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# Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle traction batteries

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## HIGHLIGHTS

- First combined environmental and cost assessment of metal anodes for Li batteries.
- Lower cell cost and climate impact for metal anode cells than for Li-ion batteries.
- The capacity of the cathode material is the key to cell cost reduction.
- The climate impact of cell production is highly dependent on the electricity used.
- Life cycle cost of battery packs relates to usage and pack design, not cell design.

## ARTICLE INFO

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## ABSTRACT

Using a lithium metal negative electrode may give lithium metal batteries (LMBs), higher specific energy density and an environmentally more benign chemistry than Li-ion batteries (LIBs). This study asses the environmental and cost impacts of *in silico* designed LMBs compared to existing LIB designs in a vehicle perspective. The life cycle climate and cost impacts of LMBs show a similar pattern: the use phase has more climate and cost impacts than the production phase. As compared to LIBs and with respect to the positive electrode, Lithium Nickel Manganese Cobalt Oxide (NMC) is preferable to Lithium Iron Phosphate (LFP). The cell cost is highly dependent on the cost of lithium metal; a cost reduction of 50% causes a cell cost reduction of 8–22% depending on the choice of positive electrode material and if the cell is optimised for power or energy. For electric vehicle usage, the total cost per km is mainly dependent on the energy consumption per km and the capacity of the positive electrode, representing cost saving potentials of about 10%. These generic results can be used as a base for investigations of other battery technology using lithium metal electrodes.

## 1. Introduction

Since their commercialization in the early 90's, Li-ion batteries (LIBs) have become a huge success, and are now found in more or less every portable electronic device. The up-scaling of different LIB chemistries is on-going for mainly automotive applications, but also for large-scale battery storages to support smart grids and renewable electricity production. There are, however, still critical issues to be addressed for electric vehicle batteries; cost reductions, environmental aspects of usage, energy density, safety, and durability. All these issues and the substantial efforts needed must, however, be put in the light of the need for vehicle manufacturers to comply with the fleet emission target of 95 g $CO_2$-eq $km^{-1}$ within EU [1].

Using a lithium metal negative electrode has the promise of both higher specific energy density cells and an environmentally more benign chemistry. One example is that the copper current collector, needed for a LIB, ought to be possible to eliminate, reducing the amount of inactive cell material. Another example is that ageing can be improved by virtue of a surplus of lithium, since lithium losses during long-term cycling is a problem for LIBs [2–4], and furthermore also non-lithium containing positive electrode materials can be used. Finally, Li metal electrodes are intrinsic to other high energy density battery concepts such as all solid state Li-batteries, Li-sulfur (Li—S) batteries, and Li-oxygen/air (Li—$O_2$) batteries.

Protecting the lithium metal is needed since otherwise lithium dendrites may form during battery cycling, leading to short-circuits and, in the worst-case scenario, to hazardous side reactions [5–7]. There are different ways of protecting lithium metal electrodes:

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mechanical and chemical (*e.g.* thin films) or using a separator acting as surface protection – here applied by using a cellulose based separator made from the Cladophora algae [8], but we emphasize that the analysis here is made on *in silico* constructed cells. Today, only a few commercial companies manufacture cells which use lithium metal electrodes, often in very special designs, for example Bolloré, Poly Plus, Solid Energy, Oxis Energy and Sion Power.

There are several environmental and geopolitical concerns for lithium based batteries. From a natural resource perspective, the amount of available lithium is constantly revised [9]. Increasing the lithium content in the cells could make it easier to establish economical recycling routes and to close the material loop for lithium, but also means more of the stock of lithium bound in operating batteries.

One aim of this article is to guide cell producers and battery pack designers on how to decrease cost and improve environmental performance, much as have been performed for Li—S batteries [10]. Life cycle assessments (LCA) is, in general, considered as a useful tool in the product development stage in order to identify environmental hot-spots and aid in directing development efforts in relevant areas [11–13]. In an application context [14], the results of LCA of traction batteries is often presented as environmental impact per vehicle kilometre. Thereby, the results can easily be compared with vehicle emission targets, *e.g.* the European passenger car fleet average standards of 95 g $CO_2$-eq $km^{-1}$ to be reached by 2021 [1].

Up to now there are few sustainability studies taking on the use of lithium metal electrodes in battery cells aimed for electric vehicles [10,15,16]. Existing studies share the prospective dilemma of trying to draw conclusions on future use in vehicles based on prototypes and demonstrators at best.

## 2. Method

Overall, cells have been designed *in silico* and the corresponding EV battery packs, created by cells connected in series to fulfil the system voltage requirements and in parallel to fulfil energy and power requirements (and as a consequence the number of cells in series depend on cell voltage and the number of parallel rows of cells depend on the energy content per cell), have been investigated in terms of energy and cost perspectives. The EVs studied were Nissan Leaf and Tesla Model S, with the corresponding vehicle requirements summarised in Table 1. The same cell-to-pack weight-ratio as the original LIB packs was used and the same energy consumption per km and mass of vehicle as the original vehicles has been assumed.

