Technology Comparison

FOSSIL FUEL VEHICLES - BATTERY ELECTRIC VEHICLES - HYDROGEN FUEL CELL VEHICLES

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Overview

- Technology
- Efficiency
- Safety
- Durability and costs
- Energy generation and need
- References

Technology

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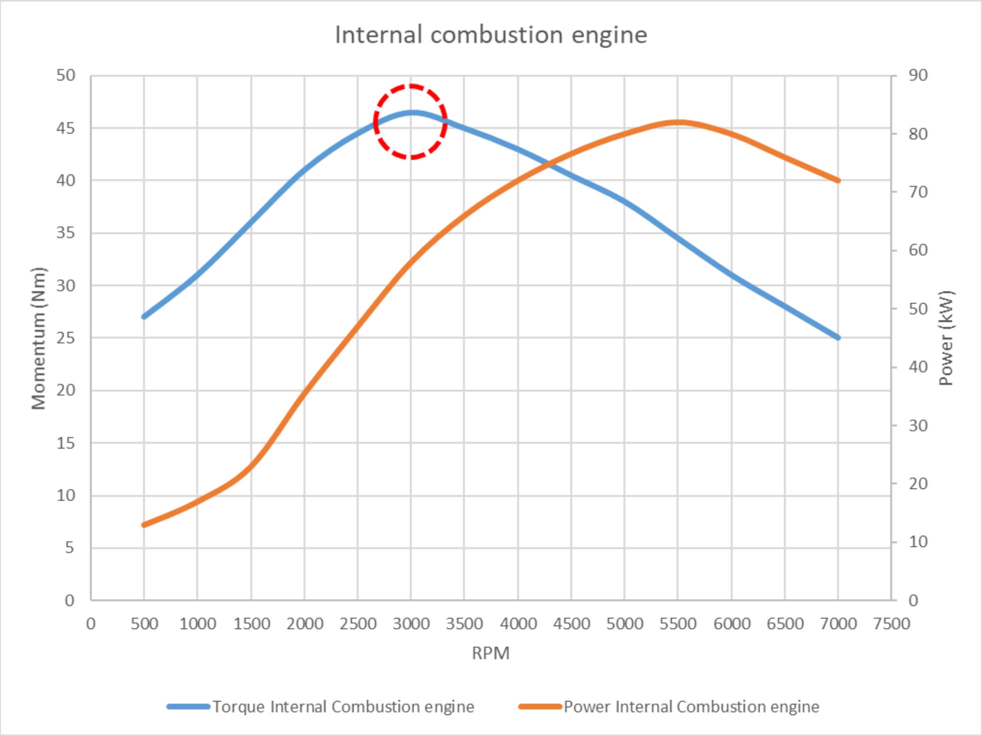
Fossil Fuel Vehicle (1)

- Internal combustion engine and gear box
  - Petrol / Diesel is burned in the engine, leading to heat and movement.
  - High torque (and power) only in optimal rpm range (see figure).
  - Low efficiency (see Chapter Efficiency).



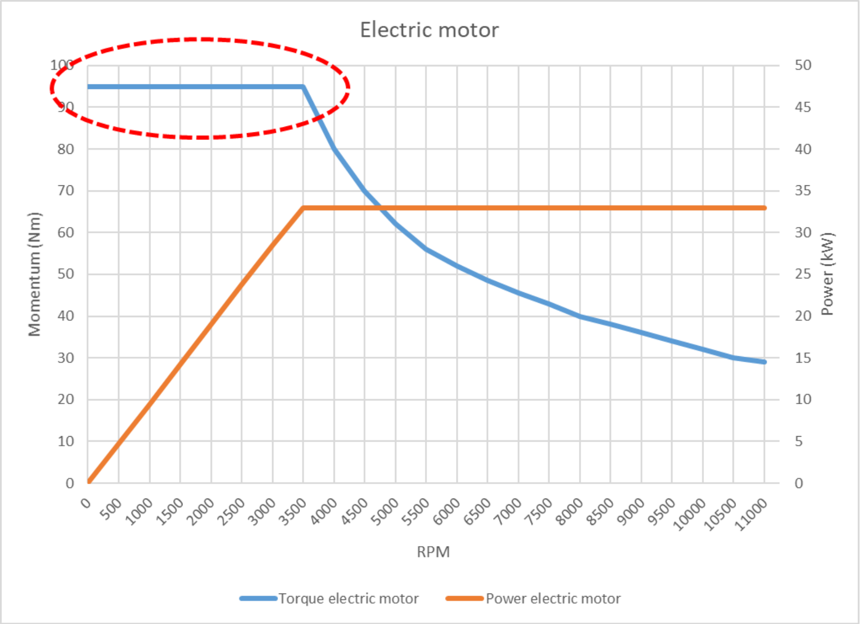
- Exhaust cleaning (catalytic converter, spark plugs, lambda sensor)
  - Rare earths are needed: Platinum, Palladium, Rhodium, Lanthanum, Yttrium and Cerium [REF-01, REF-02, REF-03].
  - A part of these elements are not recyclable because they are burned over lifetime in catalytic converter [REF-04].

