# Alternative Drive Systems: introduction

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## 1. The era of combustion engines

Up until now, progress in automotive propulsion technology has been predominantly determined by continuous improvements in combustion engine technologies. A remarkable increase in efficiency has been achieved by optimizing the combustion process, and these developments have resulted in fewer pollutants such as as $NO_x$ and CO, considerably reduced $CO_2$ emissions and an increase in the number of kilometres travelled per litre. Figure 1.1 shows how fuel consumption (100km/litre) in Germany steadily improved over a period of 25 years from 1978.

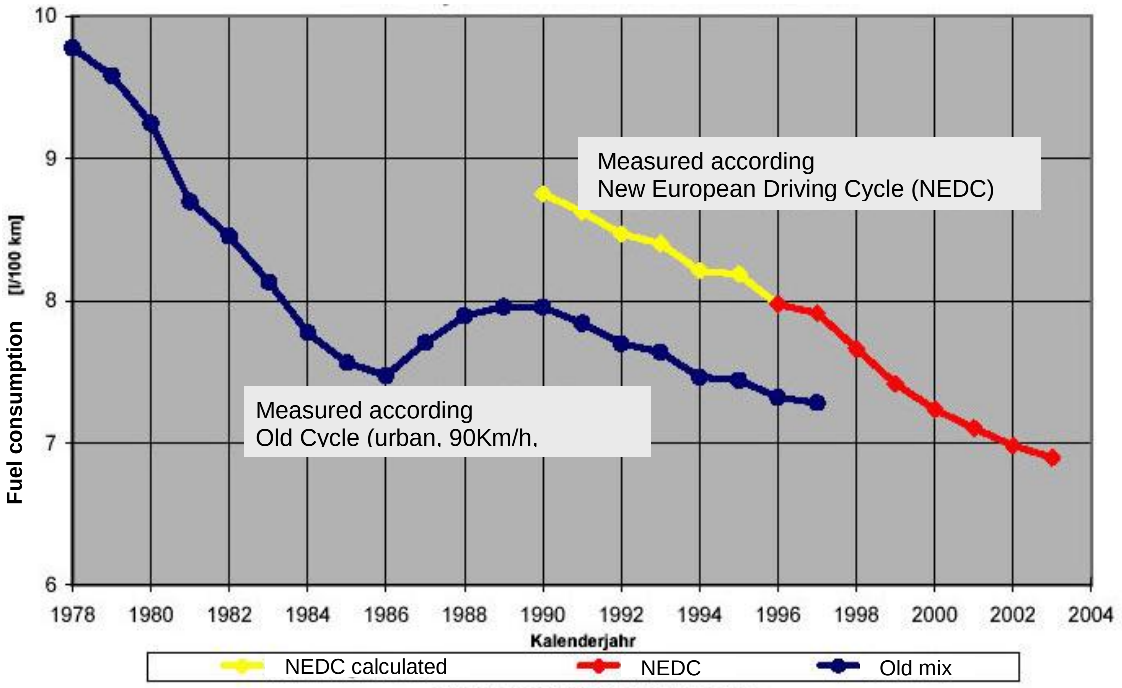



***Fig. 1.1. Increase in kilometres travelled (reduction of fuel consumption) per car in Germany 1978-2004***

However research work in the field of combustion processes is approaching to physical limits concerning the combustion process. Today's obviously dramatic consequences of climate change, caused primarily by the rise of $CO_2$ concentration in the atmosphere requires new concepts in energy production and consumption, including automobile propulsion technologies, which are no longer based on burning fossil fuels.

By burning fossil fuels we are actually blowing about 36 Gt of $CO_2$ yearly in the atmosphere. Even if a big portion of this is absorbed by increased biomass formation (~ 21 Gt) our atmosphere's $CO_2$ concentration is still increasing by the incredible amount of ~16 Gt every year (Fig 1.2)

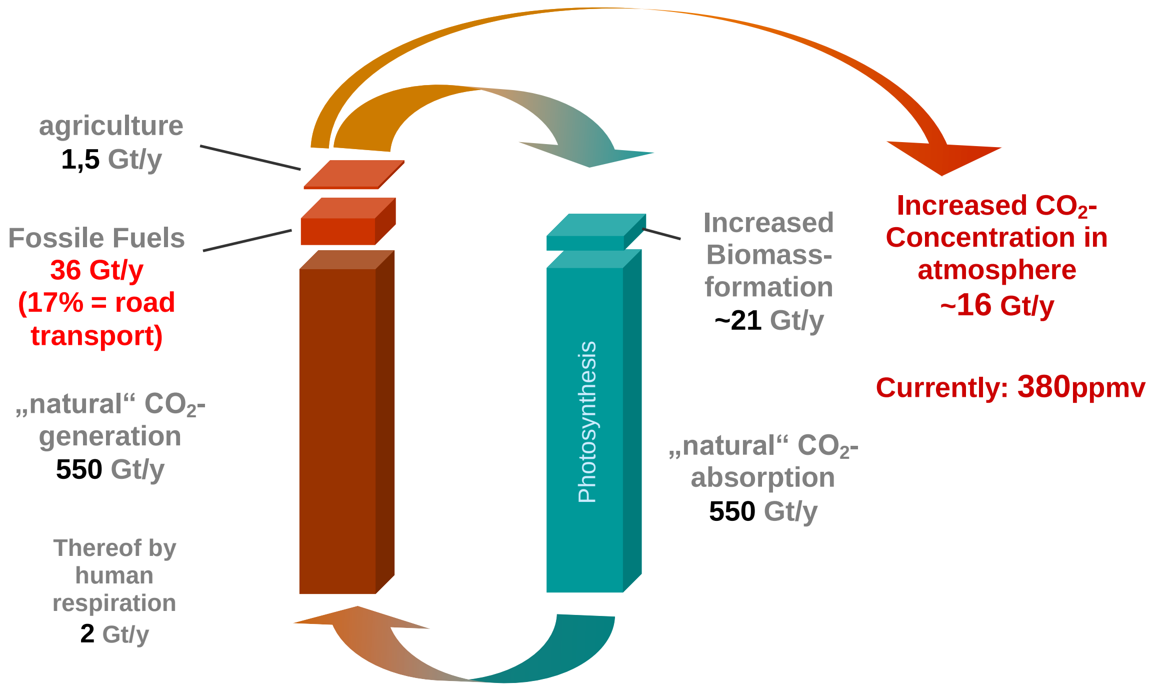



***Fig. 1.2: Changes in the carbon dioxide concentration in the atmosphere***

The increased $CO_2$ concentration (see Figure 1.3) has already caused an *anomaly* in the World's overall energy balance of *2,5 W per square meter*. This means that the absorbed energy from the sun is 2,5 W higher than the emitted energy (emitted primarily via infrared radiation). This might seem small when compared to the total irradiated energy of 1367 W per square meter beyond the atmosphere (solar constant) and about 1000 W per square meter on earth. But it corresponds to 100 times the total world energy consumption.

