A CRITICAL EVALUATION OF CATHODE MATERIALS FOR LITHIUM-ION ELECTRIC VEHICLE BATTERIES

Reinhardt, Robert; Amante García, Beatriz; Canals Casals, Lluc; Gassó Domingo, Santiago
Universitat Politècnica de Catalunya

There has been an intensive research and development focus on Lithium-ion batteries, which has revolutionized the electric vehicle market due to the batteries' high energy and power density, longer lifespan and increased safety than comparable rechargeable battery technologies.

The performance of lithium-ion batteries is achieved by packaging design, electrolyte and electrodes material's selection. This study will focus on cathode materials as they currently need to overcome critical challenges. In fact, cathode materials affect energy density, rate capability and working voltage that led to the cathode currently costing twice as much as the anode.

For this reason this study will review the cathode materials for electric vehicle lithium-ion batteries under economic and environmental perspectives. Further, actual installed lithium-ion batteries within the commercial electric vehicle market will be compared and measured against suggested economic and environmental sound materials.

Keywords: Electric vehicle; Lithium-ion; Battery; Cathode

ANÁLISIS DE DIFERENTES MATERIALES PARA EL CÁTODO UTILIZADO EN BATERÍAS DE LITIO-ION DE VEHÍCULOS ELÉCTRICOS

En los últimos años se han ampliado las investigaciones y el desarrollo en baterías de litio-ion, que ha revolucionado el mercado de vehículos eléctricos. Estas investigaciones han revertido en una mejora de la capacidad, densidad de potencia, vida útil y seguridad de las baterías de litio-ion, que las hacen mejores que otras tecnologías de baterías.

El rendimiento de las baterías de litio-ion se logra mediante el diseño del packaging, electrolitos y la selección de materiales de los electrodos. Este estudio se centrará en los diferentes materiales utilizados para los cátodos, ya que actualmente el coste del mismo es dos veces al del ánodo. De hecho, los materiales de cátodo afectan a la densidad de energía, capacidad y voltaje.

Por eso en este estudio se analizarán y compararán los materiales utilizados en el cátodo que cumplen con las prestaciones necesarias para su utilización en las baterías de litio-ion en el vehículo eléctrico tanto desde el punto de vista económico como ambiental.

Palabras clave: coche eléctrico; batería de litio-ion; cátodo

Correspondencia: Robert Reinhardt - rr.robert.reinhardt@gmail.com

Agradecimientos: The authors would like to thank the Universitat Politècnica de Catalunya (UPC), the ReViBe project TEC2015-63899-C3-1-R funded by Spanish government and the scholarship program FI-DGR 2016 by Agència de Gestió de les Ajudes Unisersitàries i d'Investigació (AGAUR), for giving us the opportunity to investigate in such an interesting and innovative field.

1. Introduction

For more than 20 years, lithium-ion batteries (LIBs) have been the predominant power source of choice for portable consumer electronics such as mobile phones and laptops as they offer higher energy densities and a longer lifespan compared to other rechargeable battery systems (Tarascon & Armand 2001; Deng 2015). In recent years, LIBs have been increasingly applied to electric vehicles[1] (EVs) and stationary storage for electricity produced by renewable sources such as wind and solar. Although LIBs have been successful on a commercial scale, in the context of EVs, there are still major challenges that must be addressed with regards to material costs, environmental impacts, cycle life, safety, energy and power that are all directly relate to the selected combination of battery materials (Dinger et al. 2010). In particular, there are issues around EV limited driving ranges and high costs of present commercially installed lithium-ion battery packs (Bonges & Lusk 2016). Hence the EV industry presently desires an augmentation of capacity and power, increase in the battery's lifetime and dramatically reduced battery pack costs. Besides this, as EVs have null tailpipe emissions that can substantially help fight issues around pollution, one might conclude that they are no issues around environmental impacts (Nealer, Reichmuth & Anair, 2015). In fact, during EV manufacturing processes the environmental impact is higher than that of internal combustion engine vehicles (ICEVs), with the battery production phase contributing significantly to emitted greenhouse gases (GHG) (Notter et al. 2010).

This is why there has been continuous research focus on all material aspects of LIBs such as electrodes, electrolyte and separator (Armand & Tarascon 2008; Whittingham 2008; Amine, Kanno & Tzeng 2014). In particular, the limited theoretical capacity and thermodynamics of the available cathode material in a typical LIB is a critical component with regards to the working voltage, energy density, rate capability and battery cost (Xu et al. 2013). In previous years, the primary research focus has been on cathode material cost reductions as it costs nearly twice as much as the anode material and has the highest weight of all materials within a typical LIB (Gaines & Cuenca 2000; Whittingham, 2008). Besides this, the gravimetric capacity of common cathode materials (e.g. $LiCoO_2$) is one-half that of anode materials (e.g. graphite) (Whittingham, 2004). Furthermore, cathode materials are a critical factor of energy density within a LIB, as it has a lower specific capacity than the most common anode material, graphite (372 mAh/g), to which it must be matched (Doeff 2012).

