Why I came to the conclusion we will drive electric cars in the future

September 3, 2018

Until recently I was convinced the Diesel engine will stay longer than most people predict because the tank to wheel efficiency is fairly good. This changed since I started doing some calculations. This article will be hard to read. Get some paper, a pen and a calculator and please check thoroughly if I'm right (I may have made a calculation error!). But I think it is worth it!

I compiled the information presented here to the best of my knowledge. I hope it will help others to do reasonable decisions.

Ricardo Erckert

1 The options we have

Individual cars are something people will not like to give up. There are concepts of car sharing but it will not make much of a difference if you own a car or if you just use a shared or rental car. The number of kilometers remains, the size of the vehicle more or less remains and thus the fuel consumption remains in the same magnitude as today.

So let's have a look at the options we have to power the car.

1.1 Diesel engine

Amoung the combustion engines the diesel engine is the one with the highest efficiency. Since the diesel scandal however this kind of engine is regarded as a severe source of pollution.

Cleaning the diesel engine is possible, but it makes the exhaust system expensive, complex and more unreliable (clogged particle filters etc.) and consumes more fuel.

Typical diesel cars consume about 6 liters per 100km. The energy contents of 6l diesel is 214.8MJ (source: https://en.wikipedia.org/wiki/Energy_density) or 59.67kWh. Driving 100km with an electric car requires about 15..20kWh. (Electric motors have an efficiency of about 95%).

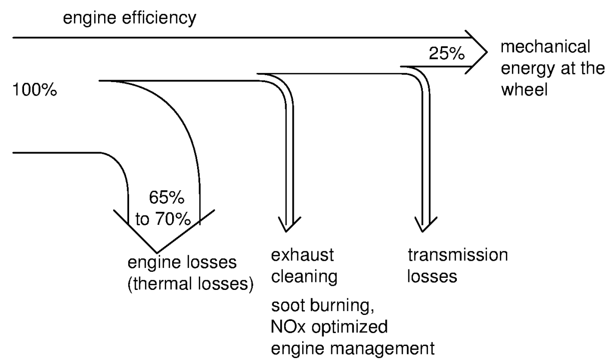

Fig.1 Losses of a typical combustion engine

So the approximate efficiency of a diesel engine is:

$$\eta_{tw_{diesel}} = 15kWh/60kWh = 25\%$$

Theoretically this can even be improved increasing the peak temperature of the Carnot-process. But higher temperatures during combustion increase NOx emissions even more. This leads to increasing requirements cleaning the exhaust gas (burning the NOx, ashing the soot etc.). The cleaning steps in the exhaust path require additional fuel and the efficiency gain is getting lost again.

1.2 Gasoline engine

The gasoline engine is regarded as a cleaner engine than the diesel. Typical gasoline engines consume about 8 lters per 100km. The energy contents of 8l of gasoline is 273.6MJ or 76kWh. The efficiency (tank to wheel) of a gasoline car thus is about:

$$\eta_{tw_{gasoline}} = 15kWh/76kWh = 19.7\%$$

In other words: switching to gasoline produces more CO2 per km than diesel.

The industry is trying to improve the efficiency of gasoline engines adding technologies such as direct injection. But this leads to a soot problem similar to the diesel engine. (source: ADAC Motorwelt 9/2018).

1.3 Electric driving with Li-ion battery

The concept of driving with an electric engine offers low pollution (at the car) and a high tank to wheel efficiency in the range of 80% to 90% (most losses are due to heating of the battery).

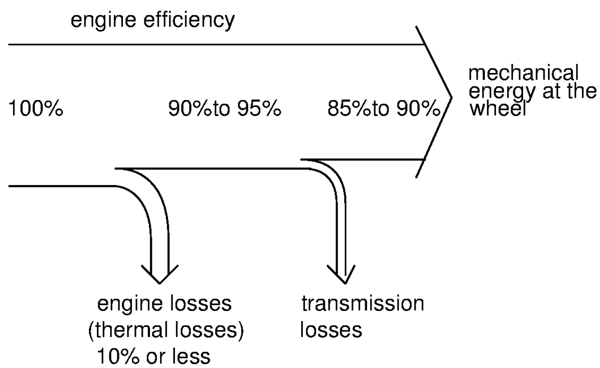

Fig.2: Tank to wheel losses of an electric car

One of the concerns however is the production of the electricity. If the electricity is produced in a classical thermal (coal or fuel) power plant the pollution problem is simply shifted from the car to the power plant.

