Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2019, Volume 7, Issue 3, pp 416-431

On the Environmental Benignity of Electric Vehicles

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Cite as: Ajanovic, A., Haas, R., On the Environmental Benignity of Electric Vehicles, J. sustain. dev. energy water environ. syst., 7(3), pp 416-431, 2019, DOI: https://doi.org/10.13044/j.sdewes.d6.0252

ABSTRACT

Electric vehicles are considered as an important means to cope with increasing environmental problems in the transport sector. Many governments worldwide have set targets to increase the number of electric vehicles, although their environmental benignity is not ensured in the scope of the policies implemented. The core objective of this paper is to investigate the overall environmental impact of electric vehicles in different regions. The analysis is based on a life cycle assessment of electric vehicles including emissions from electricity generation, vehicle production and disposal, and vehicle use. The major conclusion is that the environmental benignity of electric vehicles is very sensitive on: electricity mix (a); number of km driven per year (b) and embedded emissions in car production (c), as well as battery recycling. Yet, as shown in this paper the highest sensitivity is with respect to the electricity mix. Hence, to make electric vehicles more environmentally friendly it is most important to increase the share of renewable energy sources in electricity generation.

KEYWORDS

Mobility, Sustainability, Embedded emissions, Electricity generation, Life cycle assessment, Passenger cars.

INTRODUCTION

The transport sector accounts worldwide for 27% of final energy consumption, and for 25% of the world carbon dioxide emissions [1]. The United States, European countries, especially Organisation for Economic Co-operation and Development (OECD) countries, and China are the world's largest transportation energy consumers. Together, they account for about 55% of total energy consumption in the transport sector. Currently, transportation energy consumption is dominated by fossil fuels, gasoline and diesel, leading to different negative impacts on humans and environment.

Due to the urgent need to reduce Greenhouse Gas (GHG) emissions and local air pollution interest in electrification of mobility is rapidly increasing. However, in spite of the different supporting policies implemented in many countries, the amount of electricity used in the transport sector is still negligible. In 2016, the share of world total electricity consumption in the transport sector was only 1.7% (Figure 1). This is even for 0.7% lower than it was in 1973 [2].

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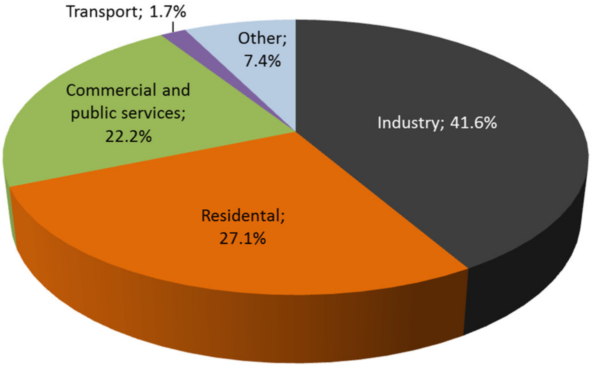

Figure 1. World electricity consumption by sectors (own compilation based on data source [2])

In the past, there were several waves of electrification of mobility. The first boom was at the turn of the 19th century. The next wave emerged in the 1990's but it disappeared very rapidly due to the limits of battery performances. With the emergence of lithium-ion batteries, which have been mostly used in the information technology sector, a new wave of enthusiasm regarding electric vehicles (EVs) started about 10 years ago.

In the meantime, EV's have been recognized by many governments as technology which can contribute to emission reductions in the transport sector [3, 4]. Due to supporting policies implemented in many countries worldwide, the number of EV's has been continuously increasing reaching more than 3 million vehicles in 2017 (Figure 2). The largest percentage of EV's in the total EV's stock exists currently in China (39%) and the USA (25%) followed by European countries, especially Norway (6%) and the Netherlands (4%) [5].

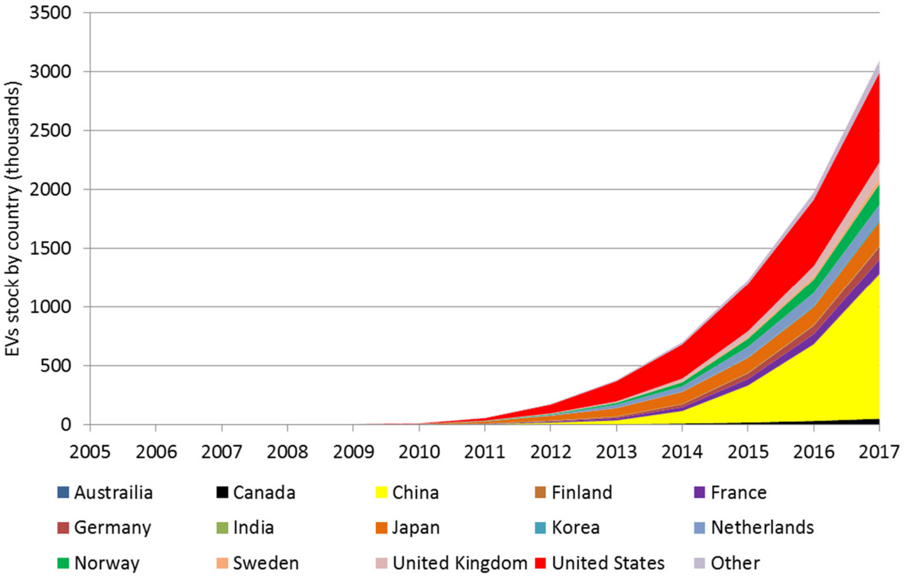

Figure 2. Development of the global stock of rechargeable EV's
(own compilation based on data source [5])

However, total number of EV's is still very low comparing to the total vehicle stock. The major reasons for the slow penetration of EV's are higher purchase prices, shorter driving range and longer charging time comparing to conventional cars, as well as limited charging infrastructure [6, 7].