### 2.1. Cells and battery pack design

First of all, none of the cells used in these calculations are to be found commercially and should be seen in the light of future potential, assuming stable lithium surfaces in contact with a liquid electrolyte is a solved issue. Accordingly, pouch format cells were designed *in silico* using a 30 μm thick lithium metal foil as the negative electrode. The minimum Li-foil thickness in order to match the amount of active cathode material is of the order of 5 μm [22], assuming all of the lithium taking part in the electrochemical reactions. From a number of reasons, it is advantageous to apply somewhat thicker foils: from a production perspective - *ca.* 20–30 μm is easier to handle, also creating a surplus of lithium which can be used as current collector, sustaining the needed mechanical properties – and furthermore removing the Cu current collector reduces complexity and the risk for additional resistances within the cell. As thinner Li-foils are possible for the electrochemical reactions, the Li-foil thickness is included in the sensitivity analysis and study how this affects the cell energy densities and cost per km.

From the cell capacity, the amount of active cathode material needed ($mAhg^{-1}$ and Ah of cells) has been calculated. The thickness of the coatings (*i.e.* mg $cm^{-2}$) results in the needed area of electrodes (and current collectors) and Li-foil. The positive electrode was chosen to be either $LiFePO_4$ (LFP) or $Li(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$ (NMC) (94 wt% active material, 3% of PVdF binder and carbon black, respectively), on a double-coated aluminium foil as current collector (20 μm thick). The practical capacities of the active materials were set to 160 (for LFP) and 180 (for NMC) mAh $g^{-1}$, respectively. The separator was soaked in a standard electrolyte of 1 M $LiPF_6$ in 1:1 EC:DMC +2 wt% VC. The volume of the electrolyte has been assumed to be twice the pore volume of the separator. The number of cycles needed for different usage conditions are discussed below.

Concerning cell design and optimization, the usable capacity of the active material (in mAh $g^{-1}$) depends on crystallinity, morphology, and surface area, properties often related to the production processes. In this study, however, these material properties have not been strived to be optimised in any way and the materials are taken at face value.

Both energy and power optimised cells were designed with capacities of 5, 10 and 40 Ah, respectively. The cell parameters have been selected based on the cells used in the reference vehicles and to be valid over a broad range of electric vehicles; from hybrids to full electric. The 10 Ah cell has been used as the base-case. The loading of positive electrode active material was set to 5 mg $cm^{-2}$ for the power-optimised cells and to 15 mg $cm^{-2}$ for the energy-optimised cells. The loading was selected to be more extreme ends according to our general cell production knowledge. The thickness and porosity of the separator were set to 10 μm and 44% for the power-optimised cells and to 40 μm and 33% for the energy-optimised cells. The pouch cell housings consist of a polymer-laminated aluminium foil assumed to correspond to 10% of the cell weight. Furthermore, the cell housing material, with a density of 0.0141 g $cm^{-2}$, consists of 30% aluminium, 30% of polypropylene, and 40% nickel (for the negative electrode connection). The costs of all cell materials are summarised in Table 2. The complete battery pack consists of battery cells, a battery management system (BMS), packaging, and a thermal management system. The battery cells constitute about half of the weight of the battery pack (Table 1).

**Table 1**
The vehicle requirements and battery pack designs [17–21].

| | Nissan Leaf | Tesla Model S |
|---|---|---|
| *System voltage (V)* | 360 | 350 |
| *Energy installed (kWh)* | 24 | 85 |
| *Power (kW)* | 80 | 270 |
| *Weight (kg)* | 294 | 618 |
| *# of cells* | 192 | 7104 |
| *Cell weight (kg)* | 0.800 | 0.045 |
| *Cells in pack (wt%)* | 52 | 52 |
| *Energy consumption (kWh $km^{-1}$)* | 0.19 | 0.24 |

**Table 2**
Costs of cell materials and the corresponding material costs for the 10 Ah LFP and NMC cells, respectively [23].

| Material | Cost (€ $kg^{-1}$) | Material cost 10 Ah LFP cell (€ $cell^{-1}$) | | Material cost 10 Ah NMC cell (€ $cell^{-1}$) | |
|---|---|---|---|---|---|
| | | Power-optimised | Energy-optimised | Power-optimised | Energy-optimised |
| LFP | 18 | 1.13 | 1.13 | – | – |
| NMC | 27 | – | – | 1.50 | 1.50 |
| Lithium foil | 62[a] | 1.24 | 0.41 | 1.10 | 0.37 |
| Electrolyte | 17.5 | 0.26 | 0.39 | 0.26 | 0.35 |
| Separator | 5 € $m^{-2}$ | 0.04 | 0.04 | 0.04 | 0.04 |
| Binder | 27 | 0.05 | 0.05 | 0.05 | 0.05 |
| Carbon black | 8 | 0.02 | 0.02 | 0.02 | 0.02 |
| Al foil | 1.2 | 0.04 | 0.01 | 0.04 | 0.01 |

[a] Cost assumption.

The cost assessment of both cells and battery packs are based on market prices of cell materials and the assumption that 75% of the cost of a cell relates to the materials [24] (Table 2), and 75% of the cost of a battery pack refers to the cells [25].