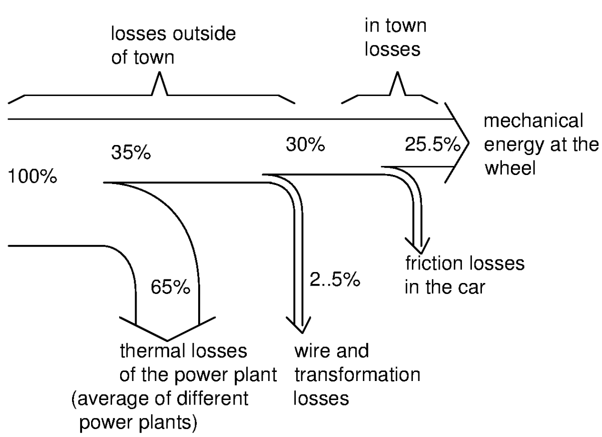

Fig.3: wheel to wheel losses of electrical driving

Furthermore the efficiency of the power plant and the losses of energy transport have to be taken into consideration. Including the power plant the wheel to wheel efficiency drops down to about

$$\eta_{ww_{Liion}} = \eta_{tw_{Liion}} * \eta_{powerplant} \approx 0.85 * 0.3 = 25.5\%$$

So electric driving with classical thermal power plants only improve the situation by taking the pollution out of town.

Things become more reasonable as soon as we produce the required electricity from renewable sources (for instance wind, solar cells, water). These sources have losses too, but as long as the energy production doesn't produce CO_2 the losses are at least climate neutral.

1.3.1 Electrical energy required

To check if electric driving can be supplied from renewable sources let's have a look at the energy required for driving in Germany. The total number of km of light vehicles in Germany in 2017 was $630.5*10^9$km. (source: https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/verkehr_in_kilometern_node.html). Assuming 20kWh per 100 km the required energy was $1.261*10^{11}$kWh. For comparison the elelctricity produced from renewable sources in germany in 2017 was 218TWh (electricity only, source https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#statusquo) or $2.18*10^{11}$kWh. This means, we can theoretically supply 100% private electric cars from renewable souces if we approximately double the number of wind power plants. (We do not want to take renewable energy away from other consumers).

The average growth rate of wind energy in the recent years was about 6-7% per year. If this speed is kept Germany could supply 100% it's light vehicles with electricity in approximately 14 years.

This however requires an enforced grit to transport the energy from the north (where the wind energy is available) to the south. This should be achievable within 14 years as well.

1.3.2 Production of Li Ion batteries

Production of batteries isn't for free. The numbers available have a very wide spread ranging from $70kgCO_{2-eq}/kWh$ (CO2 equivalent per kWh) to about $370kgCO_{2-eq}/kWh$. Most likely values are $70kgCO_{2-eq}/kWh$ to $110kgCO_{2-eq}/kWh$. (source: Mia Romare, Lisbeth Dahllöf, "The Life Cycle Energy Consumption and Greenhouse Emissions from Lithium-Ion Batteries", IVL Swedish Environmental Research Institute, Report C 243, 2017).

For some calculations lets use the middle of the "most likely" numbers: $90kgCO_{2-eq}/kWh$. As an acceptable reach of the car let's assume between 300km and 400km. This leads to a battery of 60kWh. The Carbon dioxide equivalent of our example battery of 60kWh becomes:

$$CO_{2-60kWh} = 60kWh * 90kgCO_{2-eq}/kWh = 5400kg$$

Comparison with diesel: The carbon dioxid produced from burning diesel can roughly be estimated looking at the weight of the carbon, the hydrogen and the oxigen involved in the chemical process of burning the diesel:

Rough estimation of the weight ratio:

Diesel approximately consists of 1 atom of carbon (atom weight 12) per two atoms of hydrogen (atom weight 1) leading to a total weight of 14.

