Comparing the lifetime green house gas emissions of electric cars with the emissions of cars using gasoline or diesel

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Summary

Recently, a number of predominantly German studies have questioned whether driving an electric vehicle emits less green house gas, or wether we must wait for electricity to decarbonise further.

This report explains these studies have a number of flaws and that proper calculations show electric vehicles already emit less than half the green house gasses of their fossil fueled counterparts.

If we speculate about a future in which production and driving are done on renewable energy this results in at least ten times less emissions than what is achievable with combustion engines using fossil fuels.

What follows is a list of the six biggest mistakes in studies that find electric vehicles have similar green house gas emissions as fossil fueled counterparts. The summary concludes with a matchup in terms of CO2 emissions of electric vehicles versus fossil fuel vehicles in different segments.

1 Exaggerate GHG emissions of battery production
Scaling up and smarter engineering (e.g. preserving heat in the manufacturing process) have dramatically lowered the energy that factories require to produce battery cells. At the same time the electricity used is steadily decarbonizing. All this is reducing the EV's 'climate backpack' but many EV-critical studies ignore this. Examples are Buchal, Karl and Sinn, ADAC, ÖAMTC and Joanneum Research that assume battery production will emit 175 kg CO2 per kWh of battery. They base this on one highly controversial study from 2017. But this study was updated in 2019 and concluded it was now 85 kg CO2 per kWh of battery which halves the 'climate backpack' of the electric vehicle. Mazda published a paper in 2019 using even older numers. Based on a list of recent publications we assume a range of 40 to 100 kg/kWh with a mean of 75 kg/kWh.

2 Underestimate battery lifetime
In many studies the battery (e.g. Buchal, Karl and Sinn, ADAC, ÖAMTC and Joanneum Research) the battery is assumed to last only 150 000 km. Buchal, Karl and Sinn even contrast this to a diesel car lasting 300 000 km. However, we have not seen examples where this was based on actual research. Empirical data shows modern batteries will most probably last for more than 500 000 km. New studies claim two million km is possible with current technology. Furthermore, car lifetimes are increasing in Europe and an average modern car can be assumed to last 250 000 km. That is the battery lifetime assumed in this report.

3 Assume electricity will not get cleaner over the lifetime of the car
All studies that find high EV emissions assume the electric vehicle will drive on the electricity mix it used in its first year. This is understandable since it makes calculations easier and avoids having to defend assumptions on developments in the electricity mix. However, it is also unrealistic. Just as the electricity mix has changed dramatically over the past 20 years, it will do so again over the next 20 years.
We extrapolate past developments and support our estimates using authorative sources in order to create a future time series containing developments in the electricity mix. This basically means EVs drive cleaner as time goes on. However, this positive effect is partly negated by the fact that cars drive less as they get older. Furthermore, we must add upstream emissions of electricity because of e.g. digging up

coal, electricity grid losses which we estimate to be higher than most literature at around 30%. All in all electric vehicles sold in Europe in 2020 should count on 250 g CO2eq/kWh electricity over their lifetime.

4 Use laboratory tests paid for by manufacturers themselves

Measuring CO2 emissions of cars is deeply problematic in Europe because the official numbers have become political instead of empirical. The test protocol is defined in political negotiations with manufacturers who then choose and sponsor the institutions that conduct the tests for them. This resulted in the succesful application of cheating software and even fully tests using the New European Driving Cycle (NECD) result in emissions 40% lower than reality. Most studies that are critical of EVs still use the NECD. The new WLTP is supposed to be a fresh start but doesn't address any of the aforementioned underlying problems so improvements are limited and - we fear - temporary. The WLTP is still useful for determining compliance but should not be be confused with empirical measurements of actual CO2 emissions. In this report we use road measurements (from spritmonitor.de) and independent test measurements with a good track record (from the EPA in the US).

5 Exclude or downplay fuel production emissions

New research into flaring and other sources of GHG emissions has shown that the emissions related to the production of gasoline and diesel are larger than previously thought. In order to account for the production of fuel, cars driving on gasoline should add 30% to their tailpipe emissions. Cars driving on diesel should add 24%. Emissions per litre are thus 3310 g for diesel and 3140 g for gasoline.

6 Ignore the larger system

The improvement that can be achieved with combustion engine technology is limited. First because it is a mature technology that only sees small incremental improvements. Second because producing the fuel combustion engines need in a sustainable manner is relatively inefficient and expensive.

If we abide by the Paris agreement, the entire supply chain will become low carbon. Predominantly through the use of renewable electricity which will also be used for industrial heating processes using power-to-gas. This means that the 'climate backpack' of both conventional and electric cars becomes very small. What remains is the CO2 emitted while driving. Here the electric vehicle can directly run on renewable electricity and also has the advantage of its on average four times more efficient engine.

The end result is that an energy system with enough renewable electricity will lead to electric vehicles that emit at least ten times less CO2 than cars driving on gasoline, diesel or natural gas.

Matchups of electric cars versus fossil fueled cars

The result of avoiding these errors in a matchup of three currently available car models is shown below. The GHG savings for calls sold in 2020 ranges from 54% to 82%.

Comparing the CO2eq emissions over the lifetime of two similar cars in grams/km

	Toyota Prius 1.8l 2020	**Volkswagen eGolf**
Manufacturing excl. battery	28	24
Manufacturing battery	-	11 (36 kWh battery)
Driving	140	43
Total g CO2eq per km	**168**	**78 (54% less)**
Number of km needed for EV to pay back the battery		28 000 km

	Mercedes C 220d	**Tesla Model 3**
Manufacturing excl. battery	32	28
Manufacturing battery	-	23 (75 kWh battery)
Driving	228	40
Total g CO2eq per km	**260**	**91 (65% less)**
Number of km needed for EV to pay back the battery		30 000 km

	Bugatti Veyron	**Porsche Taycan S**
Manufacturing excl. battery	40	36
Manufacturing battery	-	28 (93 kWh battery)
Driving	738	76
Total g CO2eq per km	**778**	**140 (82% less)**
Number of km needed for EV to pay back the battery		11 000 km

In the rest of this document the calculations are explained in detail and sources are provided.
An attempt was made to do this in a way that lay persons can understand.
We also gave input to an online tool that you can use yourself to make comparisons.