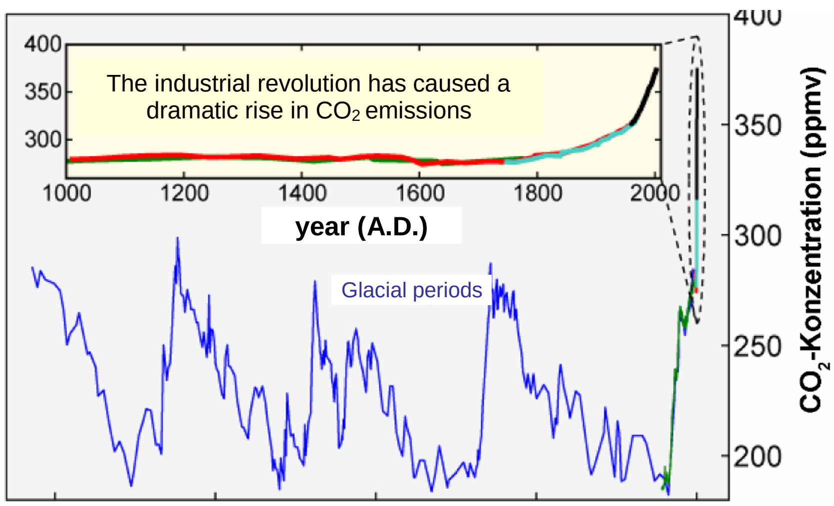



***Fig. 1.3: Changes of Carbon dioxide–concentration in atmosphere***

The imbalance is caused by the accumulation of $CO_2$ impeding infrared radiation being radiated to space from earth, while allowing solar energy, irradiated via higher frequency electromagnetic waves to reach the planet's surface (see Figure 1.4).

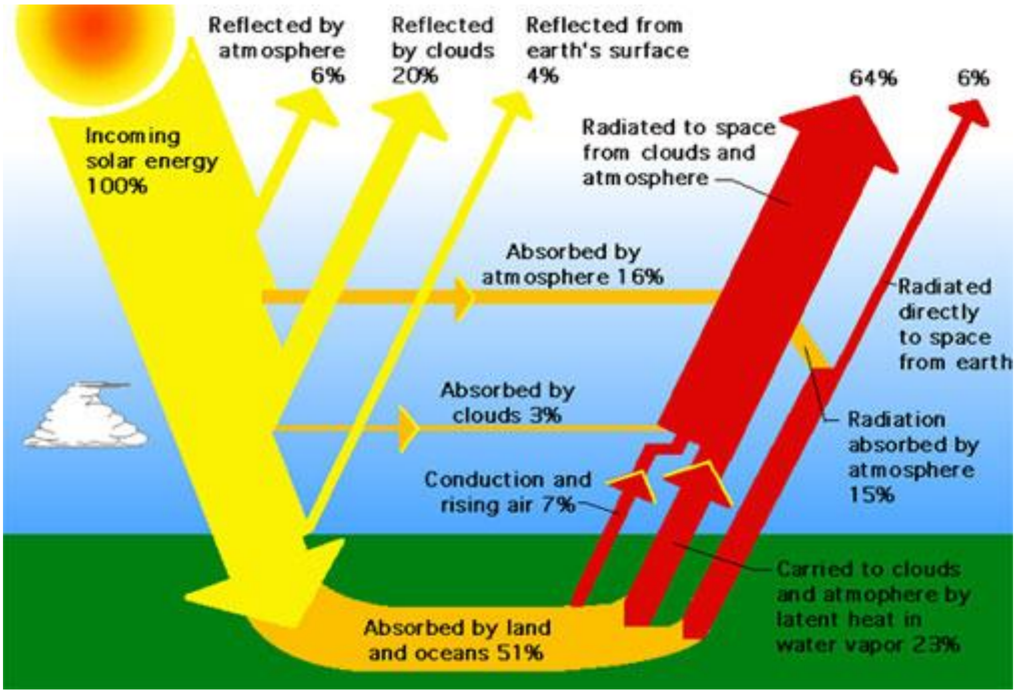



***Fig. 1.4: Global energy balance***

Nowadays climate change is considered the most threatening problem for the World. For example, Figure 1.5 shows the environmental changes that have occurred in the alpine regions as clear proof of already irreversible loss and damage. Worldwide increases in natural disasters such as hurricanes (+60% in the last 15 years) or droughts are further consequences with thousands of people killed and injured as well as considerable financial losses.

***Fig. 1.5: Glacier „Pasterze" in the province of Salzburg in 1900 and in 2000***

The rise in sea level (see Figure 1.6) as a consequence of melting polar ice caps could destroy the livelihoods of millions of people throughout this century.

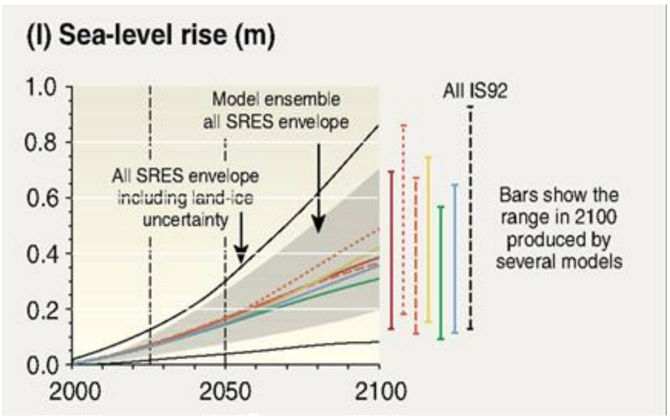



***Fig.1.6: Forecasts for sea-level rise as a consequence of melting pole***

Fig. 1.7 shows the already measured rise in the annual mean temperatures during the period 1995-2004. It can be seen that the landmasses in the northern hemisphere will be more affected and warm up faster as the have less capacity for energy storage than the big oceans.

