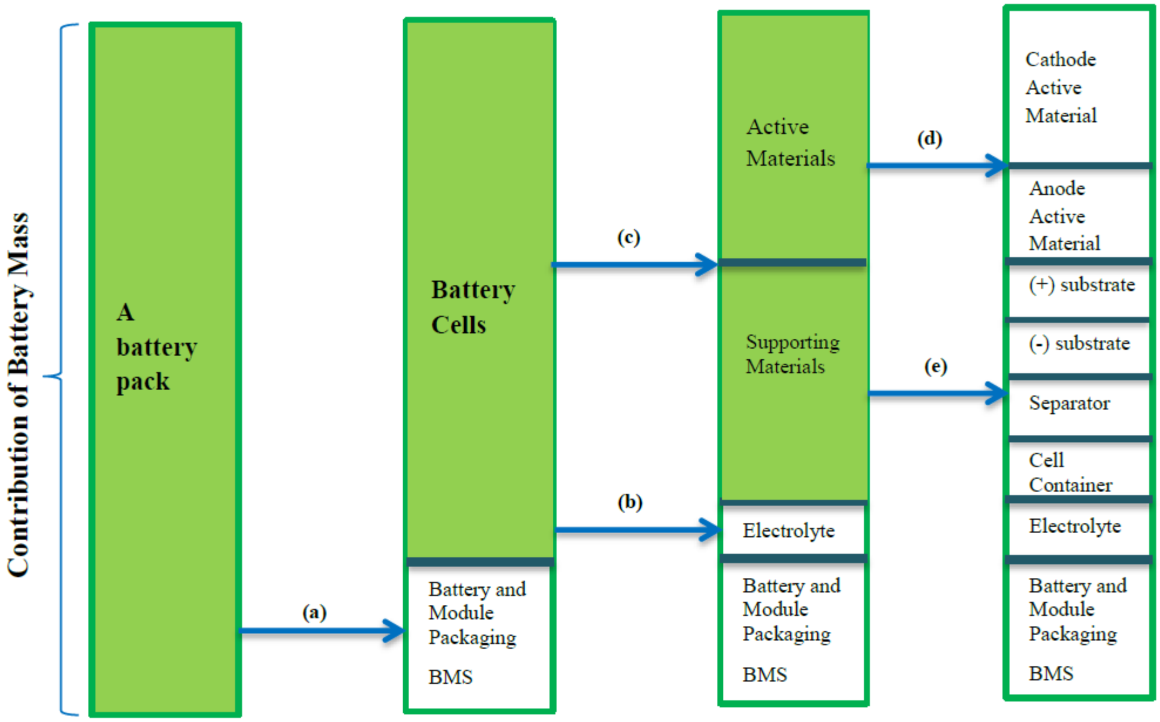


Figure 15: Overall schematic of battery pack based on desired power and energy density [15]

In order to produce LFP battery many synthesis routes exist such as solid state reaction at high temperature, co-precipitation in aqueous medium, hydrothermal synthesis, or mechanochemical activation [15], [105]. It is assumed that the production of LFP material is conducted by hydrothermal synthesis route through the reaction of iron sulfate, phosphoric acid and lithium hydroxide. The main components and electrochemical characteristics of the modeled traction battery are provided in Table 4 based on Bettez et al. (2011) study which their outcomes have been approved by several previous studies in this field.

Table 4: Electrochemical characteristics, component mass breakdown and performance of the modeled traction battery (LFP) [15]

Main components and characteristics	Li-ion battery system (LFP), details	Approximate quantities
Electrochemical Properties	Cell voltage (V)	3.4
	Capacity of pure active material, positive electrode (1C rate), (mAh/ g)	120
	Capacity of pure active material, negative electrode (1C rate), (mAh/ g)	350
	Cycle depth of discharge (DoD) (%)	75
	Charge/discharge energy efficiency (%)	90
	Cycle life expectancy (75% DoD) (cycles)	6570
Battery mass composition (%)	Positive electrode paste	24.8
	Negative electrode paste	8.0
	Separator	3.3
	Substrate, positive electrode	3.6
	Substrate, negative electrode	8.3
	Electrolyte	12.0
	Cell container, tab and terminals	20.0
	Module and battery packaging	17.0
	Battery management system (BMS)	3.0

5.2.2. Functional Unit

The definition of the advantage provided by the product system means the functional unit. It offers a reference to collect the relevant inputs and outputs of the product system.

Regarding to the main function of the product system which is power delivering to two applications, the selected functional unit for this study is “**one kilo watt-hour (kWh) delivered by a battery pack”**. The defined functional unit contains the same concept of power for both applications of the battery pack and generally could be measured by number of kWh. Consequently, it is assumed that the system boundary includes electricity consumed by the battery pack for both vehicle powertrain and stationary power application.

5.2.3. System Boundary

According to ISO 14044, system boundary of a LCA study is defined as set of criteria specifying which unit processes are part of a product system [23]. The system boundary of this study contains the entire manufacturing sequence of Li-ion battery, first use in the EV, re-purposing, and second use in the ESS. End of life of the battery would be a subject of the future study. This includes all major processes, significant materials and energy flows to the point where materials are extracted or emitted to the natural environment. As shown in Figure 17, a primary flow-diagram represents the phases included in the system boundary of this study.

The geographical system boundary is the province of Ontario Canada, for the use, re-manufacturing, and re-use phases. Battery production and vehicle production are assumed to occur in East Asia. This system boundary affects Ontario electricity grid mix used in the vehicle use and re-use into ESS (battery charging) as the reference scenario. The time boundary for production and use phase of vehicle life time is assumed to be 8 years from 2012. In other words, the study covers the current situation and it is estimated that future Li-ion batteries utilization in EVs will be in a larger scale than present. It is assumed that the re-purposed battery are employed in stationary applications for 10 years. The battery use phase in the EV and charging process is done in Ontario and uses Ontario grid mix in the determined time horizon. In addition, it is assumed that re-purposing process is operated in the determined geographical boundary and it is utilized in this area's stationary applications.

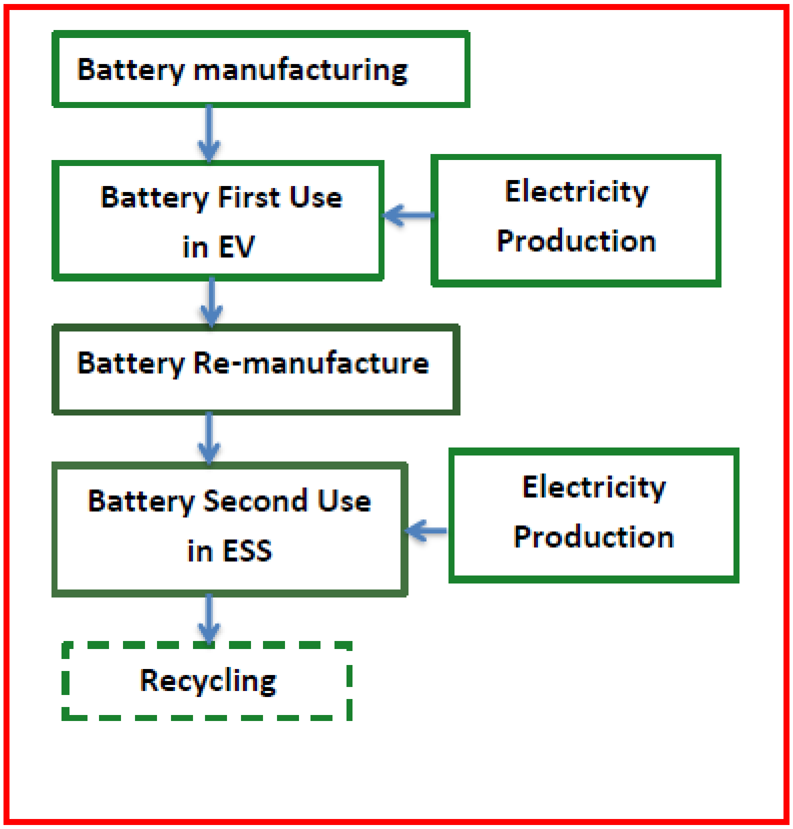


Figure 17: Overall Flowchart of LCA study- Recycling (dashed box) is not included in this assessment

5.2.4. Major Assumptions and Limitations

A summary of major assumptions applied in this study is provided in Table 5. One of the main assumptions is about mass fraction for Li-ion battery, which is based on Bettez et al. (2011) study [15]. It is assumed that 17% of the battery mass as packaging, plus 3% for the battery management system (BMS). There is an uncertainty about the conceptual border between "manufacturing" and "material production", which based on Rydh and Sandén (2005) study it is deemed that "material production" is taken as being limited to pure metals, simple plastics, or raw chemicals [106]. It is assumed that the applied infrastructure onsite at the battery assembly plant has negligible material loss or emissions in the system. Also, the transportation is excluded from this assessment because of its negligible portion in the raw material usage and emissions. the manufacturing facilities is not included in this study. About battery life time in the EV, the assumption of 8-year life time is based on the claimed auto manufacturers warranty for the battery lifespan in the electric vehicles while there is an assumption of 10-year lifetime for the second use of re-purposed battery in the ESS based on reasonable parameters necessary to support power plant life and justify installation costs. The next assumption is about electricity source which is Ontario grid mix for the use and re-use phases of the battery in comparison with natural gas resources of this province. The mentioned grid mix is estimated based on Ontario long term plans and prediction of some previous studies [90–93], [107], [108].

Table 5: Major assumptions made for Li-ion battery used in EV and re-used in stationary application

Field of assumption	**Assumed**
Chemistry of applied Li-ion battery	LiFePO4/ Graphite
Battery capacity	16 kWh- (based on Chevrolet Volt 2012)
Contribution of the battery mass	Based on the number of Majeau-Bettez et al. study
Transportation of all phases	Omitted-Assumed to be minor.
Infrastructure at the battery assembly plant	All assumed to be negligible in comparison with other stages.
Battery lifetime in the EV	8 years-Based on auto manufacturers warranty for the battery lifespan in the electric vehicle.
Battery remanufacturing	Include remanufacturing of module and battery packaging, cell container and electronics. Assumed to use 30% of electricity and heat of battery manufacturing/ Ontario grid mix in re-assembly of the battery
Battery lifetime in the second use	10 years-Assumed period of the stationary applications.
Electricity generation	• European average electricity mix, UCTE (Union for the Co-ordination of Transmission of Electricity) for battery manufacturing • Ontario grid mix for the use, re-manufacturing, and re-use of the battery based on IESO (2012): Nuclear (56.5%), hydro (22.3%), natural gas (14.6%), coal (2.8%), wind (3%), other (0.8%)

5.2.5. Allocation Procedures

A practical allocation problem appears in the LCA when a multifunction process achieves one or more functions for the product life cycle and a different function, or set of functions, for other products.

The environmental impacts related to the upstream processes of the battery use and re-use are divided to the total use of the battery during its useful lifetime in EV and not be included in the second use of the battery. The main logic of this procedure is related to the cost of the batteries: it is assumed that spent EV batteries have no economic value, therefor zero price, all economic of the process just allocated to first use of the battery in the EV.

5.2.6. Impact Categories and Impact Assessment Method

The results of the inventory analysis are assessed in the impact assessment phase, in which selection of impact categories has significant implications to the results. The selected impact categories for this study are based on data availability and previous studies results. The chosen method to weight and model the results is classification and characterization with the Dutch method ReCiPe 08 Midpoint (H) which is applied into the SimaPro, LCA software tool [109]. ReCiPe Midpoint (H) version 1.06, includes 18 impact categories and includes all the impact categories selected for this given the availability of LCI data). ReCiPe is a follow up of two methods (which were already employed in many scientific studies): Eco-indicator 99 and CML 2002 methods. Also, it integrates and harmonizes midpoint and endpoint approach in a consistent framework [110].

Cumulative energy demand (CED) method is also used to express the primary energy use over the whole life cycle. This method contains direct use as well as the indirect use of renewable and nonrenewable resources [111].

Based on the data sources used in the present study and their related limitations, the only 6 of the 18 indicator categories are represented in the final environmental LCIA category results, as summarized in

Table 6. However, this is justified as these cover the main issues relevant to EV battery analysis in the literature, and include categories related to air, water and resources.

Table 6. Table of impact categories assessing in this study

Impact Categories	**Indicators**	**Units**
Global warming potential (GWP)	CO_2 eq.	kg CO2 eq.
Particulate matter formation potential (PMFP)	Particulate matter less than 10 µm in diameter (PM10)	kg NMVOC
Freshwater eutrophication potential (FEP)	Phosphor (P)	kg PM10 eq.
Photochemical oxidant formation potential(POFP)	Non-methane volatile organic carbon (NMVOC)	kg P eq.
Metal depletion	Fe eq.	kg Fe eq.
Fossil depletion	Oil eq.	kg oil eq.

5.2.7. Primary Data sources

The main data sources for this study are datasets from established published databases and results from previous literatures. Life cycle databases are used for common processes, materials, transport steps and electricity generation. An inclusive quantitative LCA is normally accomplished using a software tool for LCA. Such tools often include databases that can be used in the inventory analysis. In the Presented study, SimaPro 7.3.0 and the format and data categories therein is used. The main generic data sets are Ecoinvent reports [111–114] and recent studies which assessed the Li-ion batteries and their application on the electric vehicles [4], [5], [14], [16], [17], [34], [115]. The requirements of the datasets which are applied in LCA studies determine the quality, completeness, and the reliability of consequences of the study. According to the method by Weidema and Wesnaes (1996) for assessing the data sources quality, the applied data sources are evaluated in 5 categories including reliability, completeness, temporal correlation, geographical correlation, and technological correlation [116]. The data sources are classified from 1 to 5, where the lower grades represent higher level of quality.

5.2.8. Process Flowchart and Initial Data Requirements

Figure 18 provides details on unit processes related to under study system. As can been seen, three main steps are defined in the system boundary including step A (battery manufacturing (1A), battery first use in EV (2A)), step B (battery re-manufacturing (1B), battery second use in ESS (2B)), and step 3 (recycling) which will be assessed in future study. Step A has been assessed in previous studies and this study attempts to adjust the results for EV application based on Ontario grid mix. The new concept of this analysis is related to step B which assesses the environmental impacts of EV batteries re-purposing and re-using in the different application. Step 3 qualitatively attends to significance of recycling process of Li-ion batteries. Figure 3 contains main unit processes and sub-processes to clarify the inventory of this study.

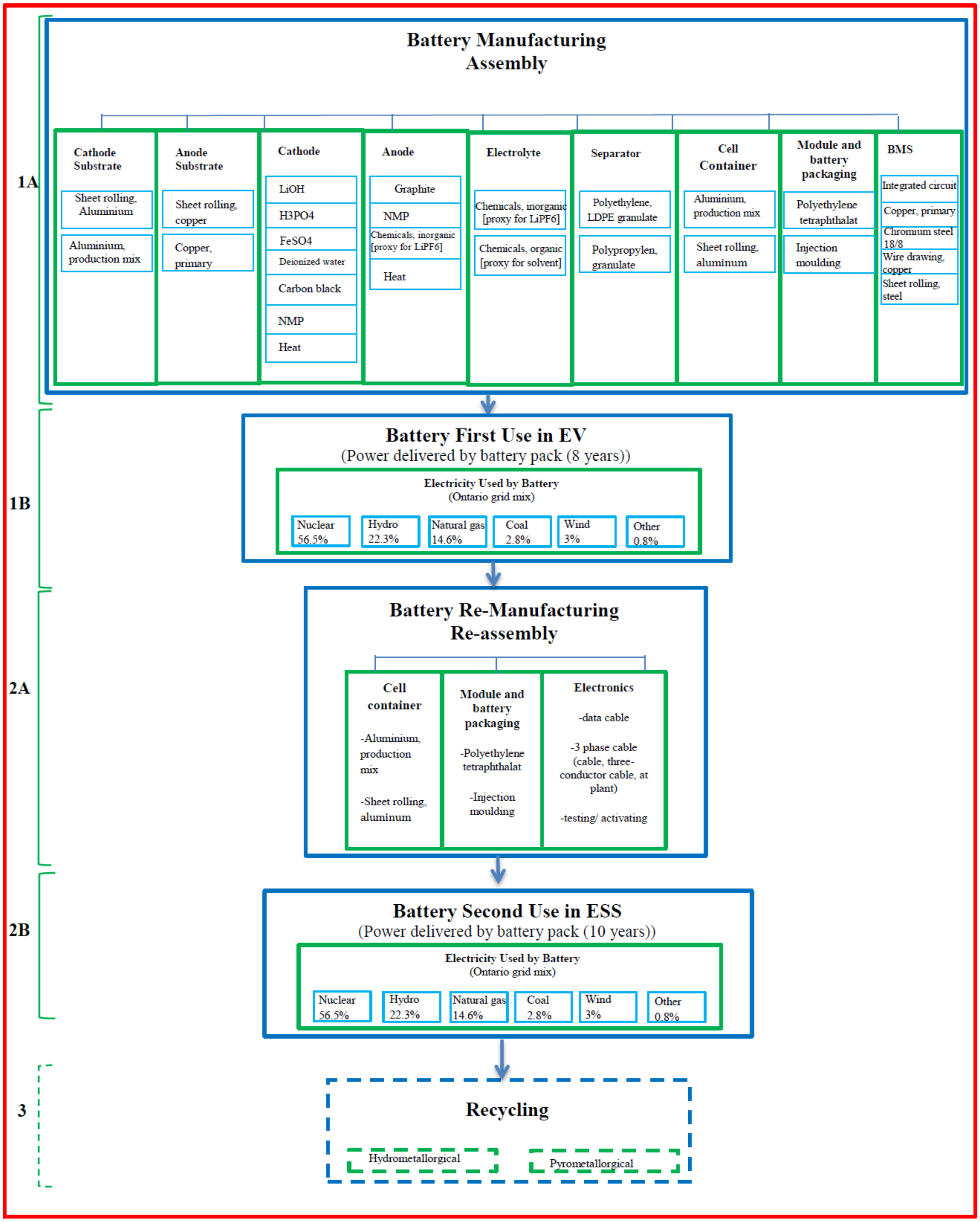


Figure 18: Flow-diagram of the system function and related unit processes-dashed boxes are not included in this assessment

5.2.9. Data Sources

Before attending to the quality of used data sources, the sources are described to show how they are relate to the overall LCA.