Calculating the GHG emissions of electric vehicles

The basic formula's one should use are simple:

$$emissions\ per\ km = \frac{\text{manufacturing emissions} + \text{driving emissions}}{\text{km driven}}$$

$$manufacturing\ emissions = sum\ of\ (battery + drivetrain + rest\ of\ car)$$

$$driving\ emissions = car\ energy\ use\ in \frac{kWh}{km} * electricity\ emissions\ per\ kWh$$

Once the factors in these formula's are determined correctly, comparisons become straightforward and incontrovertible. Our findings regarding the most important factors are as follows:

- Battery manufacturing emits approx. 75 kg CO2eq/kWh.
- The lifetime of cars sold in 2020 is best estimated as 250 000 km.
- Lifetime electricity at the charger for EVs sold in 2020 in Europe will be approx. 250 g CO2eq/km.

Battery manufacturing emissions

Most studies use outdated and thus unrealistically high assumptions regarding battery manufacturing emissions. Based on the latest data we assume 40 to 100 kg/kWh. Our best estimate is 75 kg/kWh.

Few topics are as consequential for the CO2 output per kilometre of the electric vehicle as the CO2 emitted during manufacturing of the battery. Critics of the electric vehicle present battery manufacturing as a "climate backpack" that is almost impossible to shake off.[1] We will show this is based on outdated studies and that the backpack is pretty lightweight compared to the emissions that occur during driving.

In order to talk sense we first need a metric that is independent of battery size. The metric of choice in most literature is kg CO2eq per kWh. The first term 'kg CO2eq' means that all emissions are expressed as the equivalent of kg of CO2. So for example methane emissions are included but converted to CO2 equivalents. The second term means that we divide the total electric car battery by the amount of kWh of charge it can hold. That way the metric stays the same for large and small batteries and we can easily do calculations for all cars.

These emissions are hard to establish because factories see this data as commercially sensitive. However, many scientific studies try and the most recent ones find these emissions are already too low to put the EV at a disadvantage in almost any realistic scenario, even when production takes place in coal heavy China.[2,3] They also find the emissions are dropping fast.

Initially, battery CO2 emissions where high due to (among other things) small scale production. Unfortunately many studies are still based on such outdated numbers. E.g. a 2019 scientific paper written by the product strategy division of Mazda[4] still uses numbers from 2011[5], 2013[6] and 2014[7] to come up with unrealistically high CO2 emissions. But emissions have fallen sharply in recent years.

The best example of this is a study that was recently updated while EV critics keep using the outdated version. This 2017 study is often called the 'the Swedish Study' on social media, 'the IVL study' by journalists, and (Romare and Dahllöf, 2017) by scientists.[8] It concluded emissions where pretty high: "a 150-200 kg CO2-eq/kWh battery looks to correspond to the greenhouse gas burden of current battery production". Although the study was instantly criticised for using outdated factory data[9–11], most recent articles that put electric vehicles at a disadvantage use this study as their basis. Examples from Germany are from the ADAC[12], ÖAMTC[13] and Buchal, Karl and Sinn[14,15].

An illustration of how this study often gets outside influence is found in the tool from Joanneum Research (JR) that was used by the ADAC and ÖAMTC[16]. The 171 page support document lists 11 sources for battery production data. However it is not clear how most of these sources where relevant because in the text, JR only references three sources. Zooming in on these three, the first is an example of the disconnect between science and up to date market information. It is a study by Ellingsen from 2014[7] that details the energy consuming steps in battery production, based on cycle inventory from a study by Majeau-Bettez from 2011[5] which is in turn based on older sources. So while the methods used in the publications are still valuable, their results are outdated.

The second referenced of JR (and thus ADAC and ÖAMTC) is a policy brief from the ICCT[17] that JR claims puts emissions at 175 kg CO2eq/kWh. But that is not correct. In the brief the ICCT claims that "battery manufacturing life-cycle emissions debt is quickly paid off" while not naming any number and just stating "manufacturing emissions vary by a factor of 10, indicating the need for additional research in this field". They only reference 175 kg CO2eq/kWh in the legend of a graph where it says: "The carbon intensity of battery production in this figure uses the central estimate from Romare et al. (see note c, Table 1) of 175 kg CO2e/kWh". We are back to Romare 2017 again. So if you scan the document quickly it seems there are 11 source but in reality there only are 2, one of which uses information almost ten years out of date while the other is Romare 2017.

We pointed this out and where told our sources where not available when the tool was given to ADAC. But they way they are now used in the document is curious. In a remark on page 129 JR states: "For the energy use of battery production we took 163 kWh energy per kWh of battery based on Romare 2017 and Ellingsen 2014. Newest studies estimate 16 kWh/kWh in large commercial factories and this seems possible in future Giga-unit factories."[1] This is basically admitting that outdated information was used without correcting it. Very strange.

The commentary in ifo Schnelldienst by Buchal, Karl and Sinn[14] simply uses (Romare and Dahllöf, 2017) as the only source.

But (Romare and Dahllöf, 2017)[8] was updated to (Emilsson and Dahllöf, 2019)[18] and the mean estimate dropped from 175 to 87 kg CO2eq/kWh: they basically *halved* their estimate after two years. The update concludes: "Based on the new and transparent data, an estimate of 61-106kg CO2-eq/kWh battery capacity was calculated." The report explains the change in the following way: "One important reason is that this report includes battery manufacturing with close-to 100 percent fossil free electricity in the range, which is not common yet, but likely will be in the future. The decrease in the higher end of the range is mainly due to new production data for cell production, including more realistic measurements of dry-room process energies for commercial scale factories, and solvent-slurry evaporation estimates that are more in line with actual production." Put simply: as production scales up and electricity becomes low-carbon, battery emissions decrease quickly.

In our opinion the results of the EV-critical studies of ADAC, ÖAMTC and Buchal, Karl and Sinn where already untenable for many other reasons but the update of their main source makes it an open-and-shut case. Implementing this update of basically their only source on battery manufacturing emissions immediately shows that the electric vehicle emits much less CO2 than its combustion engine counterparts, even when the other errors in the studies are not corrected, and even when comparing against natural gas and taking the high carbon German energy mix.