All these considerations led to the development of several types of cathode materials as there is not yet one ideal material that can meet requirements for all applications while being economical and environmentally friendly at the same time (Whittingham 2008; Doeff 2012). Consequently, the objective of this study is to evaluate present commercially available cathode materials for LIBs in EVs from an economic and environmental perspective.

2. Methodology

This study makes use of a three level approach whereby first of all, the characteristics of common cathode materials for LIBs are categorized and subsequently this knowledge is used to assess economic and environmental implications. Finally, proposed economical and environmentally friendly cathode materials are compared with lithium-ion battery packs that are commercially available in EV models today.

At the first level, present common cathode materials for LIBs are identified and their characteristics are summarized with respect to their specific energy and power, cycle life, voltage and commercial applications. Data were collected from selected available literature

---

[1] Including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)

on LIBs and are summarized in Table 1. It is necessary to differentiate and comprehend that LIB technologies incorporate a variety of alternative chemistries (e.g. $LiFePO_4$, $LiMn_2O_4$), electrode designs, different shapes (pouch, cylindrical, prismatic) and capacities of the individual cells that make up the pack; depending on the potential combination, there is a direct impact on performance, weight, costs and degradation rates (Sakti et al. 2015).

Table 1: Existing literature on cathode materials in lithium-ion batteries

Reference	Research Focus
[1] (Deng 2015)	Basics, progresses and challenges of lithium-ion batteries
[2] (Liu, Neale & Cao 2015)	Understanding electrochemical potentials of cathode materials in rechargeable batteries
[3] (Amirault et al. 2009)	Electric vehicle battery landscape: opportunities and challenges
[4] (Dinger et al. 2010)	Batteries for electric vehicles: outlook 2020
[5] (Nitta et al. 2015)	Lithium-ion battery materials: present and future
[6] (Lu et al. 2013)	A review on the key issues for lithium-ion battery management in electric vehicles
[7] (Huat, Yonghuang & Tay 2015)	Integration issues of lithium-ion battery into electric vehicles battery pack
[8] (Nelson et al. 2011)	Modelling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles
[9] (Hakimian et al. 2015)	Economic analysis of lithium-ion battery manufacturing
[10] (Casals et al. 2015)	Second life of electric vehicle batteries: relation between materials degradation and environmental impact
[11] (Scrosati & Garche 2010)	Lithium batteries: Status, prospects and future
[12] (Xu et al. 2012)	Recent progress in cathode materials research for advanced lithium ion batteries
[13] (Etacheri et al. 2011)	Challenges in the Development of Advanced Li-Ion Batteries: A Review
[14] (Amine et al. 2014)	Progress, challenges, and future directions of Rechargeable lithium batteries
[15] (Thackeray, Wolverton & Isaacs 2012)	Electrical energy storage for transportation - approaching the limits of, and going beyond, lithium-ion batteries
[16] (Goodenough & Park 2013)	The Li-ion rechargeable battery: A perspective
[17] (Armand & Tarascon 2008)	Building better batteries
[18] (Manthiram 2011)	Materials challenges and opportunities for lithium ion batteries
[19] (Whittingham 2008)	Materials Challenges Facing Electrical Energy Storage
[20] (Whittingham 2004)	Lithium batteries and cathode materials

At the second level, the previously identified cathode materials are analyzed and compared under economic and environmental perspectives. At the economic perspective, this study evaluates cathode material cost data from two well-established cost evaluations models, Battery Performance and Cost model (BatPac) and the PHEV cost assessment study (TIAX), as presented in Table 2 (Barnett et al. 2010; Nelson et al. 2011). The BatPac model studies cell and component masses, pack-level performance with previously modelled cell chemistries and delivers a determination of cost vs. performance characteristics (Nelson et al. 2011).