5.2.9.1. Ellingsen et al., (2013)

This recent study includes a comprehensive inventory of EV Li-ion battery and a life cycle perspective is applied in the environmental assessment of traction batteries [17].

5.2.9.2. Bettez et al.,(2011)

Bettez et al., (2011) conducted an LCA of different kind of electric vehicle batteries' production and their performance in the electric mobility. This source is one of the best related backgrounds of the study and one of the main sources of needed data for this assessment for cell components production, packaging, BMS, and battery manufacturing sections [15].

5.2.9.3. Ecoinvent Databases, (2007)

Swiss Center for Life Cycle Inventories has published comprehensive life cycle inventories of a broad number of product systems. In the current study, some of their published reports are applied to build the inventory of battery production, manufacturing and transportation phases. The main ones are "Overview and Methodology, Frischknecht et al., 2007", "Life Cycle Inventories of Electric and Electronic Equipment : Production , Use and Disposal, Hischier et al., 2007", and "Life Cycle Inventories of Packaging & Graphical Papers, Hischier, 2007" [111], [112], [114].

5.2.9.4. Simon and Weil. (2013)

New brand study of Simon and Weil, 2013 is about materials and energy flows of different lithium ion traction batteries. It is not paid to use phase of batteries in this study, but is a good source to collect data about raw material production and relevant energy flows [5].

5.2.9.5. Hawkins et al, (2012)

Hawkins et al. (2012) performed a comparative LCA of conventional and electric vehicles and provided a great inventory data about battery use phase in the electric mobility. This source is one of the important data sources for use phase of current study, just there is a limitation about their scope which is related to European grid mix and the modification is needed to apply them for a Canadian scope [4].

5.2.9.6. Samaras et al.,(2008)

Samaras and Meisterling, 2008 conducted an LCA of greenhouse gas emissions of plugin hybrid vehicles and their provided inventory is related to North America. It is predicted that their data on transportation of battery packs after manufacturing and battery use phase would be applicable in the current study [34].

5.2.9.7. Notter et al.,(2010)

Notter et al., 2010 provided life cycle inventory data on different kind of Li-ion batteries and conducted an LCA to present the contribution of Li-ion batteries to environmental of electric mobility. The collected data on battery production and application in electric vehicles are useful for this report [14].

5.2.9.8. IESO

Independent Electricity System Operator (IESO) plays an important role on Ontario’s power system and connects all contributors that generate electricity, transmitters that conduct it through Ontario province;

all businesses apply it in large amounts to local delivery companies that deliver it to residential. IESO predicts energy consumption of the province every five minutes and accumulates the best offers from generators to provide the required amount of electricity. The IESO reports is applied to get data about Ontario grid mix to use in the battery use and re-use phases [52].

5.2.10. Data Gaps

The major data gap is on the remanufacturing of batteries for the ESS. The main assumptions of this study return to the mentioned processes because of lack of experimental information.

5.2.11. Data Quality Requirements

The main data sources of the study are mentioned in the last section. The quality of the data sources used for an LCA should be valued and here, the Weidema and Wensaes assessment matrix is applied for this purpose. Table 6 presents their assessment criteria and subsequently, Table 4 is provided to collect the consequents of evaluation of data sources based on the selected method. All data sources are evaluated, the category grades are averaged, and an overall grade allocated for each data source. As can been seen in Table 7, it is found that the data quality for the cascaded use of Li-ion battery in the mobility and stationary applications based on Ontario grid mix is 2. This result depicted that the overall quality of data has been approved to be applied in this study, however they are specific data.

Table 6: Data Quality Assessment Criteria, [116]

Indicator grade	**1**	**2**	**3**	**4**	**5**
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years Difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar product conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related process or materials but same technology	Data on related processes or materials but different technology

Table 7: Data quality evaluation for selected data sources for current study

Data Source	**Provided information**	**Weidema and Wesnaes Data Quality Evaluation**						
		Reliability	Completeness	Temporal Corr.	Geographical Corr.	Technological Corr.	Average	Overall grading
Ellingsen	2013, Comprehensive data about EV batteries prod., mfg. , and vehicle use , European average	2	2	1	3	2	2	2
Majeau-Bettez	2011, detailed data about LFP batteries prod., mfg. , and vehicle use , European average	2	2	1	3	2	2	2
Ecoinvent datasets	2007, data about battery prod., mfg. , and transportation., European average	1	1	2	2	2	1.6	2
Simon	2013, detailed data about raw material prod., and mfg., European average	2	2	1	3	2	2.2	2
Hawkins	2012, detailed LCI data about battery use in EVs, European average	2	2	1	3	2	2	2
Samaras	2008, data about battery use phase, include transportation, US average	2	2	2	2	2	2	2
Notter	2010, detailed LCI data about battery use in EVs, European average	2	2	1	3	2	2.2	2
IESO	2012, data about Ontario grid mix	1	1	1	1	1	1	1
Overall data grading		2						

5.3. Inventory Analysis

5.3.1. Modeling of cascaded use of Lithium-ion battery in EV and ESS

1 kWh delivered by a Li-ion battery pack is modeled to be applied in EV by Ontario grid mix during expected life time of the battery (8 years) and re-manufactured for an additional 10-year in a stationary

application. To determine the quantities and type of materials used during the Li-ion battery (LFP) life cycle, peer reviewed inventories of previous studies and generic data sources are provided, which the inventory result is summarized in the Appendix. Following tables present the descriptions of the battery system in different phases of its life cycle.

5.3.1. 1. Manufacturing, Distribution, First use, Re-manufacturing, Re-use, and Recycling of Li-ion battery

5.3.1.1. 1. Battery Manufacturing

To model the inventory of a Li-ion battery pack life cycle during cascaded application, data are collected from previous studies [5], [14], [15], [17]. The manufacturing of components is modeled using Bettez et al. (2011) and the Ecoinvent data sources. Main components of battery pack are battery cell, module and packaging, BMS, and cooling system which is excluded from the present assessment. As presented in table 8, main components of a battery cell are cathode, anode, electrolyte, separator, cell container. The cathode and anode are merged at the battery assembly and then a thin layer (200-250 μm for high energy cells) is applied on both sides of the electrode substrates [15], [117]. In the next step, the cathode, the separator, and the anode are inserted together and all are wrapped up in the cell container. Filling the cells with electrolyte is the next step and closing the cell container. Compliance tests of cells is the next, which the cells experience a determined number of charge/discharge cycles and are mixed in modules and battery packs in the last step.

It is considerable that the battery mass composition ratio in table 4 determines the material requirements in this phase. Also, the relevant transportation to manufacturing phase and infrastructure processes are excluded from present assessment. It is assumed that a European average electricity mix, UCTE (Union for the Co-ordination of Transmission of Electricity) utilized for battery production phases [111].

Table 8. Inventory for the manufacturing of 1 kg of a LFP Li-ion battery

Inputs	Total weight	Unit	Notes	Ref.
Positive electrode paste	0.25	kg		Bettez- Table S3
Negative electrode paste	0.08	kg		Bettez- Table S3
Positive electrode substrate	0.036	kg		Bettez- Table S3
Negative electrode substrate	0.083	kg		Bettez- Table S3
Electrolyte	0.12	kg		Bettez- Table S3
Separator	0.033	kg		Bettez- Table S3
Cell container	0.2	kg		Bettez- Table S3
Module and Battery Packaging	0.17	kg		Bettez- Table S3
BMS	0.02	kg		Bettez- Table S3
Water, decarbonated	380	kg		Bettez- Table S3
Electricity	27	MJ	medium voltage, UCTE, at grid	Bettez- Table S3
Heat	2.9	MJ	light fuel oil, at industrial furnace	Bettez- Table S3
Heat	22	MJ	natural gas, industrial furnace lowNOx > 100 kW	Bettez- Table S3

In order to describe the battery system in detail, summary of battery components are concluded in following tables.

5.3.1.1.1. 1. Cathode

The main components of cathode of Li-ion batteries are positive electrode paste and substrate. Positive electrode paste includes electrochemical active material ($LiFePO_4$ in LFP batteries), a binder substance, and carbon black which increase conductivity of the electrode [115]. As summarize in Table 9, lithium hydroxide, phosphoric acid, and iron sulphate are main components of $LiFePO_4$. In this kind of Li-ion batteries, polytetrafluoroethylene (PTFE) is applied as binder and n-methylpyrrolidinone (NMP) is the ideal solvent to give the combination a slurry texture [115], [117]. The portion of active material in positive electrode is 88% of the mass, however a PTFE binder and carbon black account 8% and 5% of the mass. Positive electrode substrate works as a current collector and a physical support of electrode paste. As summarized in Table 10, positive electrode substrate is an aluminum foil, while a copper foil serves as negative electrode substrate.

Table 9. Inventory for the production of 1 kg of positive electrode paste for a LFP Li-ion battery

Inputs	**Total weight**	**Unit**	**Notes**	**Ref.**
Lithium hydroxide (LiOH)	0.4	kg		Bettez- Table S7
Phosphoric acid (H3PO$_4$)	0.566	kg		Bettez- Table S7
Iron Sulphate (FeSO$_4$)	0.87	kg		Bettez- Table S7
Deionized water	40.02	kg		Bettez- Table S7
Carbon black, GLO	0.05	kg		Bettez- table S4
Poly tetra fluoroethylene (PTFE)	0.08	kg		Bettez- table S4
N-methyl-2-pyrrolidone (NMP)	0.28	kg		Bettez- table S4
Heat	13.05	MJ	unspecified, in chemical plant	Bettez- Table S7
Emissions				
Lithium ion, to water	0.087	kg		
Iron ion, to water	0.0165	kg	unspecified	Bettez- Table S7
Phosphate ions, to water	0.027	kg	unspecified	Bettez- Table S7
waste heat	1.305	MJ	unspecified	Bettez- Table S7

Table 10. Inventory for the production of 1 kg of positive or negative electrode substrate for a LFP Li-ion battery

Inputs	Total amount	Unit	Ref.	Notes
Positive electrode:Sheet rolling, Aluminium	1	kg	Bettez- table S9	
Negative electrode:Sheet rolling, copper	1	kg	Bettez- table S9	
Positive electrode: Aluminium, production mix	1	kg	Bettez- table S9	
Negative electrode: Copper, primary	1	kg	Bettez- table S9	GLO*

* GLO = Global average

5.1.1.1.1.2. Anode

The key components of cathode of Li-ion batteries are negative electrode paste and substrate including copper current collector. Inventory of negative electrode paste in Table 11 depicts that graphite plays the most important role in this component. Wissler (2006) indicated that graphite shows properties of metal, such as thermal and electrical conductivity as well as properties of a non-metal such, as inertness, great thermal resistance, and lubricity [118]. PTFE binder and NMP are required as equal as positive electrode paste [115]. Evaporation of the NMP solvent to air is one of significant emissions of the battery production process [17], [117].

Table 11. Inventory for the production of 1 kg of anode for a LFP Li-ion battery

Inputs	Total amount	Unit	Ref.	Notes
Graphite	0.95	kg	Bettez- Table S5	
Poly tetra fluoroethylene (PTFE)	0.05	kg	Bettez- Table S5	
Nmethyl2pyrrolidone (NMP)	0.28	kg	Bettez- Table S5	
Heat	5	MJ	Bettez- Table S5	Unspecified
Emissions				
Heat waste	5	MJ	Bettez- Table S5	
Nmethyl2pyrrolidone (NMP)	0.28	kg	Bettez- Table S5	Unspecified

5.3.1.1.1.3. Electrolyte

Lithium salt ($LiPF_6$) and solvents form the electrolyte of Li-ion batteries (Table 12). The applied solvents in the electrolyte are ethylene carbonate and dimethyl carbonate, however generic “chemicals organic” and “chemicals inorganic” proxies are used in modeling [17], [115].

Table 12. Inventory for the production of 1 kg of electrolyte for a LFP Li-ion battery

Inputs	Total amount	Unit	Ref.
Chemicals, inorganic [proxy for LiPF6]	0.12	kg	Bettez- table S6
Chemicals, organic [proxy for solvent]	0.88	kg	Bettez- table S6

5.3.1.1.1.4. Separator

The separator prevents the cathode and anode from touching, whereas electrons in electrolyte are permitted to flow without high resistance. As summarized in Table 13, a porous Polypropylene and Polyethylene film form the separator of LFP Li-ion batteries [115].

Table 13. Inventory for the production of 1 kg of separator for a LFP Li-ion battery

Inputs	Total amount	Unit	Notes	Ref.
Polyethylene, LDPE granulate	0.5	kg	at plant	Bettez- table S17
Polypropylene, granulate	0.5	Kg	at plant	Bettez- table S17

5.3.1.1.1.5. Cell Container

Cell container covers the other battery cell components and compounds of a multilayer pouch and two tabs and as mentioned in Table 14, the cell containers of the Li-ion batteries are commonly formed from aluminum [17], [115].

Table 14. Inventory for the production of 1 kg of cell container for a LFP Li-ion battery

Inputs	Total amount	Unit	Ref.
Aluminium, production mix	1	kg	Bettez-table 16, S3
Sheet rolling, aluminum	1	kg	Bettez-table 16, S3

5.3.1.1.1.6. Battery Management System

BMS is any electronic system that manages a rechargeable battery (cell or battery pack), by protecting the battery from operating outside its safe operating area, monitoring its state, calculating secondary data, reporting that data, controlling its environment, and authenticating it and / or balancing it. According to Simon and Weil study, BMS for Li-ion battery is one of the significant processes of the battery manufacturing and an important technology to control undesirable processes which can cause to explosion, ignition or break of the battery [5].

BMS includes component groups of integrated battery interface system, battery module boards, high voltage system, low voltage system, and fasteners (Table 15) [17], [115], [119].

Table 15. Inventory for the production of 1 kg of battery management system for a LFP Li-ion battery

Inputs	Total amount	Unit	Notes	Ref.
Integrated circuit, logic type	0.1	kg	at plant	Bettez- table S10
Copper, primary	0.5	kg	at refinery	Bettez- table S10
Chromium steel 18/8	0.4	kg		Bettez- table S10
Wire drawing, copper	0.5	kg	Half of BMS mass (assumed)	Bettez- table S10
Sheet rolling, steel	0.4	kg		Bettez- table S10

5.3.1.1.1.7. Battery Module and Packaging

Numbers of cells are packed as modules and all modules have a casing made of Polyethylene terephthalate (PET) which is resistant to corrosion and inexpensive. The main components and electrochemical characteristics of the modeled traction battery are provided in Table 16.

