Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment

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Abstract

Many new vehicle technologies are claiming to be the best in class to reduce the impact on the environment. However what are ‘green’ or ‘clean’ vehicles? How can this be assessed in the appropriate scientific way? The underlying assessment compares the environmental aspects of mainly compressed natural gas (CNG) and Battery electric vehicles, along with Liquid Petrol Gas (LPG), Biogas (BG), plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV) and conventional diesel and petrol vehicles. As an example and context the Brussels Capital region, the centre of Belgium as well as the capital of Europe, has been chosen. The methodology is based on a comparative environmental assessment of vehicle technologies using a life cycle assessment (LCA) approach. However, a special focus is given on the potential of battery electric vehicles to reduce (or increase) the transport related emissions in the Brussels capital region. The results will answer following research questions. What are the environmental impacts (climate change and urban air quality) of these ‘clean’ vehicle technologies compared to conventional vehicles, considering the full life cycle? What is the impact of the electricity production on the total life cycle environmental performance of electric vehicle and how does the type of energy source, to produce electricity, influences the impact? What are the life cycle environmental impacts of battery technologies used in BEVs? What is the effect of BEV charging patterns on the durability of batteries? What are the effects of real world driving styles and charging patterns (peak or off-peak) on the environmental performance of BEVs and PHEVs?

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Keywords: Life cycle assessment, compressed natural gas (CNG), battery electric vehicles (BEV), Plug-in hybrid electric vehicles ((P)HEV), electricity production, batteries

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1 Introduction
Transport sector is one of the most energy intensive and carbon emitting sectors. For instance, in the European Union, transport accounts for nearly one third of the final energy consumption and a quarter of the carbon dioxide (CO₂) emissions [1]. Especially, road transport emits more nearly 70% of the CO₂ emissions from the transport sector [2]. Though Greenhouse Gas (GHG) emissions are the most commonly discussed environmental issue, there are other local and regional pollutants such as sulphur dioxide (SO₂), nitrogen oxides (NOₓ), particulate matter (PM), etc. that need to be reduced further. The damages caused by these pollutants are greater especially in the densely populated urban areas. In Europe, these air polluting emissions are being reduced dramatically by many policy measures. However, still there is a need for a significant reduction of air pollutants in the urban areas with huge populations. As an example in Brussels capital region road transport contributed 67 %, 47 % and 27% of NOₓ, PM₂.₅ and CO₂ emissions respectively, in 2012 [3]. The daily average PM₁₀ (i.e. particles < 10 µm) limit in Brussels is set to be 50 mg/m³ [4]. In half of the air quality measuring station in Brussels, this limit has exceeded for more than 35 days/year in the recent years [4]. Hence, the current transport system, which relies nearly 95% on fossil fuels [5] has to be changed by means of clean alternative vehicles. Vehicle technologies with low life cycle carbon emissions and low (or zero) exhaust emissions could be promoted in the urban environments. Nowadays, there are many alternative vehicle technologies such as battery electric (BEV), hybrid electric (HEV), plug-in hybrid (PHEV), compressed natural gas (CNG), biogas (BG), etc. available in the market. At present, the passenger car fleet in the Brussels capital region is composed mainly of diesel (65 %) and petrol (34 %) vehicles. Thanks to the energy and transport policies aiming at integrating more alternative/renewable fuels and alternative propulsion systems, new technologies are being gradually integrated in the vehicle fleet. Especially, plug-in electric and CNG vehicles are of the main interest from urban air quality improvement and climate change point of view. When changing from conventional fossil fuel vehicles towards these alternative vehicles, the technological, socio-economic and environmental trade-offs must be assessed thoroughly.
In this paper, we quantify and compare the life cycle environmental impacts of different vehicle technologies, including electric, Biogas, (plug-in) hybrid and CNG vehicles, in comparison with the conventional fossil fuel vehicles. In particular, the capability of battery electric vehicles to contribute for better urban air quality and GHG reduction in the Brussels region are discussed in detail. The influence of charging time frames on the emissions due to electricity production to charge BEVs are discussed with the scope of identifying the possibilities for further minimizing the life cycle emissions. In addition, the environmental impacts of BEV batteries, effect of charging current on battery aging, significance of recycling and material constraints for future BEV batteries are discussed as well.