For the analysis in this report we see the updated Romare study as just one of many datapoints. Another more recent datapoint is a study by Hao et al.[2] using recent data on manufacturing in coal heavy Chinese energy mix to conclude that producing NCM batteries emits around 104 kg CO2eq/kWh[2]. Another 2019 study by Yin et al. uses the well known GREET software and inputs recent numbers to arrive at 111 kg/kWh for NCM in China, thus corroborating Hao. Using the same methodology Yin pegs NCA (used in e.g. Tesla cars) at 82 kg/kWh in China. However, not all batteries are made in China. Yin estimates that in

[1] Page 129: "Für die Batterieproduktion wird ein durchschnittlicher Energiebedarf von 163 kWh Strom pro kWh Batteriekapazität angenommen (nach Romare 2017, Ellingsen 2014). Jüngste Studien schätzten den Energiebedarf für die Batterieproduktion im kommerziellen Großmaßstab deutlich unter 16 kWh/kWh (Dai 2017, Ahmed 2016), was mit zukünftigen Batterieproduktionssystemen im Giga-Maßstab machbar erscheint."

the US, emissions would be 43 kg/kWh for the NCA battery and 58 kg/kWh for an NMC battery. A 2019 study by Melin[19] pegs it at 73 kg CO2eq/kWh on average and lower when produced in Europe. A 2019 study by James Frith of BloombergNEF estimates 20-80 kg CO2eq/kWh with the median clearly on the lower side but excluding mining[20] . If there is a red thread it is that the more recent the source data, and the closer to actual measurements, the lower the emissions. This ties in nicely with the remark from Joanneum Research cited above.

A datapoint that we see as relevant because of the sheer volume of batteries produced there is the Tesla Gigafactory that recently came out with an impact report specifying the carbon footprint of battery production at the factory. From this report (and after asking for clarification from the authors) we find pack level emissions where 86.5 kg/kWh in 2017 and 76.7 in 2019 which (with linear extrapolation) would result in 71.8 in 2020.

Based on all these sources we estimate that for 2020, emissions of 75 kg CO2eq/kWh is probably the best mean value.

As time goes on, GHG emissions during battery manufacturing will become lower still due to: more efficient production, increased use of renewables, and application of new chemistries like Lithium Sulphur that also use cheaper and more abundant materials.

Battery and vehicle lifetime in km

In many studies the battery is assumed to last only 150 000 km which increases electric vehicle emissions. However, we have not seen examples where this was based on actual research. Empirical data shows modern batteries will easily outlast the car. Furthermore, car lifetimes are increasing in Europe and a modern car can be assumed to last 250 000 km.

Battery degradation

Many people have experienced that lithium batteries in cell phones seldom last more than five years. Cell phone manufacturers consider this long overdue for a replacement anyway. For electric vehicles it is different. But how different?

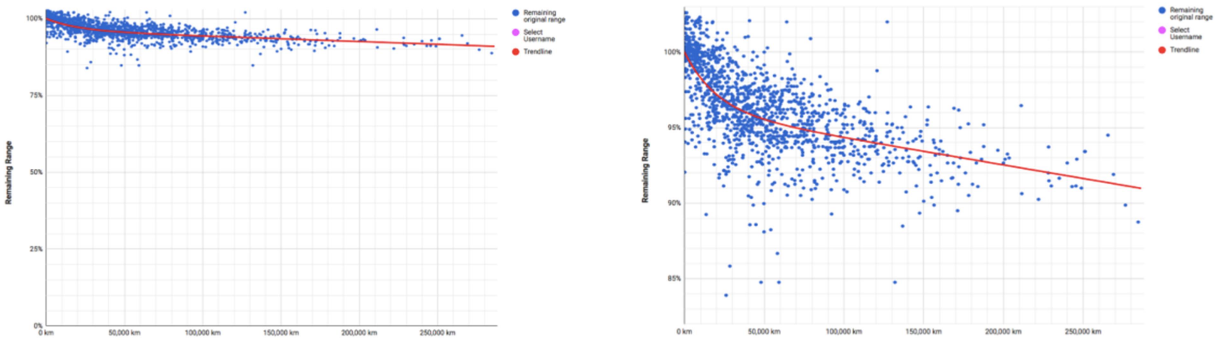
In the scientific literature, very little attention is given to the issue of battery lifetime. E.g. a 2016 study by Ellingsen et all[21] simply states:

"Lifetime is a parameter that entails uncertainty in impact assessment of vehicles regardless of powertrain configuration. Industry reports most commonly apply an EV use phase of 150 000 km (Volkswagen AG 2012, Daimler AG2012, Volkswagen AG 2013, Volkswagen AG 2014, Daimler AG 2014, Nissan Motor Co. LTD 2014). The manufacturers are likely to be somewhat conservative regarding the lifetime. We assumed a lifetime of 12 years and a yearly mileage of 15 000 km, resulting in a total mileage of 180 000 km."

Another study recently done by Mazda[4] claimed: "CO2 emissions for replacing the battery with a new one should be added when the lifetime driving distance is over 160 000 km." This choice was defended by referring to a large number of underlying sources. However, studying these sources (with estimates ranging from 100 000 to 320 000 km) reveals they don't talk about battery lifetime but car lifetime and all estimates are undefended arbitrary sources. It would have been better to simply say "we have not found sources to base an estimate of battery lifetime on but will use a number of 160 000 km."

Diving into the ample empirical data reveals that early electric vehicles sometimes had insufficient cooling which led to faster degradation (especially in warmer climates), and sub-optimal battery management (charging the battery from very low to almost 100%). But it also shows that modern car batteries usually outlast the car. Geotab just published an analysis of 6300 electric vehicles they have access to (including tool) [22] and conclude the average degradation over the first few years is 2.3% per year, almost independent of mileage. However, they say, "as a general rule, EV batteries are expected to decline non-linearly: an initial drop, which then continues to decline but at a far more moderate pace. Towards the end of its life a battery will see a final significant drop." In their fleet they haven't seen really seen cars reach this significant drop yet and they conclude "the vast majority of batteries will outlast the usable life of the vehicle".

This finding is corroborated and refined by hundreds of Tesla drivers that have recorded their private data (see figure).[23] On average they show a capacity loss of 2.5% over the first 25 000 km, an additional loss of 2.5% over the next 75 000 km and a loss of 1% for every additional 50 000 km. If we arbitrarily say the battery is end of life in a car when it has reached 80% of capacity (a questionable but customary threshold), end of life would be reached at 800 000 km.



