Transport electrification at all environmental costs? The case of large passenger duty-vehicles

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Abstract. Electrification is often highlighted as the future for transportation sector as it is considered as a zero-tailpipe emission. However, environmental impacts related to battery electric vehicles (BEVs) exist. The aim of this article is to identify the trade-off between batteries’ weight and vehicle’s autonomy from an environmental perspective in the BEVs’ development as electrified mobility will consume more critical materials but reducing tailpipe emissions. Thus, a focus on climate change and resources has been done using a life cycle assessment (LCA) methodology. Large vehicles (D-segment) for BEVs and their fossil thermic counterparts have been assessed for two time horizons (2019, 2030) in Europe. Our linear programming world energy-transport model, TIAM-IFPEN, has been used in order to assess demand and import dependency on materials through to 2050. Results show that BEVs can generate higher impacts than their inherent conventional ones and that criticality assessment should be done in order to get a complete view of BEVs’ deployment.

Keywords: life cycle assessment, IAM, electric vehicle, battery, resource depletion, criticality.

1. Introduction
The Paris Agreement sets out objectives to limit greenhouse gas (GHG) emissions in all sectors by fostering low carbon technologies. Transportation sector is brought to center stage as it accounts for almost a quarter of global CO2 emissions in 2016 [16]. The market for BEVs has grown considerably and effective public policy incentives could reinforce this perception, as they are considered as zero tailpipe GHG emissions. However, other parameters shall be considered to properly assess BEVs’ potential environmental benefits, such as the electricity production mix [25] and the battery production stage which accounts for an important part of total emissions related to the life cycle of BEVs [4].

Based on European Commission analysis [22], a substantial growth in the Lithium-ion (Li-ion) battery market is expected in the coming years. Indeed, consumer concerns about electric vehicle’s operating range could impede the massive electrification of the transport sector worldwide [31] but should drive the production of larger batteries. Knowing that BEVs’ autonomy depends on battery performance, such as capacity and energy density which in turn will impact their weight, it is likely that their environmental impacts highly depend on the battery technology and their size. In the last few years, significant improvements have been made to increase the energy density of battery [30].

The aim of this article is to identify the trade-off for BEVs’ development between battery’s weight and autonomy from a GHG perspective for large passenger duty-vehicle (D-segment) in Europe. To achieve this goal, large BEVs will be compared to their internal combustion engine (ICE) equivalents.
and their future technological improvements by 2030. Based on LCA methodology [18, 19], the primary objective is to find out how much increasing BEV’s operating range affects climate change and resource depletion indicators. The second objective is to consider the criticality issues of raw materials in a more global context as a complementary analysis. This criticality analysis will be provided by an integrated assessment model (IAM) called TIAM-IFPEN in order to develop a global three-dimensional approach taking into account geological, geopolitical and economic criteria with the transport evolution and global environmental constraints. Finally, our findings are discussed, and several insights are provided regarding resource dependency with climate constraints such as targets to limit global warming below 4°C or 2°C by 2100.

2. Materials and methods

The goal of this study is to perform a complete LCA for large passenger duty vehicles in Europe on a world-wide harmonized driving cycle (WLTC) [32] with a focus on climate change impact and resource depletion potential. The study aims at assessing the battery’s specification for which BEV generate more environmental impacts than ICE based on these two midpoints, and at evaluating resources depletion through a criticality indicator also called supply risk method [33].

2.1. Life Cycle Assessment

LCA is performed according to ISO standards [18, 19] and follows the International Reference Life Cycle Data System [20]. The choice of LCA impact’s methods complies with European Commission’s recommendations [21, 33].

2.1.1. Goal definition

This paper is intended to forecast and analyse the environmental impacts on climate change and natural resources due to the roll-out of electric light duty vehicles. The aim is both to identify environmental performances of BEVs and to contribute to future transport policy decisions in a context where several European countries (France, Great Britain, Italy, Germany, etc.) are encouraging consumers to buy BEVs. The perimeter of the study is limited to Europe and the time coverage is 2019 and 2030. The target audience are governmental political decision makers and automotive sector.