2 Methodology
In this paper, we use the Life cycle assessment (LCA) methodology for the comparative environmental assessment of vehicle technologies. LCA is a standardized methodology for the systematic assessment of environmental performance of any product or system, throughout its whole life cycle [6]. A comparative vehicle LCA study takes into account, not only the exhaust emissions, but all the emissions from different life stages such as fuel production, vehicle production, vehicle use and end of life of the vehicle. Life cycle system approach is important, because, for instance, comparison of only the exhaust emissions of a battery electric vehicle with a petrol vehicle is misleading. Though, the BEV has no emissions during operation, there are substantial amounts of emissions in the production processes of electricity and vehicle. Also, there are non-exhaust local pollutants like the particulate emissions from the abrasions of break, road and tyre that need to be accounted for correct results. Hence, the holistic system perspective is important to have a fair comparison, and to avoid problem shifting (from one life stage to another or from one geographical/ temporal boundary to another) while making decisions.
The environmental assessment vehicle technologies can be either a “well-to-wheel (WTW)” study that covers only the life cycle of the energy carrier (i.e. fuels or electricity) used to drive the vehicles as well as driving the vehicle itself or a “complete LCA”, which includes the production and recycling of the vehicle and this WTW part. The WTW life cycle can be subdivided into the “well-to-tank” (WTW) stage that focuses on the fuel supply chain, and the “tank-to-wheel” (TTW) stage, which is vehicle operation. Figure 1 illustrates the system boundary and the included unit processes of fossil fuel and electric vehicle technologies.
As in many LCA studies, we analyse the global warming potential (i.e. the greenhouse gas emissions) of different
vehicle technologies. In addition, we discuss the photochemical oxidant formation (POF), particulate matter formation (PMF) and human toxicity (HT) impact categories. In order to give more insight on the abilities of different vehicle technologies to reduce local air pollution in the urban areas, we highlight the geographical origins of the emissions.

As functional unit for comparing the environmental emissions of different vehicles, “1 km driving distance” is chosen. The vehicles are assumed to have an average life span of 14.1 years and the annual mileage of 14,865 km. The life cycle inventory of the different unit processes are obtained from [8] [9] [10] and [11]. The Recipe methodology is used to perform the impact assessment [12].

In general, the LCA results of vehicles are shown as single average value. The single value does not reflect the real-world uncertainties and variabilities of the system. Hence, they fail to provide decision-makers a broader view on the possible effects of the variability in the vehicle parameters. For instance, comparing a big electrified car with a small petrol car is misleading. The variation of parameters such as fuel consumption and weight of the cars within a given vehicle technology and segment can lead to different results and interpretations. Hence, it is mandatory to take into account the uncertainties when reporting and interpreting the LCA results. In this paper, the Range-based approach (refer[9]) is used to include the variation of the vehicle weight, the energy consumption and the emissions in the LCA results of the vehicles in the same category. The results are visualized with error bars showing the minimum, average and maximum values of the statistical distribution, in order to highlight the uncertainties.

