Carbon footprint of electric vehicles – a plea for more objectivity

Authors: Anika Regett, Wolfgang Mauch, Ulrich Wagner

Affiliation: Forschungsstelle für Energiewirtschaft (FfE) e.V. (Research Center for Energy Economics)

Introduction

In 2015, the transport sector was responsible for 25.8 % of total primary energy consumption and 27.6 % of energy-related CO_2 emissions in Germany, with a primary energy consumption of 3433 PJ and energy-related CO_2 emissions of 204 million tonnes (based on [1]). In contrast to the energy sector, emissions from transport have been at a constant level since 1990 [2].

Even though the transport sector is stagnating in this respect, moving away from the ambitious greenhouse gas reduction targets of 40 % by 2040 and 80-95 % by 2050 compared to 1990 [3] is not an option in view of the Paris Climate Agreement. Against this background, the question about the role of electric vehicles (EV) to meet climate targets arises.

The perception of EV, a technology already known since the end of the 19th century, fluctuated over the decades between electro-hype and electro-phobia. The importance of EV for resource conservation and climate protection only picked up momentum in the last decade in the course of the energy transition. In this context, the debates about the actual environmental impact of EV are often very emotional.

In May 2017, the IVL (Swedish Environmental Research Institute) published the study "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries" [4], which is a literature review of existing life cycle assessment (LCA) studies on the production and disposal of electric vehicle batteries. It received a lot of media attention and the results were discussed controversially. In the course of this debate EV were compared with conventional internal combustion engine vehicles (ICEV). The results are emission-related “payback periods” of EV of three to eight years.

As a result, the IVL published a statement [5] in July 2017 to correct misinterpretations of the study. In this statement, the authors clarify that the study provides an overview of the results of existing studies on the current state of the art of battery production, but that the technology is developing rapidly and there is a great potential for improvement. In addition, it is pointed out that the vehicle comparisons drawn up in various media are based on the 150-200 kg CO_2 equivalents (eq.) per kilowatt hour (kWh) of battery capacity produced as shown in the study and do not yet contain any future improvement potential. Furthermore, they emphasize the necessity to improve the data basis.

Here are the most important results of the study in brief:

- According to the literature review, battery production is currently associated with greenhouse gas emissions of 150-200 kg CO_2 eq. per kWh battery capacity. This applies to the assumption of an energy demand for battery manufacturing of 97-181 kWh per kWh of battery capacity produced.

- Approximately half of the emissions are due to battery and cell manufacturing, the other half to the supply of materials.
- The emission factor of the electricity used in manufacturing has a large influence on the climate impact of batteries. The carbon footprint is therefore strongly dependent on the underlying assumptions.
- The environmental impact of batteries can be improved by increasing energy efficiency and using renewable electricity in battery and cell manufacturing. The reduction of chemical use and the improvement of recycling processes offer further improvement potential. Thus, there is no conclusive answer to the environmental impact of batteries.

For decades the FfE has worked on holistic assessments of products and services [6] and was also the initiator of the German VDI-Guideline 4600 on Cumulative Energy Demand (CED) [7]. In this context, the FfE has for many years been dealing with comparisons of different drive concepts [8].

For more objectivity in the current discussion, the FfE has therefore analysed the climate impact of battery production as part of the project "Ressourcensicht auf die Energiezukunft", which is funded by the “Stiftung Energieforschung Baden-Württemberg” and the “Hans und Klementia Langmatz Stiftung”. The core results of the analysis are summarised and discussed below. A detailed explanation of the scope of the study, the methodology and the data base is contained in the supplementary document, which can be downloaded from the project website [9].

Carbon footprint of battery production: a question of how and where

The climate impact of battery production is determined by calculating the energy-related greenhouse gas (GHG) emissions relating to one kWh of EV battery produced. These include all GHG emissions associated with the provision and conversion of energy for material production and battery manufacturing. The lithium ion battery system with a capacity of 30 kWh, consisting of a nickel-manganese-cobalt (NMC) cathode and a graphite anode, has a total mass of 177 kg [10]. For the energy demand for battery manufacturing, which also includes cell manufacturing, the value stated in [11] of about 50 kWh per kilowatt hour of battery capacity is applied. A large proportion of which is traced back to energy-intensive drying processes. This energy demand originates from an industrial plant in China and is far below the values used in the IVL study. It is assumed that the energy requirement is covered by electricity with a comparatively high emission factor of 0.9 kg CO_2 eq./kWh. This emission factor reflects the share of battery-producing regions in line with the short-term trend scenario in [12] and is dominated by China with a share of 49 %.