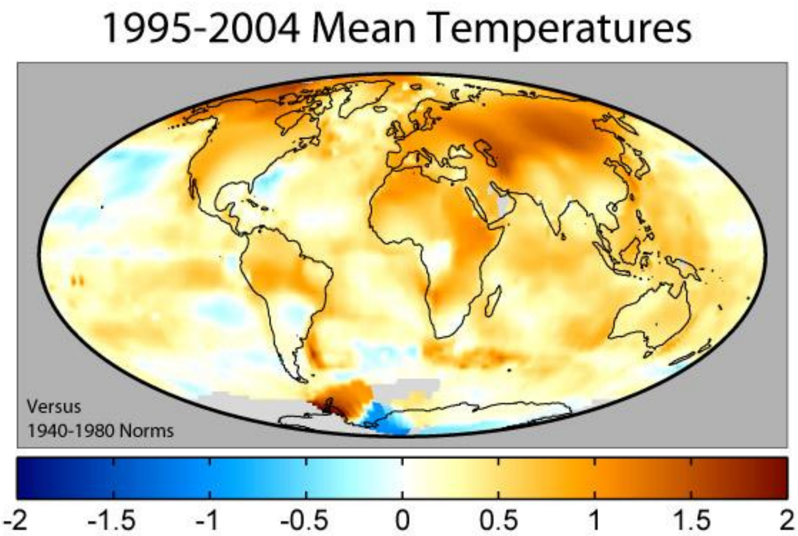



***Fig. 1.7: Measured change of annual mean temperatures in °C***

Although today road transport contributes “only” with about 17% to the overall $CO_2$ emissions (Fig. 1.8), it shows the most dramatic increase (together with aviation).

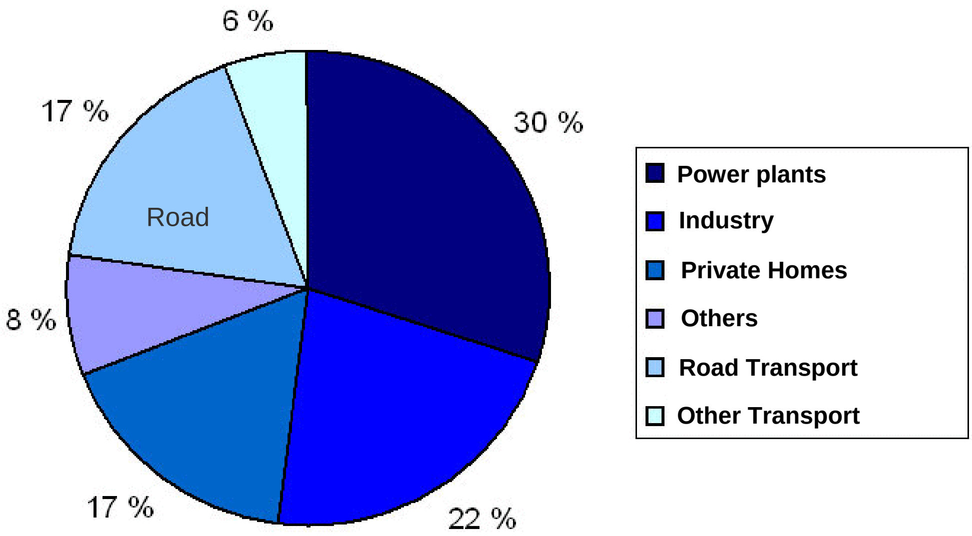



***Fig. 1.8: CO2 emitters by segments***

Furthermore, economic growth combined with rising individual affluence in Asiatic countries like China and India also results in a very high demand for more individual mobility. Fig. 1.9 shows the expected growth of the Chinese automobile market.

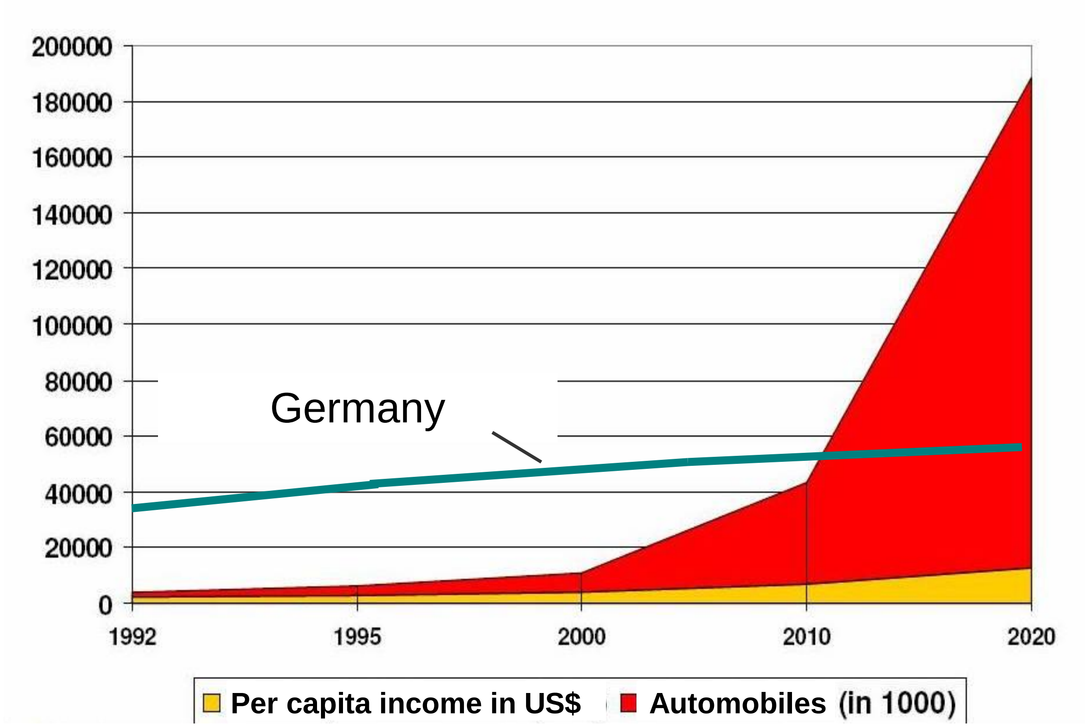



***Fig. 1.9: Expected growth in the Chinese automobile market***

The worldwide oil demand increases about 2% every year. The world oil production is not able to follow this demand. Alternative energy supplies are not increasing enough to close the gap (Fig 1.20). Oil reserves are limited and get exhausted.
The result will be a tremendous increase of oil prices in the near future (already > 100 USD/barrel in 2011).