Table 16. Inventory for the production of 1 kg of module and packaging of a LFP Li-ion battery

Inputs	Total amount	Unit	Ref.
Polyethylene terephthalate	1	kg	Bettez- table S18, S3
Injection moulding	1	kg	Bettez- table S18, S3

5.3.1.1.2. First use in EV

The first use phase includes charging and discharging the Li-ion battery in an EV. The electricity use for charging the battery during its useful life in EV is calculated based on Ontario grid mix. Use and re-use phases energy use is related to electricity usage of the battery for charging from Ontario grid mix during its useful life time in the BEV (8-year). It is assumed that Ontario grid mixture is constant and is similar to its mix in 2012 including nuclear 56.5%, hydro 22.3%, natural gas 14.6%, coal 2.8%, wind 3%, and other renewables 0.8% [52].

Based on LFP battery data [15], [34] and applied assumptions:

- A 16 kWh battery is charged with Ontario grid mix and it is 90% energy-efficient.
- A rate of 1*C* is defined as the current that is equivalent to the full capacity of the battery being charged or discharged.
- It is assumed that every day one cycle (charging/ discharging) happens, so the total number of the battery cycling would be 2920 cycles during its 8-year useful life in the EV.
- Depth of discharge (DOD): 75%

Table 17 shows the total power delivered by a Li-ion battery pack throughout its vehicle use.

Table 17. Li-ion battery first use phase in the EV per battery pack

Input	Total amount	Unit	Assumptions	Ref.
Power delivered by a battery pack for an EV	35040	kWh	Battery capacity:16 kWh Use time: 8 years (2920 cycles) DOD:75% Electricity from Ontario grid mix Total amount= (16 kWh/ cycle)* 0.75(DOD)* 2920 (cycle)	IESO 2012

5.3.1.1.3. Re-manufacturing

Spent EV battery modules, after arrival at a renovating facility, are inspected to detach modules which include apparent physical damage, leaks, or other signs of exploitation. In order to re-manufacturing of used EV batteries to prepare them for second use, EV modules are assembled at the renovating facility in new battery packs that are small enough for suitable handling and efficient to decrease installation costs on bigger systems [13], [74]. As summarized in Table 18, module and battery packaging and electronics of the used battery pack are renewed and it is assumed that required electricity and heat for reassembly process would be 30% of those of assembly process.

Table 18. Inventory for the re-manufacturing of 1 kg of a LFP Li-ion battery

Input	**Total amount**	**Unit**	**Notes**	**Ref.**
Polyethylene terephthalate	1	kg	Module and battery packaging	Bettez et al. (2011)-table S18, S3
Injection moulding	1	kg	Module and battery packaging	Bettez et al. (2011)-table S18, S3
data cable	0.00124	M	electronics category	Notter et al. (2010)-table S17
3 phase cable (cable, three-conductor cable, at plant)	8.3E-05	M	electronics category	Notter et al. (2010)-table S17
testing/ activating	0.00036	kWh	electricity-for a battery pack	Notter et al. (2010)-table S17
Electricity	8.1	MJ	Ontario grid mix/30% of electricity of manufacturing (assumed)	Bettez et al. (2011)-table S3
Heat	0.87	MJ	light fuel oil, at industrial furnace/ assumed as 30% of amount of original manufacturing	Bettez et al. (2011)-table S3
Heat	6.6	MJ	natural gas, industrial furnace lowNOx > 100 kW/30% of amount of manufacturing (assumed)	Bettez et al. (2011)-table S3

5.3.1.1.4. Re-Use in ESS

The re-use phase includes charging and discharging the repurposed Li-ion battery in an ESS. The electricity is provided by Ontario grid mix for charging the battery during its extended life in ESS. The total power delivered by a re-purposed Li-ion battery pack during its extended life is calculated based on following assumptions:

- Daily peaking power delivery of a repurposed battery is about 6.079 kWh with
- Assumed roundtrip efficiency for this process is 85% and transmission efficiency would be 90%.
- A rate of 1*C* is defined as the current that is equivalent to the full capacity of the battery being charged or discharged.
- It is assumed that every day one cycle (charging/ discharging) happens, so the total number of the battery cycling would be 3650 cycles throughout its 10-year useful life in the ESS.
- Depth of discharge (DOD): 75%

Table 19 shows the total power delivered by a Li-ion battery pack throughout its vehicle use.

Table 19. Li-ion battery second use in the ESS per battery pack

Input	Total amount	Unit	Notes	Ref.
Power delivered by a battery pack for an ESS	29004	kWh	daily peaking power delivery by a repurposed battery: 6.079 kWh Use time: 10 years (3650 cycles) Roundtrip eff.: 85% Transmission eff: 90% Electricity from Ontario grid mix Total amount=(6.079)*3650*1/(0.85*0.9)	IESO 2012, [52]

5.4. Life Cycle Impact Assessment

5.4.1. Results

5.4.1.1. Life Cycle Inventory Results

According to ISO 14040, life cycle inventory step includes the collecting and quantification of inputs and outputs of a product during its life cycle [31].

In this study, the life cycle inventory related to 1 kWh delivered by the battery pack during its lifecycle is calculated. The full results of LCI are listed in the Appendix. All input and output data are collected to be characterized in the selected environmental impact categories. Table S1 summarized the inputs of the system as raw material substances. The related sub-comportment of the substances and their total amount in the system are presented in this table as well as the amount of substances relevant to each phases of the battery lifecycle. According to Table S1, different energy sources including non-renewable and renewable sources are a significant part of inputs to this system. The total amount of lithium, in brine for 1 kWh power delivered by the Li-ion battery is 0.00017 kg, which approximately is relevant to the battery manufacturing phase. Aluminum and copper have higher shares than other metals as inputs. Table S2 includes a variety of airborne emissions produced during the battery life cycle. According to this table, carbon dioxide (biogenic, fossil, land) as output shares high amount of approximately 0.1 kg per 1 kWh delivered by the battery.

5.4.1.2. Energy Use

The primary energy use over the Li-ion battery life cycle is expressed as CED method, as depicted in Figure 19. Five main energy sources are considered: non-renewable (fossil), non-renewable (nuclear), renewable (biomass), renewable (wind, solar, geothermal), and renewable (water). Renewable (biomass) resource and renewable (wind, solar, geothermal) have negligible portions in energy usage of the battery in comparison with other energy sources. Use phase energy usage is significantly is higher than other phases, however the energy consumption of re-use phase is also major. As mentioned above, long-term charging of the battery, 8 years in first use in EV and 10 years in second use in ESS by Ontario electricity grid mix presents a significant usage of nuclear and natural gas resources. As would be expected, high percentages of nuclear source usage are related to use and re-use phases because of importance of this energy source in Ontario grid mix. The main source of energy use in manufacturing phase is associated with heat from natural gas and European electricity grid mix, which have been applied mostly for production of positive electrode, cell container and BMS. Re-manufacturing phase has the lowest energy usage throughout the battery lifecycle.

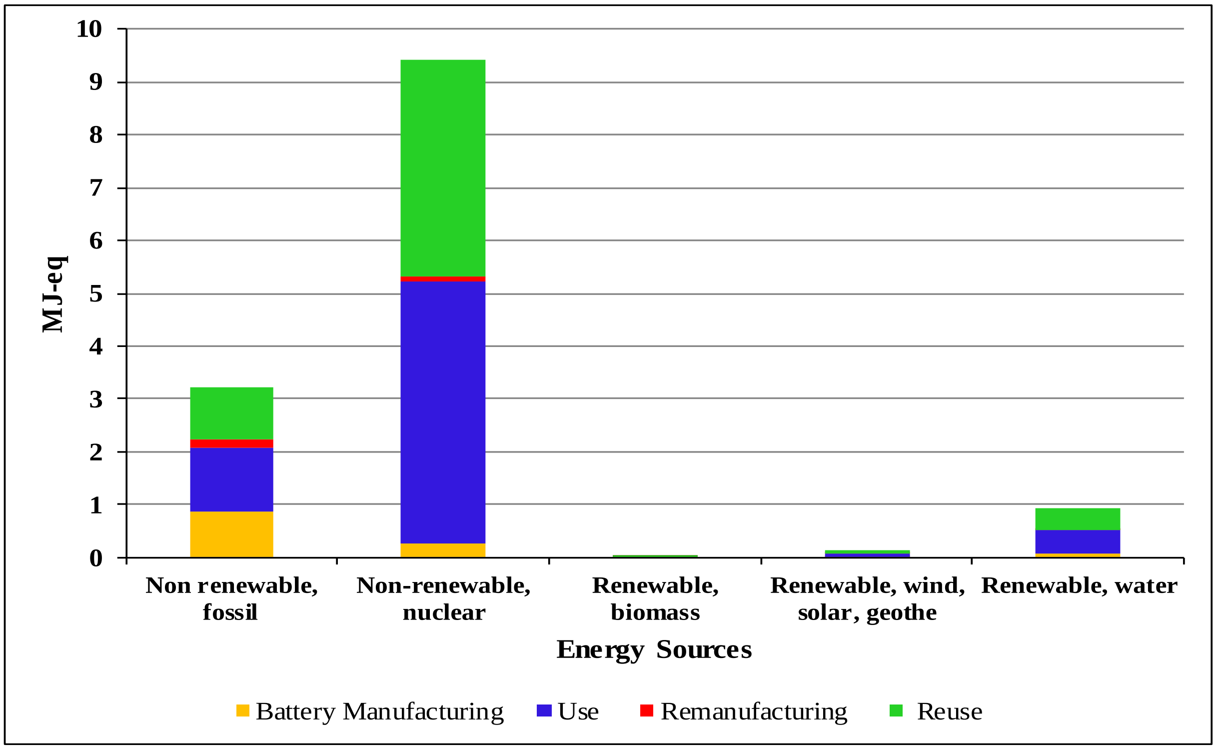


Figure 19: The Li-ion battery energy usage in the different phases of its life based on cumulative energy demand (CED) method

5.4.1.3. Environmental Impact Category Indicator Results

Results for Li-ion battery pack during its entire life cycle are presented in Figure 20 and Figure 21. The results of the study indicate that the potential environmental impacts of the Li-ion battery pack differ significantly between its life cycle phases. In Figure 20, life cycle of the battery is divided into four phases: battery manufacturing, use in EV, re-manufacturing, and re-use in ESS. As can been seen in Figure 20, all impact indicator results associated with the manufacturing phase of the battery life are considerably greater than other phases except fossil depletion impact which use phase has more significant impact. Metal depletion and freshwater eutrophication are the highest relative impacts of the battery manufacturing phase, while they are the lowest impacts of the battery re-manufacturing, use and re-use phases. In order to explain the outcomes accurately, results for different impact categories for the six life cycle phases are presented in Figure 21.

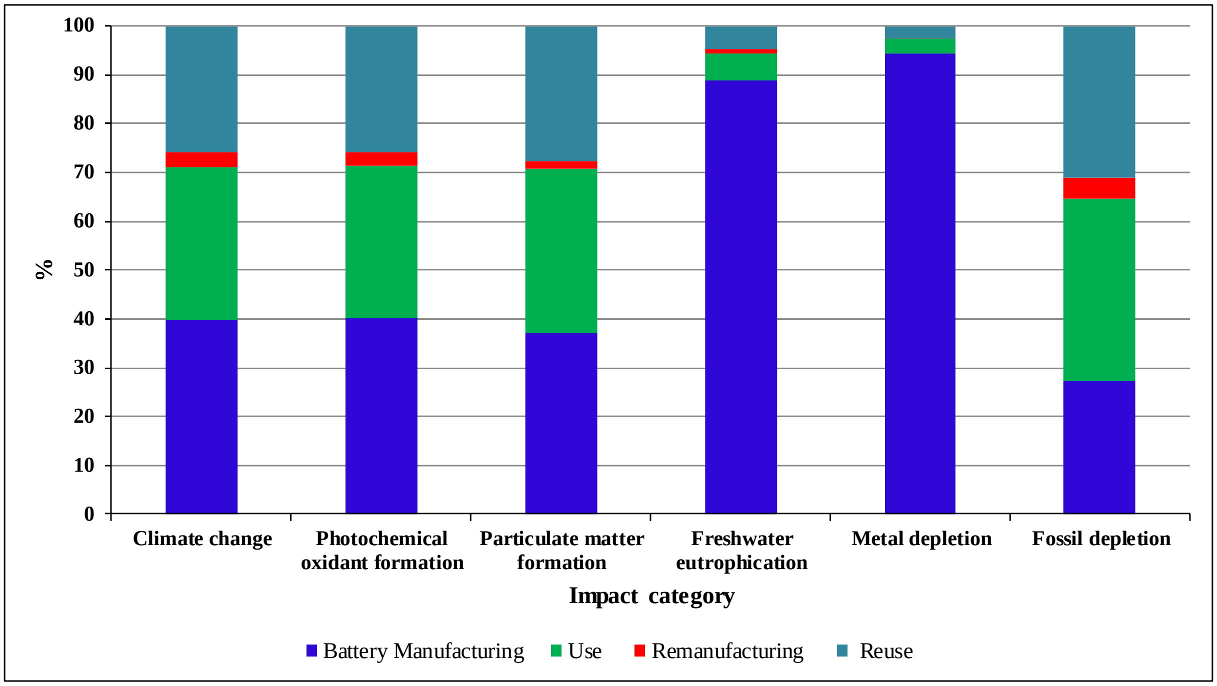
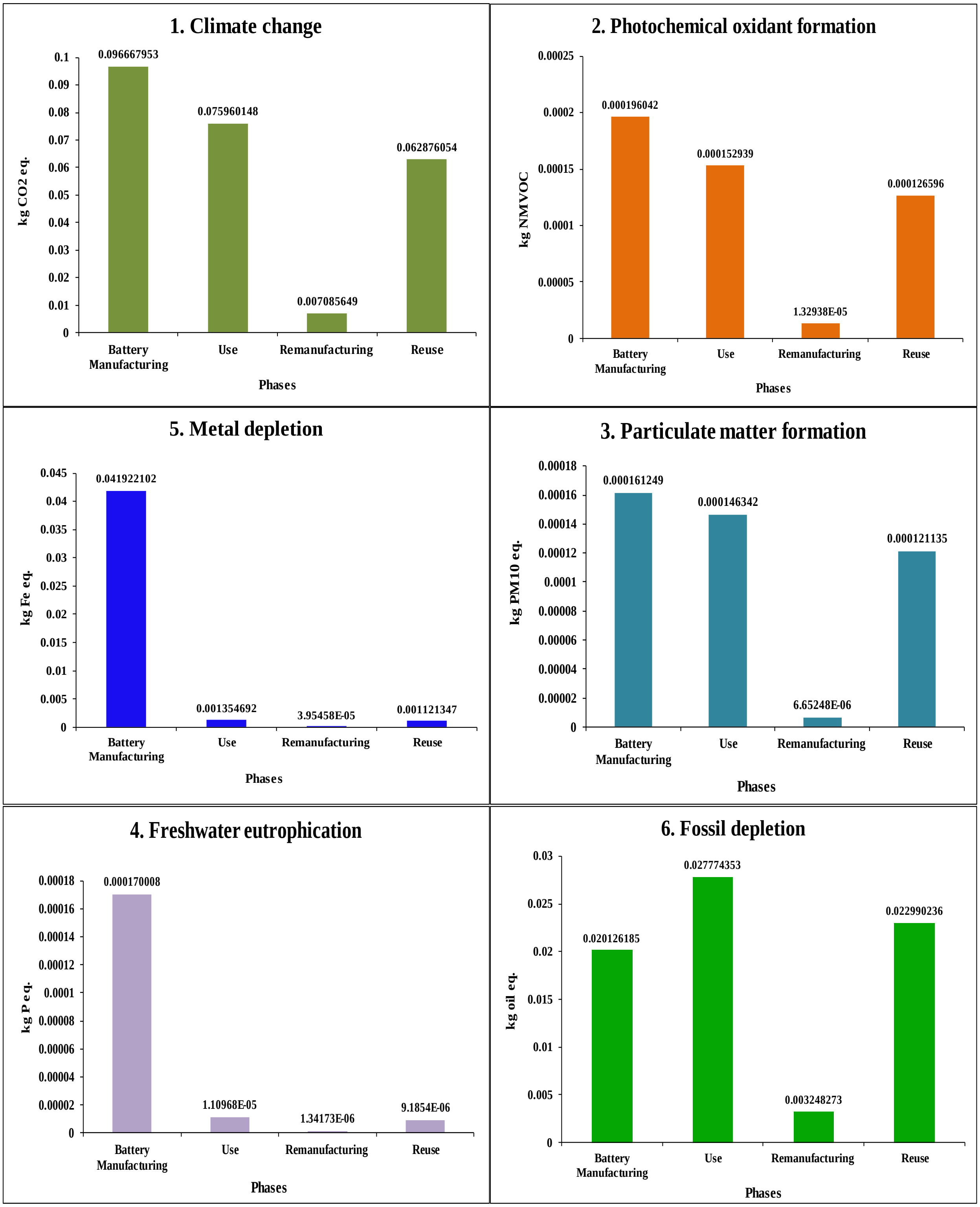


Figure 20: life cycle impact indicator results of Li-ion battery manufacturing, use, re-manufacturing, and re-use, reported quantitatively for selected functional unit, and broken down among key processes

Figure 21.1 presents the potential climate change impact associated with the battery over its life cycle. The total amount of CO_2 eq. emissions is 0.24 kg per 1 kWh delivered by the battery pack. The result shows that 40% of this quantity is generated from battery manufacturing phase, however battery use and re-use surprisingly produce significant amounts of CO_2 eq. emissions (31.3% and 26%). Positive electrode manufacturing is the main cause of the climate change impact of manufacturing phase, which significantly generated from polytetrafluoroethylene production (14.2%) which is associated with aluminum smelting. Major contributions to the climate change impact during battery use and re-use is the electricity source (Ontario grid mix).