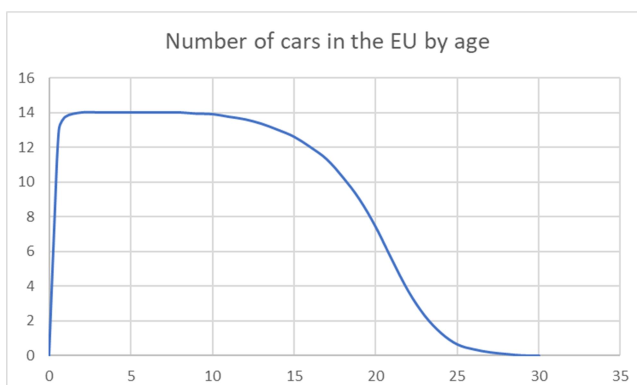
And indeed there are a few Tesla drivers who have now driven a million km. A well known driver in Germany had some problems at the start but has now driven 680 000 km with the latest motor and 480 000 km with the latest battery that still has 86% capacity.[24]

This is corroborated with many findings in the recent scientific literature. In a paper from 2019 on the extensive testing of NMC cells, Harlow et al state:" We conclude that cells of this type should be able to power an electric vehicle for over 1.6 million kilometres (1 million miles) and last at least two decades in grid energy storage."[25] Their results where achieved in the laboratory, but still: this is not science fiction.

All in all, the frequent assumption that the battery has to replaced after 150 000 km (e.g. in recent studies from the ADAC[12], ÖAMTC[13]) is not correct and has no basis in science. It's just an assumption that so far has not been challenged.

Car lifetime

A question that is harder to assess is how long electric vehicles will drive before they are scrapped. We should start by assessing how long conventional cars are driven. Since we could not find reliable calculations in the literature we constructed a calculation using data from the Eurostat database, ACEA reports and the Bundesambt in Germany.[26–28] First we looked at the age of on road vehicles. From the ACEA report we know vehicles are on average 10.8 years old. From the Eurostat database we know the number of vehicles in the brackets 0-2, 2-5, 5-10, 10-20 and older than 20 years. Based on this we fitted a curve that satisfies all criteria (see figure).



The next question is how far vehicles drive each year. The average distance travelled differs per country as can be seen in the following table (sources[26–28]):

	Austria	Belgium	Croatia	Denmark	Finland	France	Germany	Latvia	Netherlands	Slovenia	Sweden
Number of vehicles (thousands)	4,898	5,785	1,596	2,530	3,398	32,005	45,956	689	8,373	1,117	4,844
Average km/year	13,900	14,770	12,688	15,882	15,101	11,900	13,727	14,157	13,024	12,653	12,000
Petrol		9,861		13,365	11,205	8,290	12,900	10,107	10,529	10,235	8,970
Diesel		18,480		22,002	20,327	14,540	20,169	16,240	23,240	16,879	16,930

If we take the weighted average of all 111 million vehicles in this sample the distance travelled per passenger car per year in Europe is 13 202 km. Using the age distribution we just found and multiplying it by the yearly mileage tells us that the average car currently drives around 255 000 km before it is scrapped. We will round this down to 250 000 km and use it at the basis for further calculations.

We realise that this number of 250 000 is higher than in most other sources but it has the advantage of being supported by tractable data. Furthermore we think it will turn out to be conservative because it still doesn't take the differences between drivetrains into account. We already know (and the table above gives an example of this) that diesel vehicles drive more kilometres than gasoline vehicles. That's also why Buchal, Karl and Sinn[14] assumed 300 000 km as the lifetime of the diesel vehicle they compared to the electric vehicle. The first reason for diesel driving more km this is that diesel is cheaper per kilometre and the second is that the motor lasts longer. This offsets the higher sticker price and is especially interesting for people that drive a lot. Both arguments apply even more strongly to electric vehicles where cost per kilometre are even lower and the motor (and as we've seen, the battery) last even longer. If we would take the mileage of diesel cars as a benchmark, the mileage of electric vehicles would be much higher still.

Some people told us this is not what they see around them: cars seem younger than implied by our numbers. This is correct but does not contradict our findings. The reason is that cars are driven more in the first years of their life as we will detail (and graphically show) in a few pages from now. The impact of this can be explained with an example. Let's assume cars are driven 25 000 km a year in the first five years, 15 000 in the next five, 7 000 in the next five and 3 000 in the final five. That would make the mileage 250 000 km, the total age of cars 20 years and the average age 10 years. However, if you made a snapshot every time you saw a car and checked its age, the average age you found would be 6 years. That's because the younger cars are driven more and thus you see them more. Furthermore, the average age in some countries is lower than in others: affluent countries like Germany scrap or export cars much sooner than for example Poland.

All in all 250 000 km is a conservative estimate for the mileage of cars before they are scrapped in 2019 in Europe and we think it's currently the best supported number in the literature.

Recycling the battery

Recycling can reduce GHG emissions but this is not a given. Second life will lower GHG emissions but by how much is hard to quantify. In this study we take a conservative approach and ignore both.

Another point of contention is how to count second life and recycling. We start with recycling. Put very simply: if you have to melt the battery to get to the contents you save on material but you don't save on energy. So CO2 emissions might even go up if you recycle on energy that is high carbon. However, if the materials can be reused without having to melt the entire battery, large energy savings are possible.

Melin gives a good overview[19]. An example that saves energy is direct cathode recycling.[29,30]. Examples that don't are pyrometallurgical and hydrometallurgical recycling processes that often need more energy than mining.[30,31] Since most recycling will occur further in the future when the electricity grid is less carbon intensive their might still be a significant saving in GHG emissions either way buy to stay on the conservative side we have not included CO2 savings for recycling in our comparison.

Second life use is still uncertain but could be a good way to stabilize electricity grids using a large percentage of solar and wind. We already sited another study envisioning future batteries being used as grid storage for 20 years after being used as car battery[25] but it is hard to put a number on that. Second use would obviously have the potential to lower GHG emissions but since there are many ways to quantify this, putting a reliable defensible number on this so far proves elusive and mostly leads to subjective discussions that could be used to invalidate the already robust result that an electric vehicle emits much less CO2 over its lifetime. Therefore we will not quantify this advantage in this report.

