European Battery, Hybrid and Fuel Cell Electric Vehicle Congress
Brussels, Belgium, 2nd - 4th December 2015

Estimated Environmental Effects of the Worldwide Electric Vehicle Fleet – A Life Cycle Assessment in Task 19 of the International Energy Agency (IEA) on Hybrid and Electric Vehicles (HEV)

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Abstract

Electric vehicles have the potential to substitute for conventional vehicles to contribute to the sustainable development of the transportation sector worldwide, for example through the reduction of greenhouse gas and particle emissions. There is international consensus that the improvement of the environmental sustainability by electric vehicles can only be analysed on the basis of life cycle assessment (LCA) including the production, operation and the end of life treatment of these vehicles. Based on the LCA activities in the 18 member countries, the Task 19 "Life Cycle Assessment of Electric Vehicles - From Raw Material Resources to Waste Management of Vehicles with an Electric Drivetrain" of International Energy Agency (IEA) Implementing Agreement on Hybrid and Electric Vehicles (IA-HEV) analysed the LCA based environmental effects of the worldwide electric vehicle fleet in 2014 of about 700,000 Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). By the end of 2015 it is expected that about 1 million modern vehicles with an electric drive train are on the road worldwide. In the LCA of these vehicles using the different national framework conditions, the environmental effects are estimated by assessing the possible ranges of greenhouse gas emissions (CO_2, CH_4, N_2O), acidification (NO_x, SO_2), ozone formation (NO_x, CO, NMVOC, CH_4) and particle matter (PM) emissions in comparison to conventional ICE vehicles (released in 2014). The results show that the environmental effects strongly depend on the national framework condition, i.e., national mix of electricity generation. In some countries a significant reduction of these LCA based emissions of up to 80%, compared to conventional ICE vehicles, is reached due to a high share of renewable electricity. So there is evidence that under appropriate framework conditions, electric vehicles contribute to a sustainable transportation sector today, and can play a substantial role in the future with the expected increasing renewable electricity generation.

Keywords: life cycle analyses (LCA), environment, energy efficiency

1 Introduction

Electric vehicles have the potential to substitute for conventional vehicles to contribute to the sustainable development of the transportation sector worldwide, e.g. reduction of greenhouse gas and particle emissions. There is international consensus that the improvement of the sustainability of electric vehicles can be analysed on the basis of life cycle assessment (LCA) including the production, operation and the end of life treatment of the vehicles.

2 Goal of the analyses

Based on the LCA activities in the 18 member countries the Task 19 "Life Cycle Assessment of Electric Vehicles - From Raw Material Resources to Waste Management of Vehicles with an Electric Drivetrain" in International Energy Agency (IEA) Implementing Agreement on Hybrid and Electric Vehicles (IA-HEV) analysed the LCA based environmental effects of the worldwide electric vehicle fleet in 2014 in 33 countries. By the end of 2015 about 1 million modern vehicles with an electric drive train are expected by the IEA HEV and the EVI (Electric Vehicle Initiative) on the road in daily life worldwide substituting for conventional vehicles. In a LCA of these vehicles using the different national framework conditions the environmental effects are estimated by assessing the possible ranges of environmental effects. Based on the emission inventory of CO_2, CH_4, N_2O, CO, NMVOC, SO_2, NO_x and PM the potential effects on greenhouse effect, acidification, ozone formation and particles are estimated. The reference case is the substitution of modern conventional ICE vehicles (of which 50% gasoline and 50% diesel). The environmental effects of the electricity for the EVs are estimated on the current national electricity production in the 33 considered countries including grid transmission and distribution, and vehicle charging losses. Additionally, for some selected countries, a scenario with all additional installed renewable electricity from PV and wind is dedicated for use by the EVs.

3 Methodology

The applied methodology uses the results of the cooperation in Task 19 since 2011. Based on LCA activities in the 18 member countries of IEA HEV, Task 19 identified the key issues that apply to LCA of EVs & PHEVs in various international case studies and applied it to the EV fleet worldwide.

3.1 Key issues in LCA of EVs Subsections

The following key issues for applying LCA methodology to vehicles with electric drivetrains were identified by Task 19 [1] and will be explained in the following chapters:

- General issues, e.g. goal and scope, state of technology,
- Life cycle modelling approach
- Vehicle Cycle (production – use – end of life)
- Fuel Cycle (electricity production)
- Inventory analysis
- Impact assessment
- Reference system for comparison

These issues represent a summary of LCA activities in the different countries and projects, e.g. [2], [3], [4] [5], in which the Task participants are involved.