1. Climate change

2. Photochemical oxidant formation

5. Metal depletion

3. Particulate matter formation

4. Freshwater eutrophication

6. Fossil depletion

Figure 21: Environmental impact indicator results per 1 kWh of Li-ion battery functional unit for the selected categories eq.).

Because of long-term (18-year) usage of electricity for the battery charging, the mentioned amount of CO_2 eq. emissions would be more meaningful and shows that the magnitude of the emissions of battery manufacturing is greater than those of use and re-use phases. Re-manufacturing phase assigns 2.9% of the potential climate change impact, which majorly origins from heating by natural gas throughout re-assembly process.

There is a same trend for photochemical oxidant formation impact regarding battery manufacturing, use and re-use phases. However, the total amount of this impact is lower than climate change potential for 1 kWh delivered by the battery pack (Figure 21.2). Battery management system production is the major source of photochemical oxidant impact of manufacturing phase that mostly generated from the gold applied in the integrated circuit of this system. It is considerable that the main source of this kind of emissions in the use and re-use phases are electricity grid mix, which significantly generates from burned natural gas in the power plants (35.4%). The production of module and battery packaging is the main source of NMVOC emissions of the re-manufacturing phase.

Figure 21.3 shows the potential particulate matter formation impact throughout the battery life and illustrates the significant impact of manufacturing, use, and re-use phases, which 18 years of the battery charging during use and reuse phases causes this result in contrast with manufacturing phase. Negative substrate production generates the main part of this emission for manufacturing phase, which largely is related to use of copper in this component. Use phase of the battery life also have a significant portion in the particulate matter formation which is related to Ontario grid mix and natural gas plays the main role in this emission. Re-manufacturing phase has the minor portion in particulate matter formation impact as well as other emissions.

In Figure 21.4 potential freshwater eutrophication is illustrated for different phases of the battery life. Likewise other environmental categories, manufacturing is the main sources of this emission with this difference that the use and re-use phase have minor portions in the total fresh eutrophication impact (5.7% and 4.7%) and re-manufacturing phase has less than 1% of P eq. emissions. The negative substrate production has the outstanding portion in eutrophication impact of manufacturing phase (36.2%).

As can been seen in Figure 21.5, 94% of the metal depletion impact is allocated to the manufacturing phase which mainly relates to negative electrode substrate and subsequently to copper production (57%). BMS production has a significant effect on the metal depletion of the manufacturing phase, which is related to integrated circuit applied in the BMS structure (20%). The applied gold in the production of integrated circuit is the main portion in this indicator. Chromium used in the BMS has higher portion in metal depletion impact than tin used in BMS, aluminum is used in the cell container and nickel and iron in BMS. The main metal depletion associated with the use and re-use phases of the battery life cycle is related uranium of nuclear source of electricity grid mix. Re-manufacturing only allocates 0.47% of this impact category, which mostly is related aluminum used in the battery pack packaging.

As can been seen in Figure 21.6, the use phase is the main source of the fossil depletion indicator (37%). The burned natural gas in power plants of Ontario is the major reason of the fossil depletion impact (53.2%). Hard coal source applied in electricity generation is the next fossil source which is depleting. Re-use phase is same due to the battery is powered by the same grid mix. The fossil depletion impact of manufacturing phase returns to medium voltage electricity (UCTE), which is used in the battery production and mainly generated from the burned hard coal and lignite in the power plants. Fossil depletion impact is the most significant impact category of re-manufacturing phase and it generates from cell container and battery packaging production. The battery packaging is the main reason of fossil depletion impact of the re-manufacturing phase.

5.4.2. Sensitivity Analysis

5.4.2.1. Electricity Mix

In order to clarify the importance of the energy sources applied in the electricity generation, a sensitivity analysis is conducted and two kinds of clean and dirty electricity grid are assessed environmentally to be compared with Ontario grid mix as the reference scenario.

The sensitivity analysis on energy usage of battery during its lifetime presents the role of energy sources on the environmental impacts (Figure 22).

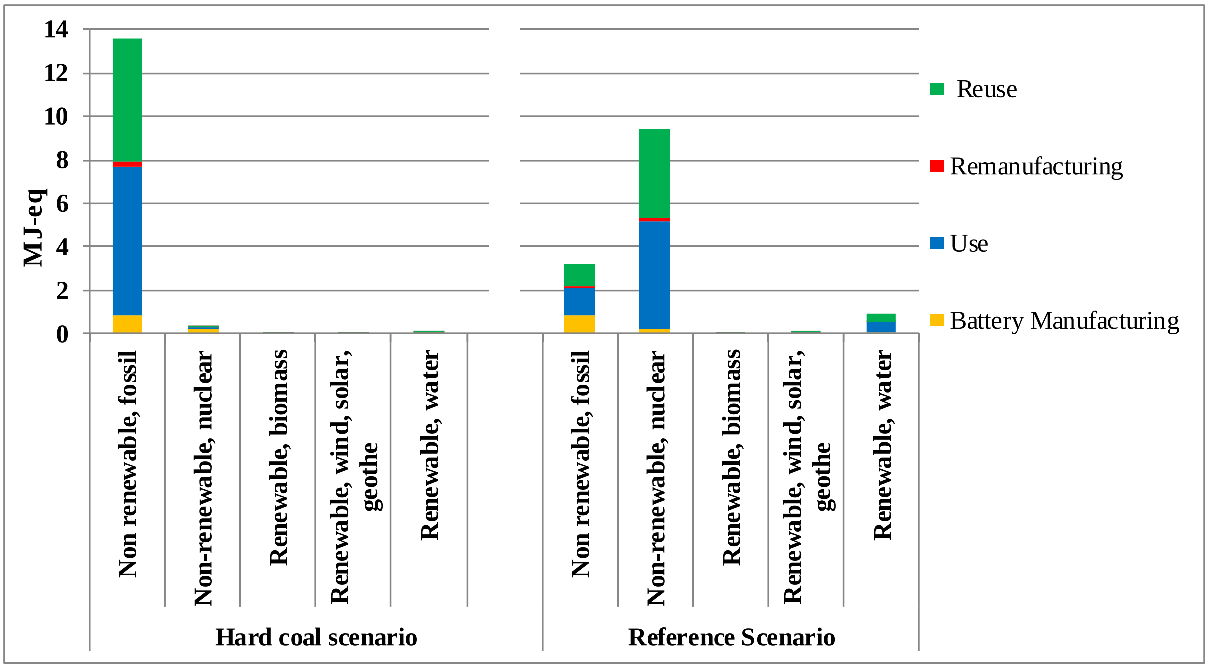


Figure 22: The Li-ion battery energy usage based on hard coal electricity for use, remanufacturing, and re-use phases in comparison with reference scenario

By utilizing hard coal electricity, obviously the portions of fossil energy sources increased in use and re-use phases, however the portion of re-manufacturing phase from fossil sources is lesser than reference scenario because of minor electricity usage of this phase in contrast with the use and re-use phases. As can been seen, the manufacturing phase has the most portion of nuclear source. However, higher energy demand from non-renewable (fossil) sources and its impact on the fossil depletion during 18 years (use and re-use) battery charging by hard coal electricity is more significant than other phases' energy usage.

Figure 23 shows the results of environmental impact categories of the Li-ion battery life cycle, which the use, remanufacturing and, reuse phases are charged by electricity generated from only hard coal.

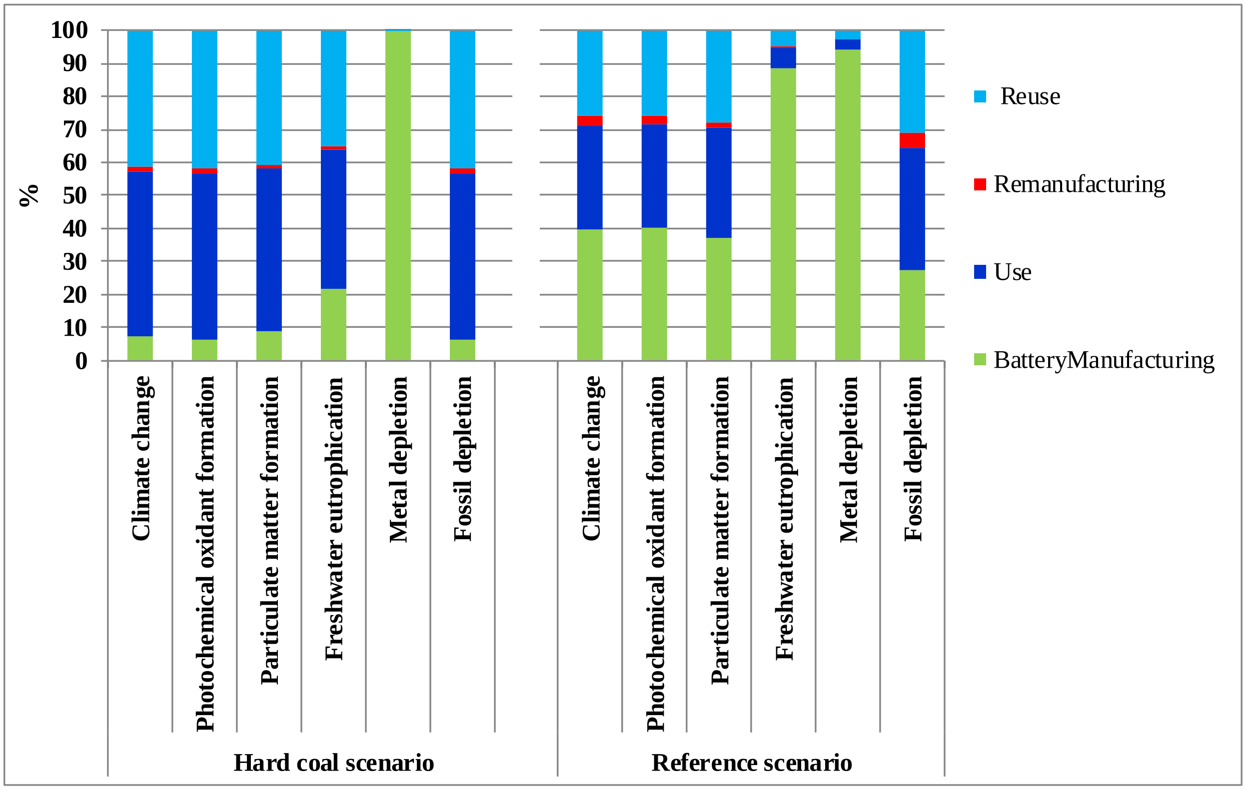


Figure 23: The Li-ion battery environmental impact in the selected categories based on hard coal electricity for use, remanufacturing, and re-use phases in comparison with reference scenario

Comparison between new results and reference scenario results illustrated that the portions of use and re-use phases in the most of categories are higher than manufacturing phase. Metal depletion is the only impact that is increased in manufacturing phase in contrast with the reference scenario, which is mostly related to copper applied in the production of negative substrate, however the total amount of this impact is less than 0.05 kg Fe eq. The re-manufacturing phase allocates slightly higher impacts than the reference scenario, though this increasing is negligible in comparison with those of the use-re-use phases. This means that long-term charging the battery by electricity generated from hard coal upsurges the environmental impacts of extended lifetime of the battery in comparison with an electricity grid mix as ON grid mix.

In order to analysis of a cleaner electricity than ON grid mix, it is assumed that the whole electricity used in use, re-manufacturing, and re-use, is generated by wind source of energy and the results of energy usage are presented in Figure 24.

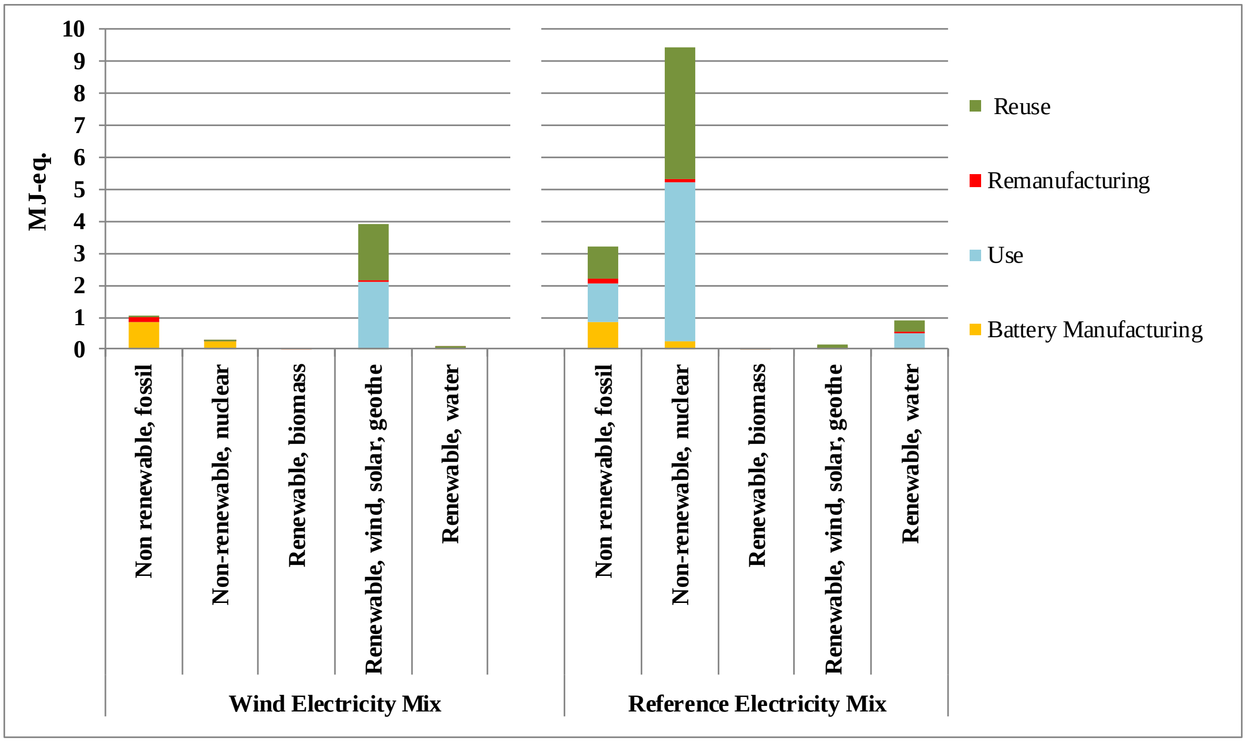


Figure 24: The Li-ion battery energy usage based on wind electricity for use, remanufacturing, and re-use phases in comparison with reference scenario

According to Figure 24, the manufacturing allocates higher amounts of energy from different energy sources, except renewable wind source which is used mostly in use and re-use phases. The notable energy usage is related to re-manufacturing phase which is higher than reference scenario; however clean electricity it is applied for testing and activating. This is caused by the battery components production which larger portion in re-manufacturing phase. The result of energy use of clean electricity highlighted that cleaner electricity could improve the benefits of the extended application of the Li-ion battery.