2.1.2. Scope definition

Two larges (D-segment) BEVs: BEV and BEV+ (BEV with an extended battery capacity), and their fossil thermic counterparts are studied for 2019 and 2030 in a European context. Battery’s technology is Li-ion battery. SimaPro® software and Ecoinvent 3.5 database [11] have been used. Vehicles were simulated over the homologated worldwide harmonized light vehicles test procedure (WLTP) as stipulated by ICCT [15]. The system boundaries comprise all stages of the energy pathway production till its use, and also the life cycle of the vehicle from cradle to grave.
Figure 1. System boundaries of the study: well-to-wheel analysis including vehicle’s life cycle assessment from cradle to grave.

The functional unit adopted is the movement of one person over 1 km within an overall European usage for a D-segment car expressed as person.km, for current time horizon (2019) and prospective (2030). The assumption of an average 1.3 persons per car is based on IFPEN expert discussions and Eurostat data.

2.1.3. Life cycle inventory (LCI)

According to the goal of the study, the LCI modelling is attributional and the Ecoinvent system model “cut-off” is selected for background data, i.e.: raw materials and manufacturing data, energy consumption, and end-of-life processes. Foreground data are based on several sources and represent the vehicle assembly [23, 24], the battery technology and sizing [29, 9, 25], the use stage (consumption and tailpipe emissions) [1, 2], the waste management (collection rate, sorting rate, etc.) [5, 6, 7], the parameters (lifetime, mileage, etc.), and the prospective choices.

Vehicles’ and tyres’ composition is modelled from a European study [23, 24] and components’ weight is based on internal IFPEN assumptions of energy and power densities as follows: bare vehicle body with options and gearbox, ICE, electric engine and generator, battery. For 2030 horizon a reduction in vehicle’s weight is considered [27] equivalent to the replacement of 30% of the vehicle's steel by an amount of aluminium weighing 65% of this 30% steel percentage. This vehicle downsizing and the improvement of engine efficiency leads to prospective energy pathway consumption for 2030.

Vehicles’ lifetime is assumed to be 10 years with a 15,000 km/year mileage and 40,000 km for tyres, according to Notter et al. [26], Hawkins et al. [14], Ellingsen et al. [10], and others.

Batteries’ chemistry is lithium-ion nickel manganese cobalt (LiNMC) technology modelled from confidential data from ADEME, the French environmental management agency. Batteries’ energy densities and masses are based on IFPEN experts, manufacturers’ feedbacks and battery’s technology improvement and existing electric fleet. Table 1 presents the characteristics data for large BEVs updated from a former LCI [4].

Expected batteries’ lifetime is 10 years after automotive sector’s feedback and current guaranties. Pollutant emissions occurring during tank-to-wheel stage are recorded according to the Euro6b norms for CO, NOx, PM, and hydrocarbon compounds (HC) for gasoline. The Euro6b HC emissions norms for diesel vehicles were extrapolated based on the Euro6c norm and future Euro7 norm (IFPEN experts) as only the total of HC and NOx was provided in the standards. CO2 correlates with fuel consumption, unlike other pollutant emissions and the low heating values (LHV) use the JRC’s values [8]. An additional emission coefficient for NOx for diesel passenger cars has been added based on the
requirements of several European member states to thereby properly assess real driving emissions. For 2030 horizon, the additional coefficient for NOx is removed and future Euro7 norm is taken.

| Year | BEV  | Battery mass [kg] | Battery capacity [kWh] | Battery energy density [Wh/kg] | WLTC consumption [kWh/100 km] | Driving range [km] |
|------|------|-------------------|------------------------|-------------------------------|-------------------------------|-------------------|
| 2019 | BEV  | 2119              | 60                     | 150                           | 21.2                          | 240               |
|      | BEV+ | 2252              | 80                     | 150                           | 21.9                          | 310               |
| 2030 | BEV  | 2059              | 80                     | 200                           | 14.6                          | 493               |
|      | BEV+ | 2159              | 100                    | 200                           | 15.0                          | 600               |

Vehicle’s electricity and fuel consumptions are estimated using an IFPEN vehicle simulator based on Simcenter Amesim™ software [1, 2]. BEVs’ use states in a European context assuming that the average electricity mix results in 460.7 g CO$_2$ eq./kWh [17]. No projection for electricity mix has been made for 2030. Biofuels’ incorporation rates at filling stations have been also excluded.

Infrastructure, roads, charging stations, consumption by auxiliary functions, emissions related to tire wear and braking are not part of the scope but should be at fleet deployment scale.