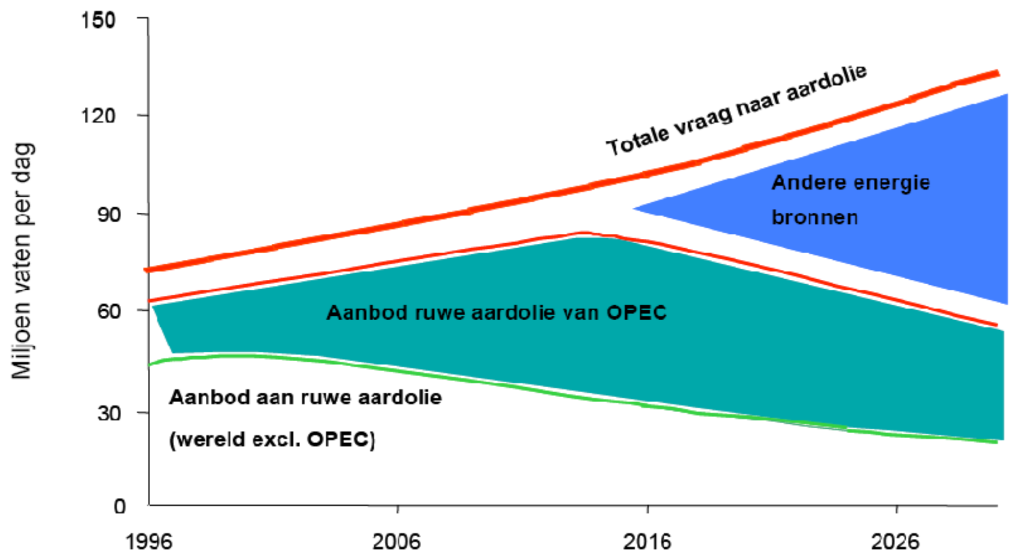



***Fig 1.10: Oil production vs. oil demand***

## 2. Efficiency of internal combustion engines

Given this threatening scenario, we urgently need a fundamental paradigm shift in vehicle propulsion technology. In order to evaluate the possible solutions it seems sensible to have a closer look at the energy balance of state-of-the-art vehicles.

First of all we are going to define the expression “effective energy” or “effective power”, which, in the case of a moving vehicle, consists of three major parts:

- friction losses
- air resistance losses (drag losses)
- breaking losses (deceleration losses)

Of course, as the new hybrid vehicles are able to recover deceleration energy the inclusion of breaking losses may not now be strictly correct. We will, therefore, only discuss the energy needed to overcome the unavoidable friction and air-resistance.

For a constant speed driving cycle (on a flat road surface), there are two *forces* to overcome: we can approximate the friction-force by the equation

$$\boxed{F_R = \mu_R \cdot F_N}$$

*$F_R$... Horizontal friction force*

*$\mu_R$ ... Friction coefficient*
*(= 0,01- 0,015 for asphalt)*

*$F_N$… Normal (vertical) force*

and the air resistance force (drag) by

$$\boxed{F_d = \frac{\rho}{2} \cdot v^2 \cdot c_d \cdot A}$$

*$F_d$... Drag force*

*$c_d$ ... drag coefficient (= 0,2 - 0,4 for cars)*

*$\rho$…. air density (= 1,2kg/m$^3$ at sea level, 20°C)*

*$v$…..velocity in m/s*

*$A$ … cross-sectional area*

The *power*, which is needed to overcome these forces, is the product of this force and the vehicle speed. It is shown in Fig. 2.1 for a middle class car:

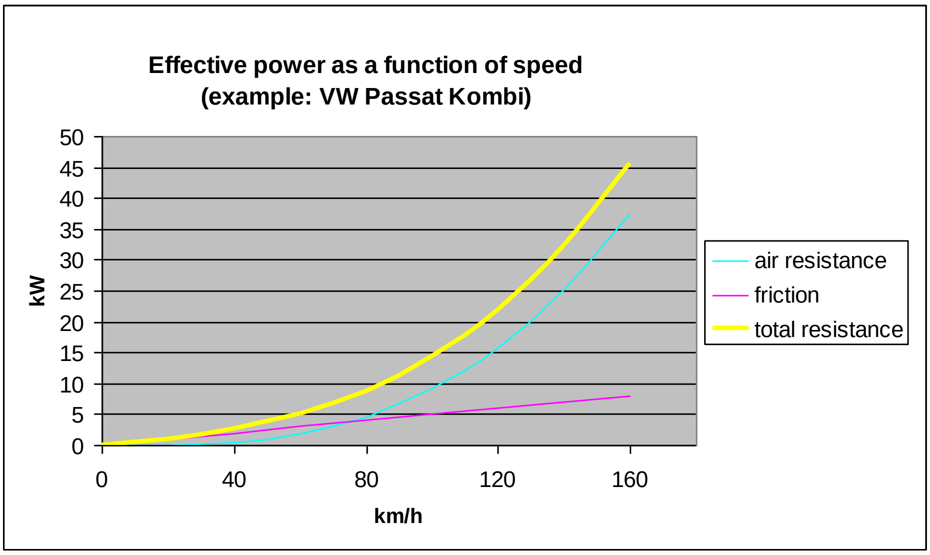



***Fig. 2.1: Necessary effective power needed to overcome friction- and air-resistance, for driving at constant speed***

Deriving the necessary *energy* for a driving distance of 100km (constant speed at plane highway), we get the relation shown in Fig. 2.2:

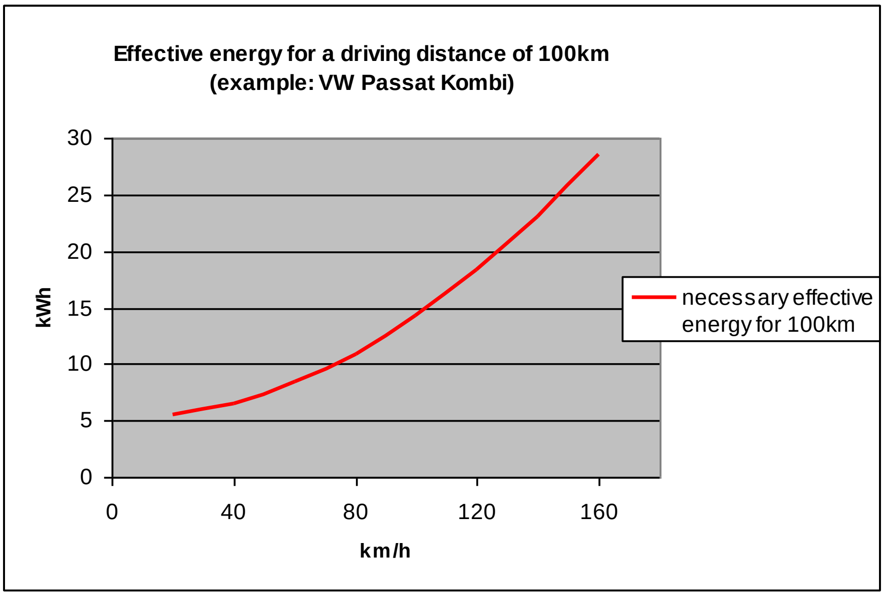



***Fig. 2.2: Necessary effective energy needed to drive 100 km and to overcome friction- and air-resistance relative to speed***

In order to compare vehicle's energy performance and to assess emission levels in representative driving conditions, the New European Driving Cycle (NEDC) has been introduced in 1996 as a common standard. It consists of 4 repeated ECE-15 cycles (Urban cycles) and an Extra-Urban driving cycle.