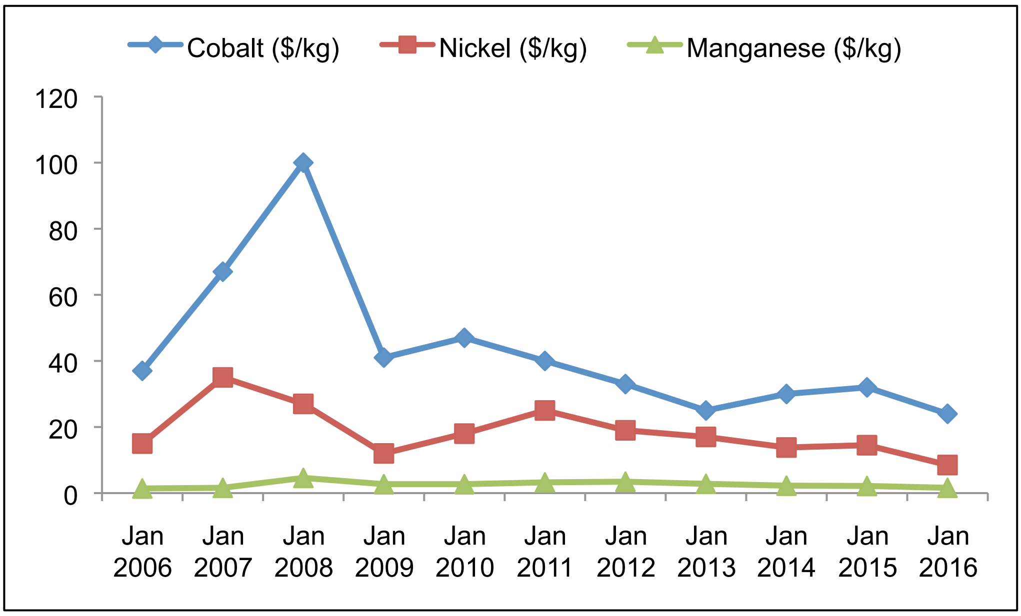
Table 2: Details of stated costs for cathode materials

Cathode Material	Abbreviation	Unit	BatPac 2010	TIAX 2010[1]	TIAX 2013[1] (update)
Phospholivine cathode	LFP	$/kg	20	15 – 20 – 25	15 – 18 – 20
Manganese spinel cathode	LMO	$/kg	10	12 – 16 – 20	12 – 16 – 20
Layered oxide cathode$_2$	NCA	$/kg	33	34 – 40 – 54	36 – 40 – 48
Layered oxide cathode	NMC	$/kg	31	40 – 45 – 53	33 – 36 – 45

$_1$ Cost represents range of values possible

The TIAX study on the other hand examines the manufacturing costs of battery packs for PHEVs whereby the major focus lies on the material selection trade-offs and power/energy optimization and capacity fade effects (Barnett et al. 2010). Both studies are evaluating costs of common cathode materials lithium iron phosphate (LFP), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). Furthermore, the fluctuations of historical raw material prices, as shown in Figure 1, are perceived in both studies. The BatPac model uses a co-precipitation of Nickel, Manganese and/or Cobalt based off a correlation with Cobalt 44 $/kg and the TIAX study applies average traded metal prices of the last 25 years with 95% confidence intervals of Cobalt 44.4±18.3 $/kg and Nickel 14.9±7.6 $/kg (Barnett et al. 2010; Nelson et al. 2011).

Figure 1: Historical 10-year prices (2006-2016) of Cobalt, Nickel and Manganese[2]



---

[2] Historical 10-year price data taken from the mining knowledge website www.infomine.com

Both studies use different input data for their cost models such as pack energy requirements, power input/output, production volumes, battery chemistries, material performance and fluctuations in raw material prices. Hence, this study determines the average cost for each cathode material based on cost data from both studies.

In 2013, TIAX published a revised study with updated cost data for the raw materials Cobalt and Nickel according to their trading prices between 2011-2012, respectively 31±5 $/kg and 20.5±4.5 &/kg (Barnett et al. 2013). Thus, the average cathode material costs are calculated using identical cost data from the BatPac model, but substituting the TIAX cost values from 2010 with their updated data from 2013 (Nelson et al. 2011; Barnett et al. 2013). The results of the calculated average costs for each cathode material under both scenarios are put in a graph and their implications are evaluated in Chapter 3.1.

At the environmental perspective, the key parameter of discussion is on GHG emissions during battery manufacturing processes as the emitted CO_2 levels during EV production currently outweigh ICEV production emissions (Nealer, Reichmuth & Anair, 2015). The majority of the emitted GHG result from battery manufacturing processes, of which the selected cathode material composition used for a desired LIBs contributes significantly; consequently, data on CO_2 emissions of the cathode materials LFP, LMO and NMC were collected from available life-cycle-analysis (LCA) studies (Majeau-Bettez, Hawkings & Stromman 2011; Notter et al. 2010; Frischknecht 2011) and are discussed in Chapter 3.2. Data on emitted CO_2 levels and energy flows of all four commercially available cathode materials following the same equations are scarce and thus subject to uncertainties. This is why the presented results should therefore be interpreted as an estimation of emissions.

At the third level, the evaluated economic and environmentally sound cathode materials for LIBs are compared to cathode materials in LIBs for commercial EVs. As the battery technology and hence the price and overall performance of a vehicle is the key selling point of any EV manufacturer, data on specific cathode material compositions in commercial EVs are generally not published by EV companies and were therefore collected from scientific journals and put in a table. Consequently, the discussion aims to critically analyze, which cathode materials are preferred amongst key industry players and how this affects overall vehicle performance and competitive advantage over other industry players.