All these existing problems as well as future challenges have been discussed in literature over the last decade. Hoyer [8] documented the history of electric and hybrid cars, while recent developments of EV's and future prospects have been investigated by

Propfe *et al*. [9]. Economic assessment of EV's is pretty good documented in literature. Weiss *et al*. [10] has analyzed the electrification of road transport with a special focus on learning rates and prices of Hybrid Electric Vehicles (HEV's) and Battery Electric Vehicles (BEV's). Business models for electric cars have been discussed by Kley *et al*. [11] and Christensen *et al*. [12]. Total costs of ownership are calculated for different cases, e.g. different types of EV's, their use in different countries or different lifetime of EV's [13, 14]. Currently, due to limited driving range of EV's and restricted charging infrastructure, BEV's are mostly used for short distances in cities, where average daily travel need is between 10 and 40 km [15]. In the future with the increasing energy density of batteries, as well as broader availability of charging infrastructure (including also possibilities for fast charging), the number of specific kilometers driven of EV's could be much higher, making BEV's more attractive and more cost-competitive with conventional cars. This could be supported also with deployment of inductive charging [16] as well as with the use of advanced materials in EV's production [17].

In spite of the current limits, EV's are widely supported by monetary and non-monetary measures implemented in many countries, as well as by policy targets set for the future. For example, according to the Paris Declaration on Electro-Mobility and Climate Change & Call to Action goal is to have worldwide more than 100 million EV's and 400 million two and three-wheelers by 2030 [18]. However, the increasing electrification of mobility leads to intensified discussion on the real environmental benefits of EV's.

Figure 3 shows different types of EV's [BEV's, HEV's, Plug-In Hybrid Electric Vehicles (PHEV's), and Range Extenders (REX's)] with different level of electrification and consequently with different contribution to the emission reductions. A comprehensive discussion of different types of EV's is provided by Ajanovic [19] and Ajanovic and Haas [20].

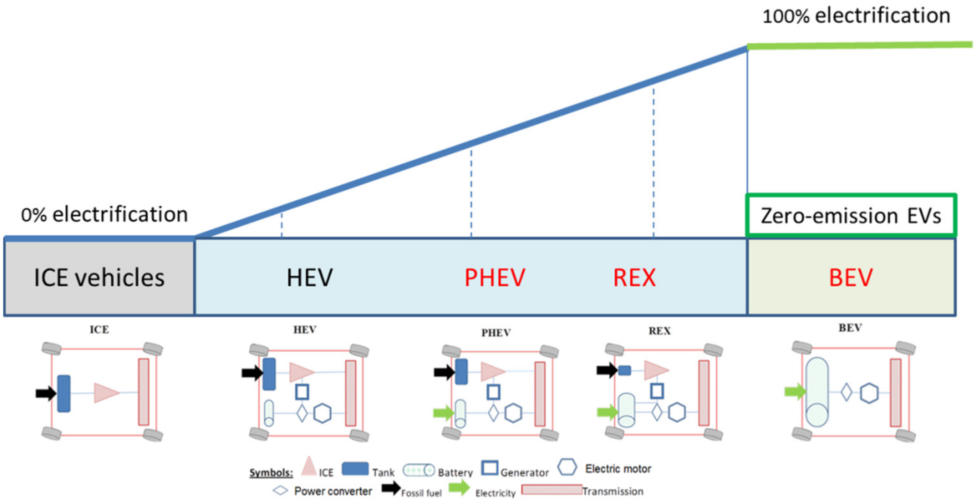

Figure 3. Level of electrification of electric vehicles in comparison to conventional internal combustion engine (ICE) vehicles (own compilation based on Ajanovic [19])

Although, HEV's are currently mostly used, due to similarity to conventional Internal Combustion Engine (ICE) vehicles, their contribution to the reduction of environmental problems is very limited. This paper focuses on rechargeable EV's (PHEV, REX and BEV), which have higher level of electrification.

The core objective of this paper is to investigate the overall environmental impact of midsize rechargeable EV's in different regions. The method of approach is based on a LCA of EV's including emissions from electricity generation, vehicle production and disposal, and vehicle use. In addition, discussion on battery recycling is conducted.

Some of the environmental issues of EV's have been addressed in several papers. The relevance of the use of electricity from Renewable Energy Sources (RES) for EV's has been discussed by Sweeting and Winfield [21] and Ajanovic [19, 20]. These papers stress that to reach full environmental benefits of EV's they have to be charged by electricity generated from RES. Anair and Mahmassani [22] provides an environmental analysis of EV's regarding GHG emissions for several electricity grid regions in the USA. Zackrisson *et al*. [23] have used LCA to optimize the design of lithium-ion batteries for PHEV's. Egedea *et al*. [24] presents a framework for the LCA of EV's to consider influencing factors in the use phase. A comparison of the life cycle GHG emissions of BEV's and ICE vehicles has been conducted by Ma *et al*. [25].

Hawkins *et al.* [26] reviewed about 50 studies on lifecycle of EV's, concluding that study-to-study comparison is very difficult due to different definition of LCA boundaries, scopes and methods. The assumptions regarding the lifetime of EV's, type and size of battery are also very different from study to study. Peters *et al.* [27] reviewed a large number of LCA analysis conducted in period 2000-2016 showing large dependency on data used and a weak base of primary life-cycle inventory data. Ellinger *et al.* [28] concludes in their work that data about manufacturing emissions of batteries differ a lot since it is very difficult to get a primary data from the battery industry.