The system boundaries chosen are shown in Figure 1.

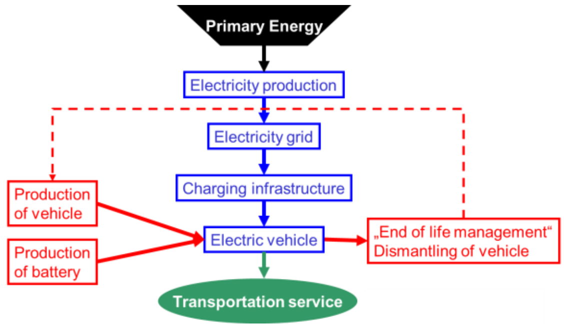

Figure 1: System boundaries [5]

3.1.1 General issues

In the goal and scope definition of the LCA, it is essential to describe the state of technology of vehicles and batteries including the assumptions for future developments. Here the substitution of new conventional vehicles is assumed, which are released on the market in 2014. In addition, possible rebound effects of substituting conventional vehicles with electric vehicles, e.g. which might result in driving environmentally-friendly vehicles more often, should be discussed or considered, because it is not certain if one kilometre driven by an electric vehicles actually substitutes for one kilometre driven by a conventional vehicle; it can be different, or even another transportation mode, e.g., a bicycle might be the substitution. There is a Norwegian study, that indicates that most users have an equal mileage as before, but about 20 % drive more after they bought an EV. Here it is assumed that the substitution rate is 0.95, reflecting that some additional kilometres driven by EVs do not substitute 100% for the kilometres driven by modern conventional ICEs.

As the key parameters influencing the environmental effects of vehicles with electric drivetrains are the electricity demand per distance travelled and the mix of technology for electricity generation, a sensitivity analysis on these two aspects is recommended. Here the current national electricity production in the considered countries is analysed and the electricity consumption by EV for real world driving cycle (i.e., considering effects of actual on-road driving such as accelerations and heating/cooling, incl. charging losses) is assumed to be in the range of 15 – 30 kWh/100 km reflecting different vehicle sizes and real life usage.

3.1.2 Life cycle modeling

The modeling of the life cycle of fuel and vehicle use is the basis for the assessment of the environmental effects of electric vehicles compared to conventional vehicles. The main issue to be addressed is the choice of an average or marginal approach for assessing the impact of electricity generation on the LCA of EVs. Also, the co-product handling method can influence the LCA results. According to ISO 14040, one preferred way of dealing with co-products is avoiding allocation of energy and emissions burden among all products, but in many cases this is not practicable. For example, heat and electricity from CHP plants and the fate of various components recovered at the end of life can better be handled with different allocation methods, e.g. based on energy, mass, market value or exergy content, or by substitution of (displaced) conventional products. Here for CHP plants the emissions are allocated based on the energy content of the heat and electricity produced.

As the modeling of battery production has a strong influence on the overall results, the following aspects must be documented in detail:

The influence of battery production in LCA of EVs, including the main environmental impacts and how they might be reduced in a future mass production of automotive batteries

- The (expected/assumed) future development of automotive battery mass production
- The influence of future recycling of automotive batteries: today there is no infrastructure in place to recycle a huge amount of automotive batteries, but from an LCA perspective an efficient recycling of battery materials might significantly reduce environmental impacts of battery production

3.2 Vehicle cycle

The vehicle cycle includes the production, use and end of life of the vehicle components, including its battery. It is generally recognised that the production of electric vehicles has a higher environmental impact compared to the production of conventional vehicles although varying estimates of the energy intensity of battery production create some disparity in estimates of electric vehicle production impacts. The estimates vary because of different approximations of the energy required to assemble the battery from its constituent parts [5] with process-level analyses generally predicting lower energy intensity than top-down studies, e.g. [4]. Therefore, the details of the battery production and its key technical data (e.g. life time of battery, energy content) must be carefully described in all LCA studies handling this component. For the materials used to produce the vehicle, the main assumptions and data (e.g., types and share of materials, electricity production mix for material production) must also be described in detail. Here it is assumed that the battery capacity of the BEV is in the range of 10 – 30 kWh, and for PHEV 4 – 15 kWh, with a vehicle life time of 10 years and annual travel distance of 14,000 km. The “electric driven” annual kilometres with the PHEV is assumed to be 9,000 km.