2.1.4. Life cycle impact assessment (LCIA) methods
As BEVs are highlighted for their low GHG emissions, climate change is the first impact category assessed, based on the recommended methodology of the JRC-European Commission [21].

Furthermore, as BEVs are critical materials’ users, resource depletion is also quantified based on the abiotic depletion indicator (ADP) from van Oers et Guinée [34] methodology for the LCA perspective, as recommended in UNEP/SETAC LCI [33].

A criticality indicator also named “supply risk method” in UNEP/SETAC LCI [33] is also considered as geopolitical and socio-economic aspects are included (section 2.2).

2.2. Raw material representation in an Integrated Assessment Model (IAM)
In addition to the LCA, metals availability contained in BEV’s batteries (copper, lithium, nickel and cobalt) are assessed with the transport sector development through to 2050 and their geopolitical consequences. We rely on our linear programming world energy-transport model, TIAM-IFPEN which has been already presented in details in Hache et al. [13] The model allows examining two climate scenarios (2°C and 4°C) in order to estimate the consequences of the fast roll-out of low-carbon technologies in the transport sector and how it is likely to significantly increase metals demand by 2050. The import dependency on metals of the European Union in its attempt to electrify its transport sector was evaluated in order to estimate how this dynamic could increase metals criticality for this area. This notion of criticality is often described as all the risks related to the production, use or end-of-life management of a raw material [12] including geopolitical risks, economic risks, production risks and environmental or social risks.

3. Results

3.1. Climate change

1 Energy consumption from the grid, including losses and efficiency. It is different from the battery consumption.
2 Driving range corresponds to the battery capacity [kWh] weighted by the battery efficiency rate (efficiency between the electricity from the grid until the actual delivery of energy to the wheels: 0.85 in 2019 and 0.9 in 2030, based on IFPEN experts) divided by battery capacity [kWh].
Figure 2 presents the results for D-segment for BEVs and their thermic counterparts for current time and 2030. Technological progress in 2030 for gasoline vehicles can be mostly observed during the well-to-tank stage, based on consumption’s reduction combined to a slightly decrease of vehicle’s mass. Regarding BEVs, technological progress is quickly moving. Based on our assumptions, BEVs in 2030 will still remain slightly below the ICE regarding their impacts on climate change but frontier is small.

3.2. Trade-off identification for mass battery of EV in 2030

From climate change results, a methodology has been developed in order to assess the mass of battery required to exceed climate change impacts of ICE engines. The following assumptions have been considered:

\[
I_{BEV,D}^3 = I_{\text{glider, BEV}, D} + I_{\text{tyres, BEV}, D} + I_{\text{battery, BEV}, D} + I_{\text{WTW, BEV}, D}
\]  

(1)

With:

\[
I_{\text{glider, BEV}, D, 2030} + I_{\text{tyres, BEV}, D, 2030} = 31.10 \text{ g CO}_2 \text{ eq./person.km}
\]

This parameter is assumed constant for D-segment BEVs through to 2030.

For the use phase, i.e. \(I_{\text{WTW, BEV}, D}\), batteries’ technologies’ improvements are tough to project. However, the in-house vehicle simulator allows to assess electricity consumption which depends on mass test, also function of the mass of battery.

The same relation between the battery’s environmental impact and the battery’s mass can be made as battery’s impact relies on parameters such as BEV’s and battery’s lifetimes, BEV’s total mileage and the battery’s emission factor (EF), considered constant on a kg-basis for both time horizon.

\[^3\] I states for impact
Thus, the BEV’s impact is a linear function of the battery’s mass. Within the framework of the abovementioned hypothesis, the results show that the mass of battery should not exceed 457.5 kg, so that its performance does not fall below that of its thermal equivalent. A literature review of existing vehicles on market allowed us to make hypothesis regarding the range of BEVs’ performances [28]. Lower boundary for capacity is 20 kWh and upper boundary is set at 200 kWh. Density is comprised between 75 Wh.kg\(^{-1}\) and 500 Wh.kg\(^{-1}\). Table 2 presents the possible couples related to the calculated battery mass.

| Mass battery [kg] | 457 | 457 | 457 | 457 | 458 | 458 | 458 | 458 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Battery size [kWh]| 80  | 105 | 160 | 185 | 55  | 110 | 135 | 165 |
| Energy density [Wh.kg\(^{-1}\)] | 175 | 230 | 350 | 405 | 120 | 240 | 295 | 360 |

Table 2. Possible couples associated with a battery mass within the defined range.