Fossil Fuel Vehicle (2)

- Brakes
  - Loss of kinetic energy (energy is converted into heat, not available for movement).
  - Generation of (partly toxic) particulate matter (fine dust) [REF-05].
- CO_2 generation during production
  - Rare earths are used in several parts of a fossil fuel vehicle. Mining these elements have a high impact on CO_2 footprint.

Battery Electric Vehicle (1)

- CO_2 generation during manufacturing of a BEV
  - Manufacturing a BEV produces 15% to 68% more emissions than manufacturing an equivalent fossil fuel vehicle [REF-06].
- CO_2 generation during use
  - 2.5x less than a fossil fuel vehicle (see Chapter Efficiency).
  - With more renewable energy sources this is getting better (for all Battery Electric Vehicles).



- Electric motor
  - Constant maximum torque available from 0 rpm (see figure).
  - Tesla Model S and Model X use an Asynchronous Induction Motor without Neodymium (rare earth) [REF-07].
  - Tesla Model 3 uses a Permanent Magnet Switched Reluctance Motor with Neodymium [REF-07].
- Energy recuperation (regenerative braking)
  - Recuperation during braking saves energy, brake discs and brake pads.

Battery Electric Vehicle (2)

- Tesla uses NCA batteries, or Nickel, Cobalt and Aluminium ($LiNiCoAlO_2$)
  - Lithium use: about 5 kg of lithium in a 70 kWh Tesla Model S battery pack, weighing ~453 kg [REF-08].
  - Cobalt use: Tesla: 2.8% (~13 kg) in Model 3, EV standard is 8% [REF-09, REF-10, REF-11]. Tesla's target for next generation battery is to be cobalt free [REF-12, REF-13].
- Lithium and cobalt recovery
  - Abundance of lithium in earth crust is 0.006%. [REF-14, REF-15]. For comparison: the abundance of copper is also 0.006%.
  - Abundance of cobalt in earth crust is 0.004% [REF-15].
- Lithium battery recycling
  - In 2019 60-70% of a lithium battery used in cars can be recycled [REF-12]. Cobalt is recycled to up to 90%. The biggest European recycling company is located in Antwerpen and owned by Umicore [REF-16].
- Motor size
  - Small size of electric motors keep space for a large trunk and often an additional frunk (front trunk).

Hydrogen Fuel Cell Electric Vehicle (1)

- Hydrogen generation
  - Hydrogen needs to be generated, in 2019 mostly by steam methane reforming. This uses energy (~30%) and produces CO_2 [REF-17].
- Storage and transport of H_2 in gas stations and in cars
  - Hydrogen is highly flammable and extremely volatile (lightest molecule in periodic system), so difficult to store.
  - 700 bar pressure needed for transport in tanks [REF-19].
  - Hydrogen-Pressuretanksystem for a car weighs ~125 kg [REF-19].
  - Hydrogen fuel cell and hydrogen tanks take space.
- Fuel cell technology
  - Fuel cells are relative expensive, using complex technology, that needs maintenance during use in vehicles.
  - Fuel cells contain rare earths (Platinum) [REF-18].