One of the most influencing factors in the LCA of vehicles is the energy consumption in the operation phase. In particular for vehicles with electric drivetrains, the impact of all auxiliary energy usage for heating and cooling must be incorporated properly. In Figure 2, an example of the contribution and range of electricity consumption in a battery electric vehicle by activity is shown in ratio “bad” / “good”; e.g., the impact of charging loss ratio of 2 – 3 means that the highest observed charging losses can be 2 to 3 times higher than the lowest charging losses, whereas in the graph the average absolute charging losses are estimated.

Also the driving behavior (e.g. urban vs. highway driving) is quite relevant for the vehicle's energy consumption. For plug in hybrid electric vehicles (PHEVs) the share of driving distance on the battery must be specified. The "electricity generated on board" versus "electricity generated off-board" must be carefully distinguished. For battery electric vehicles (BEVs) the possible driving range must be evaluated in real life conditions (see above, including heating and cooling demand). As the driving range of electric vehicles on a single charge is significantly lower compared to conventional diesel or gasoline vehicles, all details for the assumption of the daily, monthly and yearly driving distances must be described in LCA studies.

The end of life management of an electric vehicle can also influence the overall environmental effects significantly. Therefore the details of the dismantling phase must be given, including aspects of material and energy recovery, (e.g. recycling for production "close loop", which mean that the recycled material is used again in the production of the new material within the system boundaries).

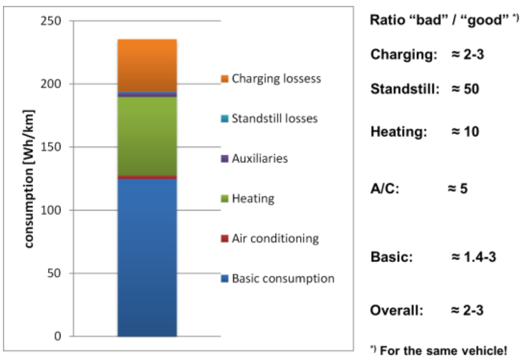

Figure 2: Possible contribution and range of electricity consumption in a battery electric vehicle [6]

3.3 Fuel cycle

The fuel cycle includes the electricity production with the supply of the fuel to power plants, the electricity distribution network and the charging station. The main issue to be addressed is the choice of the electricity generation technology and mixes, e.g. analyzing the time dependent electricity generation mix of a country: choice of the annual average electricity production or mix, or the additionally (marginal) produced electricity for meeting the electric vehicles load. In cases where significant amounts of electricity are stored, e.g. in hydro power pumping plants, the electricity mix of consumption might be more relevant for LCA than the production mix. If fluctuating renewable electricity from wind or solar power is used, the key question is whether the renewable electricity ends up in the battery of the electric vehicle or if other effects are initiated in the grid. In the best case, the production of the renewable electricity needs to be harmonised with the charging of the electric vehicle. In most of the cases, the use of only (fluctuating) renewable electricity or in some specific cases electricity from variable hydro power (not pumped storage) must be combined with an adequate electricity storage system (including storage losses). Otherwise, a realistic share of (fluctuating) renewable electricity from wind and solar along with thermal power generation from biomass or fossil fuels must be considered. Furthermore, it must be ensured that the renewable electricity for the EVs is additional to what would have been produced without the electric vehicles load, as shifting the use of the currently generated renewable electricity from a stationary application to the mobile application (i.e., for EV recharging) brings no additional environmental effects. Summarizing, it has to be born in mind that the consideration of renewable electricity for the charging of electric vehicles is justified only if this renewable energy is specifically and additionally generated for this purpose.

The four main options of connecting renewable electricity with the loading of the electric vehicles are the following (Figure 3):

"Direct connection": direct use of additional renewable electricity (PV or wind) for loading of EVs, the vehicle is only charged when the sun is shining or the wind is blowing, which is not more a theoretical than a practical solution

- "Via storage": 100% of additional electricity (PV or wind) for vehicle is stored first in battery or hydro pump storage and then it is taken from the storage in accordance of the loading profile of the vehicle
- "Stored in grid": 100% of additional renewable electricity (PV) for EVs is fed into the grid, which leads to the substitution of a thermal power plant using natural gas at that time, during the charging time of the vehicle the electricity is taken from the grid, in which the additional electricity is produced by a coal power plant.
- "Real time loading": e.g. 30% direct PV-electricity and 70% from the grid based on observations in an Austrian e-mobility

model region, in which a part of the renewable electricity is directly used for loading when it is produced and the other part is produced from a fossil power plant in the grid

In this analysis it is assumed that 20% of the renewable electricity from PV is stored in stationary battery, and 10% from wind until an EV is charged. The grid and charger losses are estimated at 5%.