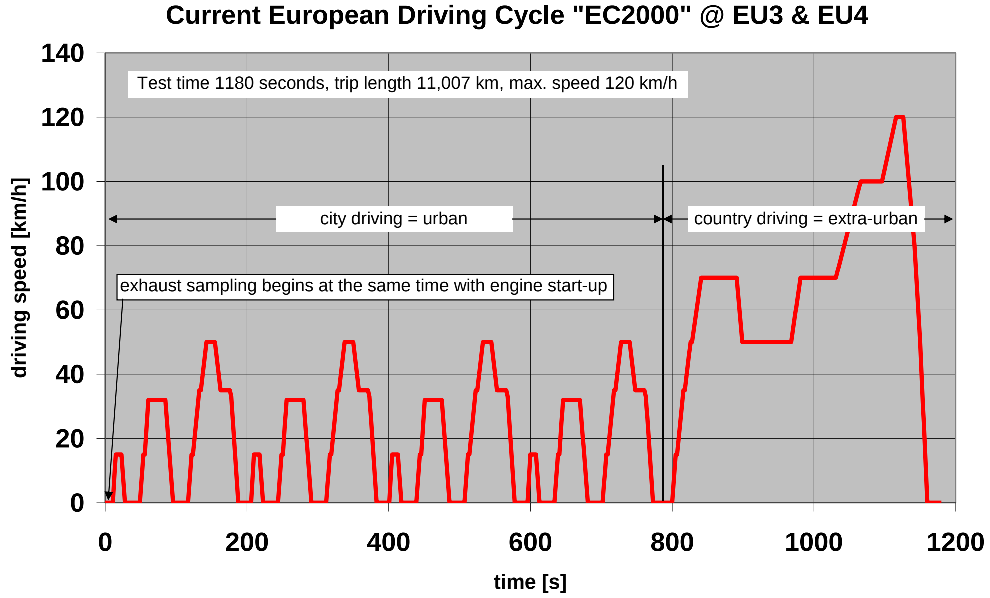



***Fig 2.3: Standardized European Driving Cycle***

Comparing the necessary effective energy needed for this cycle by specific cars [over a distance of 100km which would correlate to 9 repeated NEDCs, as each NEDC takes 11 km], we get aware of considerable differences, primarily as a result of different car size and weight.

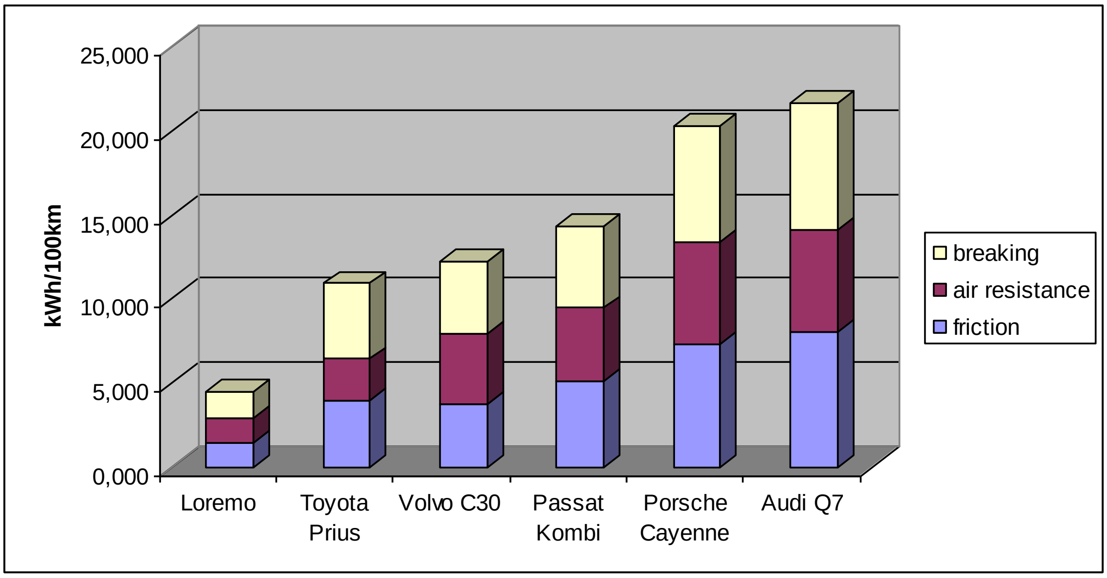



***Fig. 2.4: Comparison of necessary effective energy for different cars in a European Driving Cycle***

Note: the name LOREMO stands for Low Resistance Mobile and is the result of an initiative funded by the European commission with the purpose of investigating the limits of lightweight and aerodynamic construction.

We will now address the matter of energy efficiency with particular reference to the question of how much primary energy is needed to provide the necessary effective energy for any given driving cycle.
If we assume a 100% efficient engine, even the large Audi Q7 would only need 2,2 litres of e.g.

diesel per 100km (the energy content of 1 litre of diesel is about 9,8kWh), while the LOREMO could manage 100km with less then half a litre of diesel. So the question that has to be asked is: Why do ICE cars still consume typically between 5 and 9 litres per 100kms?

Part of the answer can be seen in Fig. 2.5 and Fig 2.6. The first figure shows the efficiency of modern petrol and diesel engines under *nominal* conditions. Thanks to all the research efforts of the last century we are approaching to the thermodynamic limit of the combustion process, but this is still a value below 40% efficiency.