Hydrogen Fuel Cell Electric Vehicle (2)

- Battery needed for temporary energy storage
  - same advantages and disadvantages as in BEV.
- Electric motor
  - Constant maximum torque from 0 rpm.
- Energy recuperation (regenerative braking)
  - Recuperation during braking saves energy, brake discs and brake pads.
- CO_2 generation during production
  - Rare earths (Platinum, Yttrium) are used in several parts of fuel cell [REF-18]. Mining these elements have a high impact on CO_2 footprint.

Efficiency

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Efficiency of Fossil Fuel Vehicle

Well-to-Tank efficiency:

- Resource: oil, refined to Diesel / petrol, transport of fuel via roads
  - Well-to-tank efficiency: <85% [REF-20].

Tank-to-Wheel efficiency:

- Combustion engine + gear box
  - Efficiency engine: ~20% on average (petrol and diesel), 37% maximum (at optimal rpm) [REF-20].

Well-to-wheel efficiency: ~17%.

Efficiency of Battery Electric Vehicle (BEV)

Well-to-Tank efficiency:

- Combined efficiency energy production (Germany, 2019): 52% [REF-23].
  - Power plants using fossil fuel (coal / methane) and renewable energy (wind, water, solar).
- Efficiency of transport (Germany, 2019): 94.3% [REF-23].
- Local photovoltaic installation (90%), using stationary battery (95%): 85,5% [REF-20].
- Efficiency of battery / charger: ~95% [REF-24].

Tank-to-wheel efficiency:

- Efficiency of electric motor (including recuperation): >95% [REF-25, REF-20].

Well-to-wheel efficiency: ~44%, higher when using more renewable sources (wind, water, solar).

Well-to-wheel efficiency (using local photovoltaic installation and renewable sources): ~77%.

Efficiency of Hydrogen Fuel Cell Electric Vehicle

Well-to-Tank efficiency:

- Efficiency of creation of Hydrogen:
  - Efficiency of creation with steam methane reforming (SMR): ~70% (In 2019 >90 % of all hydrogen is generated this way) [REF-26].
  - Efficiency of creation with electrolysis: ~80% [REF-21, REF-20].
- Efficiency of compression to 700 bar for transport: 88% [REF-20].
- Efficiency of fuel cell: ~60% [REF-20, REF-21, REF-22].
- Efficiency of battery / charging: >95% [REF-24].

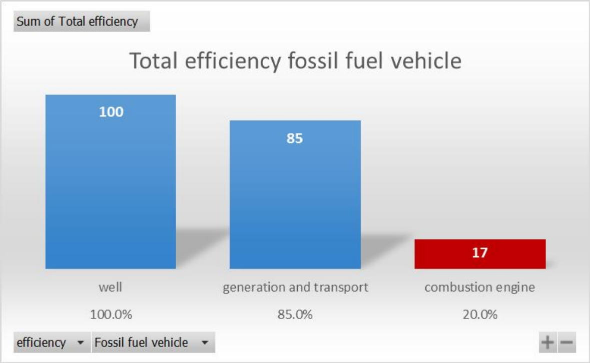
Tank-to-wheel efficiency:

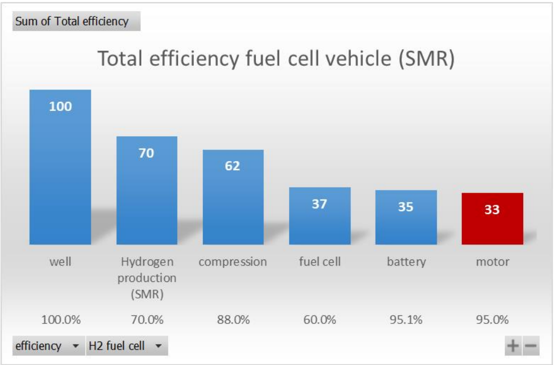
- Efficiency of electric motor (including recuperation): >95% [REF-25, REF-20]