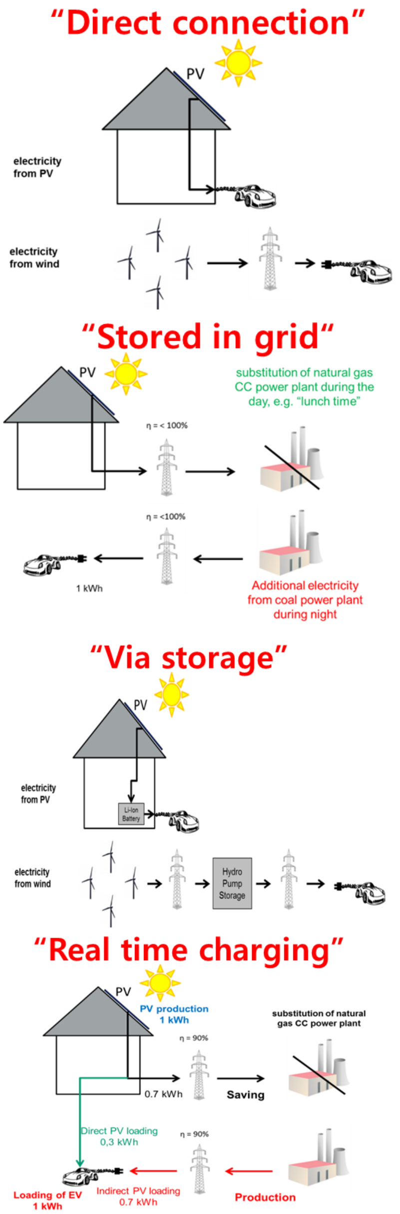

Figure 3: The four options of connecting renewable electricity with the loading of the electric vehicles [1]

3.4 Inventory analysis

The basic data for the inventory analysis must be documented with special attention given to the battery production, the vehicle production, the energy consumption of the vehicle in the operation phase, the electricity production, the charging of the vehicle, and the “end of life “ treatment of the vehicle with its battery. In general the (assumed) state of technology or its possible future development must be described. The uncertainty range of all data must be indicated properly and discussed in sensitivity analyses. Here new models released mainly between 2010 and 2014 of BEV, PHEV and ICE are considered.

Here the following emissions are considered in the inventory analysis:

- CO_2
- CH_4
- N_2O
- NO_x
- SO_2
- NMVOC
- CO
- PM

3.5 Impact assessment

The impact assessment might include a wide range of possible environmental effects, but due to limited data availability, most LCA activities concentrate mainly on the greenhouse gas emissions (GHG) and energy resource depletion, e.g., the cumulated primary energy demand. As a minimum requirement, the cumulative primary energy demand must specify the contributing share of fossil, renewable and other energy carriers. In some LCA studies, the material resource depletion, e.g., cumulated material demand and the shares of different materials are calculated, e.g., metallic raw materials and biogenic materials. Also some other impact categories caused by gaseous emissions (e.g., CO, SO_x, NO_x, particulate matter e.g. [5]) which impact acidification and ozone formation, are assessed. Generally it is observed that the mid-point impact assessment is often done for GHG emissions and primary energy consumption with high certainty and robustness. But the “end point damage assessment” and “single scoring methods,” e.g., external costs are still under discussion and/or development due to their high methodological complexity and the lack and uncertainty of data for these impacts. It is recognised that the methodological choices (e.g. modelling approach, system boundaries, determination of relevant electricity generation, etc.) add more uncertainty to mid-point impact assessment results compared to the uncertainties in endpoint modelling. This means that the characterization factors (CF), e.g.,

toxicity midpoints, are as uncertain as CF for human health damage (i.e. end point).
Here the following impacts are considered in the assessment:

- Global warming potential (CO_2, CH_4, N_2O)
- Acidification potential (NO_x, SO_2)
- Ozone formation potential (CH_4, NMVOC, NO_x, CO)
- Particulate matters (PM)