The scope of this study, with respect to the fuel supply chain (including electricity) and the choice of vehicle technologies, is limited to the Belgian. Since BEV is among the interesting options for the policy authorities of Brussels, the LCA results of these vehicles are discussed in detail. The small passenger car segment is chosen for the comparative and uncertainty assessment in this study. Petrol and diesel versions of Volkswagen golf is considered to represent the average conventional vehicle. Similar sized vehicles in the same category (e.g. Nissan Leaf, Fiat Punto, Opel Ampera, Toyota Prius…) are considered for the comparison. For BEV applications, the recent lithium based batteries seem to be more interesting and promising, because of their high energy density and power characteristics. Hence, in this study, we considered only the lithium battery for the discussion on environmental and resource aspects of BEVs.
3 Results and discussions

3.1 Climate change
As a first indicator climate change is assessed. Figure 2 compares the climate change (or) global warming potential of different family car technologies over their complete life cycle and it is expressed as g CO₂eq per km. It is visible that the battery electric vehicle charged with the Belgian average electricity mix has the lowest emissions, followed by the PHEV and biomethane vehicles. It is evident that the shares of CO₂ emissions from the manufacturing of EVs are higher than the fossil fuel vehicle, due mainly to the battery and associated electrical components. However, a big share of the impact of the lithium battery is balanced by the benefit of the recycling. In general, for EVs the recycling of specific components such as the battery pack results a big environmental benefit. Among the fossil fuel vehicles, biomethane vehicle has a lower impact, followed by the CNG vehicle. This is mainly because the whole TTW CO₂ emissions of biomethane vehicle are assumed as renewable. The WTT part of biomethane is much higher compared to the CNG vehicle. This is because the Life Cycle Inventory (LCI) modelling of biomethane (according to [13]) takes into account the methane slips during the production and upgrading processes.

The environmental impacts of electric vehicles are strongly influenced by the source of electricity, as it can be powered by a range of electricity sources including gas, coal, nuclear, and renewables such as wind, biomass and solar. The possibilities of charging EVs with locally produced renewable energy can be perceived as a mean for reducing oil dependency and enhancing the energy security. The electricity mix and the level of electrification are among the key factors influencing the environmental performance of BEVs [7] [14].

Figure 3 shows the results of the WTW CO₂ emissions of BEVs charged with different sources of electricity (including the Belgian average electricity mix for 2011), in comparison with a fossil fuel vehicles. As can be seen in Figure 3, BEV has the lowest WTW CO₂ emissions when powered with wind or Belgian electricity. In contrast, BEV powered by coal electricity has similar WTW CO₂ emissions as diesel vehicle. The figure also shows a reduction in GHG emissions with the increase in the degree of electrification from HEV, PHEV, and extended range EV (EREV) to BEV. The results are calculated assuming that the average CO₂ emissions of electricity from coal, natural gas, wind and Belgian electricity mix are 1800 g/kWh, 885 g/kWh, 642 g/kWh, 11 g/kWh and 190 g/kWh, respectively [14] [9].

![Figure 2 Climate change (or) Global warming potential of different vehicle technologies (data from [9] and[13])](image-url)
3.2 Air pollution