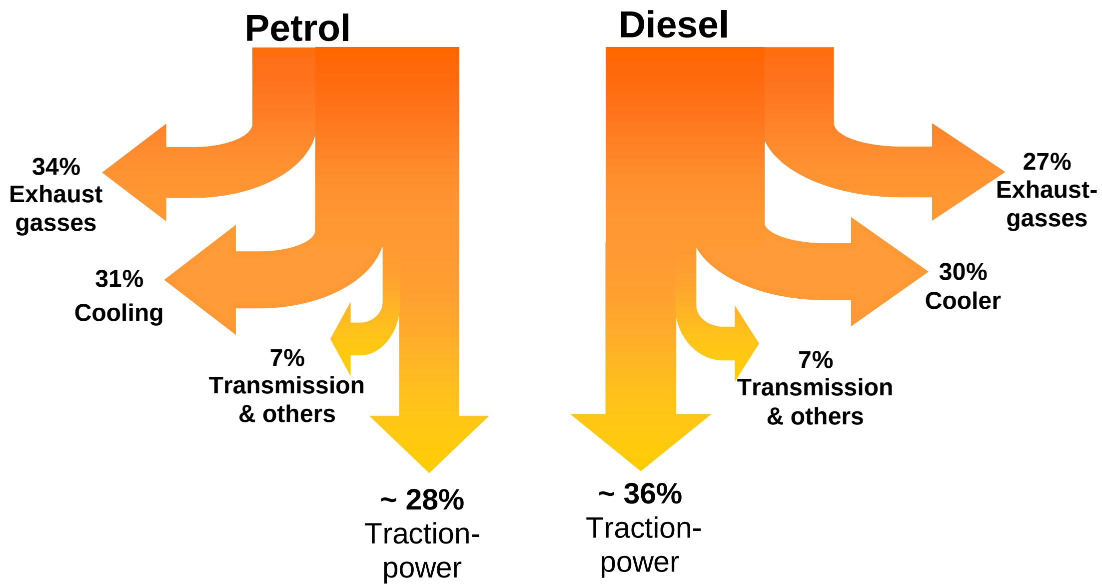



***Fig. 2.5: Efficiency of Combustion engines at nominal conditions***

When we look then at *typical driving cycles*, the overall efficiency goes down to values in the range of **16% to 20%**, which means that over 80% is just waste of energy. This is a value which is no longer acceptable in times of natural disasters as a result of climate change.

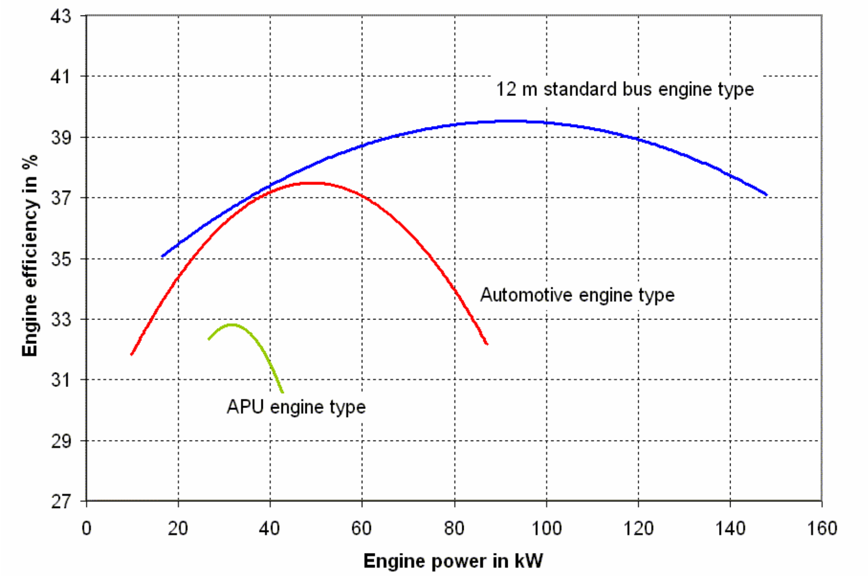
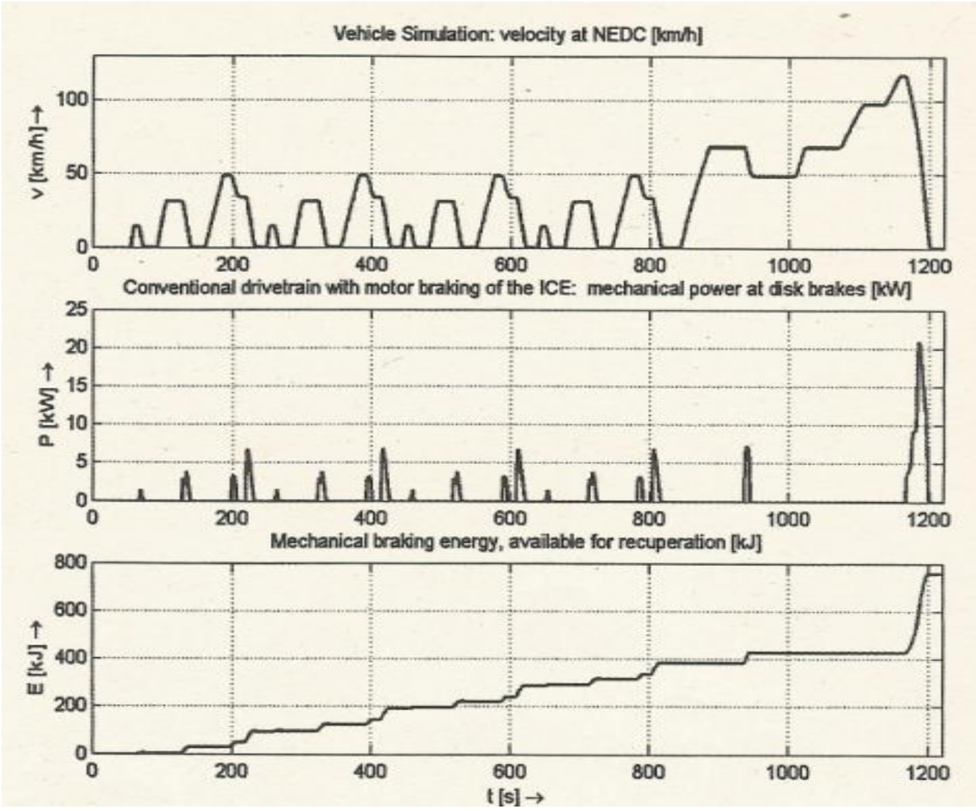



***Fig 2.6: Efficiency characteristics of 3 diesel engines for different applications***

## 3. On search for new solutions

There remain three potential areas where further efficiency improvements could be made:

- Increasing the efficiency of energy transfer to the wheels. For vehicles with ICE: fixing the operation-point of the internal combustion engine (ICE) at optimal value.
- Eliminating losses at standstill or cruising.
- Recovering braking energy.