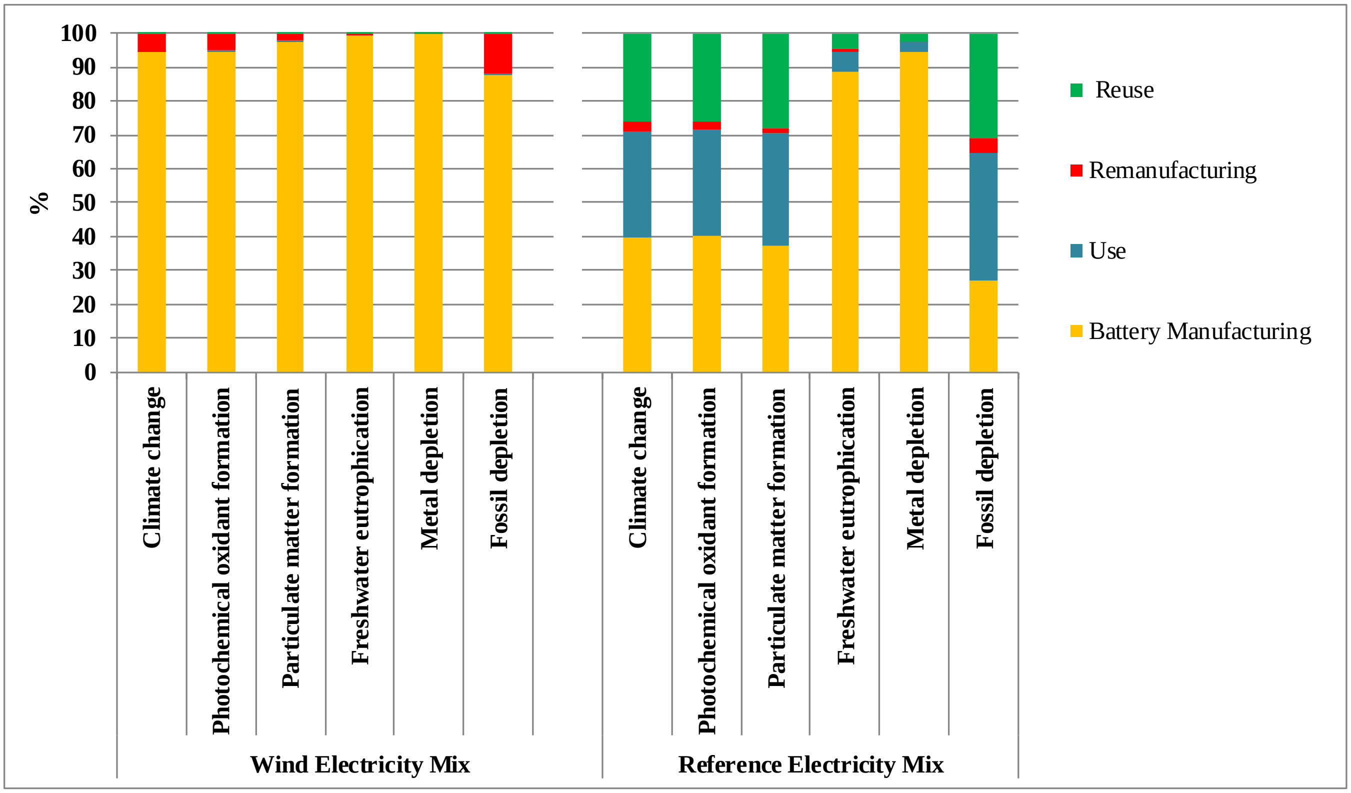


Figure 25: The Li-ion battery environmental impact in the selected categories based on wind electricity for use, remanufacturing, and re-use phases in comparison with reference scenario

Figure 25 depicts the environmental impacts of life cycle of the battery by clean electricity applied in use, re-manufacturing, and re-use phases. It is apparent that the large amounts of environmental impacts are related to only the manufacturing phase of the battery life cycle. The impacts of use and re-use phases are negligible in contrast with the re-manufacturing phase (0.08% and 0.07%). High amounts of environmental impacts of re-manufacturing phase returns to the battery components production such as cell container, battery packaging, and electronics. This result emphasized on the importance of converting the electricity grid mix to the cleaner systems and its effect on improved environmental benefits.

5.4.2.2. Battery Degradation

According to Ahmadi et al. (2014), it is indicated that energy efficiency fade effects the GHG emissions and energy use of Li-ion batteries by increasing CO_2 emissions and electricity usage during both phases of the battery's extended life. Also, it is found that the battery energy efficiency fade could be 20% after 8-year charging/discharging in the EV and it is estimated that after 10-year application in the stationary application the energy efficiency could be increased by 35%. In order to investigate the effect of the battery degradation on the environmental benefits of the Li-ion battery during its life cycle, it is assumed that whole use phase of the battery is affected by the 20% of energy efficiency fade and re-use phase of the battery experienced 35% of the degradation. Figure 26 shows the energy use of the Li-ion battery in this case.

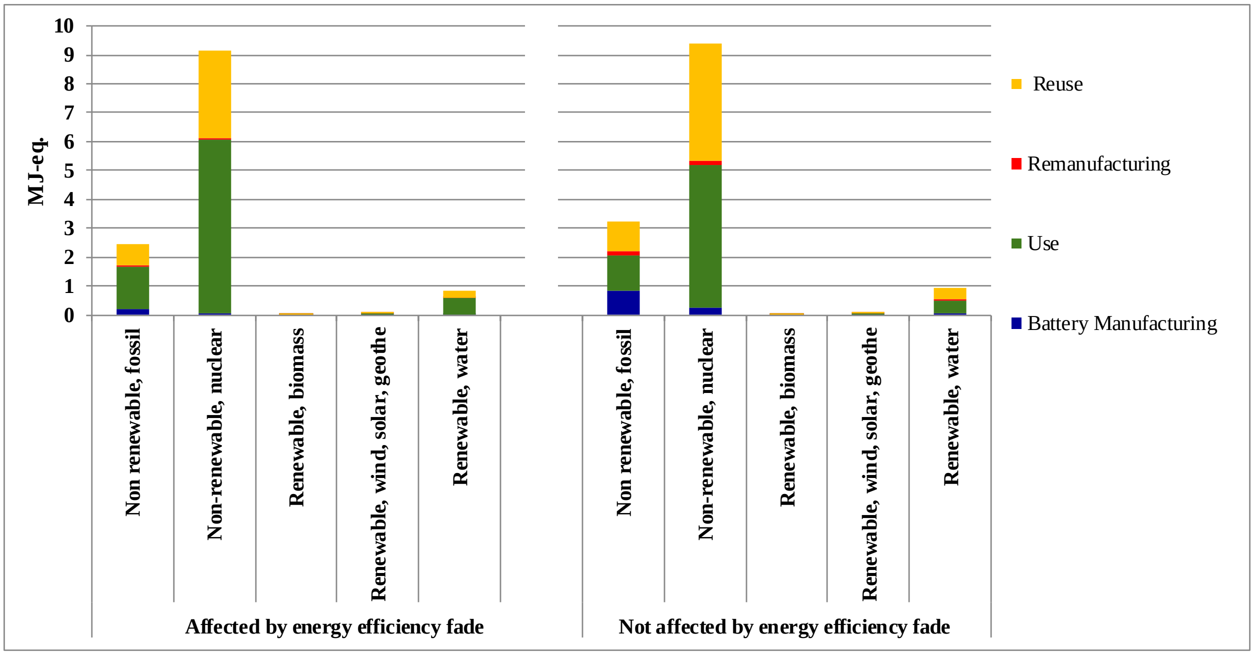


Figure 26: Energy use of Li-ion battery during its life cycle with/without energy efficiency fade effect

As can been, the percentage of use phase in all energy sources is higher than reference scenario and increasing in the re-use phase share is slighter than that. The manufacturing and re-manufacturing phases energy usage percentages are smaller than those of the reference scenario. According to the battery applies Ontario grid mix for charging and the high portion of nuclear and natural gas sources in this mix, these sources largely have been consumed in use and re-use phases.

Figure 27 presents the environmental impacts of this scenario. The potential climate change impact is meaningfully increased in the use phase (55%) in contrast with the reference scenario without effect of energy efficiency fade. Though, the degradation of the battery during re-use phase is higher than use phase, the CO_2 eq. emissions are not much more than the reference one. The portion of manufacturing, re-manufacturing, transportation, and recycling phases are slightly lower than reference scenario. This trend is approximately repeated about other five environmental impact categories. Outstanding growing of environmental impacts of the use phase of the battery in contrast with re-use phase shows that the effect of battery degradation on the battery performance and its electricity usage during use phase is mostly challenging.

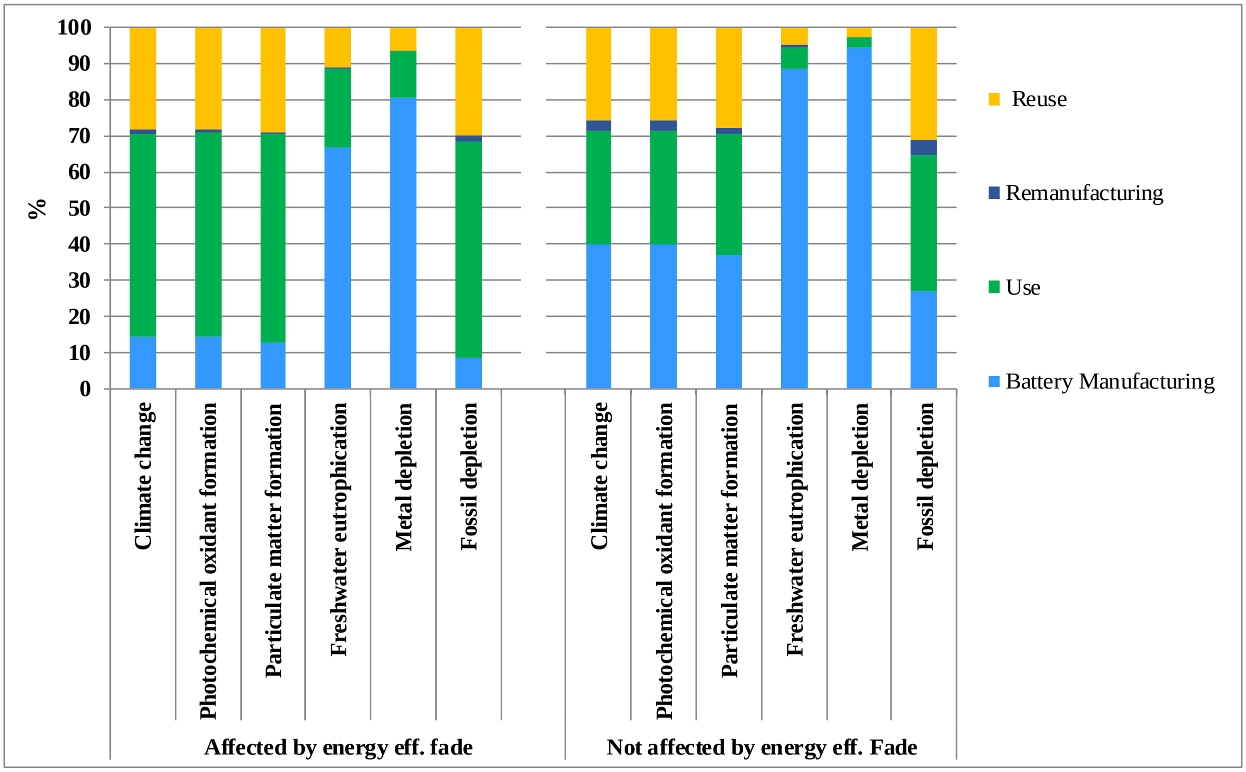


Figure 27: Environmental impacts of the Li-ion battery during its life cycle with/without assuming energy efficiency fade effect

5.5. Life Cycle Interpretation

5.5.1. Result Robustness and Benchmarking

The overall results of the study highlighted that manufacturing phase of battery life contains relatively higher environmental impacts in contrast with other life cycle stages. This outcome is confirmed with Hawkins et al. (2012) study which they conducted an comparative LCA of conventional and electric vehicles [4]. They showed that the production of batteries in electric vehicles is the main source of emissions and graphite as a component of the anode generated from hard coal coke causes climate change impact in this process [4], [34]. They also emphasized on metal depletion potential impacts and its more significant role in EV battery manufacturing than ICEV, which is clearly presented in the current results. Hawkins et al (2012) also mentioned that fossil depletion potential could not be reduced by EVs with natural gas or coal electricity and their findings are confirmed by the present results of fossil depletion impact of use and re-use phases. Bettez et al. (2011) showed that the electricity consumed by the battery during the use phase represented more than 40% of climate change potential impact and between 27%_45% of the eutrophication impacts [15]. The comparison between reference scenario (Ontario grid mix) and wind and coal electricity in this study highlighted the importance of the electricity source of the battery charging on the overall environmental impacts of the battery lifecycle. Average European electricity was applied in Bettez et al. (2011) study including higher percentage of coal and natural gas in contrast with Ontario grid mix including higher percentage of cleaner energy resources. Re-manufacturing phase is assumed that performed in the same geographical boundary of use and re-use of the battery. Therefore, Ontario grid mix is applied in testing and activating process and caused lower amounts of environmental impacts of this phase. However, the new electronics and module and battery packaging are assumed to be produced as well as battery manufacturing phase. Simon & Weil (2013) reported a high energy demand for cell finishing and BMS production, which CED method results of the present study show the same kind of energy demand [5]. Furthermore, Bettez et al. (2011) reported that production of the positive electrode materials is responsible for more than 35% of the Li-ion climate change impacts, which the current study shows the same result approximately, as mentioned in the results section. The climate change impact for manufacturing phase is greater than results of Samaras & Meisterling (2008) and Rydh & Svärd (2003) studies and it could be rationalized by different estimations for manufacturing energy requirements [34], [120]. Variances in battery designs can lead to important differences in environmental impacts [15]. Also uncertainties generated from assumptions about battery efficiency and life expectancy is a function of usage conditions, charge/ discharge rates, DOD, and temperature control. Bettez et al. (2011) expressed that a reduction of lifetime estimations by one-third could increase all categories of impacts by 30-45% [15]. So, it would be valuable to investigate about the battery performance and lifetime conditions effect on the environmental impact categories alterations in the future research. Use and re-use phases environmental impacts are related to the long-term usage (18 years) of the battery, which in comparison with the manufacturing phase they had lower portions in impacts.

5.5.2. Limitations, Recommendations, and Future Work

There is a rich source of literature about the Li-ion battery manufacturing and also about its use in the electric vehicle. However there is a significant limitation in literature regarding the EV batteries re-manufacturing and second use of them in the stationary applications. Also, there was lack of data about end of life of the batteries such as their recycling scenario specifically about EV Li-ion batteries. Therefore, in this study, there was not access to specific data regarding re-purposing, re-using, and recycling the EV Li-ion batteries. Developments of these sectors are recommended to address the present data gaps in this study. The collection of the used batteries and their recovery stages for second use and then collection of them for end of life stage and the material recycling are considerable concern for the future work.

This study assessed limited number of environmental impacts of the cascaded use of the Li-ion battery in the mobility and stationary. Future study could cover more comprehensive environmental impact categories such as human toxicity potential. This study assessed the repurposing of the Li-ion battery and second use of it into stationary application from the environmental viewpoint. Future study could compare the cascaded use of the battery in the EV and then in the stationary application with ICEV fueled with gasoline and the stationary application powered by the natural gas source. The end of life scenario including recycling of the Li-ion batteries after re-using would be assessed in the future study. The assuming battery degradation effect was assessed environmentally in the battery use and re-use phases, which could be developed in future studies by applying the practical coefficients.

5.5.4. Conclusion

This study attempted to assess the environmental feasibility of the re-purposing and re-using the EV Li-ion batteries. A cradle-to grave LCA was conducted and as concluded from the results, battery components manufacturing such as electrodes, substrates and battery management system are the main contributors to the potential environmental impacts assessed. Results depicted that the use and re-use phases allocated high percentage of environmental impacts, however these amount is related to 8 years use in the EV and 10 years re-use in ESS, which in comparison with manufacturing phase, their environmental impacts would be small enough. By Extending the life of an EV battery may raise issues of material resource availability. If implemented on a large scale, additional lithium, copper, aluminum and other metals would need to mine in order to satisfy demand resulting from a delay in material recycling, which would be an interesting consideration for energy sustainability and technology assessment.

The higher amount of freshwater eutrophication and metal depletion impacts for re-using the Li-ion battery are related to hard coal and nuclear sources of ON grid mix as the electricity source applied for the battery charging. The electricity mix used in the processes of the product system also significantly affected the resulting environmental impacts. The environmental performance of the battery is critically dependent on the combination of the battery production and electricity production impacts as well as key factors such as energy use and battery lifetime. By using clean energy sources such as wind electricity source in the battery use and re-use phases, local pollution reductions might be achieved, EV would be an appliance of moving emissions away from roads rather than reducing them globally, and the environmental benefits of the re-purposing of the batteries would be highlighted.