3.2.1 Photochemical oxidant formation (POF)

Figure 4 illustrates the photochemical oxidant formation potential of different vehicle technologies. This indicator expresses the ability of NOx and non-methane volatile organic compounds (NMVOCs) to form ozone on the ground level and it is expressed as “kg NMVOC equivalent”. Creation of ground level ozone in densely populated urban areas cause many health and environmental issues. Unlike CO₂ emissions, the pollutants included in this category are mainly local pollutants. Broader life cycle perspective (especially the geographical boundaries of unit processes) reveals that these local pollutants are emitted in different places in the world. To make this more transparent, the WTT stages of all the vehicles are divided into two parts: 1) WTT-BE, represents the pollution inside Belgium (coloured part in the graph) and 2) WTT-rest which indicates the pollutions outside Belgium (black and white parts in the graph). The BEV has the lowest overall score, followed by CNG, PHEV, and so on. The conventional vehicles have higher overall scores than CNG and electrified vehicles. Regarding the TTW emissions inside Belgium, diesel vehicle has the highest score, followed by CNG and biomethane vehicles. The WTT emissions within Belgium (WTT-BE), of conventional vehicles, represent mainly the refining and distribution of fossil fuels in Belgium. Similarly, the WTT-BE part of electric vehicles correspond mainly to the emissions from the electric power plants. Concerning the biomethane vehicles, the WTT part represents the waste collection, transportation, digestion and upgrading of biogas to methane fuel. The TTW emissions of CNG and biomethane vehicles are considered to be the same.
3.2.2 Particulate matter formation (PMF)
This impact category indicates one of the main local pollution in the densely populated areas. Particulate matters (or fine dust particles) are emitted directly from the vehicles, as primary particles and also secondary particles that are created when SO₂, NOₓ and NH₃ interact with the atmosphere. Figure 5 illustrates the scores of different vehicles for particulate matter formation in terms of PM₁₀ equivalent. The unit PM₁₀ equivalent includes both primary and secondary PM emissions. The BEV and CNG vehicle have more or less the same total score, which is the lowest among the compared vehicle technologies. Though there are less primary PM emissions from the tailpipe of methane vehicles (CNG and biomethane), the secondary PM makes up the big value in the TTW part. Nevertheless, comparison of emissions occurred inside the boundary of Belgium reveals that the BEV has the lowest score on particle matter emissions as it has no tailpipe emissions. Unlike other indicators, the PM emissions in the TTW stage of the BEV indicate the non-exhaust emissions caused by abrasions of tyres, road and brakes. One can see that the life cycle PM emissions of electrified vehicles are happening mainly outside the densely populated areas.

![Figure 5 Particulate matter formation (PMF) of different vehicle technologies (based on [10])](image)

### 3.3 Human toxicity (HT)
Apart from particulates and ozone formation, Human toxicity potential is a specific midpoint impact category that contributes to potential harm on human health. This indicator includes both the inherent toxicity and general source-to-dose relationship of the polluting substances. The toxicity potential can be evaluated in terms of carcinogenic and non-carcinogenic compounds [15]. Figure 6 presents the results for Human toxicity potential of four vehicle technologies. It is expressed in units of 1,4-dichlorobenzene (DCB) equivalents, a well-known pesticide. In all the vehicles, the largest fraction of toxic emissions originates from the mining of materials that are used in the base vehicle manufacturing (body shell and other common parts).

The CNG vehicle has the lowest human toxicity potential among the compared vehicles. This is mainly due to the low WTW toxic emissions. In the case of BEVs, the specific components such as the Li-ion battery, electric motor and power electronics, are responsible for a significant amount of the overall impact. However there is a large uncertainty on these results that can be seen from the error bars. Toxic substances are mostly discharged from the mining processes of raw materials, for vehicle manufacturing and as well as the energy carrier for electricity. The WTW stage of the BEV has higher emissions because of the mining of nuclear, coal and other fossil fuels in the fuel supply stages of electricity production. The energy intensive materials processing and tailing of mining wastes in nuclear and coal extraction contributes an important share to the human toxicity impact [7]. Intensive use of precious materials such as copper and nickel in BEV applications leads to the excessive disposal of mine tailings that contains sulphur and heavy metals. It can be said that improved waste management in the mining sites (e.g. copper mining sites in Chile, China, and Peru), could strongly change these results and reduce the human toxicity score of the BEVs. Also, the integration of more renewable energy might lead to the reduction of toxic emissions in the WTW stage of BEVs. However, all these aspects regarding the minimization of human toxicity potential of BEVs need to be researched further.
Environmental impacts: The BEVs have more emissions in the vehicle manufacturing phase compared to the conventional vehicles. This difference is mainly because of the storage battery and the associated power electronic components in the electric vehicles. Since battery plays a significant role in defining the environmental performance of the vehicle, there are many LCA studies performed particularly on battery technologies [16] [17] [18] [19]. At present, Lithium-ion batteries (Lithium Manganese Oxide (LMO), and Lithium Iron Phosphate (LFP)) are the most commonly used electricity storage units in BEVs, mainly because of their suitable specific energy density and power characteristics [20].