The analysis in this paper provides a comprehensive assessment of major environmental issues related to EV's in four selected areas, China, the USA, and Norway, and the EU-28 as a whole.

METHOD

To assess the full environmental impact of different types of automotive technologies it is necessary to consider all emissions that occur in the whole energy supply chain including battery recycling. The environmental assessment of mobility focused usually on Well-to-Wheel (WTW) analysis including upstream emissions [Well-to-Tank (WTT)] that occur during the fuel or electricity production and supply, and tailpipe emissions [Tank-to-Wheel (TTW)] that occur during the car use.

In addition to this, it is important to consider emissions related to the manufacturing and disposal of cars. In this paper a combined WTW and Cradle-to-Grave (CTG) analysis is conducted (Figure 4). Moreover, emissions related to battery production and recycling are discussed in the scope of the sensitivity analysis.

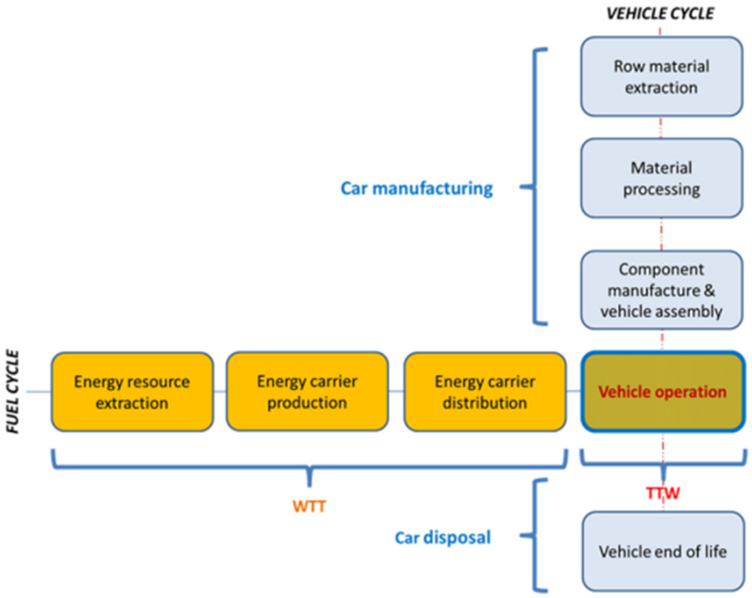

Figure 4. Method of emission assessment

In this paper the whole LCA assessment is divided in two categories: CO_2 emissions from the fuel cycle (electricity generation and vehicle use) and embedded emissions from vehicle production and scrappage.

The emission calculation is done by using the following formal framework: The total carbon dioxide emissions (CO_2) are calculated as the sum of embedded CO_2 emissions ($\mathrm{CO_2}_{\mathrm{VEHICLE\_CYCLE}}$) and the CO_2 emissions of the fuel cycle ($\mathrm{CO_2}_{\mathrm{FUEL\_CYCLE}}$):

$$\mathrm{CO_2} = \mathrm{CO_2}_{\mathrm{VEHICLE\_CYCLE}} + \mathrm{CO_2}_{\mathrm{FUEL\_CYCLE}} \text{ [g CO}_2\text{/km]} \tag{1}$$

The CO_2 emissions of the vehicle cycle are dependent on the embedded CO_2 emissions per kilometer driven and vehicle life-time [eq. (2)]:

$$\mathrm{CO_2}_{\mathrm{VEHICLE\_CYCLE}} = \frac{\mathrm{CO_2}_{\mathrm{EMB\_VEHICLE}}}{skm \times LT} \text{ [g CO}_2\text{/km]} \tag{2}$$

The total embedded CO_2 emissions of the vehicle are obtained from the sum of the embedded CO_2 emissions of different materials ($\mathrm{CO_2}_{\mathrm{EMB\_MAT}\_i}$) used in vehicle production and the CO_2 emissions of the production process ($\mathrm{CO_2}_{\mathrm{PRODUCTION}}$):

$$\mathrm{CO_2}_{\mathrm{EMB\_VEHICLE}} = \sum_{i=1}^{n} \mathrm{CO_2}_{\mathrm{EMB\_MAT}\_i} + \mathrm{CO_2}_{\mathrm{PRODUCTION}} \text{ [t CO}_2\text{/car]} \tag{3}$$

The CO_2 emissions of the fuel cycle ($\mathrm{CO_2}_{\mathrm{FUEL\_CYCLE}}$) are calculated as:

$$\mathrm{CO_2}_{\mathrm{FUEL\_CYCLE}} = f_{\mathrm{CO_2}} \times EI \text{ [g CO}_2\text{/km]} \tag{4}$$

where *EI* is electricity/energy intensity [kWh/km] of vehicles.

The specific CO_2 emission factor ($f_{\mathrm{CO_2}}$) is calculated by weighing the shares of electricity and fossil fuels:

$$f_{\mathrm{CO_2}} = \left[f_{\mathrm{CO_2}_{\mathrm{el}}} \times x + f_{\mathrm{CO_2}_{\mathrm{foss}}} \times (1 - x) \right] \text{ [g CO}_2\text{/kWh]} \tag{5}$$

The corresponding factor for electricity ($f_{\mathrm{CO_2}_{\mathrm{el}}}$) is calculated by weighing the shares of the single energy carriers (*j*) in the electricity mix:

$$f_{\mathrm{CO_2}_{\mathrm{el}}} = \sum_{j=1}^{m} f_{\mathrm{CO_2}\,j} \times q_j \text{ [g CO}_2\text{/kWh]} \tag{6}$$

where q_j represents the share of the single energy carriers in electricity generation.