3. Cathode Materials

In LIBs, the most common cathode materials are lithium cobalt oxide (LCO), LFP, LMO, NCA and NMC, as presented in Table 3. The key requirements for cathode materials for LIBs are a high free energy of reaction with lithium as well as an integration of large volumes of lithium (Deng 2015). The first commercial available cathode material, LCO, was introduced in 1991 and it has since been highly successful in commercial portable consumer electronics due to the material's high specific energy (150-200 Wh/kg) (Armand & Tarascon 2008). EV manufacturer Tesla used LCO batteries within their early Tesla Roadster model but soon switched to more stable chemistries due to low capacity, toxicity, poor safety and high cost of LCO (Amirault et al. 2009). As a result of these risks, LCO became undesirable for applications in EVs and global battery manufacturers have since opted for enhanced cheaper and safer cathode materials for EVs.

Table 3: Characteristics of commercially available cathode materials in lithium ion batteries

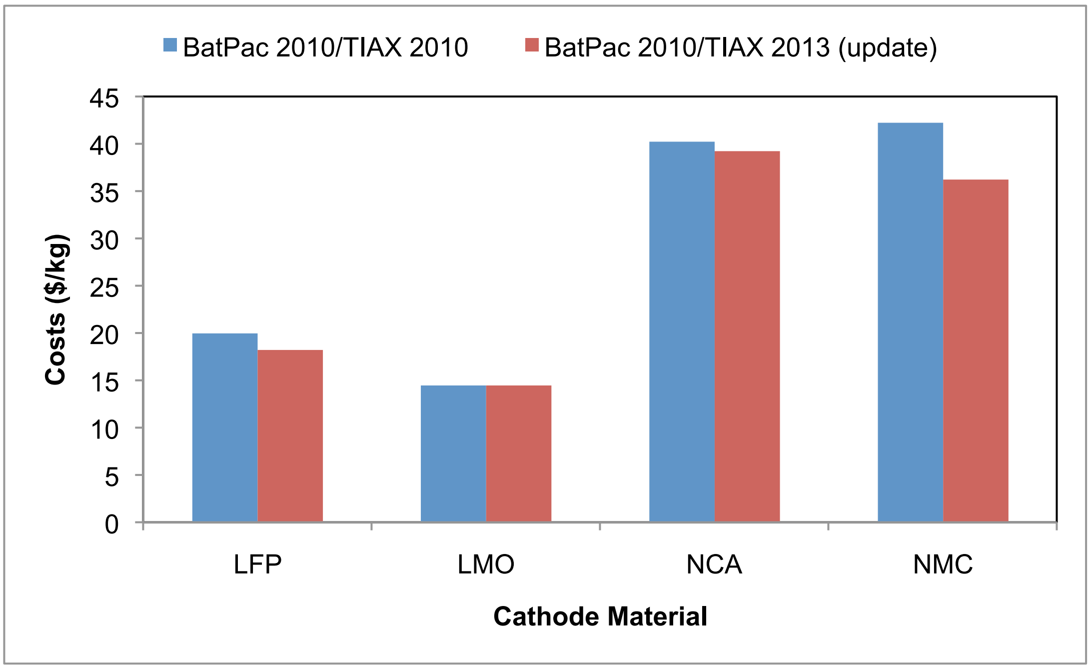
Cathode	$LiCoO_2$ Lithium Cobalt Oxide	$LiFePO_4$ Lithium Iron Phosphate	$LiMn_2O_4$ Lithium Manganese Oxide	$LiNiMnCoO_2$ Lithium Nickel Manganese Cobalt Oxide	$LiNiCoAlO_2$ Lithium Nickel Cobalt Aluminum Oxide
Abbreviation	LCO	LFP	LMO	NMC	NCA
Anode	Graphite	Graphite	Graphite	Graphite	Graphite
Type	Metal Oxides				
Specific energy Wh/kg	150-200	80-120	100-130	160-220	180-250
Cycle life	300-500	1000-2000	300-700	1000-1500	500
Voltage (V)	3.6	3.2/3.3	3.7	3.6/3.7	3.6
Applications	Portable consumer electronics, Used in early Tesla Roadster	Power tools, Electric powertrains	Power tools, Electric powertrains, Medical devices	Electric powertrains, E-bikes, medical devices, industrial	Electric powertrains, medical devices, industrial
References (see Table 1)	[1]-[11], [11], [14]-[15], [18]-[20]	[2]-[9], [10]-[12], [13]-[15], [18]-[20]	[3]-[9], [10]-[11], [13]-]15], [18]-[20]	[3],[4]-[6], [7]-[9], [10], [11], [13]-[14]	[3],[4]-[6], [7]-[9], [10], [15]

3.1 Economic perspectives of cathode materials for EVs

Cost reductions in LIBs for EVs can be achieved first and foremost by substituting battery materials, economies of scale in the production process and/or through the establishment of new material supplies; in particular, the cost of cathode materials can be decreased either by material substitution or by finding ways to attain the same materials at a lower cost (Gaines & Cuenca 2000). As cathode materials incorporate raw material transition metals such as Cobalt, Nickel and Manganese, of which some have shown substantial trading price inconsistencies over recent years, the price of specific battery materials are of some debate. In determining the average costs for the studied cathode materials, the results show that the impact of volatile raw material prices is evident, as presented in Figure 2.