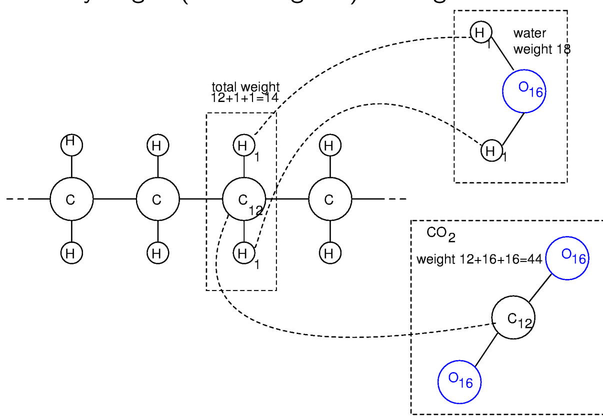

Fig.4: oxidization of a poly carbonate string

Carbon dioxide consists of 1 atom of carbon and 2 atoms of oxide (atom weight 16). The weight ratio of diesel and carbon dioxide thus becomes:

$$weightratio_{CO_2C} = \frac{12 + 2 * 16}{12 + 2} = 3.1429$$

This means burning 1kg of diesel produces 3.1429kg of carbon dioxide.

With this number a diesel equivalent of the battery production can be calculated

$$Eq_{diesel-60kWh} = 5400kg/3.1429 = 1718.2kg$$

So producing a 60kWh Li-Ion battery corresponds burning 1718.2kg of diesel. The specific weight of diesel is typically 0.832kg/lieter. The 1718.2kg of diesel thus transform into:

$$Eq_{diesel-60kWh-liter} = \frac{1718.2kg}{0.832kg/l} = 2065.1l$$

With this amount of fuel a typical diesel car can travel 34418km (calculated with 6l/100km). To create a positve benefit from driving an electric car (regarding CO_2emission) the battery must last longer than those 34000km. (This calculation only applies to the case of producing the electricity from renewable sources).

Life time of a Li-Ion battery: The life time of a Li-Ion battery strongly depends on the charging process and cathode material. High performance Li-Ion batteries for cars typically use $LiNiMnCoO_2$cathodes. These have a cycle life of 1000 to 2000 charges (source: https://batteryuniversity.com/learn/article/types_of_lithium_ion). So our example battery under ideal conditions is good for a total reach of:

$$reach_{totalideal} = N_{charge} * reach = 400000km..800000km$$

Note: This number only applies as long as the battery isn't going through fast charging! Temperatures below 5°C or above 45°C reduce life time significantly.

Since automotive envirement is rough and time after time fast charging may be required on long distance trips calculatig with a more conservative total reach of 150000km seems appropriate.

Resulting saving of greenhouse gases:

Since the break even using a Li-Ion battery is about 34000km while the (pessimistic) life time is about 150000km the green house emissions driving with an electric car goes down to:

$$eqCO_2 = \frac{34000km}{150000km} = 22.7\%$$

Note: This number only applies to electricity from renewable sources!

Cost of the battery: The production cost of a Li-Ion battery is about 265$/kWh (source: Linda Gaines, Jennifer Dunn, "Lithium-Ion Battery Production and Recycling Material Issues", Argonne National Laboratory, Project ID ES229, 2015). So out example battery costs roughly:

$$cost_{60kWh} = 60 * 265\$ = 15900\$$$

Calculating with the conservative number of a total reach of 150000km (due to non ideal charging conditions) the depreciation of the battery is:

$$cost_{km} = 15900\$/150000km = 10.6c/km$$

Compared to the typical depreciation of todays middle class cars of $40c/km$ to $60c/km$ this increase seems acceptable provided electrical energy is cheap.