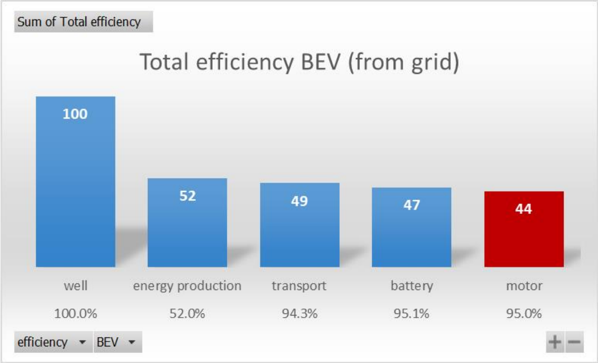
Well-to-wheel efficiency: ~38% (optimal, using electrolysis), ~33% (using SMR).

Efficiency comparison

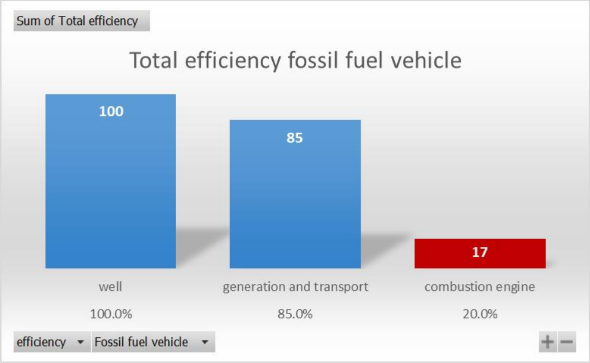
CURRENT

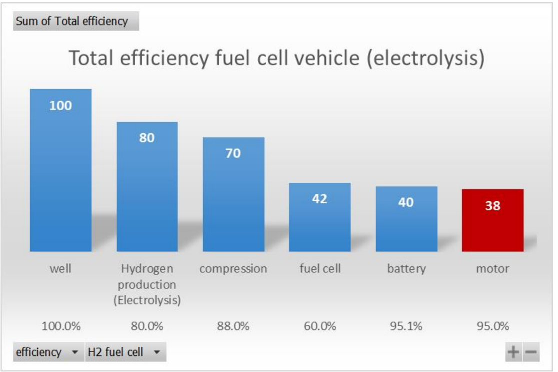


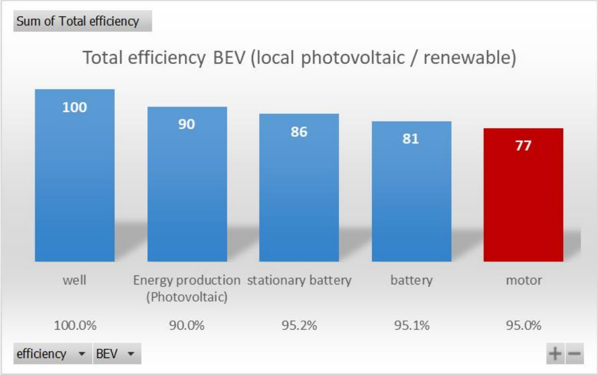




FUTURE







Total efficiency in is shown in red column

Hybrid vehicles (fossil fuel / battery electric) are situated between fossil fuel vehicle and BEV.

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Safety

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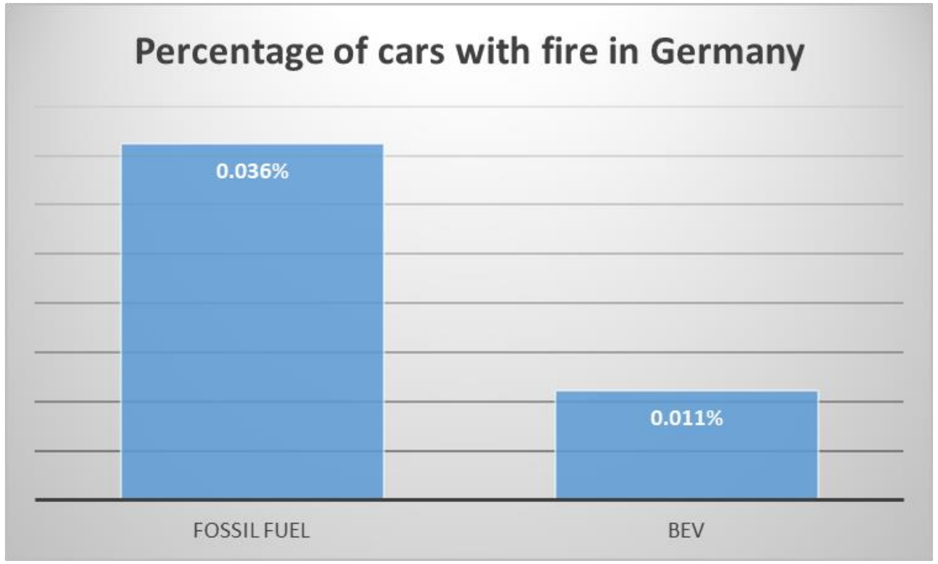
Fire Risks