The energy utilisation of the cells was varied between 60 and 90% state-of-charge (SOC), with 80% SOC as the base-case. The number of charging cycles possible (#) were calculated using the relationship: $\# = 1331*(\text{SOC window})^{-1.825}$ [26]. This relationship is directly derived from commercial LIB cells cycled for electric vehicle purposes. As any new battery technology must compete with LIB cells, our cells are assumed to have an equal cycling performance. The energy cost of driving the vehicles is based on the average costs for private customers within EU [27].

### 2.2. Life cycle assessment

The purpose of the LCA is to highlight the changes in environmental impact when using lithium metal negative electrode based batteries as compared to LIBs with respect to improved cell performance and for traction of electric vehicles. The principal functional unit is one vehicle kilometre. The LCA includes the production phase of the battery cell, use phase losses related to the battery itself, and the recycling of the battery materials. The system boundaries exclude the vehicle itself (the drive train to deliver the electricity to and from the wheels: charger, inverter, and machine), but includes the use of the battery pack in the vehicles, including electronics, wiring, packaging of modules and battery casing (Fig. 1). The model thus allows to investigate the total electricity consumption of the vehicle during the use phase and the associated impacts.

All materials found in the bill of materials (Table 3 for 10 Ah NMC cells and [28]) were tracked back to the point of resource extraction, mainly by using cradle-to-gate data from the Ecoinvent 3.3 database [29]. The Ecoinvent data contains associated inputs from natural resources and emissions, including estimated production losses. Material data not found in the Ecoinvent database or in other available databases, were either modelled (from chemicals available in the databases) using molar calculations and estimations of energy use, or replaced by data for similar materials.

The environmental impact categories for LCA used are *climate impact*, *resource depletion*, and *toxicity* and the environmental impact assessment methods used are described in Ref. [28].

### 2.3. LCA modelling

The battery cell life cycle consists of the following phases: production of the cells and battery assembly, use of the battery pack in vehicles, and battery recycling at end-of-life. The production phase model is based on the bill of material (Table 3). For the battery pack the packaging, the BMS, and the cooling system contribute by weight approximately 40%, 5% and 5%, respectively [30]. The use of the battery in the vehicle was modelled by considering the extra electricity needed to carry the battery pack's weight, and the extra electricity needed to cover charge/discharge losses [31]. The plug-to-wheel electricity efficiency was set to 90% and assumed to be the same during the charge and the discharge processes, *i.e.* 5% losses in each direction. The influence of the battery mass was modelled using an energy reduction value (ERV) of 0.65 kWh (100 kg*100 km) $^{-1}$ for the New European Driving Cycle (NEDC). With respect to recycling efficiency versus energy efficiency and cost, it is postulated that legislation and resource supply concerns will drive recycling efficiency to as much as 80% [32,33], but at the expense of energy efficiency and cost [34]. Thus it is assumed that metallic materials and easily separable plastic parts are recycled to 80%, but at such cost (economic and environmental) that only 50% of environmental impacts of virgin material production is avoided, i.e. the avoided virgin production is used as an approximation for the future recycling processes that are not yet developed. The resulting environmental impact of lithium battery recycling is calculated as the environmental impacts from the assumed transportation minus 50% of the avoided environmental impacts from avoided virgin production of recycled materials. Table 3 shows the assumption made on how much of each of the cell materials that will be recycled.

## 3. Results and discussion

### 3.1. Cell costs

The cells have been compared in terms of energy density and cost. The cell cost should only be seen/used for relative comparisons and not as actual costs. A target of 250 Wh kg$^{-1}$ was set to be of interest for vehicle application and all NMC-based cells and all the energy-optimised LFP-based cells result in attractive energy densities (Table 4).

The lowest cost is obtained for the LFP-based cells as compared to the NMC-based cells; *ca.* 7.5% lower for power-optimised cells, and *ca.* 12% lower for energy-optimised cells. There are no major differences in the cost per energy between the cell sizes; the main differences are all