First and foremost, the vast average price variances of the different cathode materials are visible. The NCA/NMC cathodes cost on average about twice as much as LFP/LMO based LIBs, respectively 40.25/42.25 $/kg and 20/14.5 $/kg. This is due to the high contents of the expensive raw materials Cobalt and Nickel in the NCA/NMC based LIBs. The market price for Cobalt and Nickel has varied dramatically in the last 25 years and thus reducing the volumes in the cathode materials will lead to a decrease of overall cathode prices and less price volatilities. In fact, the market price for Cobalt and Nickel has substantially dropped (Figure 1) since the BatPac and TIAX study were published in 2010, reaching a historical 10-year low in April 2016, with Cobalt trading for 22.50 $/kg and Nickel for 8.28 $/kg (Figure 1). Hence, in evaluating the updated TIAX cathode material costs, which are based on raw materials prices between 2011-2012, it becomes evident that decreased raw material prices have a direct impact on final cathode costs, as shown in Figure 2.

Figure 2: Average costs of common cathode materials in lithium-ion batteries



This resulted in moderate to high cost reductions for the NCA/NMC cathodes, declining by 1 $/kg / 6 $/kg respectively. Furthermore, it is assumed that these reductions were also a result of economies of scale as NCA and NMC based LIBs have been increasingly applied to EVs due to their high operating voltage (3.6V) and excellent specific energies, in that order 160-220 Wh/kg and 180-250 Wh/kg (Liu, Neale & Cao 2015; Nitta et al. 2015).

The comparison of the LFP/LMO cathodes reveals that LFP is more cost extensive as a result of the increased complexity in the manufacturing process (e.g. carbon coating) to LMO, which is relatively easy to manufacture (Nelson et al. 2011). Nevertheless, both cathodes include inexpensive earth abundant elements such as Iron and Manganese in comparison to the rare earth and expensive Cobalt and Nickel elements in NCA/NMC based LIBs. Therefore, cathode materials based on abundant elements such as Manganese should be the prevailing transition metal if a low cathode material, and thus a cost-effective LIB, is desired. But, it must also be underlined that if EV manufacturers seek low-cost cathode materials, they have to reach a compromise between overall LIB pack cost and performance of the battery. This is underlined with the low-cost lithium manganese oxide cathode ($LiMn_2O_4$) offering specific energy of 100-130 Wh/kg, in comparison to the high-cost lithium nickel cobalt aluminum oxide cathode ($LiNiCoAlO_2$) with specific energy of 180-250 Wh/kg (Lu et al. 2013).

3.2 Environmental perspectives of cathode materials for EVs

With regards to GHG during battery production processes, Aguirre et al. (2012) found that total BEV lifetime CO_2 equivalent emissions accumulate to 31,821 kg CO_2 equivalent, of which 24% are caused by battery manufacturing processes. Depending on the choice of materials, including the choice of cathode material, this directly affects emitted GHG, as presented in Table 4. It is evident that the cathode chemistries LMO/LFP are the most environmentally sound material choice with CO_2 equivalent emissions of 52 kg/kW and 166 kg/kWh compared to NMC based batteries with 200 kg/kWh. LFP achieved superior emissions to NMC due to the use of less environmental intensive materials (Majeau-Bettez, Hawkings & Stromman 2011). kg CO_2-equivalent emissions for each cathode material chemistry is directly related to whether they include scare and valuable raw materials such as Cobalt and to a lesser extent Nickel or earth abundant materials such as Manganese. This is critical, as Nickel and/or Cobalt based cathode materials such as NMC/NCA, are becoming increasingly popular in EVs with no alternative more sustainable (not dependent on materials such as Cobalt) EV battery technology arriving at market soon, as further discussed in the next chapter.