Germany:

- 15000 burning fossil fuel cars per year [REF-27] of 47 million [REF-28] = 0.032%.
- 6 battery electrical cars in 2017 [REF-29] of 54000 [REF-30] = 0.011%.

Wiener Motorensymposium 2017 [REF-29]:

- Fossil fuel cars: 90 fires / bilion driven kilometers.
- Battery electric cars: 2 fires / bilion driven kliometers.



Crash Risks

- Hybrid or all-electric cars are not inferior to fossil fuel cars in terms of safety, according to the German test company Dekra. Electric cars are "as safe as vehicles with internal combustion engine“, according to accident researcher Markus Egelhaaf [REF-30].

- With fire development, there is no greater risk of electric drives than of combustion systems. This was proved by the fire and extinguishing tests carried out with traction batteries by a vehicle manufacturer as well as further fire tests by Dekra. In violent collisions, fires in electric cars would spread even slower than in conventionally powered vehicles. No large amounts of burning liquids flow away and set fire to neighboring objects [REF-30].

- Various crash tests with hybrid and electric cars showed that safety is under control. For example: the power supply is switched off by the battery in an accident within a very short time and the voltage in the vehicle systems falls within a few seconds in the non-critical range below the limit of 60 volts [REF-30].

Other risks

Hydrogen:

- Transported at >700 bar pressure in tanks
  - Leaks in high pressure tanks in gas stations could cause fire/explosion.
  - High pressure tanks could burst during crash of fuel cell car or H_2 transport vehicle, causing extreme fire or explosions.
- Highly flammable and extremely volatile (smallest molecule in periodic system)
  - Tank and station refill processes are complex because of 700 bar pressure. Leakage can cause fire/explosion [REF-31].