The environmental scores for climate change, particulate matter formation, human toxicity and material depletion of two chemistries of lithium batteries are given in Figure 7 [16]. It is visible that in all the impact categories except the material depletion, the use phase (i.e. the electricity used to charge the battery) has a significant influence on the overall score. Hence it can be argued that the environmental performance of these batteries can be improved by charging them with renewable electricity.

Also the recycling of materials has significant benefits in human toxicity and material depletion categories. The negative values in Figure 7 mean that the emissions avoided due to the recycling of materials outweigh the emissions from the recycling process of the batteries.

Table 1 shows LCA results for different battery types used in EVs, in form of a weighted and aggregated single score according to the Eco-indicator’99 method [21]. The lithium-ion and sodium-nickel chloride technologies have the lowest scores due to their high-energy density and low system losses. The difference between “with” and “without recycling” are shown in order to highlight the environmental benefits of material recycling. The life cycle modelling in [21] assumes that almost all the recycled materials replace virgin materials. It is visible that the material recycling has a great influence on the overall score of the equipment life cycle. Hence, the potential for recycling of lithium-ion batteries has been a focus point of many studies [22]. However, only the lead acid batteries have the highly efficient recycling processes nowadays. Thus, it can be said that the latest battery technologies need to have more efficient and large-scale recycling industries if better results are to be realized [23].

Figure 6 Human toxicity potential - Comparison between BEV and ICE vehicles (based on [7] and [10])

3.4 EV batteries - Environmental impacts and lithium availability

Since energy storage batteries have a significant influence on the global environmental performance of battery electric vehicles, this section elaborates more on the environmental performance of batteries.

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Apparentl, off-imizing the emissions and the energy cost. In Belgium, vehicle monitoring test results show able. harge and different magnitudes (1.25 It, 2.5 It…10 It) of the sources such as wind and solar, causing and the working temperature of the battery are also X-ences between the WTT emissions of yearly average peak and off-regarding the key variables, and estimated that the demand for lithium might vary from 184,000 to 989,000 tons per year.

Some studies assessing the future availability of lithium for BEV applications, mostly assume that there will be a large scale recycling in the future. Also studies comparing the supply and demand of lithium for BEV market argue that there might be a scarcity of lithium in the future, and consequently the dependent industries might be threatened. However, the estimates on the availability of the global reserves of lithium have a huge uncertainty ranging from 4.6 Mt to 39.4 Mt [24]. The approximate geographical distribution of lithium resources and production in 2011 is as follows: Australia (36%), Chile (35.6%), China (17%), Argentina (7.4%), Portugal (2%), Zimbabwe (1.4%) and Brazil (1%) [26].

The growth in lithium demand implied by the future electrified vehicles scenarios is significant, especially where scenarios are concerned with environmental targets. Many studies investigated the future of lithium availability, specifically for electric vehicle applications (refer [26]). Speirs et al. [26]highlighted the data uncertainties regarding the key variables, and estimated that the demand for lithium might vary from 184,000 to 989,000 tons per year in 2050. At present, the battery market accounts for nearly 22% of the global lithium demand [16]. Literature studies assessing the future availability of lithium for BEV applications, mostly assume that there will be a large scale recycling in the future. Also studies comparing the supply and demand of lithium for BEV market argue that that lithium shortage will not pose a hindrance for the BEV industry, if proper material recycling is practiced [16].

### Materials availability:

Lithium is gaining importance in the batteries industry, particularly in BEV applications, due to high energy density and better performance at changing temperatures. In addition, for production volumes greater than 300,000 units per year, Li-ion batteries are anticipated to become less expensive [24], compared to other options. The technical and economic advantages make lithium a promising option for BEV applications. Assessing the future availability of lithium becomes obviously important in the matter of future development of BEVs. Some studies argue that there might be a scarcity of lithium in the future, and consequently the dependent industries might be threatened [25]. However, the estimates on the availability of the global reserves of lithium have a huge uncertainty ranging from 4.6 Mt to 39.4 Mt [24]. The approximate geographical distribution of lithium resources and production in 2011 is as follows: Australia (36%), Chile (35.6%), China (17%), Argentina (7.4%), Portugal (2%), Zimbabwe (1.4%) and Brazil (1%) [26].