The major contribution of this paper is that it addresses simultaneously all key impact parameters on the environmental impact of EV’s: the electricity mix, type of EV’s, travel activity and the embedded energy of the car. In addition, a discussion on the sensitivity of the impact of major parameters on the specific CO_2 emissions per kilometer driven is conducted. The impact of km driven per car and year, the fuel mix for electricity generation and the category of EV (PHEV, REX, BEV) are analyzed in detail.

EMISSIONS ASSOCIATED WITH ELECTRIC VEHICLES

The analysis of the emissions related to electric vehicles is conducted in four steps:

- WTT assessment based on different energy mix for electricity generation;
- TTW assessment which is dependent on vehicle type and use;
- Emissions related to vehicles production;
- Discussion on possible benefits of the battery recycling.

Well-to-Tank assessment: Electricity generation

While for conventional vehicles the TTW energy conversion accounts for the most of the total GHG emissions, total emissions of EV's are largely dependent on WTT emissions. In the case of conventional cars, WTT emissions are known quite well – the carbon intensity for petrol production is 0.46 kg CO_2/L [29]. However, carbon intensity of electricity could be very different depending on the primary energy sources used for electricity generation (Figure 5).

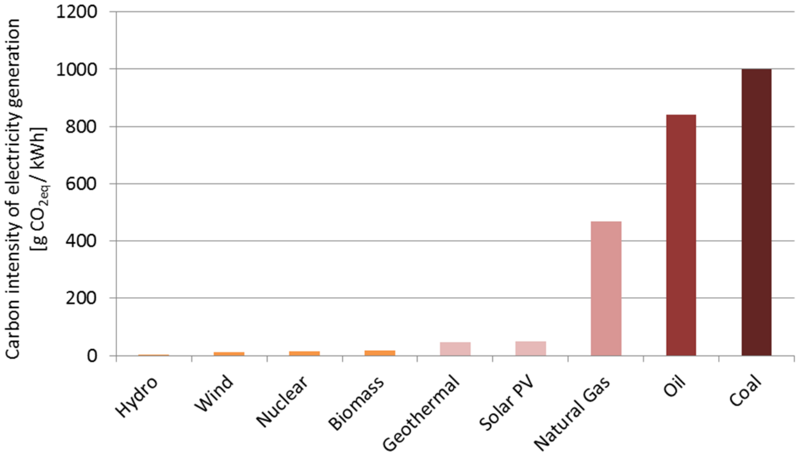

Figure 5. The carbon intensity of electricity generation (own compilation based on [30])

The total carbon intensity of grid electricity is dependent on the emissions caused during electricity generation and the losses in transmission and distribution of electricity. It is different from country to country depending on the mix of energy sources used in electricity production. The development of the mix of energy sources used in electricity generation in the EU-28 is shown in Figure 6. It can be noticed, especially in the last few years, a significant decrease in use of solid fuels and petroleum, and very rapid increase in the use of renewables.

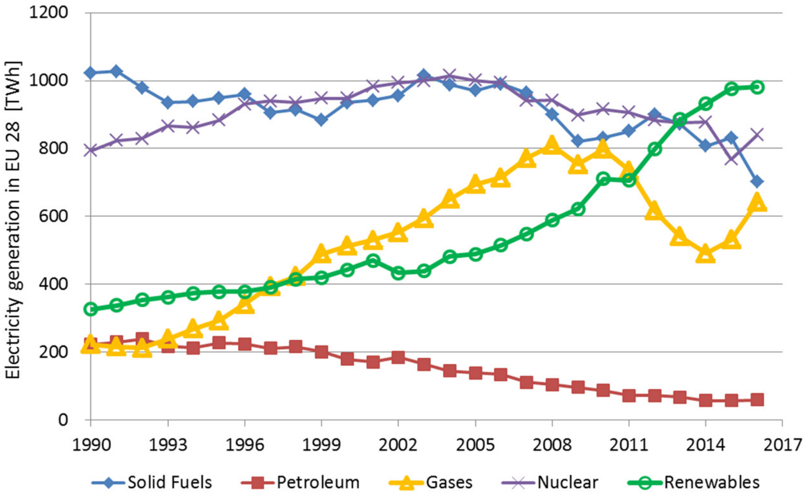

Figure 6. Electricity generation in the EU 28 (own compilation based on [31])

However, there are significant differences between carbon intensity of the electricity mix across European countries (Figure 7). While the average carbon intensity of electricity generation in the EU in 2014 was about 376 g CO_2/kWh, in some countries (Greece, Malta and Estonia) it was more than 700 g CO_2/kWh, and in some below 60 g CO_2/kWh (e.g. Sweden, France and Austria).