Table 4: CO_2-equivalent emissions of cathode material based Li-ion battery production

Reference	CO_2- equivalents kg/kWh battery	Cathode chemistry studied
Notter et al. 2010	52	LMO
Frischknecht 2011	134	Not specified
Majeau-Bettez, Hawkings & Stromman 2011	200	NMC
Majeau-Bettez, Hawkings & Stromman 2011	166	LFP

Gaines & Nelson (2009) estimated cumulative demands of cathode materials needed by 2050 for light-duty EV LIBs in the United States (U.S.), on the world reserve bases (million tons) of Cobalt (13 million tons), Nickel (150 million tons) and Manganese (5,200 million tons). It was concluded that in order to meet 2050 demands, 9% of Cobalt, 4% of Nickel and 0.12% of Manganese world reserve bases are required. This is a critical issue because prospective EV adoption rates and the demand for critical raw materials such as Cobalt will accelerate simultaneously. Even though trading prices of Cobalt and Nickel are currently low, if the demand increases these metals will become gradually rarer and hence prices will increase radically. Further, EV LIB manufacturers are importing materials (e.g. Cobalt) from leading raw material suppliers such as Russia. All of these factors indicate that there must be more aggressive recycling efforts on critical materials such as Cobalt and Nickel, which are today often motivated merely by their high economic values with some degree of disregard of how to handle other non-valuable and toxic materials. However, a comprehensive discussion of recycling issues around cathode materials from LIBs is not in the scope of this study.

What stands in a direct relationship to GHG emissions of cathode material production, is the use of more renewable energies for the entire LIB production process as well for the EV use-phase (e.g. charging). Both are strongly impacted by the electricity mix in a given country. This is further emphasized by Saevarsdottir et al. (2015) claiming that the electricity consumed during a typical LIB production process is decreased by 95% - 98% if production is moving away from less sustainable regions such as China to more sustainable energy countries such as Iceland[3].

Besides this, the in-use phase of EVs alongside a prospective uptake in sales on a global scale represents an important area for the power sector, as there will be additional electricity sales for utilities and an increased demand on the grid for charging infrastructures and related services. EVs can further serve as an energy storage channel in supplying power to

---

[3] Electricity production in Iceland causes a footprint of 18 to 23.5 g CO_2/kWh (Saevarsdottir et al. 2015)

utilities through smart grids (‘Vehicle-to-Grid’) by providing valuable services to the existing energy markets such as meet peak demands through selling the electricity from the battery while charging during off peak times. However, according to a study by the World Energy Council (2013), global total primary energy supply (by resource) will reach 17,208 million tons of oil equivalent by 2020, of which 76% originates from fossil fuels, 16% from renewables (other than large hydro), 2% from hydro (>10 megawatt) and 6% from nuclear sources. Without a doubt, this underlines that the full potential of overall energy efficiency still remains untapped, especially with the vast opportunities associated with EVs.

3.3 The commercial electric vehicle battery landscape

In the global automotive industry, leading EV manufactures are currently using different cathode materials for their LIB systems whereby LMO, NMC and NCA are the predominant materials, as presented in Table 5. In 2015, Navigant Research predicted that the global market for LIBs in light duty and medium/heavy duty vehicles will accelerate from $7.8 billion in 2015 to $30.6 billion in 2024, which underlines that this industry is currently undergoing an important economic transition.

Table 5: Cathode materials in selected commercial electric vehicles

Company	Model	EV Type	Cathode Material	Vehicle Cost[12] ($)	Driving Range[2] (km)	References
Nissan	Leaf S	BEV	LMO	29,000	135	Shen et al. 2016 Cluzel & Douglas 2012
Tesla	Model S	BEV	NCA	70,000-109,000	335-435	Lu et al. 2013 Nitta et al. 2015
General Motors	Chevrolet Volt	PHEV	LMO	33,000	61	Lu et al. 2013
Ford	Focus Electric	BEV	LMO	29,000	122	Shen et al. 2016
Fiat	Fiat 500	BEV	NMC	32,500	140	Shen et al. 2016
VW	E-Golf	BEV	NMC	29,000	134	Shen et al. 2016
BYD	E6	BEV	LFP	52,000	200	Lu et al. 2013
Renault	Zoe	BEV	NMC	25,000	210	Shen et al. 2016

[1] Vehicle costs based on commercial available electric vehicles on the U.S. market 2016

[2] Vehicle costs and driving range information from http://evobsession.com/electric-cars-2014-list/2 (updated 2016)

In evaluating Table 5, the most popular cathode materials in commercial EVs are LMO and NMC, followed by NCA and LFP. It is evident that the choice of cathode material chemistry has a direct impact on total vehicle cost and driving range.

The previously identified economical and environmentally sound cathode materials, LMO and to some extent LFP, are available in commercial EVs such as in the Nissan Leaf or Ford Focus Electric. The reason for the choice of these cathode materials is purely economic and less due to environmental concerns as a low cost vehicle towards consumers is desired.

Nevertheless, the different cathode materials used in LIBs for EVs underline that there are trade-offs between total vehicle costs (price impact of cathode material) and desired driving ranges (overall performance of cathode material), as discussed previously. Hence, most EV companies are currently selling their models at around $30,000 but with limited driving ranges of about 120-140 km in order to attract potential new customers. On the other hand, there are also market players that have aimed at substantially increased EV driving ranges with higher costs such as BYD (E6) offering 200 km and Tesla (Model S) offering up to 435 km driving ranges. This may result in competitive advantages with respect to driving ranges within the industry but the high costs of such models can represent a barrier for potential customers, as switching costs from ICEVs towards EVs are already high.