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### Table 1 Eco-indicator99 environmental scores with and without recycling for EV batteries (WTW parts are not included, based on[21])

<table>
<thead>
<tr>
<th>Environmental score (points)</th>
<th>Lead acid</th>
<th>Nickel cadmium</th>
<th>Nickel metal hybrid</th>
<th>Lithium ion</th>
<th>sodium-nickel chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>without recycle</td>
<td>1091</td>
<td>861</td>
<td>945</td>
<td>361</td>
<td>368</td>
</tr>
<tr>
<td>with recycle</td>
<td>588</td>
<td>313</td>
<td>454</td>
<td>83</td>
<td>134</td>
</tr>
</tbody>
</table>

Figure 7 Life cycle impact assessment of lithium battery technologies
3.5 **EV charging – implications for environmental performance and aging**

As aforesaid, the electricity mix plays a crucial role in defining the life cycle emissions of (plug-in) EVs. However, the electricity mix changes from one hour to another. Hence, charging the vehicle at the right time frame becomes important for further minimizing the emissions and the energy cost. In Belgium, vehicle monitoring test results show that the BEV users tend to charge their vehicles mainly during daytime, when the demand and the energy costs are already high. Rangaraju et al. [27] assessed the impact of the time of the charging on the emissions performance of BEVs by differentiating peak (8:00 till 23:00 PM) and off-peak (midnight till 8:00) charging. The results reveal that the charging time of the BEV has a significant impact on the WTT emissions. In Belgium, nuclear plants are mainly used for meeting the base load, while natural gas, coal and other flexible producing units are used for filling up the fluctuating demand. Also there is a significant share of intermittent energy sources such as wind and solar, causing fluctuations in the supply side. The inconsistency in the hourly emissions of the electricity mix occurs mainly due to the production from renewable energy sources and the marginal producing units at each hour. Thus, there are significant differences in the WTT emissions of BEV when comparing the average of different time frames of the day.

Table 2 shows the differences between the WTT emissions of yearly average peak and off-peak charging of a small electric city car (Peugeot iOn). It is assume that the car has a life time driven distance of 209470 km and an average energy consumption of 18 kWh/100 km (based on real-time monitoring of test vehicles). Apparently, off-peak charging (i.e. from midnight till 8 AM) exhibits the lowest WTT emissions for all the analysed emissions. This is because, at night, the load is met mainly by the base load nuclear plants, renewable energy sources and some flexible producing natural gas plants with better efficiency. If the vehicle is assumed to be charging during off-peak hours instead of peak hours, the WTT CO\textsubscript{2e}, PM, NO\textsubscript{X} and SO\textsubscript{2} emissions per km can be reduced by 12%, 15%, 13% and 12% respectively.