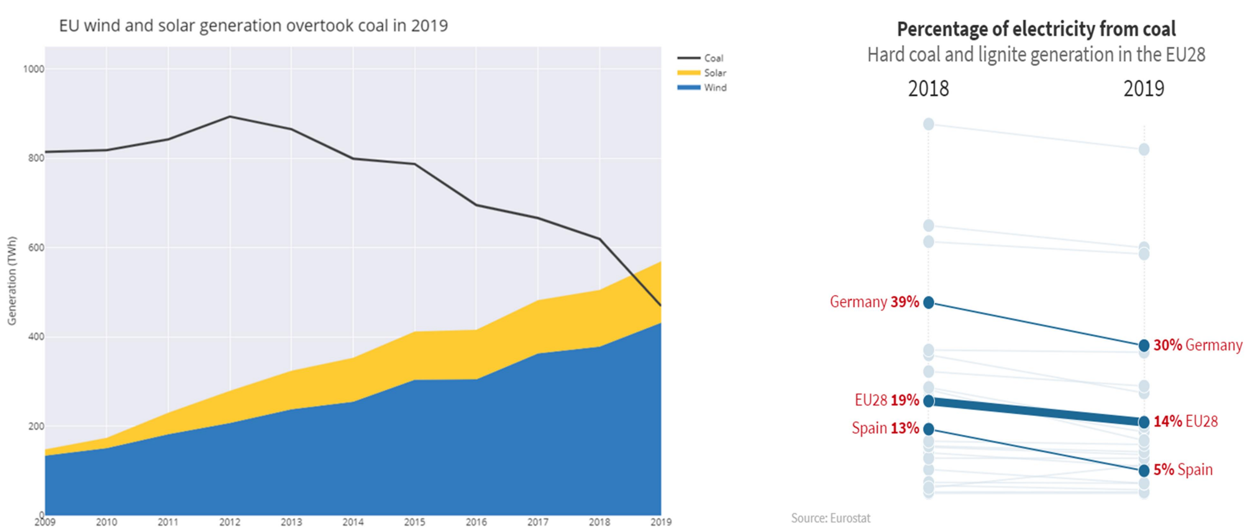
Electricity mix over the lifetime of the car

Electric vehicles sold in Europe in 2020 should count on 250 g CO2eq/kWh electricity over their lifetime. Many studies assume the electric vehicle will drive on the electricity mix it used in its first year. This is incorrect because cars stay on the road for approximately 20 years and the electricity mix is expected to change drastically over that period. Therefore we use the electricity mix over the years the vehicle is expected to be driven, weighted by the km driven per year. To this we add upstream emissions, trading and losses.

This is a complex topic that is seldom done right in the literature and therefore we go into some detail. First we determine the electricity mix over the lifetime of the EV. Then we determine the number of kilometres per year the EV drives. Finally we add GHG emissions due to upstream emissions, trading and grid losses.

The European electricity mix changes over the lifetime of the electric vehicle from 260 g CO2eq/kWh in 2019 to 117 g CO2eq/year in 2040.

Electricity generation is not a static quantity. Of all human sources of GHG emissions, electricity generation has seen the fastest decline in emissions per unit of energy and this trend is expected to continue.[32,33] Emissions of the power sector in Europe declined 32% since 2012 and 12% in 2019 alone which brings emissions for generation to 267 g CO2eq/kWh in 2019.[33] We combined numbers from the European Environmental Agency[34] and Agora Energiewende/Sandbag[33,35] to create a time series starting in 1990 and ending in 2019 and fitted a linear trendline (R^2 0.964) that shows emissions have fallen by a relatively constant 7.2 g CO2eq/kWh per year over this 29 year period. There are indication that policy based on the Paris agreement, combined with an accelerating decline in coal and adoption in solar and wind might accelerate this trend. However, in order to stay conservative we have assumed that the linear trend will continue.



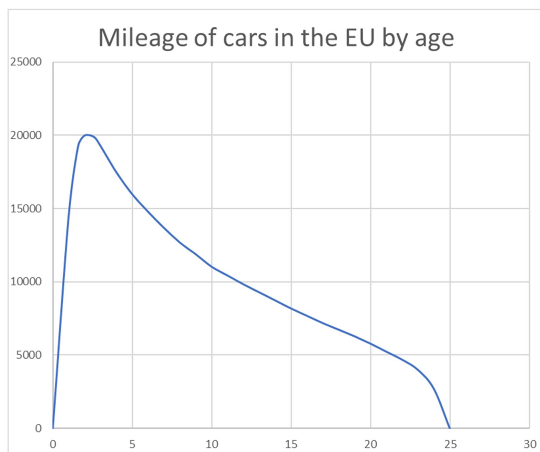
Agora Energiewende & Sandbag analysis of the European power sector in 2019[33]

This means that an electric vehicle bought in 2020 will start driving on an electricity supply that emits about 260 g CO2eq/year, but 20 years later it will drive on an electricity supply emitting just 117 g CO2eq/kWh. That is a *significant* reduction over the lifetime of the vehicle that should not be ignored (as most studies do unfortunately).

The amount of kilometers driven per year is higher when a car is still young and gradually reduces as it gets older. Therefore, most electricity is consumed when the car is young and the electricity mix is still mostly fossil fuel generated.

We can not simply take the average of the electricity mix over the lifetime of the car because cars drive more when they are younger. So in the same way that we constructed a curve of the age of cars we will construct a curve for the number of kilometers driven each year. We will also use the Eurostat database again[26] and the same age brackets. We mainly use information from 2015 because this is the most recent complete dataset and we only have this specific information from Belgium, Germany, Ireland, Croatia, Malta, the Netherlands, Slovenia, Sweden and Norway, but that still gives us more than 71 million cars to work with. The summed result is the following table. As you can see here (and as we mentioned earlier) cars don't get old in Germany. Our guess is that they are often exported.

Age (years)	<2	2-4	5-9	10-19
Belgium	12,873	20,116	16,085	12,789
Germany	19,009	16,017	15,078	2,101
Ireland	26,287	21,143	17,263	19,510
Croatia	17,869	16,647	13,652	6,651
Malta	7,143	15,208	9,167	8,125
Netherlands	11,031	19,389	14,704	5,891
Slovenia	16,160	29,737	12,953	8,005
Sweden	8,619	19,636	15,622	14,045
Norway	11,998	16,167	14,732	10,829
EU total	14,554	19,340	14,362	9,772