The limit of electrification for large cars (D-segment and above) is pinpointing as these batteries’ parameters are fully possible to electrify the large vehicles fleet.

However, environmental impacts of BEVs are also located on resource depletion as batteries’ production needs critical material. In order to assess this issue, two resource indicators are calculated: an LCA resource depletion indicator in section 3.3 and a criticality indicator in section 3.4.

3.3. Resource depletion

Based on UNEP/SETAC LCI [33] recommendations, the first approach chosen to characterize resource depletion for electric mobility is the Abiotic Depletion Potential (ADP) method [34] presented in Figure 3.

The process contribution analysis for battery’s life cycle shows that 72.3% of the impact is related to the gold. This is not surprising as CML indicator identified gold with the highest characterization factor. Gold comes from the use of printed wiring board to produce battery. Gold is followed by copper (11%), silver (4.1%), zinc (1.4%), nickel (1.7%), and tin (0.8%). Lithium contribution to CML resource depletion indicator is less than 0.003%. Cobalt has almost no contribution to this indicator. However, it is important to consider the depletion of resources throughout a geopolitical risk. For this reason, a criticality indicator, also known as supply risk indicator, is evaluated.

3.4. Criticality

Figure 4 depicts the evolution of the total cumulative demand of copper, lithium, nickel and cobalt with climate constraints. It can be observed that 96.1%, 26%, 56.9% and 93.6%, respectively for copper, lithium, nickel and cobalt, would be consumed by 2050 in the most stringent climate scenario.

Figure 4: Comparison of cumulative consumption of raw materials by regions by 2050 and their known resources in 2010.
In this case, the transport sector accounts for 26.9%, 85.6%, 40.6% and 69.8% of copper, lithium, nickel, and cobalt respectively (Figure 5). Due to the fast roll-out of electric vehicles, the D-segment represents around 20% of the transport cumulative consumption of any raw material considered while it is less than 15% of the global fleet worldwide.

![Figure 5: Evolution of the raw material consumption disaggregated by road transport segments.](image)

This implies that this segment would certainly play an important role in raw material imports for Europe because they represent around 8% of the D-segment worldwide (Figure 6). In this context, European import dependency on raw materials for batteries is on stake. The European willingness to create a battery consortium in order to limit this future risk should be considered as the development of battery recycling sector.

![Figure 6: Evolution of the global vehicle stock and the D-segment between 2020 and 2050.](image)

ICE: Internal Combustion Engine; HEV: Full hybrid vehicle; PHEV: Plug-In hybrid electric vehicle; BEV: Battery-powered electric vehicle; FCEV: Fuel cell electric vehicle

Public transport regulators in Europe should also integrate in their policies the resource depletion as they had implemented CO₂ issues in the past. More globally, European public policies dedicated to sustainable mobility (non-motorized transport, public transport) could constitute the most efficient pathway to reduce both CO₂ emissions and resources consumption.

4. Conclusion
This study presents a LCA analysis focused on the climate change impact and resource depletion potential of large (D-segment) BEVs and ICEs for two time horizons (2019, 2030) in Europe simulated over the WLTC cycle. Demand and import dependency on materials through to 2050 were assessed thanks to our linear programming world energy-transport model, TIAM-IFPEN.
Results obtained show that BEVs could be a game changer for GHG reduction according to batteries’ weight and energetic sizing. Nevertheless, batteries’ production consumes critical materials and the two resource indicators pinpoint the fact that these two methodologies should be performed in parallel in order to have a broad view of the environmental impacts of the future development of transport sector. Indeed, the resource depletion shows that raw materials such as gold or copper have more environmental impacts than others such as cobalt, nickel or lithium. However, their criticality assessment gives a more complete view by considering a tri-dimensional approach based on geological, economical, and geopolitical factors.