3.6 Reference system

Generally the reference system, which serves as the baseline for comparison, is directly linked to and dependent upon the goal and scope of the LCA. In most cases, the reference systems for electric vehicles are mainly gasoline and/or diesel ICE vehicles with their current and future technologies. As transportation biofuels become a reality on the fuel market in more countries, e.g., 7 vol-% blending of biodiesel in diesel in Austria [3], the aspects of biofuels should be integrated in the reference system more often in the future. In some countries, natural gas vehicle (including its new infrastructure) might be part of the reference systems. As described already in section 3.3, when the environmental effects of electric vehicles might be maximized by using renewable electricity, the additional renewable electricity must be generated and not be taken away from baseload electricity demand. In such case, environmental effects associated with this additional renewable electricity production, e.g., building a dam for a hydro power plant must then be considered for electric vehicles evaluation.
The fuel demand of conventional new ICE vehicle using 50% gasoline and 50% diesel is assumed in the range of 51 – 63 kWh/100 km (based on [7]). These new average ICE vehicles are sold on the market in 2014.

4 Database

The main data used are the amount of 700,000 electric vehicles in 33 countries worldwide in 2014, where only Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) are considered (Figure 4).

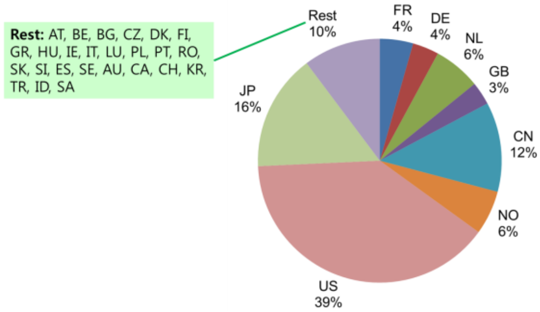

Figure 4: Vehicle Fleet Worldwide 2014 [5]

The data for the production and dismantling of the vehicles are based on an Austrian study [3] adopted with results from various case studies in IEA HEV Task 19. The data for the current national electricity production for the considered countries are based on ecoinvent 3.1 [8] and shown in Figure 5 (GHG-Emissions), Figure 6 (PM-Emissions), Figure 7 (NO_x – and SO_2- Emissions) and Figure 8 (CH_4-, NMVOC-, NO_x- and CO-Emissions). These Figures show that the emissions from electricity production are very different, generally the higher share of renewable and nuclear electricity, the lower are the considered emission to air.

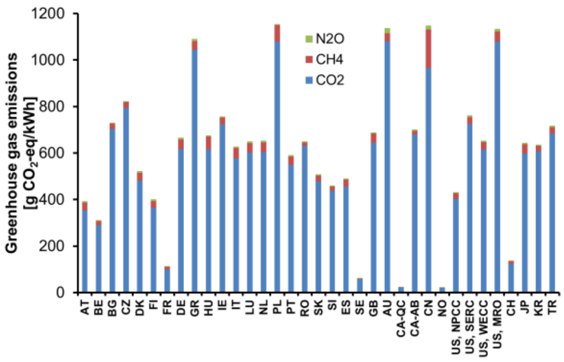

Figure 5: Estimated GHG-Emissions of electric production in the various countries (mainly based on [8])

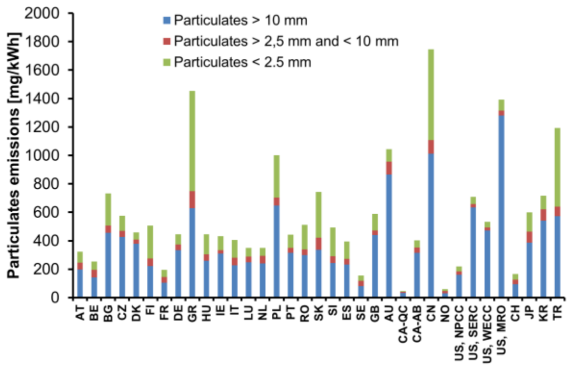

Figure 6: Estimated PM-Emissions of electric production in the various countries (mainly based on [8])

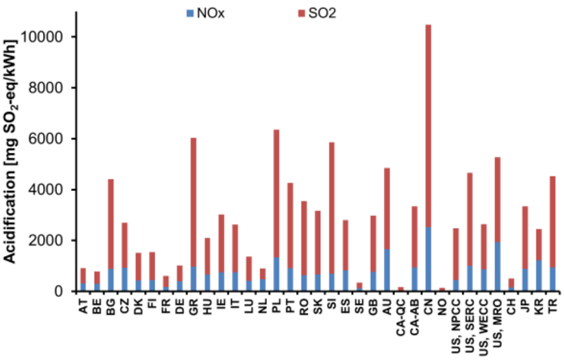

Figure 7: Estimated NO_x – and SO_2- Emissions of electric production in the various countries (mainly based on [8])