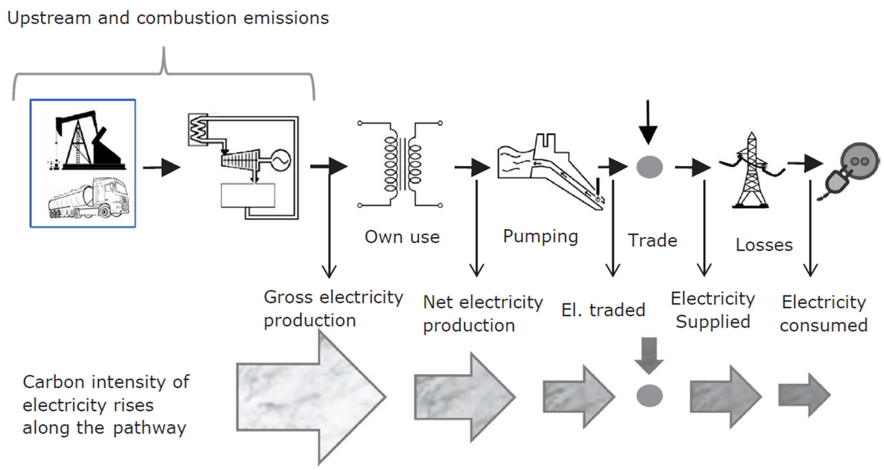


We fitted an average mileage per year for Europe that closely matched both these results and our previously explained assumption of 250 000 km per car on average. The results are shown graphically.

The weighted average of the European electricity supply over the lifetime of an EV sold in 2020 is approximately 192 g CO2eq/kWh. Adding upstream emissions, trading and grid losses brings the total carbon intensity of electricity used by electric vehicles to approximately 250 g CO2eq/kWh.

Using both the yearly mileage and the yearly electricity mix we can determine the weighted average GHG emissions of the electricity mix over the lifetime of the vehicle. The result is that EVs sold in Europe in 2020 should assume electricity production of 192 g CO2eq/kWh.

The final step we have to take is account for upstream emissions, trading and grid losses. Especially upstream emissions and trading are often forgotten but since they lead to GHG emissions they should be included. There are many possible approaches[36] but the essence of all approaches is shown in the following figure and table taken from Moro et. al.[37]



Generation	Add upstream	Add self use	Add pumping	Add trade	Add HV losses	Add MV losses	Add LV losses	**Total increase**
100%	14%	5%	1%	1%	3%	1%	3%	**31%**

Using calculations based on the 2013 energy mix for the EU electricity grid, all these factors add up to 31% of GHG emissions on top of primary production. Moro et. al is the most thorough source we could find but also produces the highest emissions. So once again we are being conservative.

Adding this 31% to the 192 g CO2eq/kWh we had already established for generation over the lifetime of the electric vehicle, brings the total to 251 which we will round off to 250 g CO2eq/kWh.

We have not used 'marginal electricity' because it is too subjective.

Some people argue that electric vehicles should use the marginal electricity mix. Simply put: try to nail down the specific energy source that was used to charge the electric vehicle. We think that is not doable yet. To do this you have to know when and where the electric vehicle charges and under what contract the electricity is produced. You also have to determine an order in which both the supply and demand of electricity get counted. And you get into almost philosophical discussions in terms of cause and effect.

Let us give an example: somebody builds an new house with (among other things) solar panels, a heat pump and a charge point for an electric vehicle that employs smart charging. This person also has a contract with a wind farm located a 1000 km away to supply extra electricity.

How do we count the electricity of the electric vehicle?

1. We could say that electric vehicles will charge when it's cheapest. We expect this development to happen because it would save the EU tens of billions annually at very little cost. Our simulations show this would largely avoid fossil fuelled supply. But it is only implemented on a small scale so far. So in what year do we assume this to be adopted by this car?

2. We could say that it all comes from wind and solar because that's where her contract points to. More generally: we know that public charge points have renewable energy contracts in most countries and that most buyers of electric vehicles also have contracts for green electricity. But counting that would make the CO2 output of the EV plummet.
3. We could try to include grid losses based on the actual contract and thus give a bonus for the energy from the local solar panel and a malus because of the wind farm far away. But we would argue that electrons don't care about contracts.
4. We could say that contracts don't matter but her own solar panels do and we could try to figure out what part of the energy goes to the electric car. On a personal level that is what we optimise for at our own home but scaling it up to Europa introduces large uncertainties.
5. We could say that the electric vehicle and the heat pump are designated 'new demand' and therefore they get counted after all the other electricity is counted. But do you count the heat pumps first or the electric vehicles? And why not count the whole new house (or a whole new factory) as new demand instead of just the electric vehicle? If you really try to program it in a model you find out there is a lot of arbitrary decisions involved.
6. We could say that new demand is fulfilled by new energy supply since they would not be there without the new supply. That would once again make the CO2 emissions of EVs plummet.
7. We could say that new demand only slows down the phasing out of current (fossil) energy sources and therefore electric vehicles mainly drive on fossil fuel. That would make the emissions of EVs go up.
8. We could look at the so called merit order and look what is the energy source with the highest marginal cost (often coal) that would be turned of if electric vehicles where turned off. However, why would we do this for electric vehicles and not for the heat pump or television or air conditioning or new factory?

Electric vehicles do not drive on 100% coal

Recently a study by Stahl Automotive Consulting appeared[38] that went all-in on the aforementioned approach and proclaimed electric vehicles drive on coal *entirely.* Building on the example above we want to reiterate why the knowledge institutions we know don't consider this the right approach:

- It's *arbitrary* to say electric vehicles are the last electricity added to the total demand. Why not heat pumps? Why not industries that electrify? Why not computers or data centers? It is a bit simplistic to take a certain demand you don't like and assume this uses 100% coal. If everybody writing a negative report on some form of energy use would to that it would quickly exceed the amount of electricity of coal fired power plants available.
- It ignores *contracts* with electricity providers and individual investments. EV owners and charge point operators often buy green electricity and combine buying an EV with buying solar panels. It is debatable how this should be incorporated but assuming the electric vehicles drive completely on coal is the other extreme.
- *The share of coal is quickly declining*. A complete phase out of coal might take ten or twenty years and as long as plants are not closed the installed capacity only reduces slowly, but the amount of electricity produced by coal is quickly decreasing. (Also see picture above.) So the

assumption that electric vehicles drive on coal only works if one ignores the development of the mix over the lifetime of the vehicle.

- *The moment of charging* should not be forgotten if one wants to adopt an approach where electric vehicles is somehow the last load to be added to the mix. Increasingly there will be moments during the day when coal is completely or almost turned off.
- *Smart Charging* is an approach where the electric vehicle charges when energy is cheapest and this coincides with the moment energy comes from wind or solar. This is increasingly seen as a low cost easy to implement solution (standards like OCPP and IEC15118 already support it) that would actually make the electric vehicle much *better* than the average mix.