***Energy content while braking in the NEDC***

Decisive gains in efficiency could be made by introducing electrical drives in powertrain systems. *Electrical drives* have some big advantages over combustion engines, such as

- No energy consumption at standstill (no minimum speed)
- Capability of energy recuperation in deceleration phases
- High efficiency motor in all operating conditions (70-90% vs. ICE 10-30%)
- Favourable Torque/speed characteristics for traction applications
- No air pollution on the spot
- Controllable pollution at energy production plant
- No engine noise

Fig 3.1 shows the typical torque/speed characteristics of speed-variable electrical drives. In practical terms, these are valid for all major motor types such as DC-motors, Brushless DC- or AC motors, regardless of whether they are asynchronous or synchronous. Differences only exist in the field-weakening region at higher speeds.

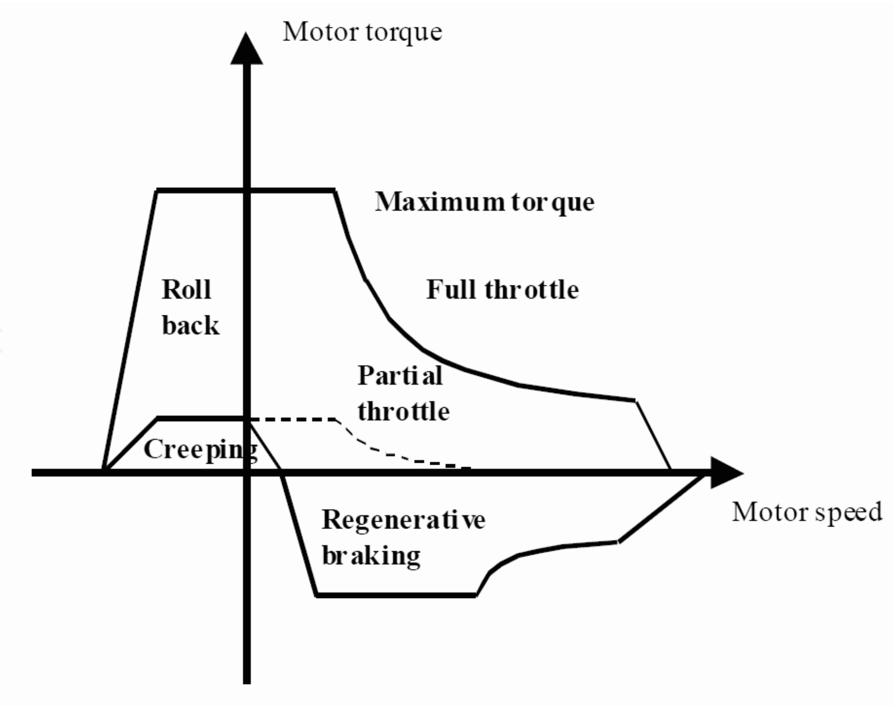
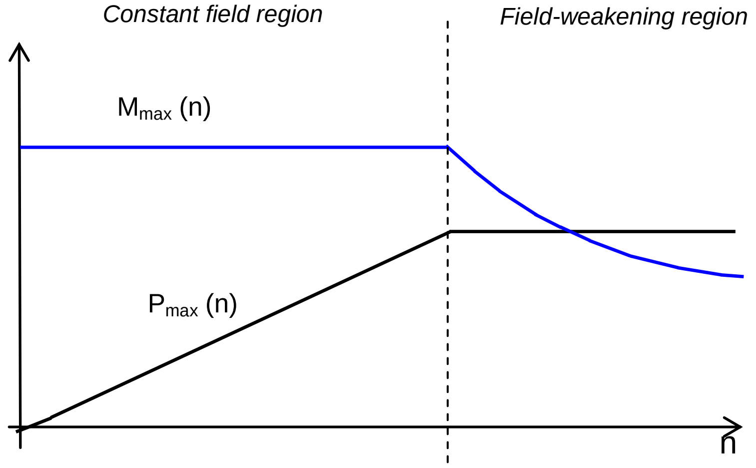



*Fig. 3.1: Typical torque/speed characteristics of speed-variable electrical drives.*




As illustrated in fig. 3.2 the efficiency we can achieve with an electrical drive is about **70%** (at *nominal* condition) when we do not take into account the efficiency of electrical power generation. As long as we are producing electrical power out of fossil fuels we would have to consider also the typical efficiency of conventional power plants achieving at the end even little overall efficiency with an electrical vehicle than with a conventional one. But if we think of renewable generation of electrical energy (e.g. by solar or wind power) the output is already electrical energy, which makes the overall energy balance of electrical cars much more competitive.

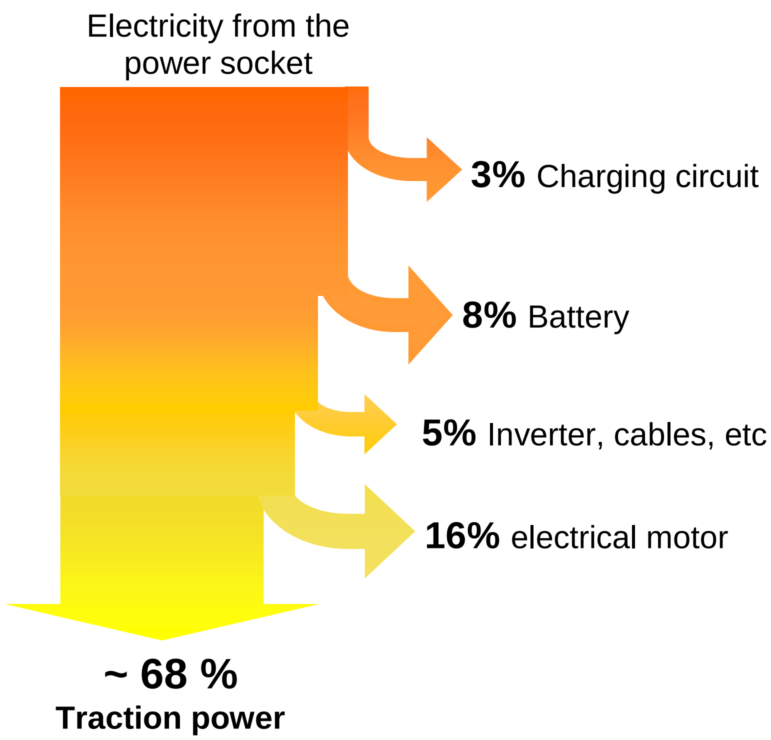



***Fig. 3.2: Efficiency of an electric drive at nominal conditions***

For *typical driving cycles*, electrical vehicles achieve efficiencies in the range of **50** to **60%**. In spite of this attractive value the area-wide introduction of electrical vehicles has not been possible yet because of the still unsolved problem of storing the electrical energy (see chapter “Batteries”) with reasonable density per weight and volume.