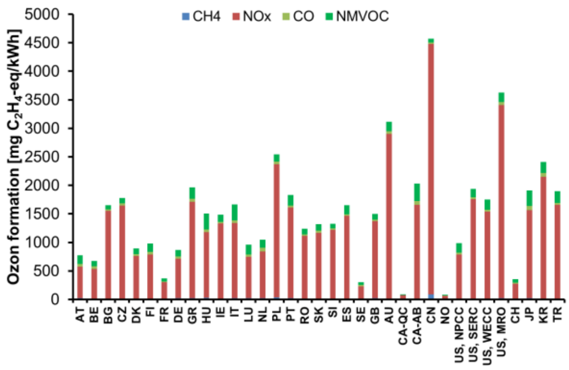

Figure 8: Estimated CH_4-, NMVOC-, NO_x- and CO-Emissions of electric production in the various countries (mainly based on [8])

The data for the renewable electricity production in selected countries (AT, AUS, FIN, DE) are based on ecoinvent [7] and shown in Figure 9 (GHG-Emissions), Figure 10 (PM-Emissions), Figure 11 (NO_x – and SO_2- Emissions) and Figure 12 (CH_4-, NMVOC-, NO_x- and CO-Emissions). These emissions from renewable electricity mainly derive from the construction and dismantling phases of the power plants, only a very small part from the operation phase caused by replacement parts. Compared to the emissions shown above for the current national electricity production the emissions from renewable electricity are significantly lower, but PV is the highest of the renewable energies due to the relative energy intensive production processes.

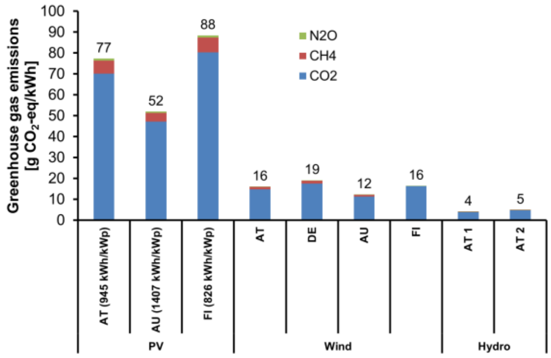

Figure 9: Estimated GHG-Emissions of renewable electricity production in selected countries (mainly based on [8])

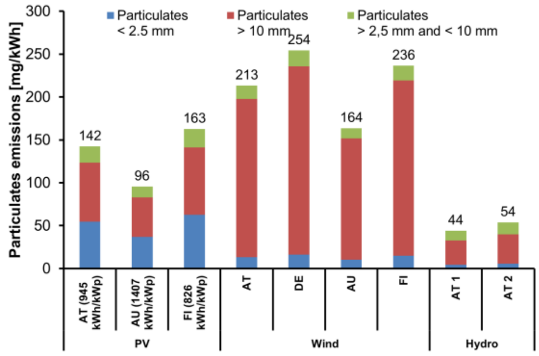

Figure 10: Estimated PM-Emissions of renewable electricity production in selected countries (mainly based on [8])

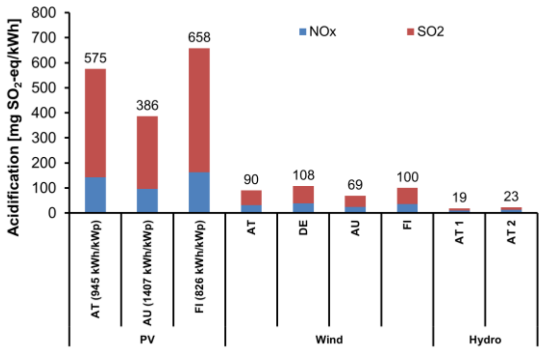

Figure 11: Estimated NO_x – and SO_2- Emissions of renewable electricity production in selected countries (mainly based on [8])