What is even more remarkable in the study by Stahl Automotive Consulting is that they propose a cleaner alternative in the form of combustion engines using eFuels. According to the source they directed us to these eFuels could cost around 15 cents per kWh in 2030[39] which is much more expensive than renewable energy (partly because about 75% of the energy is lost in the conversion from electricity to eFuel) and further losses would occur in the combustion engine (since it loses around 75% of it's energy as heat). All in all this option would require almost ten times more renewable energy, how can this have lower carbon emissions? As is usual in many studies that compare electric vehicles to alternatives (e.g. also this study by Fraunhofer on hydrogen cars[40]) this is achieved by giving electric vehicles a completely different electricity mix. While the electric vehicle drives on 100% coal, the eFuel is produced using the cleanest renewable energy possible. We think that it is more appropriate to use the same energy mix as input when comparing electric vehicles to alternatives like hydrogen eFuel.

Energy use per kilometre of driving

We use EPA measurements because they are independent and have a good track record.

This issue is frequently a problem in the literature. Many sources (e.g. Buchal, Karl and Sinn[14]) use measurement done according to the New European Driving Cycle or NEDC. This is problematic because - even apart from the use of defeat devices[41] - we know the NEDC is about 40% too low[42,43]. For an average electric vehicle the impact is limited to an advantage of 5 g CO2eq/km but for combustion engines the advantage will usually be 50-100 g CO2eq/km. This should not surprise is since this test was optimised by car manufacturers over decades in order to make their official CO2 emissions as low as possible.

The new WLTP cycle should deviate less from reality but the underlying problem has not been addressed. This underlying problem is that in Europe car manufacturers initiate the test with vehicles, conditions, locations and institutions of their choosing and since they pay for the test they can demand that everything that is not expressly forbidden by law is done to skew the results.

This problem does not exist in the United States that made the decision decades ago to task an independent organisation - with independent finances - to conduct these tests: the Environmental Protection Agency or EPA for short. And, as is to be expected, their tests conform closely to reality. Another benefit of EPA numbers is that they measure the energy use of electric vehicles at the plug and thus they include charging losses. Finally, they conveniently display the measurements of all cars they have tested on the website fueleconomy.gov. For these reasons we use EPA numbers for the emissions of different cars. If measurements are not available from the EPA (which happens for some diesel cars not sold in the US) we recommend finding another independent source, preferably doing tests of many vehicles. A good option is spritmonitor.de where there are often thousands of measurements for popular diesel cars and one could argue that it is hard to come closer to real world use. However there is an overrepresentation of German drivers which means that the German Autobahn (with its unlimited maximum speed) could drive up the energy use slightly.

Finally it is evidently important to use comparable sources for energy use of fossil fuel vehicles and electric vehicles. E.g. Stahl Automotive Consultancy[38] averages the highest and lowest measurement from one ADAC test into electric vehicles but we think a weighted average of EPA values would have been easier to defend.

Calculating the GHG emissions of conventional vehicles

The basic formula's are similar to the ones used to calculate EV emissions except for the exclusion of the battery and the replacement of electricity by fossil fuel:

$$emissions\ per\ km = \frac{manufacturing\ emissions + driving\ emissions}{km\ driven}$$

$$manufacturing\ emissions = sum\ of\ (drivetrain + rest\ of\ car)$$

$$driving\ emissions = car\ energy\ use\ in \frac{liter}{100\ km} * emissions\ per\ liter$$

Once the factors in these formula's are determined correctly we can compare against electric vehicle emissions without discussion or subjectivity.

We already discussed all these variables in the previous chapter except for emissions per liter of gasoline and diesel so we will explain that here.

Fossil fuel production

New research into flaring and other sources of GHG emissions has shown that the emissions related to the production of gasoline and diesel are slightly larger than previously thought. In order to account for the production of fuel, cars driving on gasoline should add 30% to their tailpipe emissions. Cars driving on diesel should add 24%. Emissions per litre are 3310 g for diesel and 3140 g for gasoline.

From a recent authoritative study in Science that include aspects like flaring and covers 98% of oil fields, we know that getting a barrel of oil to the refinery emits more GHG than previously thought: the global average weighted value is around 10.3 gram CO2eq/MJ.[44]