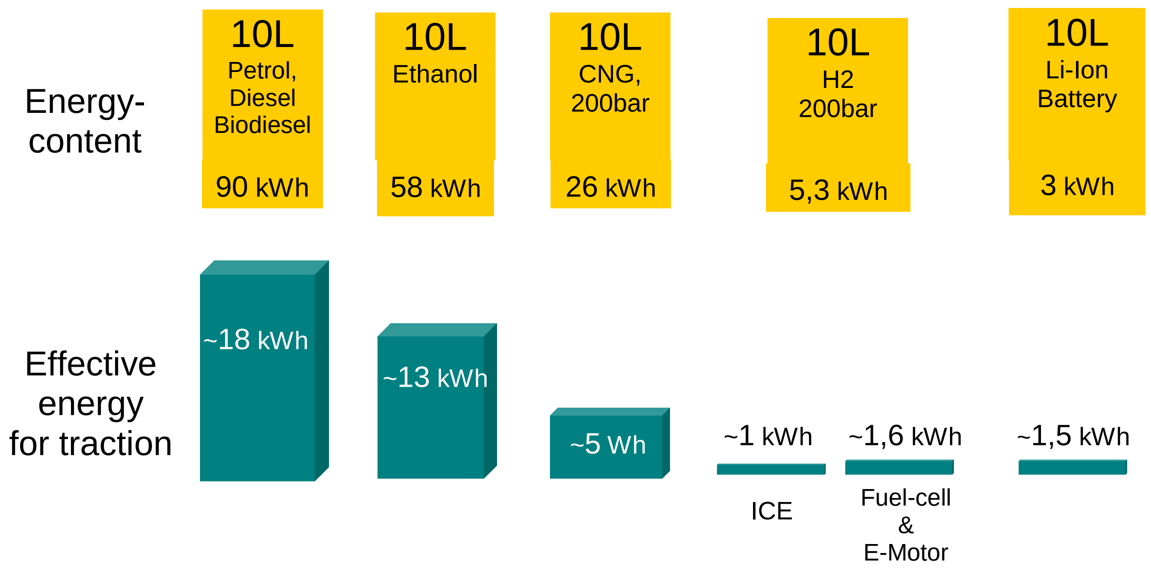



***Fig. 3.3: Energy content of fuels / batteries***

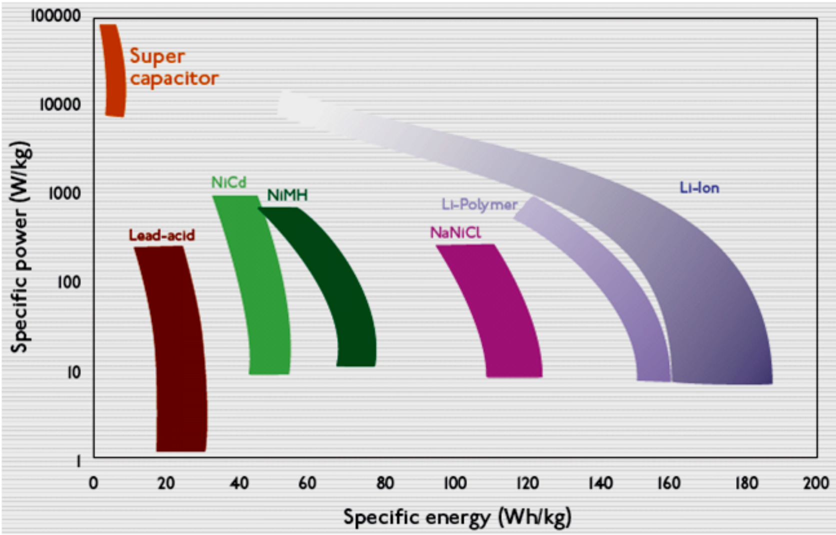
Figure 3.3 shows the energy content per liter for the different carriers of energy that can be used in vehicles, and the remaining energy available for traction.

## 4. Batteries for EVs and HEVs

Electrical energy storage is an essential component, but it is still the weakest component! Although a few electric cars with advanced batteries have been introduced, no current battery technology has demonstrated an economically acceptable combination of power, energy efficiency, and life cycle for high-volume production.

The *energy density* of a battery is a very  important feature. It is the amount of energy that can be stored in one kg of battery (Wh/kg). It depends on the type of battery (see graph below).

- Lead-acid: about 40 Wh/kg
- NiMH: about 80 Wh/kg
- Li-ion/Lipo: about 200 Wh/kg.




**Calculation example 1:**

A small EV can take 125 kg of batteries on board.

- A Lead-acid battery of 125 kg contains < 5 kWh of energy (equiv. of 0,5 liter fuel)
- A NiMH battery of 125 kg contains < 10 kWh of energy (equiv. of 1 liter fuel)
- A Li-ion battery of 125 kg contains < 25 kWh of energy (equiv. of 2,5 liter fuel)

Suppose this small EV needs 15 kWh (equiv. of 1,5 liter fuel) to drive 100 km. Then we can calculate the *maximum* range of a car equipped with each battery:

- Lead-acid: 33km
- NiMH: 66 km
- Li-ion: 166 km.

The price of the Li-ion battery pack (2010): more than 500 EUR/kWh or 12 500 EUR for 25 kWh!

**Calculation example 2:**

Compose a battery pack with Lithium ion cells for a small electric car. It will need 15 kWh of energy per 100 km in an European Drive cycle. The battery nominal voltage = 300 Volt.
The range should be 200 km.
How many cells do you need, and what is the capacity of each cell?
What would be the weight of the battery pack?

Solution:
For a range of 200 km at 15 kWh per 100 km, the battery energy must be 30 kWh.
Lithium cells have a nominal voltage of 3,7 Volt. We need 300/3,7 = 81 cells in series. Each cell should have 30 kWh/81 = 0,37 kWh. The capacity should be 0,37 kWh/3,7V = 100 Ah.
Note that this is the same capacity of the whole battery pack, as the cells are connected in series: 30 kWh /300 Volt = 100 Ah.
Since Li-ion batteries have a specific energy of 200 Wh/kg, the weight of the battery pack is: 30 kWh /200 Wh/kg = 150 kg.

A commercial car with similar specifications:

The Mitsubishi iMiEV has a range of 160 km (99 miles) with its 20 kWh lithium ion battery pack. The motor is a PMSM, power 47 kW, and 180 Nm torque. The max speed is 130 km/h.