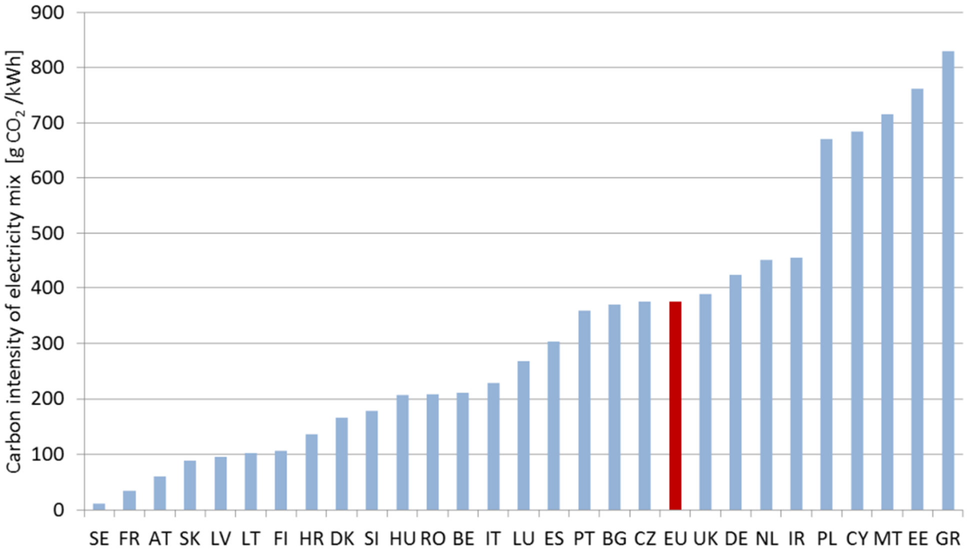

Figure 7. CO_2 per kWh electricity generated in different European countries (2014) (own compilation based on [32])

According to the EU's Energy and Climate Change Packages for 2020 and 2030 increasing use of RES in electricity generation is one of the three major targets [33, 34]. Increasing share of RES in the electricity mix should make EV's more environmentally friendly and therefore more attractive. However, as shown in Figure 6, in spite of increasing use of renewables for electricity generation in the EU, coal still makes a significant contribution.

Currently, in Europe, Norway is a leading country in promotion and use of EV's. On the other side, largest number of EV's is in the USA, China and the EU (Figure 2). However, due to very different country specific electricity mixes, contribution of EV's to the reduction of the global GHG emissions is very different. As shown in Figure 8, electricity mix in Norway is dominated by renewables (about 98%), in the USA and China by fossil energy (about 70%). In the EU-28 renewables, nuclear and coal have about the same share.

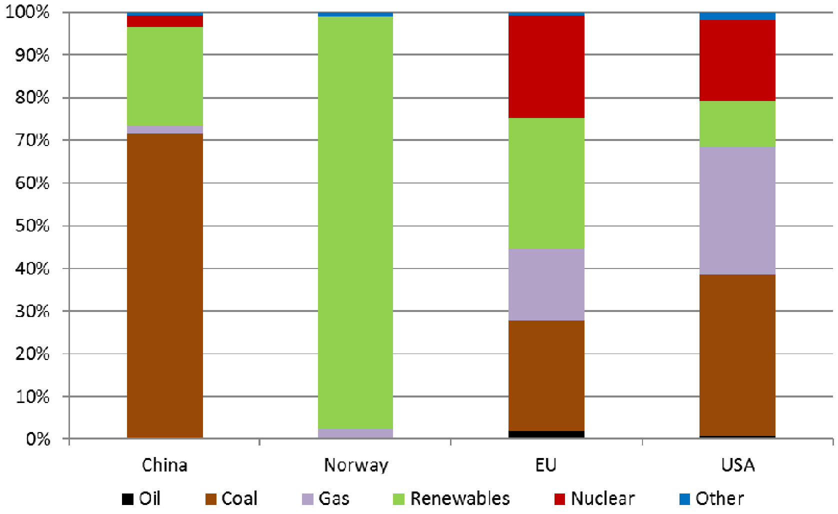

Figure 8. Electricity mix in selected countries/regions: China, the EU, Norway and USA, 2014 (own compilation based on [35, 36])

The actual electricity mix has significant impacts on the WTT emissions of EV's, as well as emissions from the EV's manufacturing, including battery.

Tank-to-Wheel assessment: Vehicle use

The emissions caused during the car use are dependent on type and energy efficiency of automotive technology. The carbon intensity of petrol combustion is about 2.3 kg CO_2/L [29]. PHEV and REX vehicles could reduce TTW emissions but these emissions are very dependent on driving behavior – to which extend is battery used and to which ICE. In our estimations, it has been assumed that 50% electricity and 50% gasoline is used in PHEV's. For REX EV's is assumed on ratio of 10% gasoline and 90% electricity.

In contrary to conventional cars which cause largest amount of emissions during the car use, BEV's have zero-emissions at the point of use making emissions from mobility more controllable. BEV's could significantly contribute to the reduction of the local air pollutions in the urban areas [37].

Emissions from vehicle production

Emissions occurring during car manufacturing and their impact on total LCA emissions are different for EV and conventional ICE vehicles. The largest difference is due the fact that BEV's have no fuel tank or internal combustion engine but instead have a battery pack, electric-drive motor, power-control electronics, and regenerative braking systems [38]. The major problem and the largest source of uncertainty for the future environmental assessment of EV's is the battery. Type and size of battery used in cars have a very high impact on the material used and manufacturing emissions.

Gasoline vehicles have only a small lead-acid battery for starting the engine and powering accessories while the engine is off, whereas BEV's rely on much larger, usually lithium-ion batteries to power the vehicle itself.

EV's and gasoline vehicles tend to have different ratios of the materials such as copper, aluminum, and steel, as well as different weight mostly due to battery. Weight and material composition of vehicles determine the majority of global warming emissions from manufacturing.