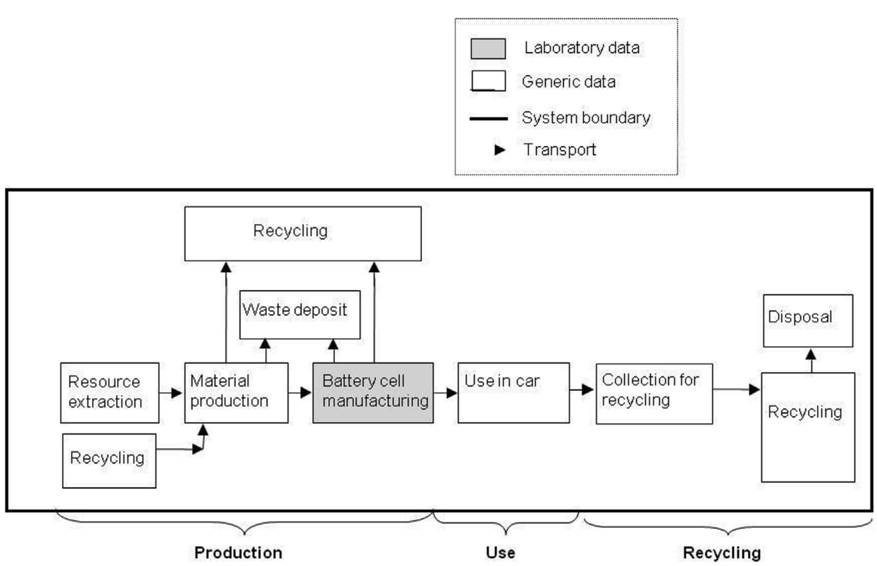


**Fig. 1.** System boundaries for the LCA of the present study.

**Table 3**
Bill of material for the 10 Ah NMC cells including recycling estimates.

| Part of cell | Material | 10 Ah NMC *energy-optimised cell* | | 10 Ah NMC *power-optimised cell* | |
|---|---|---|---|---|---|
| | | Weight (g) | Recycling (g) | Weight (g) | Recycling (g) |
| Cathode | NMC | 55.6 | 44.4 | 55.6 | 44.4 |
| Cathode | PVdF | 1.8 | Incinerated | 1.8 | Incinerated |
| Cathode | Carbon black | 1.8 | Incinerated | 1.8 | Incinerated |
| Cathode | Aluminium foil | 10.0 | 8.0 | 30.0 | 24.0 |
| Anode | Lithium metal | 5.9 | 4.7 | 17.8 | 14.2 |
| Separator | Clodophora algae | 7.8 | Incinerated | 7.8 | Incinerated |
| Electrolyte | 1 M $LiPF_6$ in EC:DEC +2%VC | 19.8 | | 13.2 | |
| Electrolyte | $LiPF_6$ (11%) | 2.2 | Incinerated | 1.5 | Incinerated |
| Electrolyte | Ethylene carbonate (48%) (48%) | 9.5 | Incinerated | 6.3 | Incinerated |
| Electrolyte | Diethyl carbonate (39%) | 7.7 | Incinerated | 5.1 | Incinerated |
| Electrolyte | Vinylene carbonate (2%) | 0.4 | Incinerated | 0.3 | Incinerated |
| Housing | | 6.6 | | 6.0 | |
| Housing | Aluminium (30%) | 2.0 | 1.6 | 2.0 | 1.6 |
| Housing | Polypropylene (30%) | 2.0 | Incinerated | 2.0 | Incinerated |
| Housing | Nickel (40%) | 2.6 | 2.1 | 2.0 | 1.6 |
| **Total mass (g)** | | **109** | **61** | **134** | **86** |

related to being energy or power-optimised cells.

From the cost calculations of the LFP- and NMC-cells, the cathode material have been shown to be 64% of the cell cost for 10 and 40 Ah cells, and 50% for 5 Ah cells. These data have been used to calculate the cost of the cells in the original battery packs for Nissan and Tesla. The resulting costs for the original cells are €10.45 for Nissan and €1.55 per cell for Tesla.

A sensitivity analysis was performed to reveal how the energy density and the cost of the cells are affected by: *i)* the cost of lithium metal, *ii*) the capacity of the positive electrode material (only for NMC-based cells), *iii)* the cost of the electrolyte, *iv)* the material share of cell cost, and *v)* the thickness of the Li— foil.

This results in the following sensitivities:

i) If the cost of lithium metal is reduced by 50%, the energy-optimised cells cost 8–10% less, and the power-optimised cells 18–22% less. On the other hand, if the cost of lithium metal is increased by 50%, the cost of the cells will increase by 10–11% for the energy-optimised cells, and by 18–22% for the power-optimised cells.
ii) For the capacity of the positive electrode material NMC an increase from 180 to 220 $mAhg^{-1}$ leads to a 10% cost reduction for both energy and power-optimised 10 Ah cells.
iii) The cost of the electrolyte strongly affects the cell cost: 7.6 to −9.3% for the energy-optimised cells, and −4.0 to −4.8% for the power-optimised cells if the cost of the electrolyte is reduced by 50%. On the other hand, if the cost of the electrolyte is increased by 50% the cell cost will increase by 7.2–9.3% for energy-optimised cells and 3.7–4.5% for power-optimised cells.
iv) The material share of the cell cost is assumed to be 75% [20], the remainder 25% referring to labour cost, equipment, maintenance, facility, and energy cost. If these other costs can be reduced and the cost share of the materials increases to 80%, the corresponding cost reduction of the cells is 7.5–7.7%. On the other hand, if the other costs increase and the cost share of the cell materials becomes only 70%, the cost of the cells will increase by 4.5–4.7%.
v) The thickness of the Li-foil affects both the energy density and cost of the cells. A reduction from 30 to 20 μm will, however, only increase the energy density of the energy-optimised cells by 1.8–1.9% and for the power-optimised cells by 4.6% (both NMC and LFP based). Increasing the Li-foil thickness by 20% from 30 to 36 μm, will decrease the energy density by a mere 1% for both chemistries.

### 3.2. Battery pack cost

The battery pack data are based on using energy-optimised 10 Ah cells for both vehicles and chemistries, and for comparison the corresponding data for the original LIB packs are included (Table 5).

The cost of the battery pack is a direct consequence of the number of cells; A pack based on LFP cells is 3–4% more expensive than a pack based on NMC cells for both vehicles studied. Hence, even if the LFP cells have the lowest cell cost (Table 4), the larger number of cells needed to fulfil the vehicle requirements overweigh (Table 6).