The sensitivity analysis results of the effect of the battery degradation effect showed that the use phase of the battery in the EV during 8 years is affected by energy efficiency fade much more than the re-using of the Li-ion batteries in the stationary application during additional 10 years. This result could confirm the environmentally feasible performance of the EV Li-ion batteries in the second use of them. The obtained results from the battery life cycle analysis could be helpful for the automakers, governments, utility companies, and energy providers to make decision about the second use, re-purposing, and re-use of the EV batteries and could bring new opportunities and risks for policy makers and stakeholders.

CHAPTER 6

6.1. Conclusion

Based on the assessment accomplished in the thesis, the re-purposing of EV Li-ion batteries would be highly beneficial from an environmental assessment approach.

In order to analyze fundamentally, a parameterized life cycle model was developed to assess the impacts of possible extension of life of electric vehicle batteries. The primary model results show a 56% reduction in life cycle CO_2 emissions by second use of EV batteries into peaking power application using clean electric power compared to using natural gas fuel for peaking power generation. Moreover, this analysis introduces the concept of energy efficiency fade by providing an initial model of the effect of energy efficiency fade on CO_2 emissions over the eight-year vehicle life plus a ten-year second use. This phenomenon presents the battery degradation importance as a technical challenge in development of re-used battery systems.

In the investigation about effective factors on the feasibility of re-purposing used EV Li-ion batteries, a simulated capacity fade model is presented for a battery used first for 8 years in a vehicle and then 10 years in an ESS. This model was developed by applying a number of experimental studies of the capacity fade of EV Li-ion battery cells with a limited number of charge/discharge cycles. This result shows the cells' capacity fading presents an exponential trend during approximately the first year of the driving cycle and continues with a linear trend. Furthermore, after repurposing and use in an energy storage application, the battery pack presents a linear trend of capacity fading with a different coefficient, which results in a further 15% loss. It is presumed that energy efficiency fade follows the same trend of changes during the expected battery lifetime as that of capacity fade. The energy efficiency fade effects the GHG emissions and energy use of Li-ion batteries by increasing CO_2

emissions and electricity usage during both phases of the battery’s extended life. Capacity fade and energy efficiency fade, two effective factors on battery reuse should be considered during life cycle analyses due to their direct environmental impacts. As such this work has demonstrated the significance of the impact of energy efficiency fade in the second use as it directly impacts the environmental and economic viability of energy load shifting arbitrage applications.

In place of investigation of comprehensive environmental benefits of cascaded use of Li-ion batteries in mobility and stationary applications, a full LCA study conducted for well-defined function of the services being compared. It is found that the high portion of the assessed potential environmental impacts are allocated to the battery components manufacturing such as electrodes, substrates and battery management system. The long-term charging of the battery during its extended lifetime (18 years) showed high percentage of environmental impacts, which in comparison with manufacturing phase, they would be minor enough. This analysis depicts that the electricity mix applied in the processes of the product system meaningfully affected the resulting environmental impacts. Therefore, by consuming clean energy sources such as wind electricity source in the battery use and re-use phases, local pollution drops might be achieved, EV would be an appliance of moving emissions away from roads rather than reducing them globally, and the environmental benefits of the re-purposing of the batteries would be confirmed. As a final point, the effect of the battery degradation was examined through energy efficiency fade effect on the battery performance and it is found that the use phase of the battery in the EV during 8 years is more sensitive to this phenomenon than the re-using of the Li-ion batteries in the stationary application during additional 10 years. This result could approve the environmentally feasible performance of the EV Li-ion batteries in the second use of them.

The obtained results from the battery life cycle analysis could be helpful for the automakers, governments, utility companies, and energy providers to make decision about the second use, re-purposing, and re-use of the EV batteries and could bring new opportunities and risks for policy makers and stakeholders.

6.2. Limitations and need for further research

This study contained within some important data gaps and uncertainties. Some of these are presented in this section.

There are foremost data gaps regarding the battery cycling experience during a long term process such as 8-year lifetime in EV application and most of present experimental data in previous studies was limited to a period of less than 1-year under laboratory conditions. Also, there is a significant limitation in literature regarding the EV batteries re-manufacturing and second use of them in the stationary applications. There is lack of data about end of life of the batteries such as their recycling scenario specifically about EV Li-ion batteries.

Fundamental uncertainties are related to the life expectancy assumptions in first and second uses of the batteries, as these are varying by charge/discharge rates, depth of discharge, and operation conditions. Limited data about failure rate of cells, which is critical for effectiveness of the battery re-purposing process, causes uncertainties in the evaluation of use second of the battery into ESS. In this study the applied assumptions about failure rate of cells were tested in sensitivity analysis, however more experimental study is necessary in future. Also, the relationship between capacity fade and energy efficiency fade which introduced in this study needs to be more investigated, quantitatively.

In this study, there was not access to specific data regarding re-purposing, and re-using of the EV Li-ion batteries. Developments of these sectors are recommended to address the present data gaps in this study. The collection of the used EV batteries for re-purposing and their recovery stages for second use and then collection of them for end of life stage and the material recycling are considerable concern for the future work.

This study evaluated limited number of environmental impacts of the cascaded use of the Li-ion battery in the mobility and stationary. Future study could assess more comprehensive environmental impact categories such as human toxicity potential. This study assessed the Li-ion battery during its entire life cycle. Future study could compare the cascaded use of the battery in the EV and then in the stationary application with ICEV fueled with gasoline and the stationary application powered by the natural gas source as presented in Figure 16. The assuming battery degradation effect was assessed environmentally in the battery use and re-use phases, which could be developed in future studies by applying the practical coefficients.

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Appendix

This supplement includes the detailed inventory data. Tables S1 and S2 present the list of measured components of this study, which is extracted from SimaPro 7.3.0.

S1: Inventory of raw material of 1kWh delivered by Li-ion battery during its life cycle

Substance (Raw material)	Sub-compartment	Unit	Total	Battery mfg,	Use	Remanufacturing	Reuse
Aluminium, 24% in bauxite, 11% in crude ore, in ground	in ground	kg	0.001656597	0.000898437	1.75406E-06	0.000754674	1.45192E-06
Barite, 15% in crude ore, in itoo iaground	in ground	kg	3.23603E-06	1.34056E-06	2.40975E-08	1.84698E-07	1.99467E-08
Basalt, in ground	in ground	kg	1.14106E-07	6.15136E-08	3.62977E-10	5.09266E-08	3.00455E-10
Borax, in ground	in ground	kg	1.3576E-08	4.13707E-10	7.11175E-09	1.5646E-10	5.88676E-09
Bromine, 0.0023% in water	in water	kg	2.99174E-10	2.49675E-10	1.74907E-11	1.58542E-11	1.44779E-11
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	in ground	kg	2.587E-11	1.42136E-11	4.13002E-13	9.69975E-12	3.41864E-13
Calcite, in ground	in ground	kg	0.006380205	0.005532964	0.000162859	0.000168806	0.000134806
Carbon dioxide, in air	in air	kg	0.00123259	0.000991183	3.08545E-05	0.000127842	2.55398E-05
Carbon, in organic matter, in soil	in ground	kg	3.56756E-07	3.49213E-07	5.10843E-10	5.28176E-09	4.2285E-10
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	in ground	kg	3.30199E-05	2.32917E-05	5.23081E-06	1.54173E-07	4.3298E-06
Chrysotile, in ground	in ground	kg	3.52327E-08	1.45205E-08	2.37978E-10	1.97032E-09	1.96987E-10
Cinnabar, in ground	in ground	kg	3.25161E-09	1.34453E-09	2.24101E-11	1.82298E-10	1.855E-11
Clay, bentonite, in ground	in ground	kg	4.86325E-05	6.67292E-06	2.24418E-05	8.25612E-07	1.85762E-05
Clay, unspecified, in ground	in ground	kg	0.001193197	0.001162593	6.42624E-06	1.68E-05	5.31932E-06
Coal, brown, in ground	in ground	kg	0.013405225	0.011180021	0.000162767	0.001268077	0.000134731
Coal, hard, unspecified, in ground	in ground	kg	0.030363664	0.008519974	0.010741094	0.001846495	0.008890946
Cobalt, in ground	in ground	kg	7.54642E-11	3.71824E-11	6.03137E-12	1.22062E-11	4.99247E-12
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in	in ground	kg	0.000558012	0.000557893	5.90334E-10	1.17283E-07	4.88649E-10

crude ore, in ground							
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	5.44647E-05	5.38111E-05	2.86408E-09	6.46976E-07	2.37074E-09
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	1.44475E-05	1.42742E-05	7.59736E-10	1.7162E-07	6.28872E-10
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	7.16216E-05	7.07621E-05	3.77126E-09	8.50791E-07	3.12166E-09
Diatomite, in ground	in ground	kg	4.2567E-12	3.40007E-13	2.10459E-12	6.06052E-14	1.74208E-12
Dolomite, in ground	in ground	kg	5.68544E-07	4.77815E-07	3.76062E-08	2.14282E-08	3.11285E-08
Energy, gross calorific value, in biomass	biotic	MJ	0.011742422	0.009316209	0.000291047	0.001380884	0.000240914
Energy, gross calorific value, in biomass, primary forest	biotic	MJ	2.47336E-05	2.42107E-05	3.54163E-08	3.66181E-07	2.93159E-08
Energy, kinetic (in wind), converted	in air	MJ	0.122224723	0.004238418	0.063588446	0.001491467	0.052635371
Energy, potential (in hydropower reservoir), converted	in water	MJ	0.940511817	0.05877833	0.464027578	0.031894805	0.38409908
Energy, solar, converted	in air	MJ	0.003183983	6.0564E-05	0.001686903	3.62869E-05	0.001396335
Feldspar, in ground	in ground	kg	4.20111E-12	4.15941E-12	2.06398E-14	2.50165E-15	1.70846E-14
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	in ground	kg	6.34157E-05	6.31942E-05	1.27106E-08	1.83752E-09	1.05212E-08
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	in ground	kg	3.20414E-05	3.19443E-05	5.5878E-09	8.67012E-10	4.6253E-09
Fluorspar, 92%, in ground	in ground	kg	0.000886936	0.000860006	1.05728E-05	1.94146E-06	8.7516E-06
Gas, mine, off-gas, process, coal mining/m3	in ground	m3	0.000232752	8.309E-05	7.05625E-05	1.71372E-05	5.84082E-05
Gas, natural, in ground	in ground	m3	0.057503583	0.00960289	0.024586269	0.002740935	0.020351297
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	in ground	kg	6.30155E-09	6.30152E-09	3.59833E-15	8.92919E-15	2.97852E-15
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	in ground	kg	1.15557E-08	1.15556E-08	6.59849E-15	1.63743E-14	5.4619E-15
Granite, in ground	in ground	kg	4.16991E-12	4.15412E-12	7.90128E-15	1.26152E-15	6.54029E-15

Gravel, in ground	in ground	kg	0.000821231	0.000658354	4.64212E-05	7.2597E-05	3.84252E-05
Gypsum, in ground	in ground	kg	5.13174E-08	3.65546E-08	8.93228E-10	1.30085E-08	7.3937E-10
Iron, 46% in ore, 25% in crude ore, in ground	in ground	kg	9.15222E-05	6.40888E-05	1.06386E-05	7.87804E-06	8.8061E-06
Kaolinite, 24% in crude ore, in ground	in ground	kg	6.90531E-06	3.70422E-06	1.27173E-07	2.96695E-06	1.05268E-07
Kieserite, 25% in crude ore, in ground	in ground	kg	4.08739E-09	2.24682E-09	7.70239E-10	4.26482E-10	6.37566E-10
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	in ground	kg	9.39704E-08	9.36596E-08	2.30103E-11	1.90136E-10	1.90468E-11
Lithium, 0.15% in brine, in ground	in ground	kg	0.000167246	0.000167246	8.24206E-14	6.9052E-14	6.82237E-14
Magnesite, 60% in crude ore, in ground	in ground	kg	2.70572E-06	2.1688E-06	2.20236E-07	1.31045E-07	1.823E-07
Magnesium, 0.13% in water	in water	kg	3.45449E-13	1.56967E-13	2.33973E-14	5.78747E-14	1.93658E-14
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	in ground	kg	6.18121E-08	9.76104E-09	2.58945E-08	4.25557E-09	2.14342E-08
Metamorphous rock, graphite containing, in ground	in ground	kg	0.000187622	0.000186506	1.78681E-09	1.1123E-06	1.47903E-09
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	in ground	kg	1.33099E-06	1.31502E-06	7.00838E-11	1.58109E-08	5.80119E-11
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	in ground	kg	1.8977E-07	1.87492E-07	9.97919E-12	2.25424E-09	8.26028E-12
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	in ground	kg	6.90314E-06	6.90237E-06	2.96389E-10	2.09317E-10	2.45336E-10
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	in ground	kg	6.95374E-07	6.8703E-07	3.65669E-11	8.26022E-09	3.02683E-11
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and	in ground	kg	7.76203E-09	6.20222E-09	5.98156E-10	4.22389E-10	4.95124E-10

Cu 0.36% in crude ore, in ground							
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	in ground	kg	1.68123E-07	1.48171E-07	8.11784E-09	2.04962E-09	6.71955E-09
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	in ground	kg	7.14943E-05	5.3209E-05	9.80884E-06	3.34695E-07	8.11927E-06
Occupation, arable, non-irrigated	land	m2a	2.07315E-06	1.60784E-06	1.42782E-07	1.8765E-07	1.18188E-07
Occupation, construction site	land	m2a	0.000222173	0.000220323	2.49359E-07	3.36181E-07	2.06407E-07
Occupation, dump site	land	m2a	0.000670932	0.000374135	0.000152906	1.38822E-05	0.000126568
Occupation, dump site, benthos	land	m2a	4.27513E-09	1.89605E-09	2.94148E-10	7.30506E-10	2.43481E-10
Occupation, forest, intensive	land	m2a	7.11483E-05	5.48262E-05	2.20164E-06	3.23587E-06	1.82241E-06
Occupation, forest, intensive, normal	land	m2a	0.000390141	0.000253784	5.27099E-06	0.000116575	4.36307E-06
Occupation, forest, intensive, short-cycle	land	m2a	6.20431E-06	6.07314E-06	8.88402E-09	9.18547E-08	7.35376E-09
Occupation, industrial area	land	m2a	3.56913E-05	1.46467E-05	9.45702E-06	3.0918E-06	7.82805E-06
Occupation, industrial area, benthos	land	m2a	3.90932E-11	1.73368E-11	2.68992E-12	6.68045E-12	2.22658E-12
Occupation, industrial area, built up	land	m2a	2.69122E-08	1.28664E-08	1.68686E-09	4.78019E-09	1.3963E-09
Occupation, industrial area, vegetation	land	m2a	9.68114E-08	6.1467E-08	7.80114E-10	3.08365E-08	6.4574E-10
Occupation, mineral extraction site	land	m2a	0.000158854	5.76176E-05	5.06248E-05	7.15052E-06	4.19047E-05
Occupation, permanent crop, fruit, intensive	land	m2a	7.37645E-08	3.85583E-08	1.1527E-08	6.6913E-09	9.54145E-09
Occupation, shrub land, sclerophyllous	land	m2a	7.25377E-06	6.25839E-06	1.98515E-07	3.36276E-07	1.64321E-07
Occupation, traffic area, rail embankment	land	m2a	1.09485E-08	5.05474E-09	7.29686E-10	1.81192E-09	6.03998E-10
Occupation, traffic area, rail network	land	m2a	1.21068E-08	5.58948E-09	8.06877E-10	2.0036E-09	6.67893E-10
Occupation, traffic area, road embankment	land	m2a	5.03277E-06	3.4125E-06	8.83921E-08	1.2086E-06	7.31666E-08
Occupation, traffic area, road network	land	m2a	5.02613E-08	2.28917E-08	3.38402E-09	8.4061E-09	2.80113E-09
Occupation, urban,	land	m2a	1.83907E-12	8.28976E-13	1.2521E-13	3.10105E-13	1.03643E-13

discontinuously built							
Occupation, water bodies, artificial	land	m2a	0.001657972	5.87202E-05	0.000860444	2.34051E-05	0.000712233
Occupation, water courses, artificial	land	m2a	0.00088745	5.12827E-05	0.000440216	3.02405E-05	0.000364389
Oil, crude, in ground	in ground	kg	0.007313442	0.004380282	0.000329515	0.001558888	0.000272757
Olivine, in ground	in ground	kg	5.42256E-09	3.52626E-09	2.18718E-11	1.85462E-09	1.81044E-11
Peat, in ground	biotic	kg	1.01847E-05	9.94371E-06	9.5302E-09	2.11182E-07	7.88863E-09
Phosphorus, 18% in apatite, 12% in crude ore, in ground	in ground	kg	0.000127652	0.000127264	2.26947E-08	3.86759E-09	1.87856E-08
Phosphorus, 18% in apatite, 4% in crude ore, in ground	in ground	kg	0.000253663	0.000252777	5.08424E-08	7.35009E-09	4.20848E-08
Rhenium, in crude ore, in ground	in ground	kg	2.56172E-13	1.58115E-13	1.62017E-14	3.48016E-14	1.34109E-14
Sand, unspecified, in ground	in ground	kg	3.65775E-06	3.42062E-06	7.4611E-10	2.3569E-07	6.17593E-10
Shale, in ground	in ground	kg	4.37153E-08	2.7697E-08	1.79102E-10	1.56767E-08	1.48252E-10
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	in ground	kg	2.53291E-08	2.53284E-08	8.00116E-14	1.98548E-13	6.62296E-14
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	in ground	kg	1.81626E-08	1.81622E-08	5.70721E-14	1.41655E-13	4.72414E-14
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	in ground	kg	1.67696E-09	1.67692E-09	5.26984E-15	1.3077E-14	4.36195E-15
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	in ground	kg	3.82998E-09	3.82988E-09	1.20356E-14	2.9866E-14	9.96245E-15
Sodium chloride, in ground	in ground	kg	0.001917705	0.001118358	4.62976E-05	7.71158E-05	3.83229E-05
Sodium nitrate, in ground	in ground	kg	9.4842E-13	9.22516E-13	5.23436E-16	2.46077E-14	4.33275E-16
Sodium sulphate, various forms, in ground	in ground	kg	3.26967E-06	1.41585E-06	1.06004E-07	1.35036E-08	8.77447E-08
Sulfur, in ground	in ground	kg	5.88666E-07	5.2372E-07	1.27446E-09	6.24949E-08	1.05493E-09
Sylvite, 25 % in sylvinite, in ground	in ground	kg	3.26329E-07	3.15093E-07	2.41127E-09	5.70531E-09	1.99593E-09
Talc, in ground	in ground	kg	9.22347E-07	4.98056E-07	9.54819E-09	4.02921E-07	7.90352E-09
Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	in ground	kg	9.40079E-13	4.30922E-13	6.3077E-14	1.565E-13	5.2204E-14