Durability and costs

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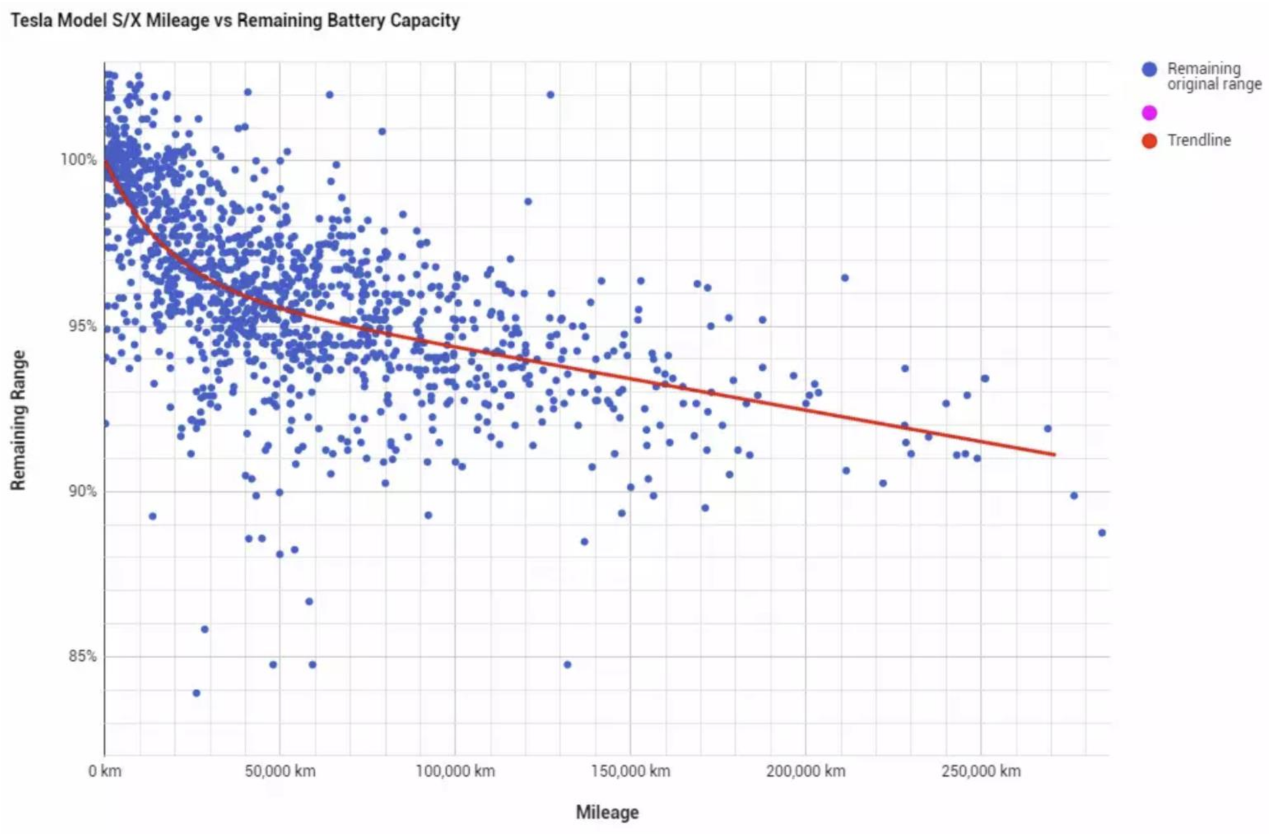
Costs of EV batteries

In average the price per kWh is dropping with 16% per year [REF-32, REF-33].

Durability of Tesla EV batteries



- An estimated mileage of 1,000,000 km is possible [REF-32].
- EV batteries can have second life as home battery (power wall) or grid stabilizer.

Tesla batteries

Tesla uses NCA chemistry, or Nickel, Cobalt, and Aluminum ($LiNiCoAlO_2$). They use this particular chemistry because it offers high energy density, long cycle life, and good charge performance. Tesla's batteries have gone through 3 stages [REF-34]:

- Stage 1 batteries (from 2009-2012 found in the Roadster and Model S) were constructed with 18650 cells. They required 11 kg of Cobalt in the cathode, per car.
- Stage 2 batteries (from 2016-2018 and powered the Model S Gen II, and the Model X) used the same 18650 cells but reduced the amount of Cobalt required in the cathode to 7 kg per car.
- Stage 3 batteries (Model 3 in 2018) are first shipped with the Model 3. Stage 3 batteries have further reduced the amount of cobalt to just around 4.5 kg per vehicle.