The total cost per km *i.e.* the cost of the battery pack and the corresponding energy cost for the total driving range show the lowest costs per km for the NMC-based battery packs: 4.0% lower cost per km for Nissan and 7.5% for Tesla, as compared to the LFP-based battery packs. Compared to the original battery packs for the vehicles, the NMC-based battery packs are 12.4% are more cost effective per km for Nissan and 22.2% for Tesla. The resulting pack costs and service life costs (€ cent $km^{-1}$) are summarised in Table 6.

The sensitivity analysis of the cost per km varies several parameters: *i)* the cell capacity, *ii)* the cost of lithium metal, *iii)* the capacity of the positive electrode material (only for NMC), *iv)* the cell weight fraction in the pack, and *v)* the energy consumption of the vehicle (Table 7).

This results in:

i) Changing from the base-case of 10 Ah cells to 40 Ah cells reduces cost by 5–5.4% for Nissan, but only by 0.3% for Tesla. The total cost

**Table 4**
Energy densities, cell costs, and cost per energy of the cells.

| Energy-optimised cells | | | | | | | Power-optimised cells | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LFP | | | NMC | | | LFP | | | NMC | | |
| Capacity (Ah) | 5 | 10 | 40 | 5 | 10 | 40 | 5 | 10 | 40 | 5 | 10 | 40 |
| Energy density (Wh $kg^{-1}$) | 265 | 279 | 290 | 346 | 366 | 384 | 217 | 226 | 234 | 284 | 298 | 309 |
| Cost (€) | 1.4 | 2.8 | 11.1 | 1.6 | 3.2 | 12.6 | 1.9 | 3.8 | 15.0 | 2.0 | 4.0 | 16.1 |
| Cost (€ $kWh^{-1}$) | 82.3 | 82.0 | 81.8 | 79.1 | 78.9 | 78.7 | 111.1 | 110.8 | 110.6 | 100.9 | 100.7 | 100.5 |

**Table 5**
The battery pack data and the corresponding data for the original LIB packs.

| | Nissan | | Tesla | | Nissan (original) | Tesla (original) |
|---|---|---|---|---|---|---|
| *Chemistry* | LFP | NMC | LFP | NMC | LMO-NMC | NCA |
| *# cells in series* | 106 | 90 | 103 | 88 | 96 | 97 |
| *# parallel rows* | 7 | 7 | 24 | 24 | 2 | 73 |
| *# cells in total* | 742 | 630 | 2472 | 2112 | 192 | 7104 |
| *Pack weight (kg)* | 173 | 132 | 583 | 446 | 294 | 618 |
| *Energy (kWh)* | 25 | 25 | 84 | 84 | 24 | 85 |
| *Energy density (Wh kg$^{-1}$)* | 146 | 191 | 144 | 188 | 82 | 138 |

per km is, however, between 1.1 and 1.3% regardless of chemistry and vehicle.

ii) A 50% cost reduction of the Li metal decreases the total cost per km by 2% for the NMC-based cells and by 2.5% for the LFP-based cells, and is valid for both Nissan and Tesla.
iii) If the capacity of the NMC material increases by 10%, the total cost per km is reduced by 3.3 and 6.0% for Nissan and Tesla, respectively.
iv) Increasing the cell weight fraction in the battery pack from 52 wt% (Table 1) to 60 wt% reduces the total cost per km up to 2%.
v) The largest prospects for cost reduction are related to the energy consumption of the vehicle, 10% reduction reduces the cost per km by at least 7% for Nissan and 5% for Tesla.

The thickness of the Li− foil will also affect the cost per km. By using a 20 μm thick foil instead of 30 μm, the cost for the Tesla will be reduced by 2.9–3.5% and for the Nissan 1.5–2.0%. The results are due to both lower cell cost and increased energy density of the cells.

In addition, increasing the cell cost ratio of the pack cost from 75% [25] by reducing the cost of other battery pack components (*e.g.* thermal system, control unit, fuses) will reduce the service life cost. By a cost ratio of 85%, these savings are 2.8–2.9%. On the other hand, with a lower cell to pack cost ratio, the service life cost increases by 3.6–3.9% at a ratio of 65% and the results are similar for both chemistries and independent of vehicle type.

Overall, large potential for cost reduction is related to factors not related to the cell or the cell chemistry: for NMC-based battery packs these accounts for 57% for Nissan and 45% for Tesla, while for LFP-based battery packs 61% Nissan and 60% for Tesla. Furthermore, the cost reduction potential which *is* related to the cells and the cell chemistry differs between the two vehicles; for Tesla, the cost and thickness of Li-foil and the capacity of the NMC cathode dominates, while for Nissan the cell capacity is also important. Finally, using the vehicles on different markets will create differences due to different energy costs. The service life cost was calculated for EU, Sweden, US, China, and Japan [27,35] (Fig. 2). Note that the actual service life cost of a vehicle will in many cases involve a mixture of electricity costs since cell production today is concentrated to Asia. The use phase electricity cost, which will be paid directly by the owner of the vehicle, is in all cases larger than the production electricity cost (often twice as large), see Table 6 or Figs. 7 and 8. Note that the use phase electricity cost span 3.5–5 € cent km$^{-1}$ is very competitive compared to combustion engine vehicles in most regions of the world.