4.0 Conclusions

This study highlights that the economic and environmental performance of commercially available cathode materials for LIBs directly impacts overall EV cost and performance. Both, at the economic and environmental perspective, LMO/LFP based LIBs perform superior compared to NCA/NMC cathodes due to the absence of the expensive and rare transition metals Cobalt and Nickel, that directly impact total cathode costs and CO_2 emissions during battery manufacturing processes. However, this means that if low-cost cathodes are desired, overall EV performance will be reduced resulting in limited driving ranges. For this reason, EV companies currently have to reach a compromise between driving ranges, that are directly dependent on the overall performance of the cathode material, and affordable total vehicle cost, which relates to the choice and cost impact of cathode material and hence the total battery pack cost, towards their consumers.

So far, there is no battery that can satisfy both, economic and environmental concerns while offering an overall excellent performance. Nevertheless, the ongoing improvements on cathode materials in LIBs in the last two decades have provided one promising solution towards a low carbon future with a society that is less dependent on motorized vehicles.

References

Aguirre, K., Eisenhardt, L., Lim, C., Nelson, B., Norring, A., Slowik, P. & Tu, N. (2012) Lifecycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle. [online] University of California, Los Angeles. Available: http://www.environment.ucla.edu/media/files/BatteryElectricVehicleLCA2012-rh-ptd.pdf [Accessed 25th March 2016]

Amine, K., Kanno, R. & Tzeng, Y., (2014). Rechargeable lithium batteries and beyond: Progress, challenges, and future directions. *MRS Bulletin*, 39(05), pp.395–401.

Amirault, J., Chien, J., Garg, S., Gibbons, D., Ross, B., Tang, M., Xing, J., Sidhu, I., Kaminsky, P. & Tenderich, B. (2009). The Electric Vehicle Battery Landscape : Opportunities and Challenges. University of California, Center for Entrepreneurship & Technology (CET), Berkeley: USA.

Armand, M. & Tarascon, J.-M., (2008). Building better batteries. *Nature*, 451(7179), pp.652–657.

Barnett, B., Rempel, J., Ofer, D., Oh, B., Sriramulu, S., Sinha, J., Hastbacka, M. & McCoy, C. (2010). PHEV battery cost assessment [PowerPoint presentation]. U.S. Department of Energy Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation, 7-11 June, Washington, D.C.

Barnett, B., Rempel, J., & Hyung, Y.E. (2013). PHEV battery cost assessment [PowerPoint presentation]. U.S. Department of Energy Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation, 13-17 May, Arlington.

Bonges, H.A. & Lusk, A.C., (2016). Addressing electric vehicle (EV) sales and range anxiety through parking layout, policy and regulation. *Transportation Research Part A*, 83, pp.63–73.

Casals, L.C., García, B.A., Aguesse, F. & Iturrondobeitia, A. (2015). Second life of electric vehicle batteries: relation between materials degradation and environmental impact, *The International Journal of Life Cycle Assessment,* 20, pp. 1-12.

Cluzel, C. & Douglas, C. (2012). Cost and performance of EV batteries. [online]. Elemententergy. Available: http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf [Accessed 28th March 2016].

Deng, D., (2015). Li-ion batteries: basics, progress, and challenges. *Energy Science & Engineering*, 3(5), pp.385–418..

Doeff, M.M. (2012). *Battery cathodes*. In: Brodd, R.J. ed. Batteries for sustainability: selected entries from the encyclopedia of sustainability science and technology. New York: Springer Science & Business Media, pp. 5-49.

Dinger, A., Martin, R., Mosquet, X., Rabl, M., Rizoulis, D., Russo, M., & Sticher, G. (2010) Batteries for Electric Cars - Challenges, Opportunities, and the Outlook to 2020. [online] Boston Consulting Group. Available: https://www.bcg.com/documents/file36615.pdf [Accessed 11th March 2016].

Etacheri, V. Marom, R., Elazari, R., Salitra, G. & Aurbach, D. (2011) Challenges in the development of advanced Li-ion batteries: a review. Energy & Environmental Science, 4(9), pp.3243–3262.

Frischknecht R. (2011). Life Cycle Assessment of Driving Electric Cars and Scope Dependent LCA models. In: 43. Ökobilanz-Diskussionsforum, Zürich: Switzerland.

Gaines, L. & Cuenca, R., (2000). Costs of Lithium-Ion Batteries for Vehicles. [online] Argonne National Laboratory. Available: http://www.anl.gov/energy-systems/publication/costs-lithium-ion-batteries-vehicles [Accessed 15th March 2016]

Gaines, L. & Nelson, P., (2009). Lithium - Ion Batteries : Possible Materials Issues. [online] Argonne National Laboratory. Available: https://www.researchgate.net/publication/267550161_Lithium-Ion_Batteries_Possible_Materials_Issues [Accessed 18th March 2016].