Availability of raw materials: Until recently Lithium was regarded as a limiting factor. Exploring the big Salars in South America this limit can be regarded as resolved. Now the limiting factor for producing Li-Ion batteries is the cobalt used in the cathodes of the batteries! (source: Linda Gaines, Jennifer Dunn, "Lithium-Ion Battery Production and Recycling Material Issues", Argonne National Laboratory, Project ID ES229, 2015) The estimated reach of the cobalt is 11 years of mass production of lithium ion batteries with cathodes made of $LiNiMnCoO_2$. Building cathodes without cobalt is possible, but these batteries have a lower cycle life.

Recycling of Li-Ion batteries: Recycling of Li-Ion batteries currently is far from being resolved. Some materials used in Li-Ion batteries (mainly the Ni and Co contents) are high toxic.

1.3.3 Conclusions regarding electrical driving with Li-Ion batteries

1. Replacing gasoline and diesel engines with electrical engines powered from Li-Ion batteries makes sense provided the electric energy is produced from renewable sources.

2. If the energy is supplied from non renewable sources we can just as well continue driving with diesel or gasoline.
3. Building enough power plant capacity (renewable) for Germany can be accomplished within 14 years.
4. An enforced power grid is required.
5. battery depreciation is expected to be about 10c/km.
6. Current show stoppers are the availability of the cathode material (Co) and the fact, that there is no efficient battery recycling in place yet.

1.4 Electric driving with fuel cells

Fuel cells can help to reduce the size of the Li-Ion battery. Currently existing fuel cells can't completely replace the battery because fuel cells require a certain start up time (t1 to t2) and a certain ramp down time (t4 to t5). During the start up time the engine of the car must be supplied from the battery. Once the fuel cell has reached it's propper operating point (t2) the fuel cell can be used to recharge the battry (t2 to t3).

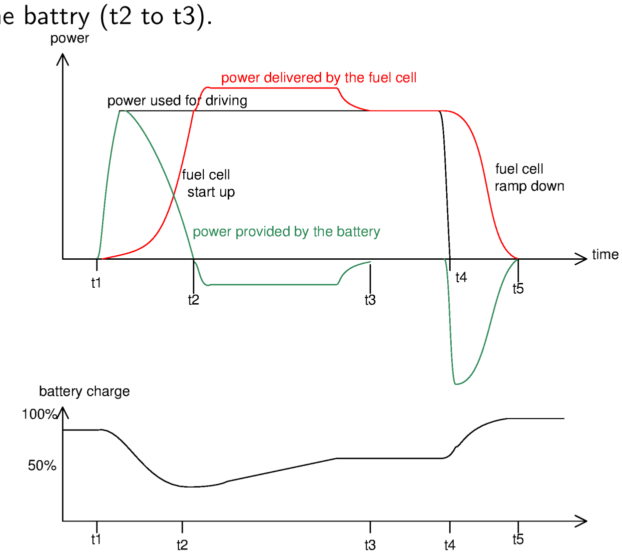

Fig.5: drive cycle of a fuel cell powered car

When the car is stopped the fuel cell will continue to deliver enery during the ramp down time (t4 to t5). So propper energy management of a fuel cell powered vehicle should charge the battry to about 70%-80% while driving and use the ramp down phase of the fuel cell to charge the battery from the driving level back up to 100%. A combination of fuel cells with Li-Ion batteries can reduce the battery size to about 5..10kWh. The recycling effort for the batteries would be reduced by about factor 6.

1.4.1 Efficiency of fuel cells

The tank to wheel efficiency of fuel cells ranges from 20% (DMFC, direct methanol fuel cell) to 60% (PEM, Polymer Electrolyte Membrane) .

(source: https://www.mpoweruk.com/fc_comparison.htm).

High temperature fuel cells offer the possibility to use the exhaust heat for a Carnot process. A high temperature fuel cell combined with a turbine can achieve 70..80%. But this complex and fragile technology only makes sense for stationary systems in the MW range.

Thus a typical fuel cell tank to wheel efficiency is in the range of 50%.

Producing hydrogen requires an electrolysis process. So the wheel to wheel efficiency of fuel cells can be expected to be around 30%.