Taking into account the assumptions and data documented in detail in the supplementary document, the energy-related GHG emissions amount to just under 106 kg CO_2 eq. per kWh of battery capacity produced. The contribution analysis in **Figure 1** shows that about 40 % of the emissions are attributable to the electricity demand in battery manufacturing (including cells) and almost a quarter to the production of NMC active material.

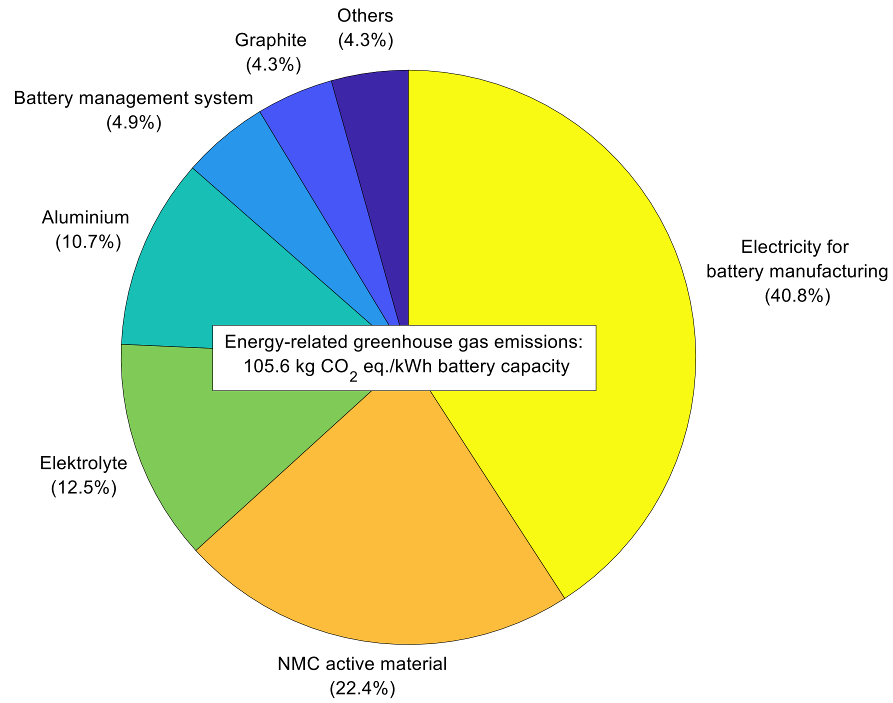

Figure 1: *Climate impact of battery production and share of processes*

However, the energy demand in battery manufacturing is subject to uncertainties and is in previous LCA studies according to [13] mostly in the range of less than 10 kWh to just under 170 kWh per kWh of battery capacity produced. Furthermore, as discussed in the IVL study [4], the emissions associated with this electricity demand are strongly dependent on the electricity mix prevailing at the battery production site. Therefore, in **Figure 2** the energy-related GHG emissions of the entire battery production in kg CO_2 eq. per kWh battery capacity are shown as a function of the electricity demand for battery manufacturing and the emission factor of the electricity used in the manufacturing process.

It can be seen that the carbon footprint of the traction battery improves considerably if the production process takes place in countries with a low emission factor of electricity or if the electricity demand is covered by renewable energy systems (RES). In case the electricity demand is kept at about 50 kWh per kWh of battery capacity for an industrial battery production, but the current German electricity mix is assumed for the emission factor, the emissions from battery production are reduced to 87 kg CO_2 eq. per kWh of battery capacity. If the electricity for battery production is increasingly supplied from RES, the energy-related GHG emissions from battery production approach the emissions for raw material extraction and production of 62 kg CO_2 eq. per kWh battery capacity.