**Table 7**
Summary of cost reduction potentials of total cost per km.

| | NMC-based battery pack | | LFP-based battery pack | |
|---|---|---|---|---|
| | Nissan | Tesla | Nissan | Tesla |
| Cell capacity: from 10 to 40 Ah | 1.9 | 0.6 | 2.4 | 0.7 |
| −50% cost Li metal | 2.0 | 2.0 | 2.5 | 2.5 |
| −10 μm Li-foil | 1.5 | 2.9 | 2.0 | 3.5 |
| +10% NMC capacity | 3.3 | 6.0 | N/A | N/A |
| 60 wt% cells in pack | 1.2 | 1.7 | 0.8 | 2.0 |
| −10% energy consumption | 7.3 | 5.1 | 7.2 | 5.2 |
| +10%- units cell cost in pack (75–85) | 2.8 | 2.8 | 2.9 | 2.9 |
| % Total cost saving potential | 20.0 | 21.1 | 17.8 | 16.8 |

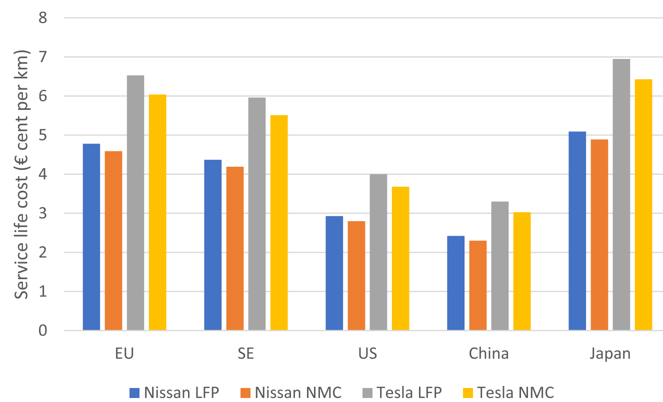


**Fig. 2.** The service life cost for different regions/countries for Nissan and Tesla vehicles using battery packs of either LFP- or NMC-based cells.

### 3.3. Life cycle assessment

#### 3.3.1. Battery environmental impacts

The LMBs based on NMC result in the lowest climate impact for both vehicles (Figs. 3 and 4). For Nissan, the use phase has the largest climate impacts for the LMBs, while for the original NMC LIB the production phase dominates climate impacts. The recycling climate gains are much smaller than the use and production phase climate impacts for all three batteries in both vehicles. This comparative insignificance of the recycling phase is confirmed by other studies [36]. This way of modelling recycling does not consider that recycling of LMB cells to likely be more challenging and do require different processes than recycling of LIB cells, nor that there may be a larger economic incentive to recycle LMB cells than LIB cells. Hence, it is not possible to estimate if recycling of LMBs will lead to more or less impact than recycling of LIBs. Due to the poor data on recycling, which in turn is due to that recycling processes for traction batteries are not yet fully developed, the

**Table 6**
The cost of battery packs for Nissan and Tesla. The energy cost is based on the average energy cost within EU [27].

| | Nissan | | Tesla | | Nissan (original) | Tesla (original) |
|---|---|---|---|---|---|---|
| *Chemistry* | LFP | NMC | LFP | NMC | LMO-NMC | NCA |
| *Pack cost (€)* | 2759 | 2651 | 9191 | 8887 | 2676 | 14688 |
| *Pack cost per kWh (€ kWh$^{-1}$)* | 109 | 105 | 109 | 105 | 112 | 185 |
| *Pack cost per km (€ cent km$^{-1}$)* | 1.17 | 1.09 | 1.60 | 1.43 | 1.31 | 2.75 |
| *Energy cost per km (€ cent km$^{-1}$)* | 3.61 | 3.50 | 4.93 | 4.60 | 3.93 | 5.01 |
| *Total service life cost (€ cent km$^{-1}$)* | 4.78 | 4.59 | 6.53 | 6.04 | 5.24 | 7.76 |

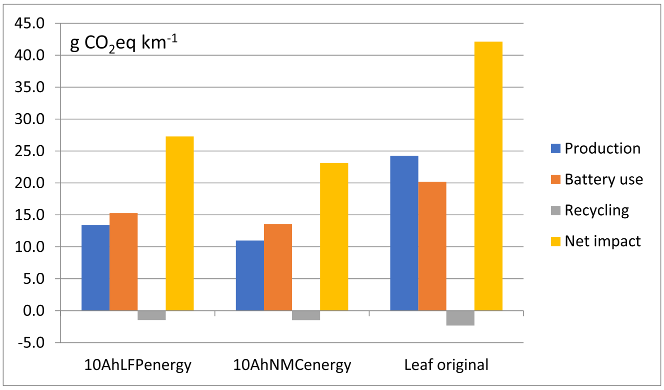


**Fig. 3.** Climate impact of three different batteries for Nissan.

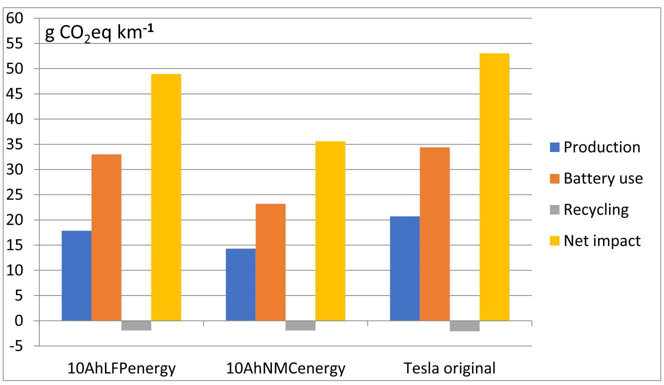


**Fig. 4.** Climate impact of three different batteries for Tesla.

recycling phase will not be further discussed in this paper.