1.4.2 Hydrogen production

Today hydrogen is produced from fossil fuels. If we want to reduce our CO_2 footprint the production of hydrogen must be based on renewable energy and electrolysis. The required energy for a fuel cell based light vehicle supply becomes:

$$Energy_{peryear} = 1.261 * 10^{11} kWh/(year * 0.3) = 4.2033 * 10^{11} kWh/year$$

(see calculations done in 1.3.1) This number is only about a factor 2 away from the total renewable electricity production of Germany in 2017 ($2.18*10^{11} kWh$ in 2017). If we want to supply a fuel cell based light vehicle traffic from wind energy alone we will have to tripple the existing wind power. This would take about 30 years (part of this increase must come from repowering already existing wind generator sites with more modern and bigger wind power generators. Depreciation times of running wind generators are in the range of 20 years. So replacing existing generators with more powerfull generators will not take place before 20 years).

These numbers show that in Germany replacing Li-Ion systems by fuel cells will start to make sense in about 20 years (assuming renewable energy production keeps growing at a rate of 6-7% per year)

2 Conclusion

A transition from gasoline and diesel to electric driving takes a certain time. Once this transistion reaches a certain production volume the prices will go down and the whole system will feed back. (higher production volume => lower production cost => increasing acceptance). The availability of electrical energy from renewable sources is a key factor for the acceptance of electrical driving.

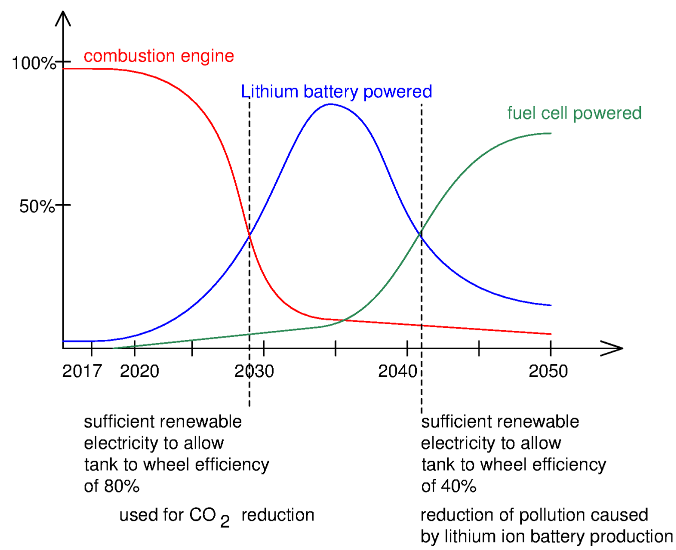

Fig.6: A plan how to reach electric driving with low pollution

1. Building up the required capacity of renewable energy is possible within about 14 years
2. The cost of battery depreciation is about 10c/100km which is an acceptable number.
3. As soon as the cars have a reach higher than 300km these cars will be accepted.
4. The transition will start to feed back in about 14 years (first flipping point)
5. Fuel cells can reduce the battery production foot print once we approximately tripple the energy production from renewable energy.
6. The transition from Li-Ion systems to fuel cell systems can become significant in about 20..30 years (second flipping point) depending on the availability of renewable energy used to produce hydrogen in high volume.

3 What is needed to achieve a low pollution and CO_2 neutral system for light weight vehicles

From the considerations described above the following actions are needed to achieve a low pollution and carbon dioxide neutral car ecosystem.

1. Keep building further wind power generators at the same rate as for the last 5 years.
2. Start development of electric cars (base on Lithium batteries) now.

3. Reach mass production of electric cars between 2025 and 2030
4. Phase out production of gasoline and diesel cars about 2030
5. Establish Li-Ion battery recycling in parallel with mass production (or even earlier)
6. Start replacing Li-Ion based energy storage from 2030 to 2040
7. After 2040: Use fuel cell powered systems for long distance (>50km) and Li-Ion based systems for short distance (< 50km)

3.1 What happens if we don't act?

German industry strongly depends on the automotive sector. If we don't act other countries will (China is already pushing strongly!). If we wait too long Germany will loose a big part of it's industry.