In addition, the carbon footprint of battery production is strongly dependent on the electricity demand in battery production. While the present analysis builds on data from the industrial plant in [11], the carbon footprint worsens for the electricity demand of pilot plants as shown in Figure 2. The lower specific energy demand of industrial plants can be explained by economies of scale and process optimisation.

The results illustrate the strong dependence of the battery's carbon footprint on the state of the art of the production process and the location of the production plant. For the production of battery cells and systems on an industrial scale, a reduction in power consumption and thus an improvement in the climate balance can be expected in the future. Furthermore, the energy supply should be taken into account when choosing a location for new production plants, as this has a strong effect on the carbon footprint of the batteries produced.

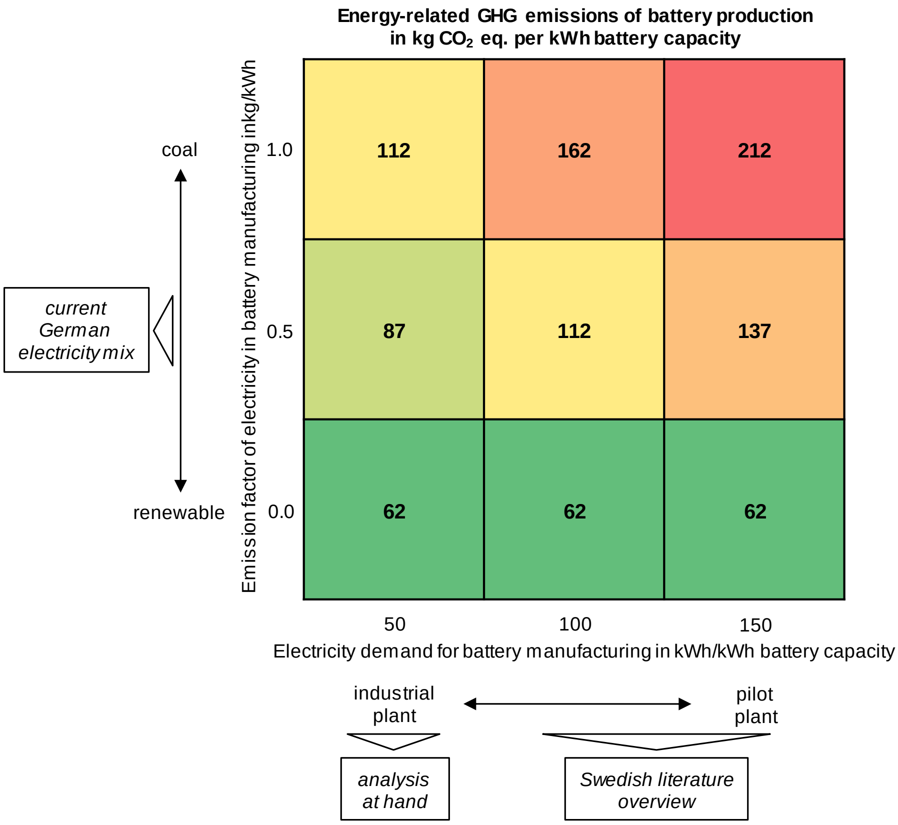

Figure 2: *Impact of electricity demand and the emission factor of electricity in battery manufacturing on the greenhouse gas (GHG) emissions of battery production*

Electric vs. gasoline vehicle: the dependence on charging electricity

During the discussion of the IVL study, the question of the so-called "payback period" of an EV compared to an ICEV arose. Therefore, in the following, the calculated 105.6 kg CO_2 eq. per kWh of battery capacity produced from Figure 1 is put into context by means of a simplified vehicle comparison. It should be noted that this value is based on the assumptions described above and therefore does not reflect the best case in Figure 2. This comparison is intended in particular to clarify the dependence of a vehicle comparison on the charged electricity. Since the focus is not on displaying absolute values for the entire vehicle production, the climate impact of the other vehicle components is taken from Hawkins et al. [15].

According to [15], the production of vehicles in Germany amounts to GHG emissions of approx. 6.6 t CO_2 eq. for an ICEV and 6.8 t CO_2 eq. for an EV without battery system. The fact that these values lie in the same order of magnitude corresponds with the results of the comparison of the CED of conventional and electric drive trains carried out at the FfE and the University of Bayreuth [16]. Taking into account a battery system with a capacity of 30 kWh and a share of battery production according to [12] (Asia 57 %, US 20 %, Europe 12 % and other regions 11 %) the total emissions for the production of an EV including battery amount to 10 t CO_2 equivalents.