Tin, 79% in cassiterite, 0.1% in crude ore, in ground	in ground	kg	6.90669E-07	6.90609E-07	2.1951E-11	8.51105E-12	1.817E-11
TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	in ground	kg	1.16623E-05	5.11521E-06	8.08483E-07	2.0101E-06	6.69223E-07
TiO2, 95% in rutile, 0.40% in crude ore, in ground	in ground	kg	2.69733E-10	2.60591E-10	8.46631E-15	9.12495E-12	7.00799E-15
Transformation, from arable	land	m2	6.30806E-07	3.42107E-07	6.68471E-10	2.87368E-07	5.53327E-10
Transformation, from arable, non-irrigated	land	m2	3.68189E-06	2.82699E-06	2.62031E-07	3.45268E-07	2.16896E-07
Transformation, from arable, non-irrigated, fallow	land	m2	2.01029E-07	1.09025E-07	2.12819E-10	9.15812E-08	1.76161E-10
Transformation, from dump site, inert material landfill	land	m2	5.81595E-08	3.55901E-08	8.68186E-10	2.14558E-09	7.18642E-10
Transformation, from dump site, residual material landfill	land	m2	1.35072E-06	1.21243E-06	3.83649E-08	6.41795E-08	3.17565E-08
Transformation, from dump site, sanitary landfill	land	m2	3.69521E-08	6.65167E-10	4.02276E-10	1.53021E-10	3.32984E-10
Transformation, from dump site, slag compartment	land	m2	2.7589E-09	1.05582E-09	6.29252E-12	6.74399E-10	5.20864E-12
Transformation, from forest	land	m2	3.27434E-07	3.16427E-07	1.67264E-09	2.54747E-09	1.38453E-09
Transformation, from forest, extensive	land	m2	3.77447E-06	2.47997E-06	5.61814E-08	1.0494E-06	4.65042E-08
Transformation, from forest, intensive, clear-cutting	land	m2	2.21583E-07	2.16899E-07	3.17288E-10	3.28054E-09	2.62635E-10
Transformation, from industrial area	land	m2	1.25278E-06	3.47274E-08	6.55765E-07	1.72509E-08	5.4281E-07
Transformation, from industrial area, benthos	land	m2	3.68405E-13	1.63058E-13	2.53863E-14	6.30513E-14	2.10135E-14
Transformation, from industrial area, built up	land	m2	7.18154E-08	7.14991E-08	1.81512E-11	2.62181E-12	1.50247E-11
Transformation, from industrial area, vegetation	land	m2	1.22509E-07	1.21969E-07	3.09638E-11	4.4725E-12	2.56303E-11
Transformation, from mineral extraction site	land	m2	2.72997E-06	2.16707E-06	9.94824E-09	5.11745E-07	8.23466E-09
Transformation, from pasture and meadow	land	m2	7.97314E-06	2.51708E-06	2.80578E-06	2.56907E-07	2.32248E-06
Transformation, from pasture and meadow, intensive	land	m2	2.85186E-09	2.15418E-09	2.13842E-10	2.81772E-10	1.77008E-10
Transformation, from sea and	land	m2	3.9223E-08	3.68402E-08	2.95342E-10	7.31144E-10	2.44469E-10

ocean							
Transformation, from shrub land, sclerophyllous	land	m2	6.99205E-06	1.5718E-06	2.78854E-06	2.55986E-07	2.30822E-06
Transformation, from tropical rain forest	land	m2	2.21583E-07	2.16899E-07	3.17288E-10	3.28054E-09	2.62635E-10
Transformation, from unknown	land	m2	1.923E-05	3.97553E-06	8.08962E-06	3.91247E-07	6.69619E-06
Transformation, to arable	land	m2	1.12884E-06	7.79956E-07	7.42687E-09	3.08111E-07	6.1476E-09
Transformation, to arable, non-irrigated	land	m2	3.68657E-06	2.83098E-06	2.62244E-07	3.4555E-07	2.17073E-07
Transformation, to arable, non-irrigated, fallow	land	m2	2.20977E-07	1.21737E-07	2.52905E-10	9.87331E-08	2.09342E-10
Transformation, to dump site	land	m2	5.04679E-06	2.62507E-06	1.26172E-06	9.86194E-08	1.04439E-06
Transformation, to dump site, benthos	land	m2	4.27513E-09	1.89605E-09	2.94148E-10	7.30506E-10	2.43481E-10
Transformation, to dump site, inert material landfill	land	m2	5.81595E-08	3.55901E-08	8.68186E-10	2.14558E-09	7.18642E-10
Transformation, to dump site, residual material landfill	land	m2	1.35072E-06	1.21243E-06	3.83649E-08	6.41795E-08	3.17565E-08
Transformation, to dump site, sanitary landfill	land	m2	3.69521E-08	6.65167E-10	4.02276E-10	1.53021E-10	3.32984E-10
Transformation, to dump site, slag compartment	land	m2	2.7589E-09	1.05582E-09	6.29252E-12	6.74399E-10	5.20864E-12
Transformation, to forest	land	m2	1.8534E-06	1.54804E-06	4.13579E-08	1.67549E-07	3.4234E-08
Transformation, to forest, intensive	land	m2	4.7382E-07	3.6511E-07	1.46683E-08	2.15583E-08	1.21417E-08
Transformation, to forest, intensive, clear-cutting	land	m2	2.21583E-07	2.16899E-07	3.17288E-10	3.28054E-09	2.62635E-10
Transformation, to forest, intensive, normal	land	m2	3.10368E-06	2.00312E-06	4.05423E-08	9.46305E-07	3.35589E-08
Transformation, to forest, intensive, short-cycle	land	m2	2.21583E-07	2.16899E-07	3.17288E-10	3.28054E-09	2.62635E-10
Transformation, to heterogeneous, agricultural	land	m2	3.69246E-10	1.64418E-10	2.53298E-11	6.28986E-11	2.09667E-11
Transformation, to industrial area	land	m2	3.77293E-07	1.52657E-07	9.96863E-08	3.56537E-08	8.25154E-08
Transformation, to industrial area, benthos	land	m2	3.49479E-08	3.49442E-08	1.19619E-12	6.43009E-13	9.90151E-13
Transformation, to industrial area, built up	land	m2	3.72568E-07	1.61917E-07	1.11692E-07	5.41124E-09	9.24529E-08

Transformation, to industrial area, vegetation	land	m2	6.42091E-08	6.35246E-08	3.03303E-11	3.26977E-10	2.51059E-11
Transformation, to mineral extraction site	land	m2	5.08854E-06	2.49076E-06	1.09341E-06	5.58582E-07	9.05071E-07
Transformation, to pasture and meadow	land	m2	9.66253E-07	9.62938E-07	1.92428E-10	3.70226E-11	1.59282E-10
Transformation, to permanent crop, fruit, intensive	land	m2	1.03839E-09	5.42791E-10	1.62267E-10	9.41944E-11	1.34316E-10
Transformation, to sea and ocean	land	m2	3.68405E-13	1.63058E-13	2.53863E-14	6.30513E-14	2.10135E-14
Transformation, to shrub land, sclerophyllous	land	m2	1.44859E-06	1.24974E-06	3.96416E-08	6.71525E-08	3.28134E-08
Transformation, to traffic area, rail embankment	land	m2	2.54767E-11	1.17621E-11	1.69795E-12	4.21626E-12	1.40548E-12
Transformation, to traffic area, rail network	land	m2	2.80032E-11	1.29286E-11	1.86633E-12	4.63438E-12	1.54485E-12
Transformation, to traffic area, road embankment	land	m2	3.8532E-08	2.58347E-08	6.42319E-10	9.73525E-09	5.3168E-10
Transformation, to traffic area, road network	land	m2	5.62605E-10	2.56815E-10	3.78108E-11	9.39164E-11	3.12979E-11
Transformation, to unknown	land	m2	1.42596E-06	2.05937E-07	6.56301E-07	1.76197E-08	5.43254E-07
Transformation, to urban, discontinuously built	land	m2	3.66331E-14	1.65127E-14	2.49411E-15	6.1771E-15	2.0645E-15
Transformation, to water bodies, artificial	land	m2	1.08052E-05	3.86254E-07	5.60544E-06	1.52887E-07	4.63991E-06
Transformation, to water courses, artificial	land	m2	1.09846E-05	6.34763E-07	5.44889E-06	3.74309E-07	4.51033E-06
Ulexite, in ground	in ground	kg	5.99037E-08	5.99013E-08	2.92931E-13	7.26954E-13	2.42474E-13
Uranium, in ground	in ground	kg	1.68856E-05	4.57171E-07	8.8482E-06	2.29765E-07	7.32411E-06
Volume occupied, reservoir	in water	m3y	0.007766938	0.000723183	0.003694843	0.000259443	0.003058408
Volume occupied, underground deposit	in ground	m3	2.3673E-08	1.52952E-08	5.0679E-10	7.38255E-09	4.19496E-10
Water, cooling, unspecified natural origin/m3	in water	m3	0.006210076	0.001437702	0.002374934	0.00031896	0.001965853
Water, lake	in water	m3	1.56918E-05	1.41439E-05	6.11988E-07	4.02758E-07	5.06574E-07
Water, river	in water	m3	0.004001763	0.002147408	0.000980682	4.89291E-05	0.00081176
Water, salt, ocean	in water	m3	5.37984E-05	3.63145E-05	5.46611E-06	5.50503E-06	4.52458E-06
Water, salt, sole	in water	m3	4.40043E-06	2.61466E-06	2.62319E-07	7.74026E-07	2.17135E-07
Water, turbine	in water	m3	9.258165174	0.526398464	4.601288535	0.307816973	3.80871909

use, unspecified natural origin							
Water, unspecified natural origin/m3	in water	m3	0.000377638	0.000247136	4.72774E-05	9.43303E-06	3.91339E-05
Water, well, in ground	in water	m3	0.000138999	0.000117174	6.53021E-06	6.98126E-06	5.40539E-06
Wood, hard, standing	biotic	m3	2.9508E-07	2.37398E-07	7.84746E-09	3.09714E-08	6.49574E-09
Wood, primary forest, standing	biotic	m3	2.29427E-09	2.24577E-09	3.2852E-12	3.39667E-11	2.71933E-12
Wood, soft, standing	biotic	m3	8.15564E-07	6.41083E-07	2.05248E-08	9.82853E-08	1.69894E-08
Wood, unspecified, standing/m3	biotic	m3	4.62292E-11	4.09374E-11	2.53091E-13	4.80456E-12	2.09496E-13
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	in ground	kg	1.69728E-05	9.4203E-06	1.17483E-08	7.52858E-06	9.72466E-09
Zirconium, 50% in zircon, 0.39% in crude ore, in ground	in ground	kg	1.28558E-12	5.89365E-13	8.62391E-14	2.14E-13	7.13845E-14

S2: Inventory of airborne emissions of 1kWh delivered by Li-ion battery during its life cycle

Substance	Unit	Total	Battery Manufacturing	Use	Remanufacturing	Reuse
Aerosols, radioactive, unspecified	Bq	0.023189	0.000200757	0.012424997	0.000266987	0.010284798
Aluminium	kg	3.19615E-05	1.48431E-05	9.06424E-06	5.08387E-07	7.50293E-06
Ammonia	kg	7.07E-06	5.69388E-06	6.73571E-07	1.25449E-07	5.57549E-07
Ammonium carbonate	kg	4.6E-11	4.33987E-11	1.0896E-13	2.39263E-12	9.01918E-14
Antimony	kg	6.21E-08	6.17718E-08	9.96214E-11	8.6171E-11	8.24617E-11
Antimony-125	Bq	1.21E-08	1.02261E-08	4.17607E-10	5.57222E-10	3.45674E-10
Argon-41	Bq	0.108489	0.094528537	0.001057911	0.005916096	0.000875686
Arsenic	kg	4.4E-07	4.35643E-07	1.7822E-09	7.20935E-10	1.47522E-09
Barium	kg	8.11E-08	2.16884E-09	4.25355E-08	1.09279E-09	3.52087E-08
Benzene	kg	3.12E-06	3.3396E-09	1.68463E-06	3.32111E-08	1.39445E-06
Benzene, ethyl-	kg	8.97E-09	5.3092E-09	4.44982E-10	1.78482E-09	3.68334E-10
Benzo(a)pyrene	kg	3.88E-09	2.10571E-09	4.49577E-12	1.76525E-09	3.72137E-12
Beryllium	kg	1.77E-09	4.72644E-11	9.26952E-10	2.38146E-11	7.67285E-10
Boron	kg	3.62E-07	2.96407E-07	4.45511E-09	4.03695E-08	3.68772E-09