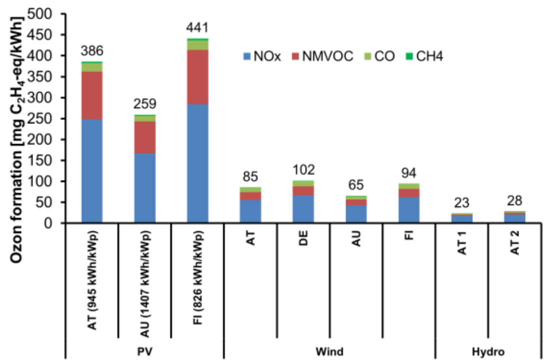

Figure 12: Estimated CH_4-, NMVOC-, NO_x- and CO- of renewable electricity production in selected countries (mainly based on [8])

5 Results

The results of the assessment are shown below, whereas the shown ranges of the estimation are due to variation in:

- Emissions of national electricity production
- Electricity consumption by EVs
- Fuel consumption of substituted conventional ICEs
- Emissions and energy consumption of real world driving cycles
- Data availability, uncertainty and consistency, e.g., PM emissions

The results of the environmental effects of EVs compared to conventional ICEs are shown in Figure 13 (GHG-Emissions), Figure 14 (PM-Emissions), Figure 15 (NO_x – and SO_2-Emissions) and Figure 16 (CH4-, NMVOC-, NO_x- and CO-Emissions).

Generally it can be observed that the share of fossil produced electricity has a substantial influence on the emissions. In countries with a relative high share of renewable or/and nuclear electricity, the estimated emission reduction is significant (e.g., NO, FR, AT) whereas in countries with a relative high share of fossil electricity, an increase of emissions occur (e.g., PL, CH). The range of uncertainty in relation to the electricity demand of the EVs is relatively high in countries with a high share of electricity from fossil fuels. Summing up the 700,000 EVs and PHEV in the considered countries, an average emission reduction is estimated, except for acidification potential where an increase is estimated.

The estimation of the average environmental effects of BEVs and PHEVs substituting diesel/gasoline show

- GHG-reduction: - 20%
- PM < 10 reduction: - 60%
- Acidification increase: + 40%
- Ozone reduction: - 30%,

but the possible range is significant, e.g. GHG emissions from reduction to increase.

In Figure 17 and Figure 18, a pure renewable electricity production for EVs is considered, showing that all emission are significantly lower compared to conventional ICE vehicles.

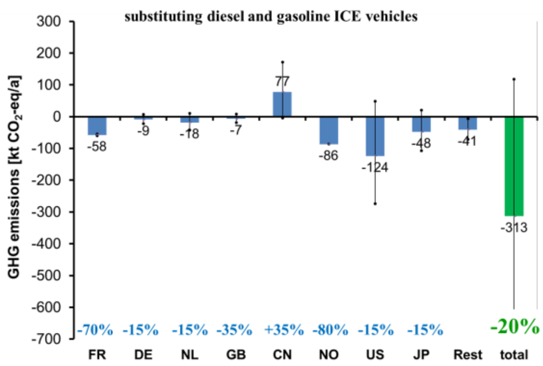

Figure 13: Estimated GHG-Emissions of Electric Vehicles Worldwide (2014)

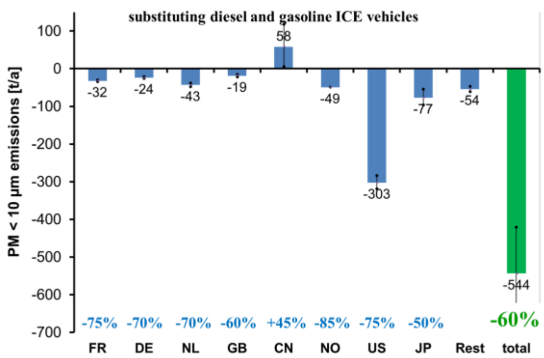

Figure 14: Estimated PM-Emissions of Electric Vehicles Worldwide (2014)

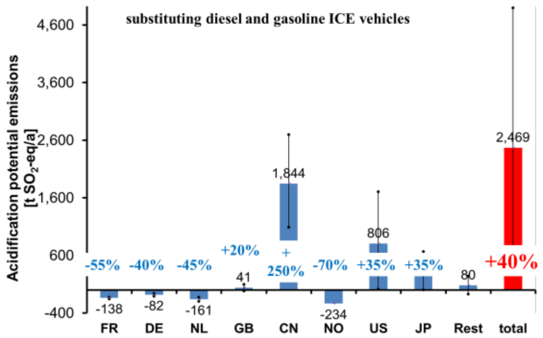

Figure 15: Estimated NO_x – and SO_2-Emissions of Electric Vehicles Worldwide (2014)