Energy generation and need

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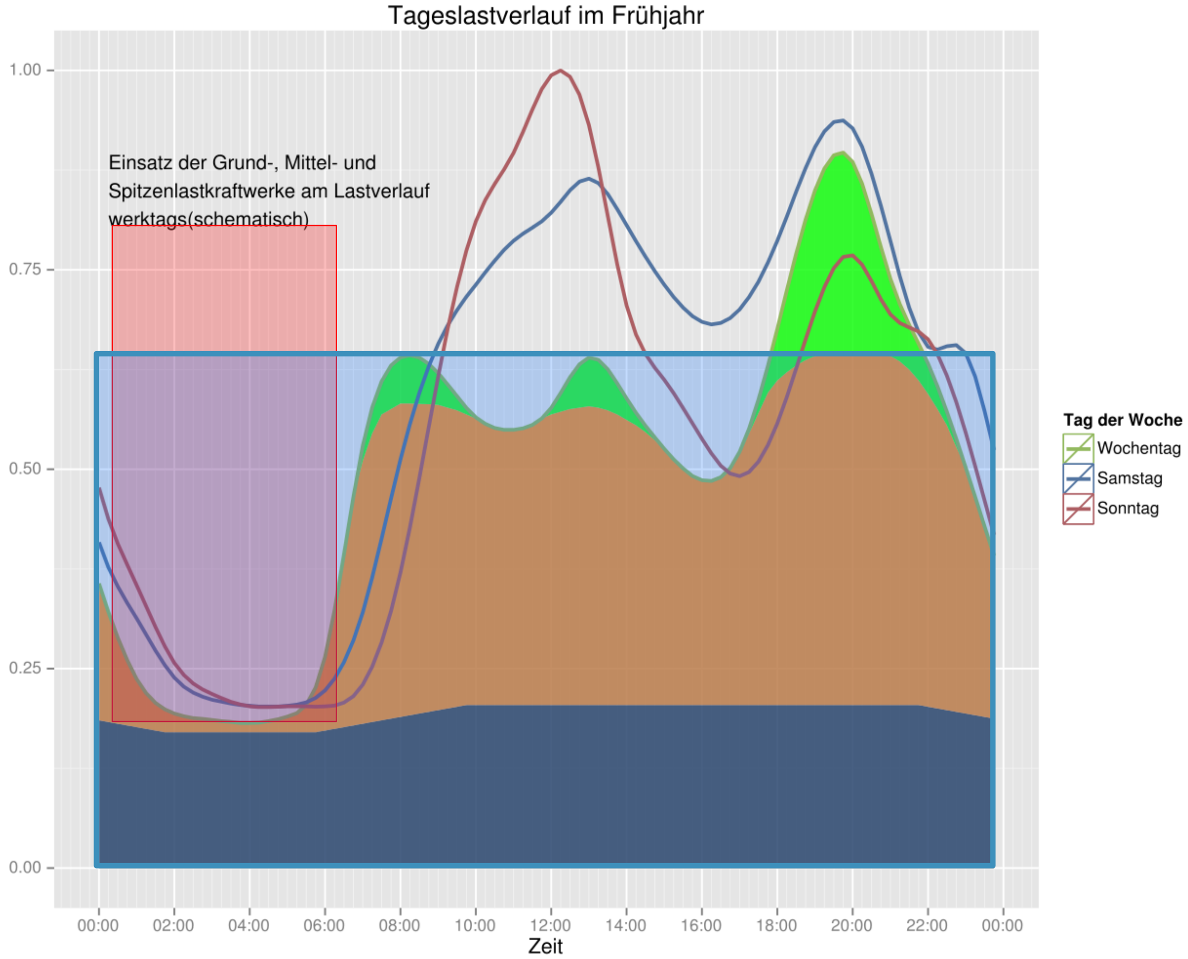
Energy production

- Electrical energy generation in Germany (2018): 646,8 TWh [REF-35]
  - Generated power on average = 646.8 TWh / year = 1.77 TWh / day.
  - Distribution over the day is shown in figure [REF-36].
  - **25% (~442 GWh) can be generated during 6 hours at night at this moment (see figure, red square).**



Notice: grey and orange parts in figure can be generated continuously, green only during peaks.

Energy need

- Number of cars in Germany (2018): 47 million [REF-37].
- **Average driven distance per car per day in Germany: <50 km [REF-38].**
- Energy need for charging vehicles in Germany:
  - Assumptions:
    - 40 million of 47 million cars are BEVs,
    - All cars are charging at night,
    - ~10 kWh recharged during night (> 50 km),
    - No local photovoltaic installation is used.

→ **40 million x ~10 kWh = ~400 GWh** → This can already be delivered at this moment.