Bromine	kg	4.09E-08	3.30069E-08	5.86942E-10	4.92916E-09	4.85842E-10
Butane	kg	1.44E-06	2.30321E-10	7.79325E-07	1.51286E-08	6.45087E-07
Butane	kg	6.14E-07	4.10601E-07	2.51777E-08	1.06366E-07	2.08409E-08
Butene	kg	6.96E-08	6.24691E-08	4.3104E-10	5.24573E-09	3.56794E-10
Butyrolactone	kg	7.92E-07	7.9155E-07	6.05439E-18	1.50424E-17	5.0339E-18
Calcium	kg	4.55E-06	1.21742E-07	2.3876E-06	6.13406E-08	1.97634E-06
Carbon-14	Bq	1.359823	0.801107124	0.224004021	0.102198267	0.18541945
Carbon dioxide, biogenic	kg	0.001105	0.000758657	2.57378E-05	5.32885E-05	2.13045E-05
Carbon dioxide, fossil	kg	0.094652	0.004632921	0.047178542	0.002134488	0.039052064
Carbon dioxide, land transformation	kg	8.85E-06	8.32277E-06	1.09798E-07	1.84435E-07	9.0885E-08
Carbon disulfide	kg	5.7E-06	5.68488E-06	6.4273E-10	1.63847E-08	5.3202E-10
Carbon monoxide, biogenic	kg	1.24E-06	8.74646E-07	4.93346E-09	3.53943E-07	4.08367E-09
Carbon monoxide, fossil	kg	0.000215	8.51354E-05	3.72222E-05	6.14569E-05	3.08107E-05
Cerium-141	Bq	1.91E-07	1.61258E-07	6.58534E-09	8.78697E-09	5.45102E-09
Cesium-134	Bq	9.16E-09	7.72321E-09	3.15395E-10	4.20839E-10	2.61069E-10
Cesium-137	Bq	1.62E-07	1.36907E-07	5.59094E-09	7.46011E-09	4.6279E-09
Chlorine	kg	3.19E-06	3.16612E-06	4.07131E-09	1.57162E-09	3.37003E-09
Chloroform	kg	3.28E-06	3.27854E-06	3.17773E-10	7.20778E-12	2.63037E-10
Chromium	kg	1.15E-07	8.477E-08	1.62955E-08	5.61676E-10	1.34886E-08
Chromium-51	Bq	1.22E-08	1.03334E-08	4.21987E-10	5.63067E-10	3.493E-10
Cobalt	kg	1.13E-08	3.00774E-10	5.89879E-09	1.51547E-10	4.88272E-09
Cobalt-58	Bq	1.71E-08	1.43896E-08	5.87635E-10	7.84094E-10	4.86415E-10
Cobalt-60	Bq	1.51E-07	1.27119E-07	5.19121E-09	6.92675E-09	4.29702E-09
Copper	kg	1.21E-06	1.21153E-06	7.25426E-10	1.61903E-09	6.00471E-10
Cumene	kg	5.89E-08	5.11306E-08	7.41281E-10	6.28606E-09	6.13596E-10
Cyanide	kg	2.2E-08	1.83268E-08	1.79288E-11	8.49246E-11	1.48406E-11
Dinitrogen monoxide	kg	2.29E-06	4.00636E-07	9.39375E-07	9.42462E-08	7.77568E-07
Ethane	kg	2.13E-06	3.40826E-10	1.153E-06	2.23825E-08	9.54394E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	7.87E-07	7.87154E-07	1.13718E-16	2.82288E-16	9.40753E-17
Ethane, 1,2-dichloro-	kg	2.14E-07	2.00238E-07	3.78918E-10	1.31572E-08	3.13649E-10
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	4.14E-08	3.36041E-10	2.2202E-08	4.74452E-10	1.83777E-08

Ethane, hexafluoro-, HFC-116	kg	3.97E-08	2.15437E-08	3.50173E-11	1.81379E-08	2.89856E-11
Ethanol	kg	2.46E-08	1.84461E-08	1.19198E-09	3.1336E-09	9.86661E-10
Ethene	kg	1.88E-07	1.21678E-07	3.82815E-09	5.67637E-08	3.16876E-09
Ethene, chloro-	kg	1.06E-07	9.95721E-08	9.40677E-12	6.67004E-09	7.78646E-12
Ethylene oxide	kg	1.06E-08	6.66378E-09	1.06247E-11	3.90636E-09	8.79462E-12
Ethyne	kg	8.76E-07	8.7533E-07	1.19648E-10	3.42466E-12	9.90388E-11
Fluorine	kg	8.53E-07	2.28138E-08	4.47425E-07	1.14949E-08	3.70356E-07
Fluosilicic acid	kg	4.65E-08	2.51788E-08	4.09258E-11	2.11983E-08	3.38763E-11
Formaldehyde	kg	1.34E-07	1.03005E-07	2.94756E-09	2.3719E-08	2.43984E-09
Formic acid	kg	1.61E-09	1.5772E-09	2.30719E-12	2.38548E-11	1.90978E-12
Furan	kg	4.58E-10	4.47852E-10	6.747E-13	6.77407E-12	5.58483E-13
Heat, waste	MJ	2.355628	0.314144814	1.071052468	0.065859882	0.886564264
Helium	kg	1.84E-08	1.0185E-08	8.2002E-10	3.15364E-09	6.78772E-10
Heptane	kg	7.51E-08	4.31424E-08	4.30968E-09	1.35201E-08	3.56734E-09
Hexane	kg	1.23E-06	1.97152E-10	6.67392E-07	1.29557E-08	5.52434E-07
Hydrocarbons, aliphatic, alkanes, cyclic	kg	1.19E-08	6.64338E-09	1.02552E-11	5.26282E-09	8.48872E-12
Hydrocarbons, aliphatic, alkanes, unspecified	kg	1.68E-07	1.28645E-07	5.35834E-09	2.54938E-08	4.43537E-09
Hydrocarbons, aliphatic, unsaturated	kg	5.69E-08	4.55657E-08	6.12886E-10	7.76865E-09	5.07316E-10
Hydrocarbons, aromatic	kg	1.11E-05	4.73249E-09	6.01711E-06	1.17129E-07	4.98067E-06
Hydrocarbons, chlorinated	kg	2.2E-07	2.05736E-07	6.32928E-13	1.37753E-08	5.23906E-13
Hydrogen	kg	1.7E-06	4.59485E-07	4.58556E-07	5.99349E-08	3.7957E-07
Hydrogen-3, Tritium	Bq	213.5203	4.671706437	112.6014201	2.768393454	93.20588682
Hydrogen chloride	kg	1.11E-05	1.95809E-06	4.72376E-06	3.8036E-07	3.91009E-06
Hydrogen sulfide	kg	2.93E-08	2.45581E-08	7.38822E-10	1.82005E-09	6.11561E-10
Iodine	kg	2.16E-08	1.75862E-08	3.17223E-10	2.47422E-09	2.62582E-10
Iodine-129	Bq	0.001205	0.000811033	0.000133107	0.000103073	0.00011018
Iodine-131	Bq	0.064013	0.037401487	0.011834673	0.002562211	0.009796157
Iodine-133	Bq	0.085887	5.38275E-06	0.046496187	0.000897691	0.038487244
Iodine-135	Bq	0.186279	9.94967E-06	0.100846502	0.001946927	0.083475747
Iron	kg	1.52E-05	4.0717E-07	7.98543E-06	2.05156E-07	6.60994E-06
Krypton-85	Bq	0.339671	0.295945963	0.003326219	0.018518	0.00275328

Krypton-85m	Bq	0.016795	0.014319405	0.000443376	0.000818875	0.000367005
Krypton-87	Bq	0.006653	0.005727403	0.000126628	0.000341377	0.000104817
Krypton-88	Bq	0.006566	0.005629293	0.000145977	0.000329653	0.000120832
Krypton-89	Bq	0.001689	0.001432506	5.15138E-05	7.99651E-05	4.26406E-05
Lanthanum-140	Bq	6.74E-08	5.68514E-08	2.32166E-09	3.09784E-09	1.92176E-09
Lead	kg	1.1E-06	1.09564E-06	2.20802E-09	2.59166E-09	1.82769E-09
Lead-210	Bq	0.041812	0.006555664	0.018520643	0.001146439	0.015330472
m-Xylene	kg	1.01E-09	8.47911E-10	2.97629E-11	5.35901E-11	2.46363E-11
Magnesium	kg	1.4E-06	3.73409E-08	7.32332E-07	1.88146E-08	6.06188E-07
Manganese-54	Bq	6.27E-09	5.29183E-09	2.16104E-10	2.88353E-10	1.7888E-10
Mercury	kg	4.98E-09	3.91342E-09	4.39805E-10	1.9643E-10	3.64049E-10
Methane, biogenic	kg	1.42E-05	7.72478E-07	7.17292E-06	2.75131E-07	5.93739E-06
Methane, chlorodifluoro-, HCFC-22	kg	1.12E-05	1.1166E-05	2.84691E-15	4.22517E-15	2.35575E-15
Methane, dichloro-, HCC-30	kg	9.78E-08	9.77427E-08	9.5483E-12	2.49216E-13	7.90361E-12
Methane, dichlorodifluoro-, CFC-12	kg	2.67E-07	2.66866E-07	1.00254E-14	5.1521E-10	8.29851E-15
Methane, dichlorofluoro-, HCFC-21	kg	2.24E-09	2.23951E-09	3.23543E-19	8.03147E-19	2.67657E-19
Methane, fossil	kg	0.000502	3.59636E-07	0.000271706	5.46437E-06	0.000224905
Methane, monochloro-, R-40	kg	3.84E-09	9.06503E-12	2.07256E-09	4.35257E-11	1.71556E-09
Methane, tetrachloro-, CFC-10	kg	3.27E-07	3.26773E-07	4.2453E-11	4.98838E-12	3.51405E-11
Methane, tetrafluoro-, CFC-14	kg	3.58E-07	1.93895E-07	3.15158E-10	1.63242E-07	2.60872E-10
Methane, trifluoro-, HFC-23	kg	7.13E-07	7.12571E-07	1.02945E-16	2.55545E-16	8.51628E-17
Methanol	kg	1.27E-06	1.26397E-06	2.92093E-09	3.77825E-09	2.4178E-09
Methyl acrylate	kg	2.15E-09	2.15247E-09	1.14806E-15	2.84887E-15	9.50307E-16
Methyl amine	kg	2.85E-07	2.85327E-07	4.30495E-17	4.25301E-16	3.56423E-17
Molybdenum	kg	2.44E-08	6.51676E-10	1.27807E-08	3.28353E-10	1.05792E-08
Monoethanolamine	kg	1.77E-08	1.63927E-08	7.01872E-10	2.6584E-11	5.80975E-10
Nickel	kg	8.6E-07	8.52146E-07	1.39334E-09	2.53567E-09	1.15334E-09
Nitrate	kg	1.2E-07	3.21234E-09	6.30006E-08	1.61857E-09	5.21488E-08
Nitrogen oxides	kg	0.000135	4.61831E-05	3.75969E-05	1.07518E-05	3.11209E-05
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	3.77E-05	7.88705E-06	1.57594E-05	9.34975E-07	1.30449E-05

Noble gases, radioactive, unspecified	Bq	12233.91	7794.036593	1632.419428	997.5285553	1351.23607
Ozone	kg	3.99E-07	3.14143E-07	3.47186E-09	6.24076E-08	2.87383E-09
PAH, polycyclic aromatic hydrocarbons	kg	1.39E-07	6.86231E-08	6.9383E-09	5.72763E-08	5.74319E-09
Particulates, < 2.5 um	kg	2.72E-05	2.23683E-05	1.48308E-06	1.52673E-06	1.22762E-06
Particulates, > 10 um	kg	8.25E-05	3.23094E-05	2.18603E-05	8.86363E-06	1.80949E-05
Particulates, > 2.5 um, and < 10um	kg	2.43E-05	1.94108E-05	2.67113E-07	4.14312E-06	2.21103E-07
Pentane	kg	1.79E-06	2.86706E-10	9.67845E-07	1.87882E-08	8.01134E-07
Phenol	kg	3.92E-08	3.55162E-08	8.65891E-12	3.59719E-09	7.16742E-12
Phenol, pentachloro-	kg	1.07E-09	1.04368E-09	2.74493E-12	1.27068E-11	2.27212E-12
Phosphorus	kg	4.59E-08	4.52506E-08	1.29208E-10	2.22592E-10	1.06952E-10
Phosphorus trichloride	kg	2.35E-05	2.34945E-05	x	x	x
Polonium-210	Bq	0.061225	0.010263071	0.026585869	0.001916801	0.022006467
Potassium	kg	2.4E-06	6.40423E-08	1.256E-06	3.22683E-08	1.03965E-06
Potassium-40	Bq	0.007596	0.00109	0.003382889	0.000265862	0.002800188
Propane	kg	1.1E-06	1.75464E-10	5.93331E-07	1.1518E-08	4.9113E-07
Propane	kg	4.65E-07	2.99895E-07	2.19917E-08	7.65211E-08	1.82036E-08
Propene	kg	1.92E-07	1.71398E-07	1.57652E-09	1.54436E-08	1.30496E-09
Propene	kg	6.24E-09	5.28026E-09	5.92117E-11	6.58803E-10	4.90125E-11
Propionic acid	kg	2.49E-08	3.97785E-12	1.34657E-08	2.61401E-10	1.11462E-08
Protactinium-234	Bq	0.005041	0.000112632	0.002656955	6.6045E-05	0.002199296
Radioactive species, other beta emitters	Bq	0.006827	0.000545344	0.0033756	9.7206E-05	0.002794155
Radium-226	Bq	0.14731	0.008706809	0.074533421	0.002089945	0.06169508
Radium-228	Bq	0.001337	0.000399448	0.000458155	7.89802E-05	0.000379238
Radon-220	Bq	0.190932	0.048650403	0.070781353	0.010317279	0.058589303
Radon-222	Bq	535790.4	14322.55159	280894.5445	7227.290708	232510.6121
Scandium	kg	5.01E-08	1.34018E-09	2.62837E-08	6.75262E-10	2.17564E-08
Selenium	kg	5.98E-08	4.98183E-08	5.11665E-09	5.04343E-10	4.23531E-09
Silicon	kg	3.12E-06	8.33777E-08	1.63521E-06	4.20106E-08	1.35354E-06
Silicon tetrafluoride	kg	1.52E-09	1.5141E-09	3.84379E-13	5.55207E-14	3.1817E-13
Silver	kg	2.1E-09	5.60626E-11	1.0995E-09	2.82476E-11	9.10113E-10
Silver-110	Bq	1.62E-09	1.36785E-09	5.58594E-11	7.45344E-11	4.62376E-11

Sodium	kg	8.23E-07	2.19953E-08	4.31374E-07	1.10825E-08	3.5707E-07
Strontium	kg	5.09E-08	1.36064E-09	2.6685E-08	6.85572E-10	2.20885E-08
Sulfate	kg	2.09E-05	1.62059E-05	1.34426E-06	8.07959E-08	1.11271E-06
Sulfur dioxide	kg	0.000864	8.58038E-06	0.00045993	1.4926E-05	0.000380707
Sulfur hexafluoride	kg	4.4E-09	3.8127E-09	4.107E-11	2.75382E-10	3.39957E-11
Thorium-228	Bq	0.000829	0.000219974	0.000302871	4.37043E-05	0.000250702
Thorium-230	Bq	0.019894	0.004072955	0.008518082	0.000216935	0.007050847
Thorium-232	Bq	0.001033	0.000392883	0.000304385	6.50366E-05	0.000251955
Thorium-234	Bq	0.005045	0.000112654	0.002658704	6.60821E-05	0.002200744
Tin	kg	5.48E-08	5.46104E-08	9.07963E-11	6.08676E-11	7.51567E-11
Titanium	kg	9.15E-07	2.44506E-08	4.79527E-07	1.23197E-08	3.96929E-07
Toluene	kg	4.8E-06	2.37619E-09	2.59705E-06	5.06733E-08	2.14971E-06
Tungsten	kg	5.66E-09	1.5141E-10	2.96946E-09	7.62892E-11	2.45797E-09
Uranium-234	Bq	0.053668	0.004954721	0.026238077	0.000670655	0.021718583
Uranium-235	Bq	0.002342	6.261E-05	0.00122791	3.15936E-05	0.001016404
Uranium-238	Bq	2.42E-07	1.41772E-07	5.4296E-08	1.04823E-09	4.49435E-08
Uranium-238	Bq	0.055023	0.005801589	0.026408909	0.000821678	0.021859989
Uranium alpha	Bq	0.223719	0.006030361	0.11725564	0.003022716	0.09705842
Vanadium	kg	1.04E-07	7.48546E-08	7.71904E-09	1.15673E-08	6.38944E-09
water	kg	0.000178	0.000173023	2.63021E-06	4.74559E-07	2.17716E-06
water	kg	6.58E-08	6.57824E-08	1.6006E-12	4.28617E-12	1.3249E-12
Xenon-131m	Bq	0.030634	0.026326596	0.000623527	0.00155785	0.000516125
Xenon-133	Bq	0.977239	0.838065165	0.021466966	0.049149874	0.017769293
Xenon-133m	Bq	0.004122	0.003579136	5.10127E-05	0.000221009	4.22258E-05
Xenon-135	Bq	0.40047	0.343572076	0.008677056	0.020183143	0.007182438
Xenon-135m	Bq	0.236479	0.202660261	0.005319516	0.011850326	0.004403232
Xenon-137	Bq	0.004631	0.003927161	0.000141075	0.000219262	0.000116775
Xenon-138	Bq	0.040656	0.034621828	0.001110224	0.001969462	0.000918989
Xylene	kg	2.81E-06	1.79791E-09	1.51853E-06	2.97053E-08	1.25696E-06
Xylene	kg	3.61E-08	2.13049E-08	2.40035E-09	6.21648E-09	1.98689E-09
Xylene	kg	2.5E-07	1.97242E-07	2.86514E-09	3.43203E-08	2.37162E-09
Zinc	kg	4.06E-07	3.87475E-07	1.69861E-09	1.53204E-08	1.40602E-09

Zinc-65	Bq	3.13E-08	2.64234E-08	1.07906E-09	1.43982E-09	8.93194E-10
Zirconium-95	Bq	3.06E-08	2.58279E-08	1.05474E-09	1.40737E-09	8.73063E-10