Based on literature, vehicle manufacturing emissions of the conventional ICE vehicles are in the range between 4 and 7 kg CO_2/kg curb weight of vehicle. However, estimating manufacturing emissions for EV's is more complicated, due to limited number of studies and the greater variation of their results [38]. They are very dependent on battery used. Depending on technology, total battery production emissions are estimated to be in a range between about 50 to 270 kg CO_2/kWh in the older studies [38, 22, 39-42], and between 150 and 200 kg CO_2/kWh in the most recent studies [43-45]. In the majority of earlier studies emissions from the material processing are not included. The energy use from current buttery manufacturing is in the range from 350 and 650 MJ/kWh [43]. Currently, about 60% of the total battery emissions is coming from the manufacturing. A discussion on the impact of the battery production location and electricity mix is provided by Romare and Dahllöf [43]. For example, in countries with the high share of RES (e.g. in Sweden and Norway) emissions from battery manufacturing could be for about 60% lower in the comparison to the USA. However, currently, most lithium-ion batteries are produced in Japan and South Korea where approximately 25% to 40% of electricity is produced by coal [44].

The battery capacity varies in different types of EV's and it is a key factor in determining operating range of EV's. A larger battery means a larger driving range but also a higher weight of vehicles as well as a larger amount of the emissions from car manufacturing due to the battery.

In literature, manufacturing emissions are usually given in gram of CO_2 per kilometer driven, assuming lifetime between 150,000 and 288,000 km. However, this is very optimistic assumption knowing that current use of EV's is mostly limited to urban areas where the driving range is between 10 and 40 km per day. In most studies, it is not specified which size of cars and batteries are considered. All this results in a very broad portfolio of data related to emissions of EV's.

The range of emissions from vehicle cycle for different categories of cars is given in Table 1.

Table 1. The range of vehicle cycle emissions according to literature [46-50]

	[t CO_2/car]	Numbers used in this paper
Gasoline ICE	2.0-10	6
PHEV	2.5-9.5	8.25
REX	2.7-12	10.05
BEV	2.8-20	10.50

In this paper midsize cars with 80 kW power and battery capacity in range from 10 (PHEV's) to 30 (BEV's) kWh have been analyzed.

Battery recycling

In the EU, a very good system for collecting and recycling of lead acid batteries is already in place according to the EC directive 91/157/EEC [51] with a recycling rate of about 90% [52]. In the case of lead acid batteries, about 96% of the materials in the battery are recovered [53].

However, currently less than 5% of lithium-ion batteries are recycled in the EU. The recycling plants for lithium-ion car batteries are still in their infancy. Some of the major reasons for this are still very low number of EV's, which are at the end of life, various battery-chemistries used and designs, as well as the high cost of recycling. The cost of full recycling of battery is about 1 EUR per kg, and the value of the recovered materials is just a third of that [54]. Currently, mostly recovered materials from batteries are cobalt and nickel. Moreover, the quality of some materials after recycling is below battery grade. For example, lithium is currently not recovered in a form usable for the re-use in battery production. In addition, the current low number of vehicle batteries available for recycling limited opportunities for technological learning and economic of scale.

The assessment of the GHG emissions from the recycling is very different from study to study depending on the assumptions made regarding chemistries used, recycling process, assumed quality of the output, as well as other modelling assumptions [43]. According to Tesla, re-processing of the recycled battery outputs back to batteries has the potential to decrease emissions by about 70% [43]. This appears currently rather as wishful thinking given other statements in literature, where the potential reduction of GHG emissions from battery recycling is in the range from 7% to 17% [44]. In general, it is indicated that large GHG savings with a small process demand can be made by recycling aluminium, steel and plastics from the pack and module [43].

Currently, in the most cases, recycling add GHG emissions to the life cycle (Table 2). In the best case, some small emission reductions are possible if hydrometallurgy is used, a reduction of about 12 kg CO_{2eq} per kWh battery. However, there are several potential battery recycling pathways that could lead to the net savings of 1 to 2.5 kg CO_2 per kg of battery recycled [44].

Table 2. Total life cycle GHG emissions from battery production and recycling [43]

Battery grade material production (incl. row material mining and refining 18-50 kg CO_2/kWh) [kg CO_2/kWh]	48-212 (60-70)*
Manufacturing (component and cell + battery assembly) [kg CO_2/kWh]	20-110 (70-110)*
Recycling [kg CO_2/kWh]	−12-15 (15)*

* Most likely values

RESULTS: TOTAL EMISSIONS OF ELECTRIC VEHICLES

EV’s are widely promoted as environmentally friendly technology and many governments worldwide have provided different incentives with the goal to increase use of EV’s and finally to reduce local air pollutions and GHG emissions from the transport sector.

However, as discussed above, total emissions of EV’s are dependent from the emissions caused during the vehicle production and use, and especially from the emissions caused during the production of electricity which is used in EV’s. The use of EV’s in selected countries/regions, which are very active in promotion and use of EVs – China, the USA, the EU and Norway – and also have very different specific electricity mix, is analyzed in this paper to stress the impact of electricity mix on total environmental benefits of EV’s.

Total CO_2 emissions per km driven for various types of EV’s and different electricity mixes in the selected countries are shown in Figure 9 compared to gasoline vehicles. An average driving range of 15,000 km is assumed.

In contrary to ICE vehicles, which have the same CO_2 balances in all analyzed countries, rechargeable EV’s show significant differences in their environmental benefits in China, the USA and Norway. Only in Norway, clear advantage of rechargeable EV’s can be seen. In the USA, total emissions of rechargeable EV’s are almost in the same range with conventional cars. The worst situation is in China where rechargeable EV’s caused higher emissions then conventional cars. The only advantage in this case is that these emissions could be easier controlled, and that in spite of the overall higher emissions, local emissions and pollutions could be reduced what is also of high priority in most urban areas in China.