<table>
<thead>
<tr>
<th>WTT emissions</th>
<th>CO\textsubscript{2e} (g/km)</th>
<th>PM (g/km)</th>
<th>NO\textsubscript{X} (g/km)</th>
<th>SO\textsubscript{2} (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>36</td>
<td>0.012</td>
<td>0.031</td>
<td>0.013</td>
</tr>
<tr>
<td>Off-peak</td>
<td>32</td>
<td>0.011</td>
<td>0.026</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Secondly, the mode of charging (fast or normal charging) might also influence the performance and aging (i.e. durability) of lithium batteries. The rapid aging of the battery will have a substantial effect on the environmental performance of BEVs, because it will cost more than one battery to cover the life time driven distance of the vehicle. Omar et al. [28] thoroughly assessed the aging parameter of lithium-ion phosphate (LFP) based batteries, investigating different charging currents, temperature, depth of discharge, etc. The tests subject was a 2.5 Ah 3.3 V rated LFP battery, tested with 100% depth of discharge and different magnitudes (1.25 It, 2.5 It...10 It) of the charging current. The testing was conducted under normal room temperature (around 25°C). When fast charged with 2.5 It, instead of 1.25 It (3.5 A), the number of cycles to reach 80% remaining capacity drops from nearly 2900 to 1600. The higher the numbers of cycle means the higher the durability of the battery. Apparently the number of cycles decreases with the increase in the charging current. However, this study was conducted on smaller cells compared to the EV batteries. For an EV, equipped with a 300 V, 80 Ah – 24 kWh battery pack with the normal charging current of 0.125 It (10 A), the semi fast charging 1 It (80 A) is acceptable, but extreme high current (160 or 320 A) charging is not advisable. Also the frequency of fast charging in comparison with the normal charging needs to be accounted in order to obtain the realistic effect of fast charging on the aging of battery. Apart from the charging currents, the depth of discharge at each charging and the working temperature of the battery are also important factors to be considered while analysing the durability.

4 **Conclusions**

The comparative LCA of vehicle technologies reveal that the plug-in electric vehicles (BEV and PHEV) tend to have the lowest greenhouse gas emissions, followed by the biomethane vehicles. Also the results show that the WTT
CO₂ emissions of a European average BEV can vary from 175 g CO₂e/km to 2 g CO₂e/km, depending on the electricity source and assumptions used. The BEV exhibits 31 g WTT CO₂e/km (maximum), when charged with the Belgian average electricity mix in the year 2011. The life cycle CO₂ emissions tend to reduce with the increase in the level of electrification from HEV, PHEV and EREV to BEV.

Regarding the local pollution, BEV has the lowest score on POF, while both CNG and BEV has more or less the same amount of life cycle PM emissions. However, when looking into the local emissions that are emitted inside the perimeter of Belgium, the BEV has a better performance among all the compared vehicles. Hence, the electric propulsion seems to be a better option for city driving, mainly because of their zero tailpipe emissions and high energy efficiency. Also, the emissions from electric power plants are discharged through high chimneys in a controlled manner, mostly out of city limits.

Manufacturing of batteries and power electronic equipment are responsible for a major fraction of toxic emissions in the life cycle of EVs, due to mining (outside Belgium). Also, in the WTW stage of plug-in EVs, the mining of nuclear, coal and fossil fuels in the fuel supply chains has a substantial amount of emissions of toxic substances. Toxic substances are discharged mainly in the mining process of materials and fuels. Thus, the mining process and waste management should be improved.

The results in the reviewed literature show that the time of charging of the EVs play a crucial role in defining the overall emissions performance. If the vehicle is charged during off-peak hours instead of peak hours, the WTT CO₂e, PM, NOₓ and SO₂ emissions per km can be reduced by 12%, 15%, 13% and 12% respectively, when the Belgian electricity mix for 2011 is considered.

Concerning the lithium availability for EV batteries, literature studies assessing the future availability of lithium particularly for EV applications, mostly assume that there will be a large scale recycling in the future. The studies comparing the supply and demand of lithium for EV market argue that that lithium shortage will not pose a hindrance for the EV industry, especially with a proper material recycling.

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5 Bibliography

This study was performed under the framework of the project "Brussels Research on the Opportunities of Electric Mobility" (IGBE), 2015. The studies concerned the lithium availability for EV batteries, literature studies assessing the environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles in a market and fuel perspective. The BEV is shown to have a better performance in terms of life cycle energy efficiency and overall emissions performance. If the vehicle is charged during off-peak hours, the WTT CO2 emissions are 0–0.000–0.000–0.000–0.000 g CO2/km, depending on the extent of recycling. Hence, the electric drive vehicles in a market perspective have a lower environmental impact compared to conventional vehicles. The aging parameters and development of cycle life model, 2010. NRC, “National Research Center: Transitions to alternative vehicles and fuels,” Washington DC, USA, 2013.

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