For Tesla, the NMC-based LMB provides significantly less climate impact, while the LFP-based LMB has only marginally smaller impact than the original NCA LIB. For Tesla, the use phase has the largest impacts for the LMBs as well as for the original NCA LIB.

The general trend that all the LMB cells and especially the NMC-based cells show the lowest environmental impact, is true also for toxic impacts and resource depletion. The scientific base for calculating toxics and resource depletion is, however, not very solid [15]. Abiotic depletion during the use phase for the LFP battery, due to higher electricity consumption per km, makes the LFP battery score higher than the NMC battery, while diminishing cobalt and nickel resource supplies could start limiting the NMC technology around 2030 [37].

### 3.3.2. Dominant climate impacts during production phase

The energy needs for cell production and cell assembly dominate the climate impacts of battery production for both Nissan and Tesla (Fig. 5). The importance of production energy for battery cell production and assembly is confirmed by many studies [38]. Upstream manufacturing of the other components (rest-of-pack), the cathode, the lithium metal foil (graphite for LIBs), as well as the electrolyte, also give noticeable contributions. The rest-of-pack, largely underestimated in early LIB studies [39], is now acknowledged to involve a major climate impact [30,40]. For the NMC and NCA cathodes: cobalt, nickel and lithium give dominant climate impacts. For the LFP cathodes all constituent materials contribute about the same. Overall there is not much difference between the different chemistries nor between the vehicles with respect to which parts that give dominant climate impact contributions. The NMC LMB gives overall lowest climate impacts for the production and recycling phases, mainly due to its higher energy density, requiring less materials for the same function. In efforts to improve the batteries, it is worth to remember that the use phase losses (due to weight-induced and electric conversion losses) are larger than the

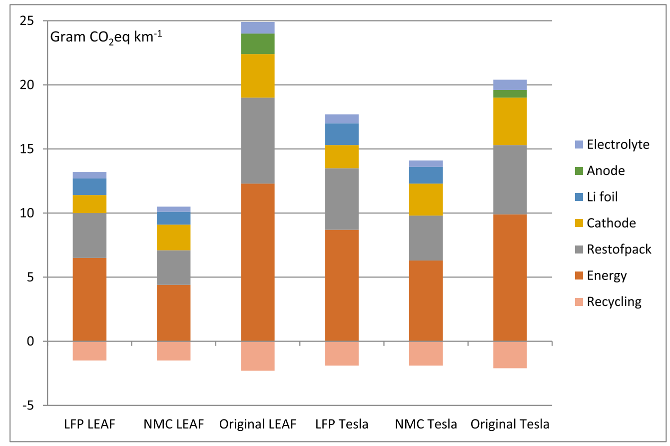


**Fig. 5.** Dominant climate impacts in the production and recycling phases.

production impacts for all batteries except the NMC LIB for Nissan LEAF. Thus, production improvements must not decrease battery efficiency nor increase battery weight.

### 3.3.3. Sensitivity to electricity mix

The *battery use* (Figs. 3 and 4) does not itself include the total propulsion impact during vehicle use, even if the losses related to battery efficiency and weight contribute. The total propulsion impact will change drastically with the electricity mix in different markets (Fig. 6). With European average electricity, the climate impact is more than 90 g $CO_2$-eq km$^{-1}$. This is about ten times higher climate impact than with Swedish average electricity.

The production related climate impact would be reduced significantly (by 62%) if battery cells were produced using Swedish electricity compared to European electricity, as $CO_2$ emissions from energy use dominate cell production climate impact (Fig. 5). The climate impacts are by no means extreme: 53 and 499 g $CO_2$eq. kWh$^{-1}$ for low voltage used for propulsion and 45 and 484 g $CO_2$eq. kWh$^{-1}$ for high voltage used for production, respectively, while some markets have climate impacts well over 1000 g $CO_2$eq. kWh$^{-1}$ [29] and green certified electricity has a possibility of less than 10 g $CO_2$eq. kWh$^{-1}$ [29].

It should further be noted that with European electricity the indirect emissions from Nissan LEAF is close to the European tail-pipe regulation for light-duty vehicles 95 g $CO_2$-eq km$^{-1}$ to be reached by 2021 [1].

## 3.4. Combined climate and cost results

The combined climate and cost impacts (using European electricity) largely show a similar pattern: the use phase has more climate and cost impacts than the production phase: NMC cells shows lower climate impact and cost than LFP cells, and both LMBs show advantages over the original LIB packs (Figs. 7 and 8).