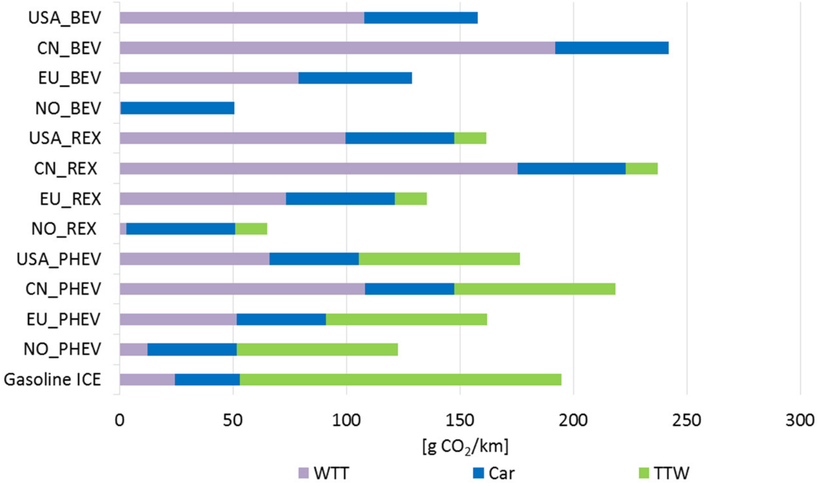

Figure 9. Total CO_2 emissions per km driven for various types of EV’s and different electricity mixes in selected countries/regions: China, Norway, the EU and the USA

However, the results shown in Figure 9 are sensitive on the assumptions regarding the total number of vehicle kilometers driven over vehicle lifetime in all countries, in some more in some less. These are shown in detail in Figure 10.

It is obvious that, due to the impact of embedded emissions, total CO_2 emissions per km driven are decreasing with the increasing number of vehicle kilometers driven. However, the impact of the number of kilometer driven is moderate compared to the effect of the generation mix. While for gasoline cars for 23,000 km driven total emissions per km are about 16% lower than for 8,000 km, for BEV’s in China, the USA and Norway it is 21%, 31% and 65% less emissions, respectively. This is because in Norway the emissions from the fuel cycle are close to zero.

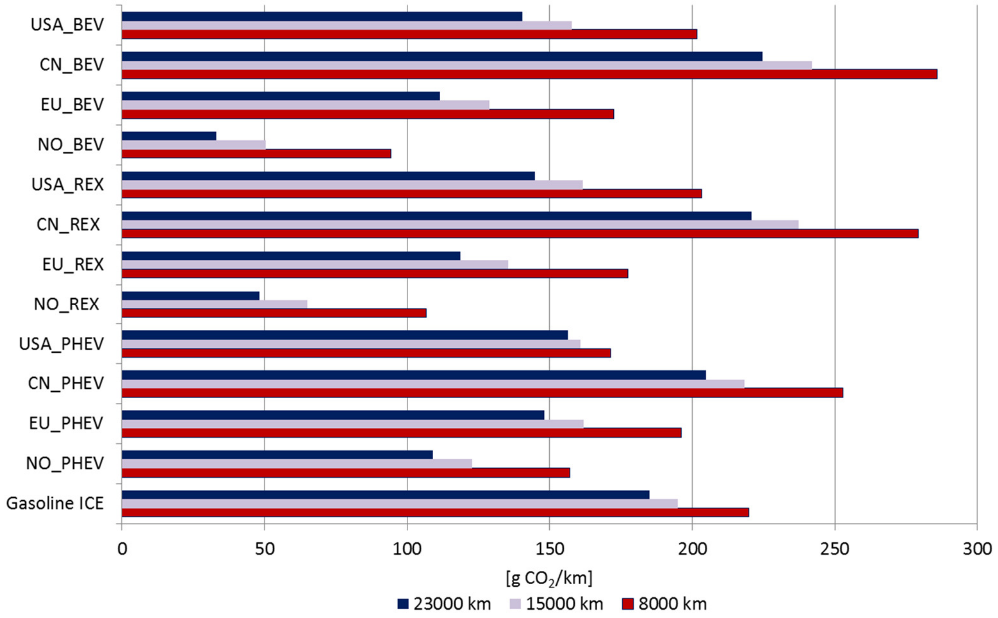

Figure 10. Total CO_2 emissions per km driven for different numbers of vehicles km driven in selected countries/regions

Moreover, CO_2 emissions of PHEV's and REX are sensitive on the assumptions regarding the use of electricity and fossil fuels in car. For example, Samaras [42] has calculated total GHG emissions of PHEV's in the USA assuming different ratios of electricity and gasoline – 30:70, 60:40 and 90:10 – however, the largest difference is about 30 g CO_2 per km driven.

For the average EU, electricity mix in 2010 is estimated that BEV's and PHEV's (assuming 50:50 electricity and gasoline ratio in PHEV's) could contribute to the reduction of emissions in comparison to conventional cars up to 75 g CO_2 per km [40].

Similar analysis for BEV's has been conducted by Wilson [50], showing very high emissions per km driven in China, Indonesia, Australia, South Africa and India. On the other side, Paraguay, Iceland and Sweden are also countries in which E-mobility could provide clear environmental benefits.

As discussed above, the impact of battery recycling is still heavily disputed. Especially the possible magnitude of a reduction of CO_2 emissions due to battery recycling varies very widely, from 7% to 70% as cited above. In Figure 11, a comparison of the overall CO_2 emissions per km driven is shown for two different cases, with "No recycling" and "50% recycling".