Goodenough, J.B. & Park, K.S.S., (2013). The Li-ion rechargeable battery: A perspective. *Journal of the American Chemical Society*, 135(4), pp.1167–76.

Hakimian, A., Kamarthi, S., Erbis, S., Abraham, K.M., Cullinane, T.P. & Isaacs, J.A. (2015) Economic analysis of CNT lithium-ion battery manufacturing. *Environmental Science: Nano*, 2, pp.463–476.

Huat, S.L., Yonghuang, Y. & Tay, A.A.., (2015). Integration issues of Lithium-ion battery into electric vehicles battery pack. *Journal of Cleaner Production,* 113, pp. 1032-1045.

Liu, C., Neale, Z.G. & Cao, G., (2015). Understanding electrochemical potentials of cathode materials in rechargeable batteries. *Materials Today,* 19(2), pp.109–123.

Lu, L., Han, X., Li, J., Hua, J. & Ouyang, M. (2013). A review on the key issues for lithium-ion battery management in electric vehicles. *Journal of Power Sources*, 226, pp.272–288.

Majeau-Bettez, G., Hawkins, T.R. & Stromman, A.H., (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology*, 45(10), pp.4548–4554.

Manthiram, A., (2011). Materials challenges and opportunities of lithium ion batteries. *Journal of Physical Chemistry Letters*, 2(3), pp.176–184.

Navigant Resarch (2015). Advanced energy storage for automotive applications. [online]. Navigant Research. Available from: https://www.navigantresearch.com/research/advanced-energy-storage-for-automotive-applications [Accessed 28th March 2016]

Nealer, R., Reichmuth, D. & Anair, D.,(2015). Cleaner cars from cradle to grave: how electric cars beat gasoline cars on lifetime global warming emissions. [online] Union of Concerned Scientists. Available: http://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf [Accessed 1st April 2016].

Nelson, P.A., Gallagher, K.G., Blook, I. & Dees, D.W., (2011). Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles. [online] Argonne National Laboratory. Available: http://www.ipd.anl.gov/anlpubs/2011/10/71302.pdf [Accessed 17th March 2016]

Nitta, N., Wu, F., Lee, J.T. & Yushin, G. (2015). Li-ion battery materials: present and future. *Materials Today*, 18(5), pp.252–264.

Notter, D.A., Gauch, M., Widmer, R., Wager, P., Stamp, A., Zah, R. & Althaus, H.J.(2010) Contribution of Li-ion batteries to the environmental impact of electric vehicles. *Environmental Science and Technology*, 44(17), pp.6550–6556.

Saevarsdottir, G., Tao, P., Stefansson, H. & Harvey, W. (2015) Potential Use of Geothermal Heat in Lithium- Ion Battery Production. In: World Geothermal Congress 2015,pp.1-6, Melbourne: Australia.

Sakti, A., Michalek, J.J., Fuchs, E.R.H., & Whitacre, J.F. (2015) A techno-economic analysis and optimization of Li-ion batteries for light-duty passenger vehicle electrification. *Journal of Power Sources*, 273, pp.966–980.

Scrosati, B. & Garche, J., (2010). Lithium batteries: Status, prospects and future. *Journal of Power Sources*, 195(9), pp.2419–2430.

Shen, P.K., Wang, C.Y., Jiang, S.P., Sun, X., & Zhang, J., eds. (2016). Electrochemical energy – advanced materials and technologies, Boca Raton, FL: CRC Press.

Tarascon, J.M., & Armand, M., (2001). Issues and challenges facing rechargeable lithium batteries. *Nature*, 414, pp.359–367.

Thackeray, M.M., Wolverton, C. & Isaacs, E.D., (2012). Electrical energy storage for transportation—approaching the limits of, and going beyond, lithium-ion batteries. *Energy & Environmental Science*, 5(7), p.7854.

World Energy Council (2013). World Energy Resources. World Energy Council Report, p.468.

Whittingham, M.S., (2004). Lithium batteries and cathode materials. *Chemical Reviews*, 104(10), pp.4271–4301.

Whittingham, M.S., (2008). Materials Challenges Facing Electrical Energy Storage. *MRS Bulletin*, 33(04), pp.411–419.

Xu, B., Qianm, D., Wang, Z. & Meng, Y.S. (2012). Recent progress in cathode materials research for advanced lithium ion batteries. *Materials Science and Engineering R*, 73(5-6), pp. 51–65.

Xu, J., Dou, S., Liu, H. & Dai, L. (2013). Cathode materials for next generation lithium ion batteries. *Nano Energy*, 2(4), pp.439–442.