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The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions

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Greenhouse gas (GHG) emission reductions possible with battery electric vehicles (BEVs) are underestimated in the scientific literature. The following causes are identified and illustrated: overestimating battery manufacturing, underestimating battery lifetime, assuming an unchanged electricity mix over the lifetime of the BEV, using unrealistic tests for energy use, excluding fuel production emissions, and lack of system thinking. In an example calculation, BEVs reduce emissions from 244 to 98 g/km. In a fully renewable system, BEV emission could decrease to 10 g/km.

The internal combustion engine is a mature technology that's being superseded by battery electric vehicles (BEVs). BEVs are becoming cheaper than conventional cars,[1] and current technology could already electrify over 70% of transport energy demand and lead to a large reduction in greenhouse gas (GHG) emissions.[2] BEVs also lower the system costs of a fully renewable system if the moment of charging is optimally chosen (''smart charging''), especially when combined with bidirectional charging (''vehicle to grid'' or V2G).[3] A few studies, however, seem to show only small benefits.[4] A recent study by Buchal et al. even claims that a diesel vehicle (the Mercedes C 220 d) emits less GHG emissions than an equivalent BEV (the Tesla Model 3 with a 74 kWh NCA battery and 450 km range).[5] Using this comparison as an example, common flaws in assumptions and methodology are pointed out, and it is shown that a future-oriented systemic approach is needed to fully appreciate the potential of batteries in general and BEVs in particular.

GHG emissions during battery production are the Achilles heel of BEVs. Care must be taken to use correct assumptions about battery manufacturing and about the battery lifetime. Doing this, recent studies[6] imply battery production adds around 16 g of GHG per km. But, based on conservative assumptions,[4] Buchal et al. claim 73–98 g/km.[5] For the manufacturing of the rest of the vehicle, an impact of 27 g/km is assumed for the diesel car and 24 g/km for the BEV. This is explained below and shown in Table 1.

Regarding GHG emissions during battery production, it is assumed that 65 kg of GHG is emitted for every kWh of battery produced. The claim by Buchal et al. of 145–195 kg/kWh[4,5] is deemed unrealistic. The first and most GHG-intensive step in battery production consists of extracting and refining raw materials. Older studies put emissions of this stage at 48–216 kg/kWh.[4] Newer studies make a distinction between production location and chemistry, e.g., in the US, 43 kg/kWh for lithium nickel cobalt aluminum (NCA) batteries and 37–58 kg/kWh for lithium nickel manganese cobalt (NMC) batteries, and in China (with a coal intensive electricity mix), 82 kg/kWh for NCA and 105–111 kg/kWh for NCM.[6,7] The next and final phase is manufacturing the cells and putting them in packs. This phase was sometimes estimated at 70–110 kg/kWh,[4] but newer and more detailed studies that take into account high-volume manufacturing estimate 2–5 kg.[6] Adding everything up and taking a weighted average mix of origins and chemistries results in around 65 kg of GHG per kWh of battery manufactured. New chemistries like lithium sulfur promise a further reduction in cost and environmental footprint.[8] In order to make a complete accounting, emissions during production of the rest of the vehicle must also be taken into account. For this, emissions of 8,000 kg GHG are assumed.[5] Since the BEV drivetrain is lighter, this might result in 1,000–2,000 kg less GHG for the BEV. A conservative 1,000 kg is used here.

Regarding battery lifetime, it is important to note that great strides have been made in recent years. Currently, cars are scrapped when motor maintenance becomes too expensive. Since the electric motor outlasts most other car components without maintenance, the motor will no longer be the bottleneck for a BEV. Buchal et al. assume the battery becomes the new bottleneck and will be scrapped after 150k km while a diesel would last 300k km.[5] But current batteries are estimated to last at least 1,500 to 3,000 cycles before they lose 20% of capacity,[8] giving an electric car with 450 km of range a battery lifetime of 450k to 1,350k km. Increases to between 5,000 and more than 10,000 cycles are expected in 2030.[8] Advances like solid-state

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Table 1. Life Cycle GHG Emissions in g/km of a Diesel Car and BEV

	Buchal et al.[5]	Hoekstra et al.[9]	Renewable Future
Diesel Car Total	170	244	153
Driving	143	217	150
Manufacturing	27	27	3
BEV Total	189–214	95	10
Driving	73	55	6
Manufacturing	100–125	40	4
(Battery)	(73–98)	(16)	(2)

Analogous to Buchal et al.,[5] this scenario assumes comparing a Mercedes C 220 d as the diesel car and a Tesla Model 3 with 74 kWh NCA battery as the electric vehicle. To make Buchal et al. relevant to a wider audience, the German electricity mix was replaced with the average European electricity mix. The German mix would result in increased driving emissions of 16 g/km for Buchal et al. and 18 g/km for Hoekstra et al.[9] The Renewable Future scenario is speculative but illustrates the impact of the integral system approach.

electrolyte could further increase the lifetime while making batteries nonflammable. Thus, the 300k km that is assumed for the diesel seems a conservative value for the battery and is adopted here, but it seems probable that future BEVs will last much longer than current cars.