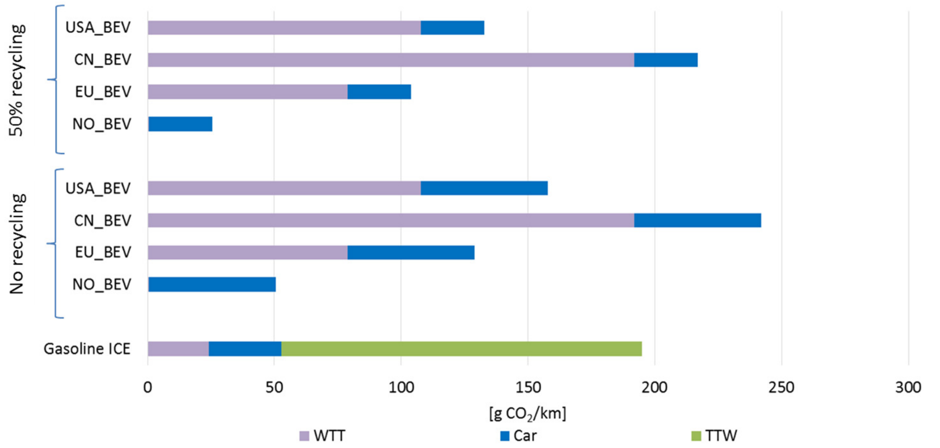

Figure 11. Impact of battery recycling on total emissions

It can be seen that even a reduction of the embedded emissions in the cars by 50% due to the battery recycling would not significantly change the overall balance between EV's and conventional cars. In the case of recycling, total emission reduction is about 25 g CO_2/km for the average number of km driven (Figure 11). However, as shown in Figure 10, the impact of travel activity is between 15 and 40 g CO_2/km. Hence, battery recycling lies somewhere in the middle of the impact of km driven.

Finally, the major finding is that the impact of the electricity mix is dominating, followed by travel activity and battery recycling.

CONCLUSIONS

The public tends to judge the environmental benefits of cars usually by their energy consumption and emissions at the point of use. However, the whole effects of mobility on the environment have to be based on LCA analyses over the vehicle's entire lifetime.

The major conclusions of our analysis are: EV's could contribute to solving some of the problems in the transport sector. However, they cannot be considered automatically to be environmentally benign. The specific conditions in every country/region have to be considered very carefully.

As analyzed in this paper, the environmental benignity of EV's is sensitive on:

- Electricity mix;
- Travel activity (number of km driven per year);
- Embedded CO_2 in car production.

As shown in this paper, the highest sensitivity is with respect to the electricity mix. Since BEV's are locally emission-free, their WTT emissions have a great impact on the total environmental performance. Considerable differences can occur depending on the regional electricity mix. However, the full environmental benefits can be obtained only in combination with electricity from RES. Due to difference in electricity mix used in different countries, the environmental impact of EV's could be very positive as well as negative. The sources for electricity generation may lead to major setbacks in the emission reduction through electrification of mobility. The most important issue to make EV's more environmental friendly is to increase the use of RES in electricity generation, what is already one of the priorities of the European energy and climate policy.

Travel activity has multiple impacts on the emissions. On the one side, a lower number of km driven per year means lower energy consumption. On the other side, using CO_2 per km driven as an indicator implies that the car is the more environmentally benign the more km are driven with the car per year. With the higher number of km driven per car, the impact of emissions embedded in car is lower. This implies that a good option could be to use EV's for car sharing where the number of km driven is relatively high. It is simply more favorable to drive, for example, 24,000 km with one car than three times 8,000 km with three cars.

In addition, battery recycling plays a considerable role in reduction of CO_2 emissions. Moreover, some of the materials used for battery productions are limited, and their mining and refining is associated with negative environmental impacts. Currently, many governments support the use of EV's with different measures and policies but clear framework for lithium-ion battery collection and quality of recycling is still lacking. Today we have about 3 million EV's on the road worldwide. In 6 to 10 years, we will have 3 million batteries to salvage. The idea of second life for these batteries will not solve but rather delay this problem. It is now of highest priority that the policymakers in all countries promoting EV's become aware of this problem and try to find solutions which will not create new environmental problems.

NOMENCLATURE

CO_2	total carbon dioxide emissions	[g CO_2/km]

$\mathrm{CO}_{2_{\mathrm{EMB\_MAT\_}i}}$	embedded carbon dioxide emissions of material *i* (e.g. steel)	[t CO_2/car]
$\mathrm{CO}_{2_{\mathrm{EMB\_VEHICLE}}}$	embedded emissions of vehicles	[t CO_2/car]
$\mathrm{CO}_{2_{\mathrm{FUEL\_CYCLE}}}$	emissions in fuel cycle	[g CO_2/km]
$\mathrm{CO}_{2_{\mathrm{PRODUCTION}}}$	emissions of the production process	[t CO_2/car]
$\mathrm{CO}_{2_{\mathrm{VEHICLE\_CYCLE}}}$	emission in vehicle cycle	[g CO_2/km]
EI	electricity intensity	[kWh/km]
f_{CO_2}	energy emission coefficient	[g CO_2/kWh]
j	energy carrier for electricity generation	[-]
LT	lifetime of vehicles	[year/car]
skm	specific number of kilometer driven per year	[km/year]
q_j	share of energy carrier *j* in electricity generation	[%]
x	share of electricity in fuel mix (e.g. 50% for plug-in hybrid electric vehicles)	[%]

Abbreviations

BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
EV	Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
PHEV	Plug-in Hybrid Electric Vehicle
RES	Renewable Energy Sources
REX	Range Extender
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel

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Paper submitted: 12.02.2018
Paper revised: 29.11.2018
Paper accepted: 03.12.2018