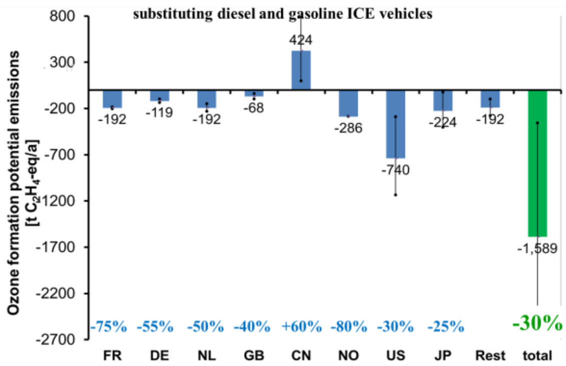

Figure 16: Estimated CH_4-, NMVOC-, NO_x- and CO-Emissions of EVs Worldwide (2014)

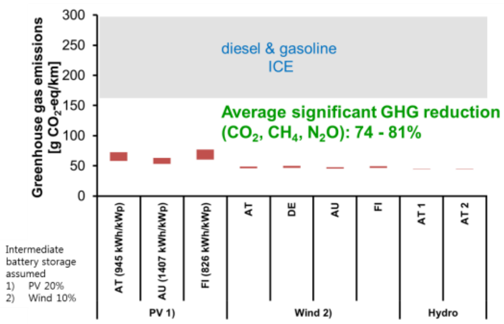

Figure 17: GHG Emissions of Electric Vehicles - Renewable Electricity

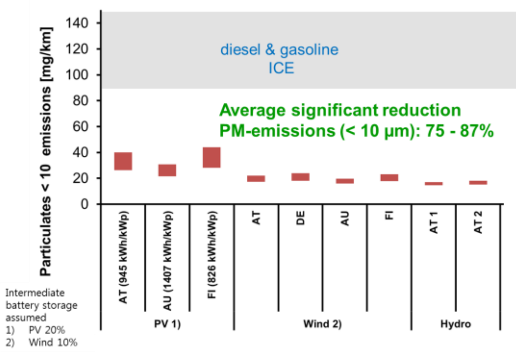

Figure 18: PM (< 10 µm)-Emissions of Electric Vehicles – Renewable Electricity

6 Conclusions

The main conclusions are:

- Environmental Assessment of EVs has been conducted based on Life Cycle Assessment compared to conventional vehicles
- about 700,000 EVs worldwide are on the road (end of 2014): Main countries US, JP, CN, F, DE, NO
- Estimation of average environmental effects substituting diesel/gasoline shows
  - GHG-reduction: - 20%
  - PM < 10 reduction: - 60%
  - Acidification increase: + 40%
  - Ozone reduction: - 30%
- Broad estimated ranges are mainly due to variation in:
  - Emissions of national electricity production
  - Electricity consumption of EVs at charging point
  - Fuel consumption of substituted conventional ICEs
  - Data availability, uncertainty and consistency, e.g., PM
- Additional renewable electricity with adequate charging maximizes environmental benefits
- Loading strategies are essential for further significant reductions

The results show that the environmental effects depend on the national framework condition, e.g., national electricity generation. In most of the countries, a significant reduction of these LCA based emissions of up to 90% is reached. So there is scientific evidence that under appropriate framework conditions, electric vehicle can substantially contribute to a sustainable transportation sector in the future.

Acknowledgments

The work in IEA Task 19 is financed by the participating countries (Austria, Germany, Switzerland and USA), and their member institutions (EMPA; DLR, ARGONNE and JOANNEUM REREARCH).
Jennifer B. Dunn and Amgad Elgowainy acknowledge support from the Vehicle Technologies Office of the Office of Energy Efficiency and Renewable Energy of the United

States Department of Energy, under contract DE-AC02-06CH11357.
The ExCo of IEA HEV under the Chair of Urs Muntwyler additionally financed the presentation at EEVC 2015.

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Professional experiences:
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- greenhouse gas assessment of products and services
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- Research Group Leader "Smart Energy Systems and Lifestyles" at JOANNEUM RESEARCH, Austria
- Lecturer: Vienna University of Technology; University of Graz; University of Applied Science, University of Applied Science Kapfenberg, Danube University Krems
- Austrian Team Leader in IEA Bioenergy Task 42 "Biorefinery".