## 4. Conclusions

It should be pointed out that the cells are ideal. They are designed *in silico* utilizing metallic lithium as anode in combination with a liquid electrolyte and the strategy of a very special separator here chosen. Hence they are, and should, only be used to evaluate the future potential of LMBs – given that the cells actually will work – and solved in the manner (other solutions might be more/less expensive and have other effects). In such a case, however, these LMBs do show lower cost, lower climate impact, lower abiotic depletion potential, and lower toxicity than similarly designed LIBs, for both the NMC- and LFP-based cells. The main reason is the higher energy density obtained, which lowers the battery weight and thus the amounts of all materials and,

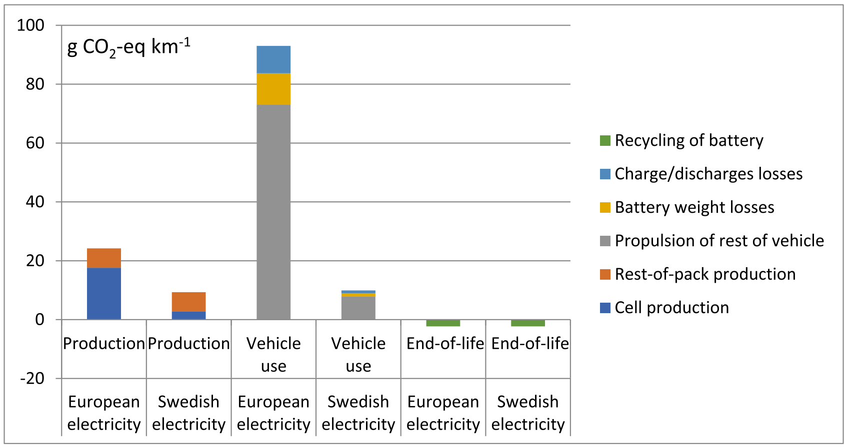


**Fig. 6.** Climate impact of Nissan original battery produced and used with European average electricity (left) or with Swedish average electricity.

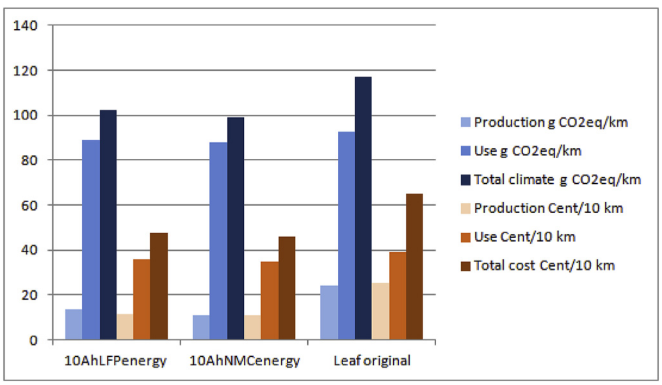


**Fig. 7.** Battery climate and cost impacts for Nissan.

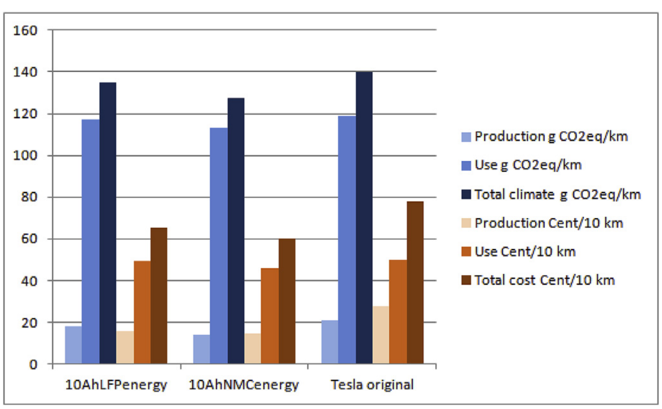


**Fig. 8.** Battery climate and cost impacts for Tesla.

most importantly, the vehicle electricity consumption. The energy needed for cell manufacturing and battery assembly, the Li-foil, and the cobalt and the nickel in the NMC positive electrodes dominate the climate impact of the production. The cell material cost is dominated by the cost of the active materials (NMC/LFP, Li-foil), while the total cost per kilometre is dominated by the electricity cost.

From a service life cost perspective, a large potential for cost reduction is related to issues not related to the cell or cell chemistry: the energy consumption to drive the vehicle and the weight and the cost of "rest-of-pack" – accounting for 57% of the cost reduction potential for NMC-based packs for Nissan and 45% for Tesla, and 60–61% for the LFP-based packs for both Nissan and Tesla. It is therefore logical and wise that all major car manufacturers now strive to integrate battery pack design and assembly in their core competence.

Sensitivity calculations using a Swedish average electricity mix for production of the cells and propulsion of the vehicles show that production impacts and propulsion impacts can be reduced considerably by producing battery cells at locations with carbon lean electricity. The climate impact of the electric vehicle use phase confirms conclusions from other studies [41–43] that electric vehicles driven using European (or global) average electricity have indirect climate impact at the same level as the up-coming European tail-pipe $CO_2$ regulation at 95 g $CO_2$ $km^{-1}$. Using a more carbon lean electricity mix could reduce these impacts by 90% or more. On the other hand, coal based electricity generation would almost double the indirect use phase $CO_2$ emissions from electric vehicles.

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