The results of the comparison in **Figure 3** apply to compact class vehicles with consumption values of 5.9 l/100 km for the gasoline-powered ICEV and 17.3 kWh/100 km for the EV as well as the other assumptions and data inputs described in the supplementary document. The emissions in the operation phase are determined on a Well-to-Wheel basis, and thus also include the supply of fuels and electricity. However, it must be taken into account that the payback mileage and periods shown below are based on the assumption that the annual mileage, service life and utilization of both vehicle types are in the same order of magnitude. Potential advantages of ICEV, which result from larger ranges, are not covered by this comparison.

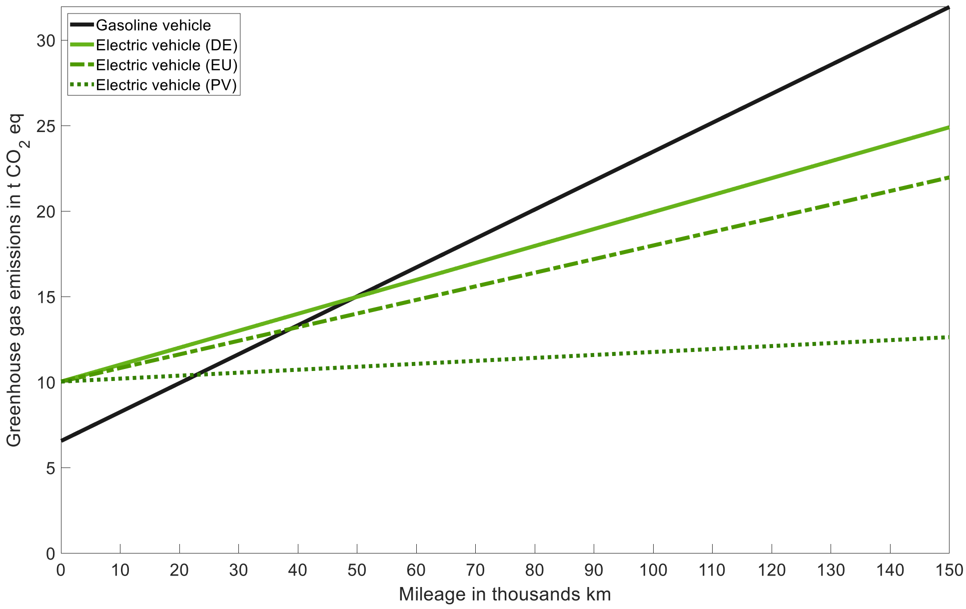

Figure 3: *Climate impact of a gasoline and a battery electric compact-class vehicle as a function of mileage and charging electricity (DE: German electricity mix, EU: European electricity mix, PV: photovoltaics)*

It can be seen that if the EV is charged with the German electricity mix from 2015 (emission factor: 0.58 kg CO_2 eq./kWh, share of RES: 29 %), from an emissions perspective it performs better than a gasoline vehicle at approximately 50,000 km. For an average annual mileage of about 14,000 km according to [17], the calculated distance corresponds to a payback period of 3.6 years. This is reduced to just under 2.8 years for the EU electricity mix (0.46 kg CO_2 eq./kWh) and to 1.6 years for electricity from PV (0.1 kg CO_2 eq./kWh).

The results also show that even in the case of an electricity mix still dominated by conventional power plants, the additional emissions for the production of the EV are offset by the lower emissions during operation. This is due to the lower efficiency of the combustion engine compared to an electric motor. Only when the emission factor of the charged electricity exceeds 0.98 kg CO_2 eq./kWh, the operational emissions of a gasoline ICEV are lower than those of an EV.

A sensitivity analysis shows that the payback period of the EV does not only depend on the charged electricity, but also on other parameters. The payback period increases from 1.6 to 2.1 years for charged electricity from photovoltaics, if the EV is compared to a diesel vehicle, which is characterised by lower operational GHG emissions than the gasoline vehicle. Furthermore, the payback period depends on the size of the traction battery and amounts to 2.6 years in case of a simplified scaling of the results for the 30 kWh battery system to a 50 kWh battery. However, current trends indicate an increase in energy density in the future, which in return leads to a decrease in specific GHG emissions per kWh battery capacity. In addition, the carbon footprint can be reduced to 62 kg CO_2 eq. per kWh battery capacity (compare Figure 2), if renewable electricity is deployed in battery production. In this case, the payback period decreases from 1.6 to 1.4 years, assuming charged electricity from photovoltaics.

Potential for improvement through circular economy

The circular economy is one way of reducing resource consumption and environmental impacts. The question to which extent the circular economy approaches in **Figure 4** can reduce the emission and resource impact of batteries as a core element of electric mobility is therefore the subject of the project "Ressourcensicht auf die Energiezukunft" [9]. In this context, the effects of circular approaches such as sharing concepts, reuse/second life applications and battery recycling on energy-related GHG emissions and the demand for critical raw materials such as lithium and cobalt are investigated.

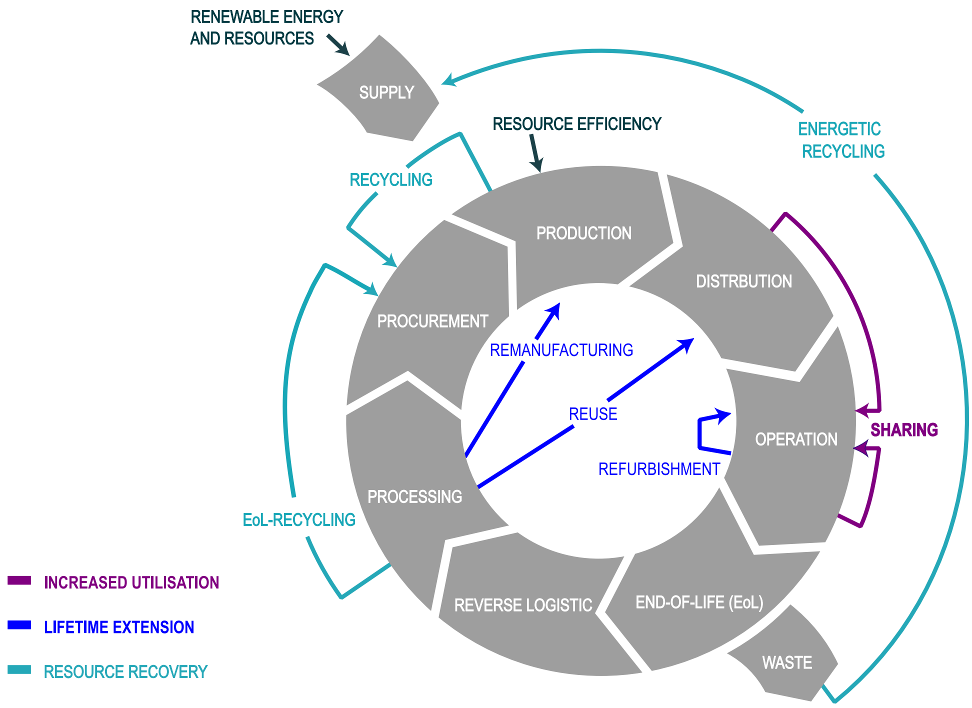

Figure 4: *Overview of possible circular economy approaches in different life cycle phases (own illustration based on [18])*

Conclusion

While in the past the perception of electric vehicles changed between "panacea" and "placebo", we are now at a point where electric mobility has irreversibly picked up speed. It is undisputed that an electrically powered vehicle is considerably more efficient than a vehicle with a combustion engine. The higher cumulative energy demand for the production of the electric vehicle - in particular the traction battery - currently reduces this advantage. However, for one thing, there is still considerable potential for improvement in the production of traction batteries. For another thing, electric vehicles (with battery or fuel cell) are from today's perspective the only notable and indispensable option for an efficient and comprehensive integration of renewables energies in the transport sector. Now, the decisive factors are increased research and development of traction batteries, the charging infrastructure and vehicle operational management (e.g. charging management for grid relief, reliable range indication).