References

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References (1)

- [REF-01] - https://de.wikipedia.org/wiki/Lambdasonde
- [REF-02] - https://de.wikipedia.org/wiki/Z%C3%BCndkerze#Elektrodenmaterial
- [REF-03] - https://de.wikipedia.org/wiki/Metalle_der_Seltenen_Erden#Verwendung
- [REF-04] - https://de.wikipedia.org/wiki/Fahrzeugkatalysator#Kritik
- [REF-05] - https://de.wikipedia.org/wiki/Bremsstaub
- [REF-06] - https://cleantechnica.com/2018/02/19/electric-car-well-to-wheel-emissions-myth/
- [REF-07] - https://electrek.co/2019/04/05/tesla-model-s-new-electric-motors/
- [REF-08] - https://batteryuniversity.com/index.php/learn/archive/is_lithium_ion_the_ideal_battery
- [REF-09] - https://ecomento.de/2018/06/04/panasonic-und-tesla-arbeiten-an-elektroauto-batterien-ohne-kobalt/
- [REF-10] - https://cleantechnica.com/2018/02/11/nope-cobalts-not-problem-ev-revolution-will-march/
- [REF-11] - https://cleantechnica.com/2018/03/04/exciting-developments-nmc-811-lithium-battery-technology/
- [REF-12] - https://cleantechnica.com/2018/06/17/teslas-cobalt-usage-to-drop-from-3-today-to-0-elon-commits/
- [REF-13] - https://ecomento.de/2018/11/21/so-aufwaendig-ist-das-recycling-von-elektroauto-batterien/
- [REF-14] - https://en.wikipedia.org/wiki/Lithium#Terrestrial
- [REF-15] - https://de.wikipedia.org/wiki/Cobalt#Vorkommen

References (2)

- [REF-16] - https://de.wikipedia.org/wiki/Lithium-Ionen-Akkumulator#Recycling
- [REF-17] - https://de.wikipedia.org/wiki/Brennstoffzellenfahrzeug#Wasserstofferzeugung_und_Energiekette
- [REF-18] - https://www.energate-messenger.de/news/187455/weniger-platin-in-der-brennstoffzelle
- [REF-19] - https://de.wikipedia.org/wiki/Brennstoffzellenfahrzeug#Druckwasserstoffspeicherung
- [REF-20] - https://de.wikipedia.org/wiki/Wasserstoffwirtschaft#Wirkungsgrade_in_einer_Wasserstoffwirtschaft
- [REF-21] - https://de.wikipedia.org/wiki/Well-to-Tank
- [REF-22] - https://de.wikipedia.org/wiki/Brennstoffzelle#Elektrischer_Wirkungsgrad,_Kosten,_Lebensdauer
- [REF-23] - https://de.wikipedia.org/wiki/%C3%9Cbertragungsverlust
- [REF-24] - https://batteryuniversity.com/learn/article/comparing_the_battery_with_other_power_sources
- [REF-25] - https://electrek.co/2018/04/24/regenerative-braking-how-it-works/
- [REF-26] - https://de.wikipedia.org/wiki/Dampfreformierung
- [REF-27] - https://de.wikipedia.org/wiki/Fahrzeugbrand
- [REF-28] - https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/bestand_node.html
- [REF-29] - https://autorevue.at/ratgeber/statistik-brennen-elektroautos
- [REF-30] - https://ecomento.de/2018/06/26/dekra-experte-elektroautos-so-sicher-wie-verbrenner/

References (3)

- [REF-31] - https://www.spiegel.de/auto/aktuell/norwegen-wasserstofftankstelle-explodiert-toyota-reagiert-a-1271980.html
- [REF-32] - https://steinbuch.wordpress.com/2015/01/24/tesla-model-s-battery-degradation-data/
- [REF-33] - https://electrek.co/2016/11/01/breakdown-raw-materials-tesla-batteries-possible-bottleneck
- [REF-34] - https://insideevs.com/news/338743/everything-you-ever-wanted-to-know-about-tesla-batteries/
- [REF-35] - https://de.wikipedia.org/wiki/Stromerzeugung#Bruttostromerzeugung_nach_Energietr%C3%A4gern
- [REF-36] - https://de.wikipedia.org/wiki/Bedarf_an_elektrischer_Energie
- [REF-37] - https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/jaehrlich/2019_b_barometer.html;jsessionid=A7728A768EBB9C36FB1E489EB1909687.live11294?nn=2084378
- [REF-38] - https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/verkehr_in_kilometern_node.html

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