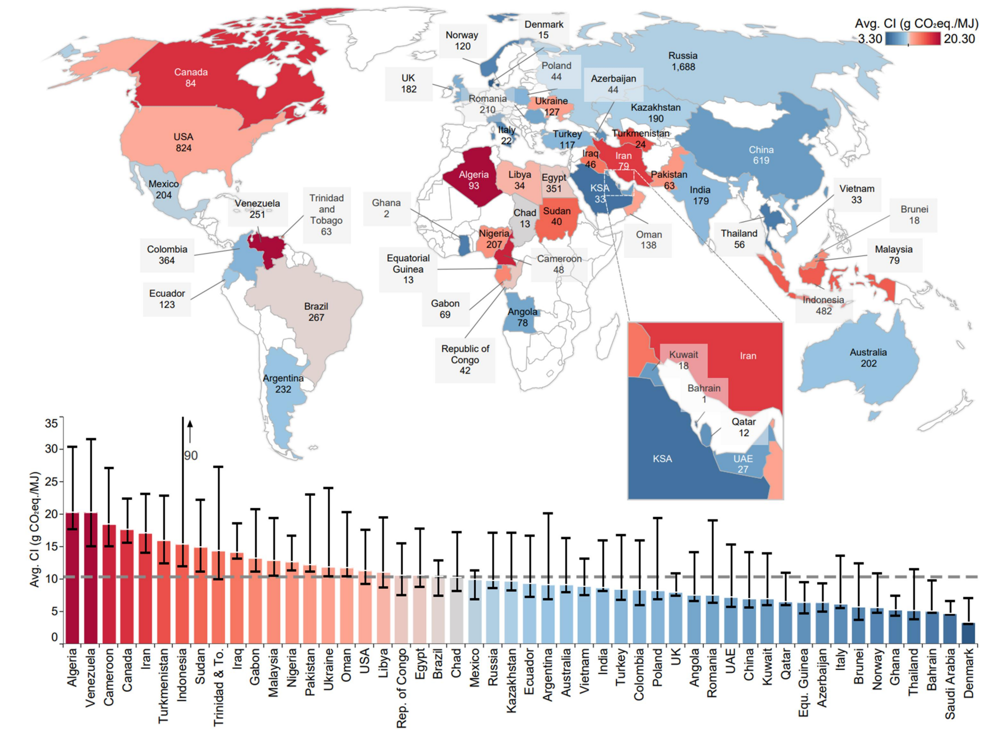


Fig. S22. Estimated global crude oil upstream carbon intensity (2015): national volume-weighted-average upstream GHG intensities in g CO_2eq./MJ crude oil delivered to refinery (color) with corresponding error bars (5-95%ile of Monte Carlo simulation to explore the uncertainty associated with missing input data, see SM section 1.7 and 2.4). Map shows number of fields analyzed below each country name. The global volume-weighted CI estimate is shown by the dashed line (~10.3 g CO_2eq./MJ). Reference year is 2015. Only countries with ≥0.1% of global oil production share are mapped (see the SM Results Data Excel file for full list). Color scheme reflects national volume-weighted-average CI: dark blue for lowest CI, dark red for highest CI.

The next step is refining oil. A recent study for the EU looked at this topic in depth and estimated that refineries add 10.2 gram CO2eq/MJ for gasoline and 5.4 for diesel.[45] However, refineries outside of Europe and North America have higher emissions[46] and account for around half of world production[47] so this is probably a conservative estimate when estimating global numbers.

For Europe, fuel distribution adds just over 1 gr CO2eq/MJ.[48]

This brings the total for fuel production to 21.5 gr CO2eq/MJ for gasoline and 16.7 for diesel. We must multiply this by 33.5 MJ for a litre of gasoline and 38.3 MJ for a litre of diesel.[49] This means that in addition to the tailpipe emissions, a car running on gasoline emits 720 gr CO2eq per litre and a car running on diesel emits 640 gr CO2eq per litre. So this comes on top of the 2420 gr/l for pure gasoline and 2670 gr/l for pure diesel.[50] That brings the total to 3140 g/l for gasoline and 3310 g/l for diesel.

We are sidestepping the discussion on the CO2 emissions related to biofuels by taking pure fossil fuels and not the mix you might find on the market. Biofuels can be produced with low CO2 emissions (e.g. from waste, algae, double cropping and unused fallow land) but even then CO2 emissions are not zero and that is how they are counted now. Furthermore, a large part of the biofuel that is currently used actually has a larger CO2 footprint than gasoline and diesel if you include indirect land use change in your calculations (palm oil is a notorious example) and although some of these are phased out they are still counted as zero emission in official European publications. By taking pure gasoline and diesel we avoid that these issues get tangled into the discussion of electric vehicles versus combustion engine vehicles.

Future developments will reduce EV emissions further

Where the improvement potential of mature combustion engine technology in terms of green house gas emissions is very limited, the improvements possible with electric vehicles are considerable.

Imagine a future where renewable electricity is ubiquitous. Currently solar panels and windmills already decrease emission by 90%[51] even though they are predominantly manufactured using fossil fuels. If mines and factories would use renewable energy to manufacture windmills and solar panels, the emissions of renewable energy would eventually become almost zero. Now imagine mining operations and steel manufacturing factories using this almost no-carbon energy to produce cars and batteries. The end result would be electric cars that are produced and driving without causing any significant CO2 emissions. Resource use would still be a problem (especially if the number of cars would continue to grow and recycling would be lacking) but CO2 emissions would not.

This is just speculation and a feasibility study of this perspective out of scope for this report but to show the change could be faster than most experts expect we will leave you with a historical perspective.

Horse drawn carriages and the unsolvable manure problem

By the end of the 19th century, large cities where "drowning in horse manure"[52] due to horse drawn cabs, carts, busses and drays. Each horse produced about 15 kilo's of manure *per day* and in 1894, The Times predicted that "In 50 years, every street in London will be buried under 9 feet (2,75 meter) of manure".[53] Later this became known as the "Great Horse Manure Crisis of 1894".[52] Apart from the filth and stench this caused, it also attracted flies that spread typhoid fever and other diseases. In 1898, the world's first international planning conference convened in New York. It was abandoned after 3 out of the planned 10 days because none of the delegates could see a solution to the growing manure crisis.[54]

Combustion engines replace horses and solve the manure problem

The manure crisis was solved by the ascendance of cars with internal combustion engines. Germany played an instrumental role in the development of the internal combustion engine with inventors like Nikolaus Otto, Karl Benz, Rudolf Diesel, Felix Wankel and Ferdinand Porsche and with businessmen like Gottlieb Daimler and Wilhelm Maybach. The pictures illustrate how quick and total the transition from horses to cars came about.

Fifth Avenue New York on April 15 1900 (one car) and March 23 1913 (one horse).[55]

Combustion engines and the unsolvable CO2 problem

With enough effort, internal combustion engines might become ever more silent, although it is currently hard to imagine cities without the low hum of trucks and the high whine of pizza delivery scooters. The success with the EU VI standard for trucks shows great strides are possible in the reduction of particulate matter exhaust from the tailpipe but the dieselgate scandal shows it is neither simple nor cheap.

The efficiency of a hybrid vehicle could *theoretically* become almost 50% higher than in todays cars, but that would require a range of breakthroughs that are currently not on the horizon. Furthermore, the consumer interest in large SUVs with powerful motors outstrips the modest advances in efficiency, and if we take road testing as our benchmark there has been basically no improvement of CO2 emissions per kilometre in the last 20 years.[56–58]

Carbon dioxide emissions are a fundamental trait of internal combustion engines that will never go away. Just as horses produce manure, internal combustion engines produce CO2. It is inherent in the long process of forming fossil fuels that was started by plants that used solar power to bind CO2 and store it as plant matter. To get the solar energy out of fossil fuels you have to bind it to oxygen (O2) and release carbon dioxide (CO2).

Electric motors replace combustion engines and solve the CO2 problem

However, just as the 'unsolvable' problem of manure from road transport was solved with the introduction of the internal combustion engine, the 'unsolvable' problem of CO2 emissions from road transport can be solved with the introduction of the electric vehicle.

This does not mean that electric cars should replace bicycles and public transport. Cars have other drawbacks like their incompatibility with dense and safe cities, their resource requirements, and the impact on the ecology that is linked to resource use. But they could certainly replace conventional cars and largely eliminate GHG emissions from cars in the process.

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