5. References
[1] Badin F, Le Berr F, Briki H, Dabadie J, Petit M, Magand Sand Condemine E 2013 WEVJ 6.
[2] Badin F, Berr F, Castel G, Dabadie J, Briki H, Degeilh Pand Pasquier M 2015 WEVJ 7 475.
[3] Bouter A, Ternel Cand Melgar J 2019 LCA Study of Vehicles Running on NGV and bioNGV.
[4] Bouter A, Hache E, Ternel Cand Beauchet S 2020 Int J Life Cycle Assess 22 1441.
[5] Off J Eur Communities L 269 pp 34–43.
[6] Off J Eur Union L 310 pp 11–27.
[7] Off J Eur Union L 266 pp 1–13.
[8] European Commission 2014 Well-to-wheels analysis of future automotive fuels and powertrain in the European context. Description, results and input data per pathway. WTT_Appendix_4_v4a/APRIL2014.
[9] Ellingsen L A-W, Majeau-Bettez G, Singh B, Srivastava A K, Valøen L Oand Strømman A H 2014 J Ind Ecol 18 113.
[10] Ellingsen L A-W, Singh Band Strømman A H 2016 Environ. Res. Lett. 11 54010.
[11] Frischknecht R et al. 2005 Int J Life Cycle Assess 10 3.
[12] Graedel T E, Harper E M, Nassar N T, Nuss Pand Reck B K 2015 Proceedings of the National Academy of Sciences of the United States of America 112 4257. Available at https://www.pnas.org/content/pnas/112/14/4257.full.pdf.
[13] Hache E, Seck G, Simoen M, Bonnet Cand Carcanague S 2019 Appl Energ 240.
[14] Hawkins T R, Singh B, Majeau-Bettez Cand Strømman A H 2013 J Ind Ecol 17 53.
[15] ICCT ed 2014 The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU. Working paper.
[16] IEA 2017 CO2 Emissions from Fuel Combustion Statistics (OECD).
[17] IEA 2017 World Energy Statistics and Balances.
[18] ISO 2006 Environmental management - life cycle assessment - principles and framework (Geneva: International Organization for Standardization) 13.020.60.
[19] ISO 2006 Environmental management - life cycle assessment - requirements and guidelines (Geneva: International Organization for Standardization) 13.020.10 ; 13.020.60.
[20] JRC - European Commission 2010 ILCD Handbook. General guide for LCA - Detailed guidance.
[21] JRC - European Commission 2012 Recommendations for Life Cycle Impact Assessment in the European context. - based on existing environmental impact assessment models and factors (Luxembourg: Publications office of the European Union).
[22] JRC - European Commission 2018. Available at http://www.averefrance.org/Uploads/Documents/1548933066974482d1b51c56632ad2f02a4078ec5fkjna29440enn.pdf.
[23] Nemry F, Leduc G, Mongelli Iand Uihlein A 2008 Environmental Improvement of Passenger Cars (IMPRO-car) (Luxembourg: Publications Office).
[24] Nemry F et al. 2009 Feebate and Scrappage Policy Instruments. Environmental and Economic Impacts for the EU27 (Luxembourg: OPOCE).
[25] Nordelöf A, Messagie M, Tillman A, Ljunggren Söderman Mand van Mierlo J 2014 Int J Life Cycle Assess 19 1866.
[26] Notter D A, Gauch M, Widmer R, Wäger P, Stamp A, Zah R and Althaus H-J 2010 Environ Sci Technol 44 6550.

[27] PE International AG and Gingko 21 2013 Elaboration selon les principes des ACV des bilans énergétiques, des émissions de GES et des autres impacts environnementaux induits par l'ensemble des filières de véhicules électriques et de véhicules thermiques, VP de segment B (citadine polyvalente) et VUL à l'horizon 2012 et 2020. Etude réalisée pour le compte de l'ADEME.

[28] Peters J F, Baumann M, Zimmermann B, Braun J and Weil M 2017 Renew Sust Energ Rev 67 491.

[29] Sullivan J L, Gaines Land Systems E 2010 A review of battery life-cycle analysis. State of knowledge and critical needs (United States).

[30] Thackeray M M, Wolverton C and Isaacs E D 2012 Energy Environ. Sci. 5 7854.

[31] Tran M, Banister D, Bishop J D and McCulloch M D 2012 Nature Clim Change 2 328. Available at https://www.nature.com/articles/nclimate1429.pdf.

[32] Tutuianu M, Bonnel P, Ciuffo B, Haniu T, Ichikawa N, Marotta A, Pavlovic J and Steven H 2015 Transp Res D Transp Environ 40 61. Available at http://www.sciencedirect.com/science/article/pii/S1361920915001030.

[33] UNEP SETAC LCI 2019.

[34] L. van Oers et al. 2002 Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook.