Can Electric Vehicles Contribute Significantly to Greenhouse Gas Reduction?

Electromobility

Environment & Energy BSc

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Introduction

One of the most pressing environmental issues of our time is climate change. Limits and objectives of reducing and constraining greenhouse gas concentrations (GHGs) are active and fordered in a bigger effort to mitigate the negative impacts of a changing climate. This is one of the primary initiatives of the Paris agreement to which 186 countries have signed nationally determined contributions (UNSD, 2021). One of the growing approaches to reduce CO_2 levels is a shift in the transport industry from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs). Incumbent in this transition, is the growing use and demand in Lithium-ion batteries as the shift gains progressive traction.

With a fastly growing BEV use and plans to phase out ICEVs by some automakers and countries by 2030 (T&E, 2021), the question arises; can BEVs really lower GHG emissions? In understanding this transition more acutely, this report focuses on the relationship between the BEV use and related GHG emissions, primarily in the form of carbon dioxide emissions and carbon dioxide equivalent emissions.

State of the Electromobility Industry

Over the last decade, the utilisation and development of batteries has rapidly increased as electromobility has increased. Electromobility is often purported as the solution to emissions caused primarily in the transport section. At a first glance, this seems logical to assume; traditional vehicles combust fuels and therefore emit GHGs, while electric vehicles only use electric power for propulsion. But are electric vehicles really carbon free?

There are many further aspects of the life cycle to consider than just the use or driving phase of the vehicle before one can conclude that electromobility is a better approach to the traditional systems in reducing GHGs. Nonetheless the question still stands; how exactly can electric vehicles emit and are these emissions greater, less than or equal to those of conventional vehicles while being driven.

A very important tool to take into consideration is a Life Cycle Analysis (LCA). LCAs help articulate exactly where strengths and weaknesses of a product or process may lie, by analysing the entire “life” of the item, from material extraction to end-of-life (Golovanov and Marinescu. 2019).

Traditional Propulsion and Electric-Propulsion

Internal combustion engine vehicles (ICEVs) combust petroleum products such as diesel and gasoline to propel themselves. This combustion energy is converted to a linear energy in the movement of the pistons in the engine, which is then attached to a gear, for rotational movement (Golovanov and Marinescu. 2019). The process of combustion alone emits carbon dioxides. Impurities in the fuel also cause emission of other gases such as NO_x and SO_2 during combustion.

In the propulsion process, the combustion of the fuel can be given as:

$$\boxed{\text{Fuel} + \text{Oxygen} \rightarrow \text{Carbon Dioxide} + \text{Water}}$$

Eq. 1.0: Simplified equation of combustion of fuels in ICEVs

In equation 1.0 it becomes clear that fuels used in the combustion process, whether diesel or petrol, will always emit carbon dioxide. Also, the greater the amount of fuel, the greater the amount of CO_2 emissions. That means, during the use phase, ICEVs will accumulate increasing CO_2 emissions proportional to their fuel use. For this reason graphs and figures following in this report uses a medium car travelling distance of 225000 km over its lifetime.

On the other hand, during operation electric vehicles utilise electricity from their traction batteries to power a motor, which is connected to an axle with wheels. DC supply is converted to AC for the electrical motor. The battery pack is composed of many hundreds of smaller Lithium ion battery cells, which are connected in a circuit. Exact circuit configurations and number of battery cells changes with the car and battery producer.

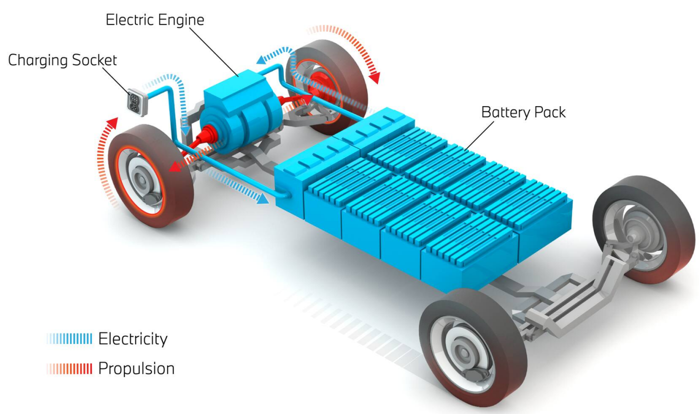

Fig. 1.0 Simplified Propulsion in Battery Electric Vehicles (BEVs), taken from BMW (2019).

Life Cycle Overview of Electric Vehicle

In order to better understand the electromobility industry, the simplified LCA of an electric vehicle should be analysed.

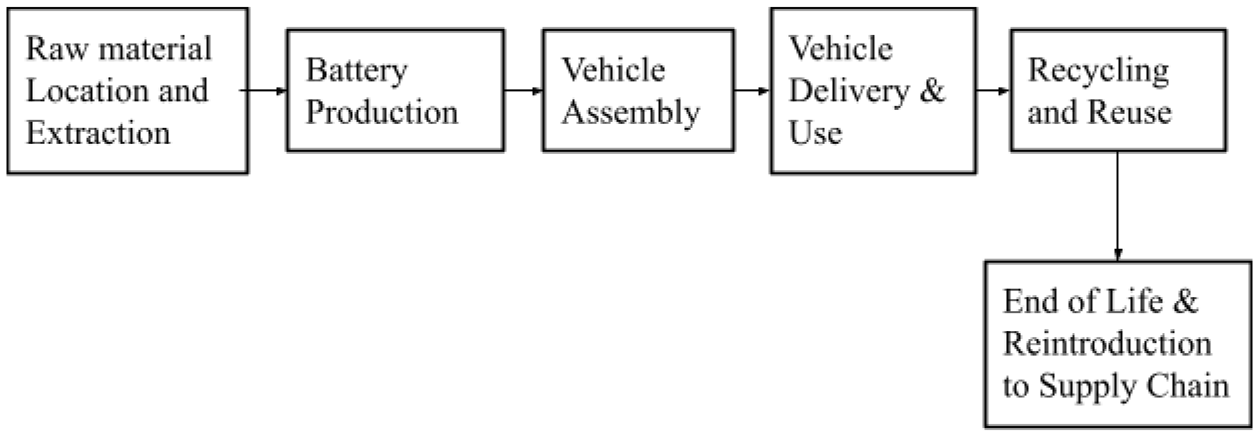

Fig.2.1 Simplified stages of the life cycle of an electric vehicle.

When looking at the carbon intensity then 2 processes are especially important to consider; battery production and vehicle delivery and use .

Raw material extraction and battery production are heavily energy intensive processes, which emit significantly large amounts of CO_2. According to T&E (2020), later emission ranges from 61 to 106 kg CO_2e/ kWh for battery production, while previous estimates ranged from 150 to 200 kg CO_2e/ kWh. These values were considered for LiNMC (Lithium-Nickel-Manganese-Cobalt) batteries which are the predominant battery used by automakers today. Important to consider at this stage is that battery production is a life cycle process innate to electric vehicles and not ICEVs.

Another important consideration used to derive these carbon values is the energy mix of the country where the battery is produced and where the BEV is driven and recharged. This not only influences emissions from the battery production stage of the life cycle, but perhaps even more so, the driving-phase or well-to-wheel impact of an electric vehicle (T&E, 2020).

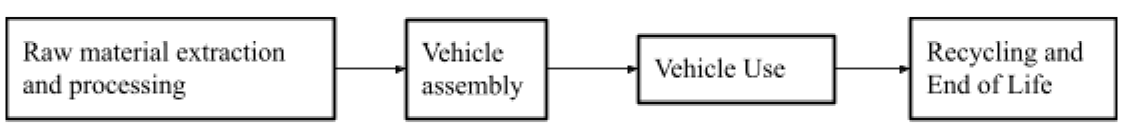

Fig. 2.2 Simplified LCA of an ICEV

As mentioned previously, one may assume lower emissions due to the use of electricity instead of petrol as fuel. This seems even more so to be the case when analysing the simplified LCA stages of these two types of vehicle in Figure 2.1 and Figure 2.2. Therefore, can BEVs really emit less CO_2 emissions than ICEVs?

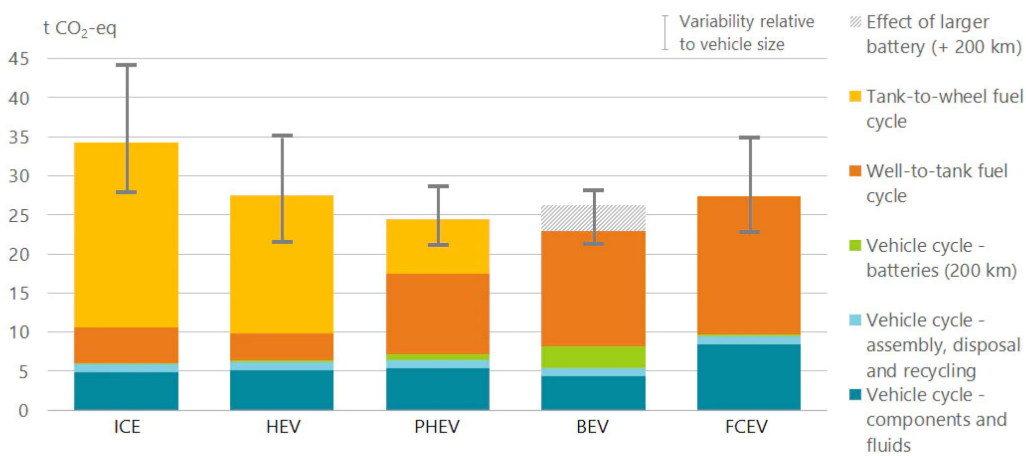

Fig. 3.0 The tonnes of CO_2 equivalent emitted at different stages of use for vehicle types: Internal Combustion Engine (ICE), Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV).

Source: IEA (2019)

Figure 3.0 portrays mid-size vehicles with similar performance. For BEVs a vehicle with 200km range is included with an additional vehicle of 400km range being displayed in the shaded area. The sensitivity bars represent the case for small cars (lower bound) and large cars (upper bound). Figure 3.0 also shows ICEs have the greatest combined CO_2 emissions, followed by HEV, FCEV, PHEV and finally BEV. Important to note, is that many assumptions are taken in order to make such a simplified diagram of a complex industry. For one, a global energy mix is taken as 518g CO_2/kWh which represents the source of the electricity, heavily driven by a large portion of nonrenewable energy. Secondly, FCEVs are assumed to rely on hydrogen produced primarily from steam methane reforming.

What is useful about Figure 3.0 for this report is that it stratifies the individual life stages of BEVs and ICEVs with the corresponding equivalent of CO_2 emissions. Immediately, the tank-to-wheel efficiency of ICEs, HEVs and PHEVs is seen. This is a primary limiting factor in the immense challenge for these vehicles to lower their CO_2 emissions. As seen in Equation 1.0 combustion of fossil fuel will always yield CO_2, and, the more these vehicle types are driven the more CO_2 they emit. BEVs and FCEVs on the other hand emit most strongly in the well-to-tank phase. That is, the electricity production phase which is a function of how clean the electricity was produced. This in comparison to fossil fuel, is an adjustable CO_2 emmtive parameter. When electricity would be provided from renewable sources, the CO_2 equivalent emissions for this process would decrease enormously based on figure 3.0 (IEA, 2019).

Impact of Source of Electricity & Energy Mix

When it comes to carbon emissions and driving electric vehicles, the most influential source of the emissions is the energy mix. Electric cars have the potential to emit a trivial amount of CO_2 during the use-phase of the vehicle. How a country's energy is then therefore organised, alludes to the degree of pollution incumbent by vehicle use and battery production (Helmers and Weiss, 2017). Therefore, the more emitting the energy industry of a country, the more emissions can be expected during the use of the electric car. Since countries have different methods of producing energy, for example coal combustion, nuclear fission, hydro-electric dams etc., the emissions will vary based on the share of the method used in the country. For this reason, the term ‘energy mix’ refers to the energy consumed of a country from various aggregated primary and secondary energy sources (T&E, 2020).

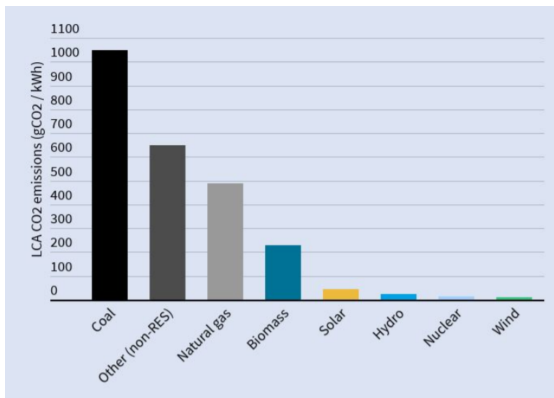

Fig. 4.0 Life-cycle intensity of CO_2 of different sources of electricity (T&E, 2020)

Figure 4.0 shows the life-cycle intensity of CO_2 of different sources of electricity. Important to note is that the emissions during plant construction and plant decommissioning are also considered here. Based on Figure 4.0, highest CO_2 emissions occur when coal is the energy source (~1050g CO_2/kWh) while when renewable sources are used, the emissions are less than 70g CO_2/kWh. It then follows, that electric vehicles powered by an energy mix with higher proportions of non-renewable resources and biomass are heavier polluters than those supplied from renewable

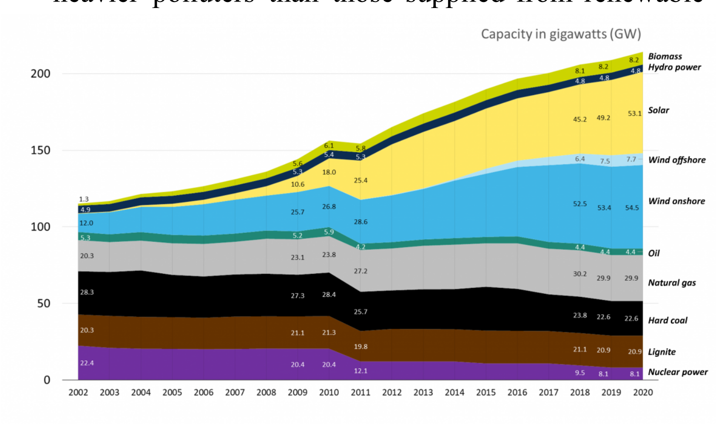

Fig 5.1 Installed net power capacity of Germany (Appunn et al, 2021).

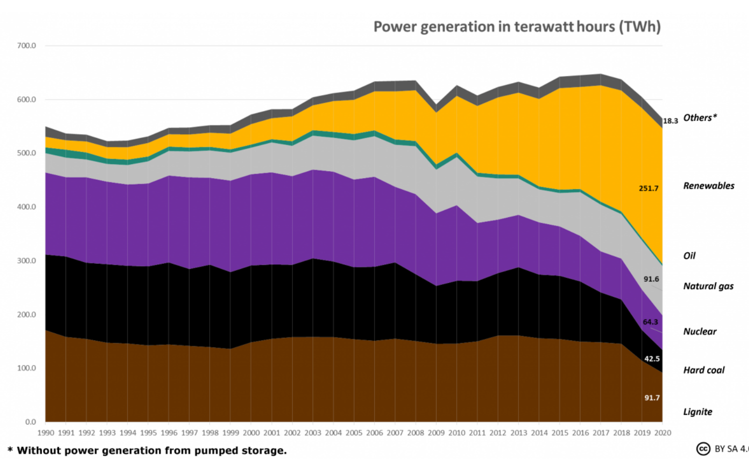

Fig 5.2 Gross power production in Germany, 1990-2020 (Appunn et al, 2021)

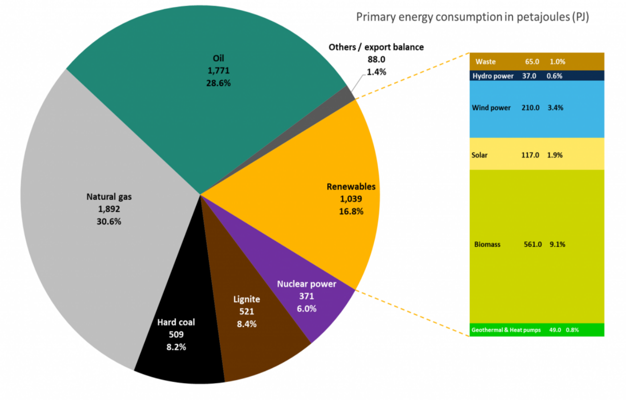

Fig 5.3 Energy sources' share in primary energy consumption in first half of 2021, Germany. (Appunn et al, 2021)

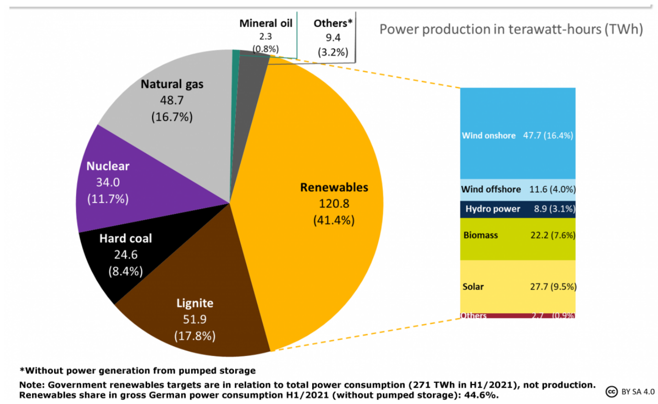

Fig. 5.4 Share of energy sources in gross German power production during the first half of 2021 (Appunn et al, 2021).

Based on the data presented so far, a greater share of renewable power should correlate to lower CO_2 emissions. Is this really the case?

Figures 5.1 - 5.4 show Germany's installed net power capacity, gross power production, share of energy sources and consumption.

In Figure 5.3 and Figure 5.4, the differences between the percentages of renewable energy consumed (16.8%) and produced (41.4%) is a noteworthy issue. This is a critical issue when considering whether BEVs contribute significantly to GHG reduction. Also important to highlight is the limiting nature of renewable energy sources. This point is seen as the discrepancy between installed capacity in Fig. 5.1 and the difference of energy consumption. The intermittent nature of renewables results in the need to utilise more energy from nonrenewable sources to meet electricity demand such as coal. This results in a more carbon intensive grid. Both electricity and petrol are secondary energy sources. The more renewable the energy source the lower the amount of pollution during the driving phase. An energy infrastructure that omits sufficient storage of the renewable electrical power has to use more electricity from unrenewable sources to meet the baseline demand of the grid. That means, not only should renewable sources comprise a higher share in the energy grid, but sufficient storage and utilisation of this renewable energy, especially when it comes from intermittent sources, should be included in the country's energy infrastructure to reduce its carbon intensity (Appunn et al, 2021).

CO_2-Emissionen im Strommix [g CO_2 je kWh] — Quelle: EUPD Research 2021

	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez
00:00	349	227	297	294	314	362	408	413	450	368	433	396
01:00	346	222	293	287	305	348	399	401	443	362	429	390
02:00	342	217	293	284	301	341	390	393	438	352	425	387
03:00	341	216	290	284	302	340	385	393	437	359	426	385
04:00	343	220	297	290	306	344	386	399	442	368	430	388
05:00	355	232	310	301	319	357	393	414	455	389	441	400
06:00	367	247	322	304	318	360	389	421	464	407	451	414
07:00	373	253	311	288	295	342	360	403	449	407	450	418
08:00	374	253	290	263	268	318	327	373	419	400	440	419
09:00	367	247	273	235	242	294	296	346	393	386	430	416
10:00	359	239	253	203	216	274	273	322	366	372	420	410
11:00	354	232	240	183	200	259	257	302	341	361	412	407
12:00	350	229	235	172	192	250	247	291	324	351	412	409
13:00	353	228	238	167	189	245	242	288	315	349	424	419
14:00	364	233	246	168	189	245	242	292	320	356	444	431
15:00	380	244	263	176	197	251	250	306	340	374	469	437
16:00	389	258	292	198	210	265	269	328	377	398	476	429
17:00	379	264	323	239	240	288	300	360	420	413	460	417
18:00	373	260	335	279	276	320	333	390	454	411	454	418
19:00	372	259	333	301	305	352	364	414	462	404	456	421
20:00	368	254	330	306	324	376	393	427	462	400	460	422
21:00	363	246	326	307	332	388	409	431	468	394	456	418
22:00	359	243	323	305	333	386	413	432	468	386	454	416
23:00	351	235	316	296	326	383	417	432	457	373	448	409

Fig. 6 Emissions of CO_2 from the energy mix at different times of the year in Germany. (EUPD, 2021).

Another interesting point to consider; not only do CO_2 emissions vary by share of energy mix and compatible grid storage and management options, but also by time of year, month, and time of day. These fluctuations are proportional to differences in seasonal demand and differences in output in production areas. For example, February was the month with the most favourable conditions for wind power, as a result CO_2 emissions for this time are lower compared to January and March. Similarly, growth in solar power capacity and utilisation is responsible for the all time lowest emissions in summer around lunch time. Here again, the intermittency and inconsistency of renewables limits the CO_2 emission saving potential. Interestingly however, for 2020 minimum values of 87g CO_2 per kWh were recorded, and a maximum of 664g CO_2/ kWh (EUPD, 2021). That is a substantial difference between peak renewable energy utilisation and peak nonrenewable energy utilisation.

Vehicle Production and Battery Production Carbon Footprint

Battery production is a significant step of the LCA regarding carbon intensity. ICEV and BEV production (without battery) emissions are relatively similar over their lifetime (IEA, 2019). The differences are therefore seen primarily in the emissions of the battery pack of BEVs. When it comes to manufacturing eco-efficiency, a high production capacity and an electricity mix with low carbon intensity are important in lowering the carbon intensity of battery production. Here especially, economies of scale play an important role. That means, the larger the production volume of cells the greater the potential to reduce GHG emissions in the form of kg CO_2 eq/kWh. Therefore, larger production facilities have a greater chance at reducing the GHG emissions of the industry (Philippot et al, 2019).

<u>Table 1:</u> GHG Emission of a battery pack manufactured at Different Scales (adapted from Philippot et al, (2019)).

Annual Cell Production (cells)	7×10^7	1×10^8	5×10^8	1×10^9	2×10^9
Impact of GHG emissions (kg CO_2 eq/kWh)	168	157	123	114	107

As the number of battery cells produced increases, the CO_2 eq/kWh decreases.

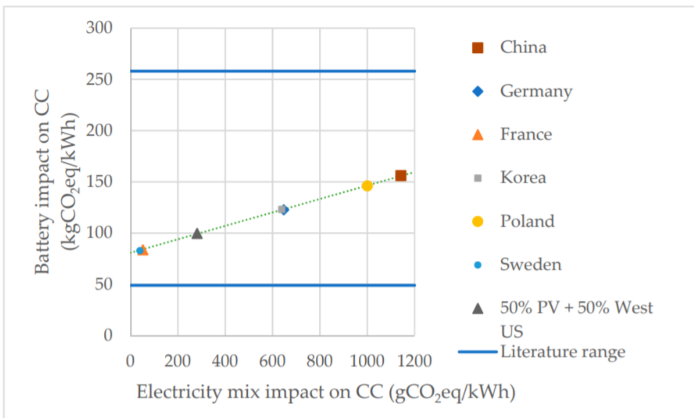

Fig 7.0 Carbon dioxide equivalent emissions per kWh emitted for a battery pack manufactured in different countries with different energy mixes (Philippot, 2019)

Therefore, in order to reduce the GHG emissions during battery production it is important to increase the production volume (number of cells per plant), conduct the operation in an electricity mix with low carbon intensity and increase the energy density of the batteries (Philippot et al, 2019).

Afterlife and Recycling of Batteries

The end of life potential of electric vehicle batteries is currently under development, and already quite broad. Traction batteries can be repurposed as storage options to stabilise home and grid electricity use and consumption. Following such, batteries can further be recycled with the primary components being recovered and reintroduced into earlier production phases of the supply chain. These two steps; reuse and recycling can significantly impact the GHG emissions of an electric vehicle by reducing the demand of mined batteries in earlier steps of the supply chain. Previous life cycle analyses had not considered these 2 measures in the total energy demand; instead of repurposing and reuse, the recycling was only considered (Wewer et al, 2021). Especially of importance here, is the possibility of the traction to be reused for grid storage solutions. As seen earlier, the lack of storage and grid management solutions according to EUPD (2021) created a huge difference in CO_2 emissions; with a total emission difference between minimum and maximum values of 577g/kWh in 2020. Here BEVs have an unrealized potential to further reduce CO_2 emissions indirectly by aiding in stabilising electricity derived from renewable sources.

This sentiment is further reinforced by further literature. According to Golovanov and Marinescu (2019), not only have many production models of traction batteries superseded their expected lifetime, they also have a significant afterlife reusability. Contemporary batteries lose an estimated 4-5% capacity each year. At the end of 7 years the batteries would reach the 70% capacity limit, after which they can be repurposed for energy storage solutions. This secondary storage application can be residential or industrial, assisting in grid management solutions, which become increasingly important as the share of renewable energy in the mix also increases. These second life life applications extend the usability of these components, decreasing demand for batteries in grid storage, newer electric vehicles and more, and therefore reducing the CO_2 impact after the battery is produced, and in other sectors.

Overall Assessment

After having looked at the carbon intensities for various steps of the LCA of BEVs, some important deductions so far can be made:

- The CO_2 impact of BEVs is significantly high during battery production.
- The use of renewable energy in the energy mix alludes to the carbon intensity during the use phase of BEVs.
- The ability of the grid to utilise full renewable energy capacity is important in CO_2 emissions.
- Both battery production emissions and driving emissions, which are the most carbon intensive stages of BEV's life cycle, are highly dependent on the energy mix of the country.

With so much possible variation in the carbon intensity from the composition of the energy mix to the time of year and day that electricity is produced, it is clear that BEVs can contribute significantly to GHG emissions. The interesting question now is, how do these carbon intensities compare to the current mobility industry dominator ICEVs? For this question, we can take a look at Figure 8.1 from T&E (2020).

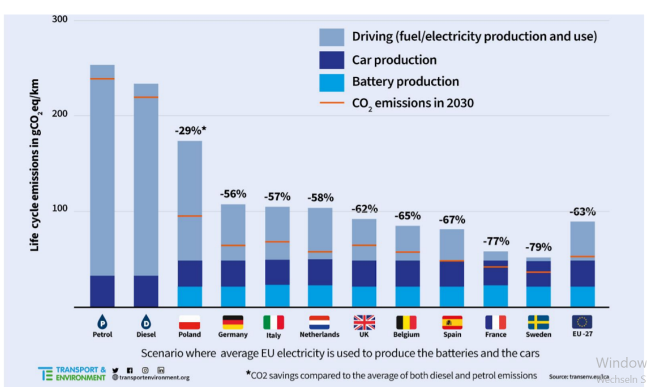

Fig 8.1 Lifetime Carbon dioxide emissions from BEVs, petrol and diesel car from different energy mixes in the EU (T&E, 2020)

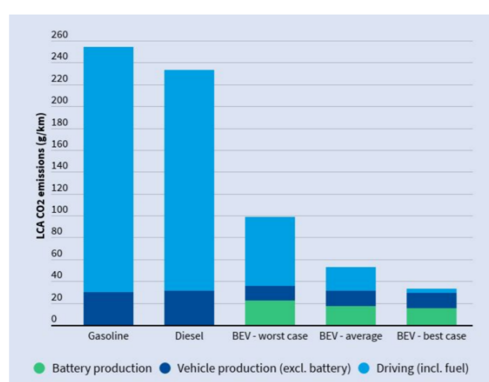

Fig. 8.2 Lifetime CO_2 emissions of an electric car, compared to diesel and petrol cars, in 2030 (T&E, 2020).

Figure 8.1 shows the emissions which can be saved depending on different energy mixes in the EU, compared to the diesel and petrol averages. Even in countries where renewables comprise a smaller portion of the energy mix and electricity use (Poland and Germany) BEVs still emit less carbon dioxide equivalents than the petrol and diesel counterparts over the course of their lifetime use. The result is, diesel and petrol cars emit almost 3 times as much CO_2 equivalents over the course of their lifetime, despite the less complicated LCA in Figures 2.1 and 2.2. In Figure 8.2, T&E (2020) goes on to give the best, average and worst case scenario for the different vehicle types over different energy mixes in the EU, assuming the cars are driven for 225000 km over their lifetimes. Clear to see is, even in the worst cases BEVs outperform ICEV models substantially.

This finding is further reinforced by Helmer & Weiss (2017), "when charged with electricity of a carbon intensity of 467 g CO_2 equivalents/kWh (which resembles the carbon intensity of the electricity mix in the EU in 2008), a reference electric vehicle is associated with a well-to-tank carbon intensity of 60–76 g CO_2 equivalents/km." This is quite close to the values presented by T&E (2020) in Figure 8.2 for the worst case (~100 gCO_2/km) and the EU27 average (~ 50g CO_2 equivalents/km). Interesting to note, is the improvement in CO_2 emissions/km for the EU average from the data from in 2008 (by Helmer & Weiss (2017)), and 2020 (by T&E (2020)) showing an approximate reduction in the EU average of 10-16g CO_2/km over the 12 years.

Conclusion

All the findings and data deductions suggest that the lifecycle carbon footprint of BEVs tends to be most intensive due to the electricity mix used in battery production factories and when recharging the car (Philippot et al., 2019). Even for the most CO_2 intensive grids in the EU, BEVs still contribute less to CO_2 emissions than ICEVs (T&E, 2020). Furthermore, the well-to-wheel GHG emissions of a global average EV are lower than the global average ICE (IEA, 2019). Lastly, not only can BEVs contribute to less GHG emissions, their afterlife potential as storage systems helps develop grid management for nonrenewable electricity to be utilised more efficiently in the grid.

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