This contribution is a plea for more objectivity. On the one hand, the communication of scientific results by scientists or science journalists requires a simplification of complex facts. On the other hand, the underlying assumptions and the validity of the results presented must not be neglected, as this can lead to serious misinterpretations, as in the above-mentioned case of the Swedish study.

References

[1] Rasch, M., Regett, A.; Pichlmaier, S. et al.: Eine anwendungsorientierte Emissionsbilanz - Kosteneffiziente und sektorenübergreifende Dekarbonisierung des Energiesystems in: BWK Ausgabe 03/2017, S. 38-42. Düsseldorf: Verein Deutscher Ingenieure (VDI), 2017

[2] Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen. Dessau: Umweltbundesamt (UBA), 2018

[3] Sechster Monitoring-Bericht zur Energiewende - Berichtsjahr 2016. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi), 2018.

[4] Romare, M.; Dahllöf, L.: The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries - A Study with Focus on Current Technology and Batteries for light-duty vehicles. Stockholm: IVL Swedish Environmental Research Institute, 2017

[5] IVL comments to reactions in media on battery study. In: www.ivl.se/english/startpage/top-menu/pressroom/news/nyheter---arkiv/2017-07-03-ivl-comments-to-reactions-in-media-on-battery-study. Stockholm: IVL Swedish Environmental Research Institute, 2017

[6] Verbund-Forschungsvorhaben zur „Ganzheitlichen energetische Bilanzierung der Energiebereitstellung (GABIE)“. Munich: Forschungsstelle für Energiewirtschaft (FfE) e.V., 1996

[7] VDI-Richtlinie 4600: Kumulierter Energieaufwand (KEA) - Begriffe, Berechnungsmethoden. Düsseldorf: Verein Deutscher Ingenieure (VDI) e.V., 2012

[8] Corradini, R.; Krimmer, A.: Systemvergleich alternativer Antriebstechnologien - Primärenergetische Analyse der Herstellung und Nutzung alternativer Antriebstechnologien im Vergleich zu konventionellen Systemen für den Pkw-Bereich. München: Forschungsstelle für Energiewirtschaft (FfE) e.V., 2003

[9] Regett, A. et al.: Laufendes Projekt: Ressourcensicht auf die Energiezukunft - Bewertung des Potenzials der Kreislaufwirtschaft zur Senkung des Ressourcenverbrauchs von Schlüsseltechnologien der Energiewende. In: https://www.ffe.de/themen-und-methoden/ressourcen-und-klimaschutz/698-ressourcensicht-auf-die-energiezukunft. München: Forschungsstelle für Energiewirtschaft e.V. (FfE), 2018

[10] BatPac Version 3.1. Lemont: Argonne National Laboratory (ANL), 2017

[11] Dai, Q. et al.: Update of Life Cycle Analysis of Lithium-ion Batteries in the GREET Model. Lemont: Argonne National Laboratory (ANL), 2017.

[12] Thielmann, Axel et al.: Energiespeicher-Roadmap (Update 2017) - Hochenergie-Batterien 2030+ und Perspektiven zukünftiger Batterietechnologien. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung (ISI), 2017.

[13] Ellingsen, L. et al.: Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. In: Transportation Research Part D: Transport and Environment 55, 82-90, 2017.

[14] The ecoinvent Database, Version 3.4. In: www.ecoinvent.org. Zurich: ecoinvent, 2017

[15] Hawkins, T. et al.: Comparative environmental life cycle assessment of conventional and electric vehicles - supporting information. In: Journal of Industrial Ecology 17(1), 53-64, 2013.

[16] Knodt, J.: Analyse und Vergleich des Kumulierten Energieaufwandes (KEA) der Antriebsstränge für konventionelle und elektrische Automobile. Bayreuth/München: Universität Bayreuth/Forschungsstelle für Energiewirtschaft (FfE) e.V., 2011

[17] Kurzbericht - Verkehr in Kilometern, Jahr 2017. Flensburg: Kraftfahrt-Bundesamt (KBA), 2017

[18] Circular Advantage - Innovative Business Models and Technologies to Create Value in a World without Limits to Growth. Dublin: Accenture, 2014