Driving emissions are where the BEV realizes big gains on the diesel car. Care must be taken to calculate the electricity mix *over the lifetime* of the BEV. For the diesel, GHG emissions during fuel production (predominantly from refineries) should be included. All energy use should be based on realistic road tests or numbers of the US Environmental Protection Agency (EPA). This leads to 55 g GHG per km for the BEV and 217 g for the diesel vehicle. This is explained below and shown in Table 1.

Regarding diesel emissions while driving, Buchal et al. assume the diesel uses 4.5 L per 100 km based on the lowest number for this car in the New European Driving Cycle (NEDC).[5] Adding 21% emissions for diesel production (which is often forgotten) leads them to assume 141 g. But the NEDC notoriously underestimates emissions, and taking the lowest value compounds this error. (EPA values are closer to reality.) Using the average of over 3,000 road tests for this specific model from spritmonitor.de gives a more realistic 6.9 L per 100 km. Taking into account the aforementioned emissions during diesel production, this results in 217 g/km.

BEV emissions while driving should be based on the electricity mix over the lifetime of the vehicle. This leads to around 55 g GHG per km for Europe and 73 g per km for Germany. To calculate this accurately for a specific BEV, assumptions must be made about lifetime (here 17 years), yearly mileage (26k km in the first year and 1k less per year thereafter), and energy use per km (0.161 kWh/km based on EPA measurements). This should be combined with assumptions about the current GHG intensity of the electricity mix *and its change over time*. For Europe, the mix emitted was 447 g/kWh in 2013.[10] This includes energy use of the electricity network itself, pumping, trade, and distribution losses. Taking 447 g/kWh results in 73 g/km. But in reality, the EU mix has emitted on average 9 g/kWh GHG *less every year* and was below 400 g/kWh in 2019. Assuming this trend continues, the weighted average over the lifetime of the car is 55 g/km, not 73 g/km. Buchal et al. take the German mix, which they put at 550 g/kWh. Viewed statically, this implies that the BEV emits 89 g/km. But according to laws, plans, and predictions, the German mix will reduce by about 15 g/year over the lifetime of the BEV, and this makes 73 g/km a more accurate estimate. Most estimates of EV emissions (e.g., those of the IEA) and even some thorough studies into BEV emissions[10] leave out this critical part of the calculation.

Taking an integral system perspective further highlights the potential of batteries and BEVs. One could imagine a future in which not only the cars themselves but the entire automotive supply chain runs on renewable electricity. Batteries could run mining equipment that retrieves the ore from which batteries, solar panels, and windmills are made. Solar and wind produce hydrogen that (in combination with batteries) makes the production of steel and aluminum almost zero emission, which in turn makes the manufacturing of batteries, cars, solar panels, and wind turbines almost zero emission. Car batteries also absorb excessive solar and wind, stabilize the grid, and reduce the amount of stationary batteries that are needed. It is not an exaggeration to say that in such a scenario, the GHG emissions of batteries could be further reduced by a factor of ten or more.

Furthermore, batteries are applicable in trucks, trains, ships, and even planes. For example, heavy trucks drive large but relatively constant distances per day. This makes intensive use of the batteries and would make the payback time for truck batteries even better than that for regular cars. The same is true for ferries. Diesel trains could be replaced by battery electric trains that need only a very limited amount of overhead wire, thus making electric trains economic on many more routes. Planes are still hard to electrify economically, partly due to their untaxed cheap fuel, but a carbon tax could make short distance battery electric planes economical.

However, the fact that we could theoretically make electric cars almost zero emission does not imply that private car ownership for 11 billion people is sustainable. Other planetary boundaries would come into play, such as resource scarcity, biodiversity, and livable cities. Recent studies found that shared autonomous vehicles with a size dependent on the trip made could (depending on implementation) result in a further 10-fold reduction in use of raw materials, energy, particulate emissions, and spatial footprint, especially when combined with (electric) bikes and public transport. Therefore, models will increasingly need to look beyond mere GHG emission reduction and address other planetary and societal constraints as well.

Scientific research could establish how models can be constructed that find quick and cost-effective transition pathways toward such futures.[9] In a way, this mirrors the approach of climate science, but while climate science is looking at the *consequences* of GHG emissions emitted over time, such a model would look at limiting the *sources* of GHG emissions over time. What is needed is a realistic representation of a socio-technical complex adaptive system in which learning curves, positive feedback loops, and emergent behavior from heterogeneous actors can quickly take the system to a new state.[9] Such models could also point to policy measures that maximize innovation by start-up companies while minimizing delays by incumbents. They could show our best options in limiting the damage of climate change and establish the true potential of batteries and BEVs.

DECLARATION OF INTERESTS

The author is affiliated with the Einhoven University of Technology (researcher) and with Zenmo Simulations (founder).

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