Electrical Vehicle

CONTENTS

- Microgrids, e-Mobility and Electric Vehicle (EV)
- Car Motion Equation / Vehicle Wheel Force and Power
- EV classification
- Battery EV
- Hybrid EV
- Plug-in HEV
- Fuel Cell EV

Microgrids and e-Mobility

Growth of Electric Vehicles (EV) deployment is driven by several factors :

- Emissions reduction (especially in urban areas)
- Energy Efficiency (Electric motor more efficient than ICE)

EV is a major factor of diffusion of e-mobility, which in turns affects the microgrids development, since the charging infrastructure can be effectively built on them, using Renewable Energy Sources and Energy Storage .

The **two worlds of Power Systems and e-Mobility cross together**

These principles are summarized in few statements included in a report issued by the international organization IRENA

- **Source : IRENA (2017), Electric Vehicles: technology brief,**
- **International Renewable Energy Agency, Abu Dhabi.**

Renewable Energy and e-Mobility

***EV deployment requires four concurrent strategies**:*

(i) electrification of vehicles;

(ii) provision of sufficient charging equipment;

(iii) decarbonisation of the electricity generation;

(iv) integration of electric vehicles into the grid.

*EV deployment growth would allow a **higher share of variable renewable energy** (VRE) in the power system, via five areas of interaction:*

*(i) actively using the mobile battery storage system in the vehicle (**V2G**);*

*(ii) use of second-hand batteries in a "second life" role as stationary battery storage systems **(SLB);***

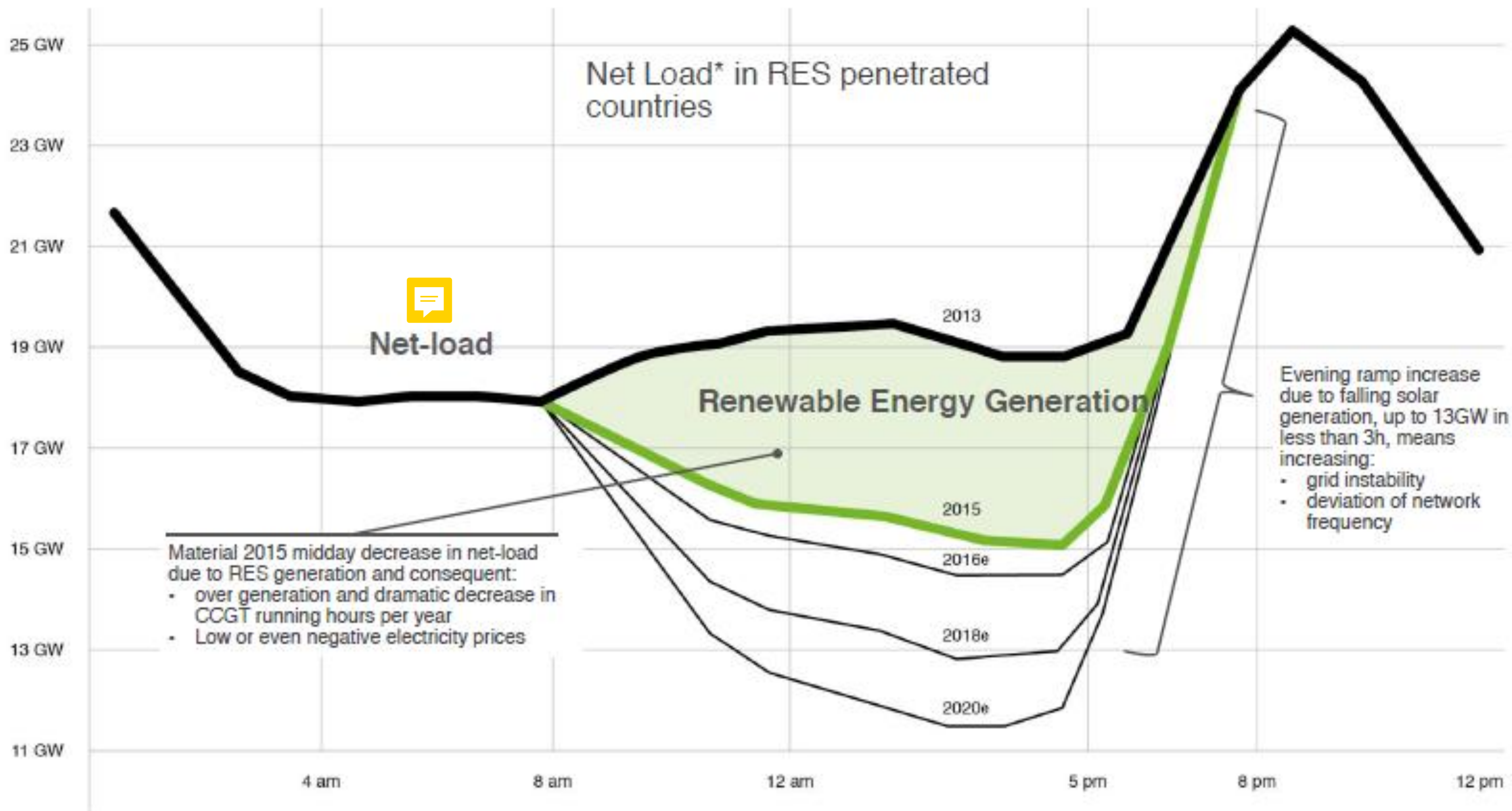
(iii) widespread deployment of charging technologies and infrastructure;

(iv) evolution in the charging behaviour of EV owners;

(v) provision of other ancillary services from EVs to the grid, such as frequency regulation, shaving peak demand, power support to enhance operation, and reserve capacity to secure the grid by stored energy in its batteries.

Renewable Penetration – Duck Curve

Renewables penetrated countries need Grid Support



* **Net Load** means the difference between the forecasted load and expected electricity production from RES. The Graph shows the net-load in a typical March day in California

Electric Vehicle

An electric vehicle (EV) is powered, at least in part, by electricity.

EVs can be divided into categories, with **different configurations of "Powertrain" and ways of refilling energy** :

- Battery Electric Vehicle **(BEV)**
- Plug-In Hybrid Electric Vehicle **(PHEV)**
- Hybrid Electric Vehicle **(HEV)**
- Extended Range Electric Vehicle **(EREV)**
- Fuel Cell Electric Vehicle **(FCEV)**

BEVs and PHEVs are referred to as **Electrically Chargeable Vehicles (ECV)**

EV characteristics :

- Equipped with one or more electric machines (EMs)
- Includes an energy storage system (ESS) other than the fossil fuel tank.
- EMs provide propulsion power (partially or full)

Vehicle wheel force and power

The instantaneous wheel power Pwheel (W) is the product of the instantaneous wheel force Fwheel (N) and vehicle speed v (m/s)

$$P_{wheel} = v\, F_{wheel}$$

Vehicle's wheel force is the sum of :
aerodynamic force, rolling resistance of tires on the road,

$$F\ wheel = \frac{\rho}{2} C_d A v^2 + C_r mgcos\alpha + mgsin\alpha + m\frac{dv}{dt}$$

road gradient, and acceleration force

EV Classification

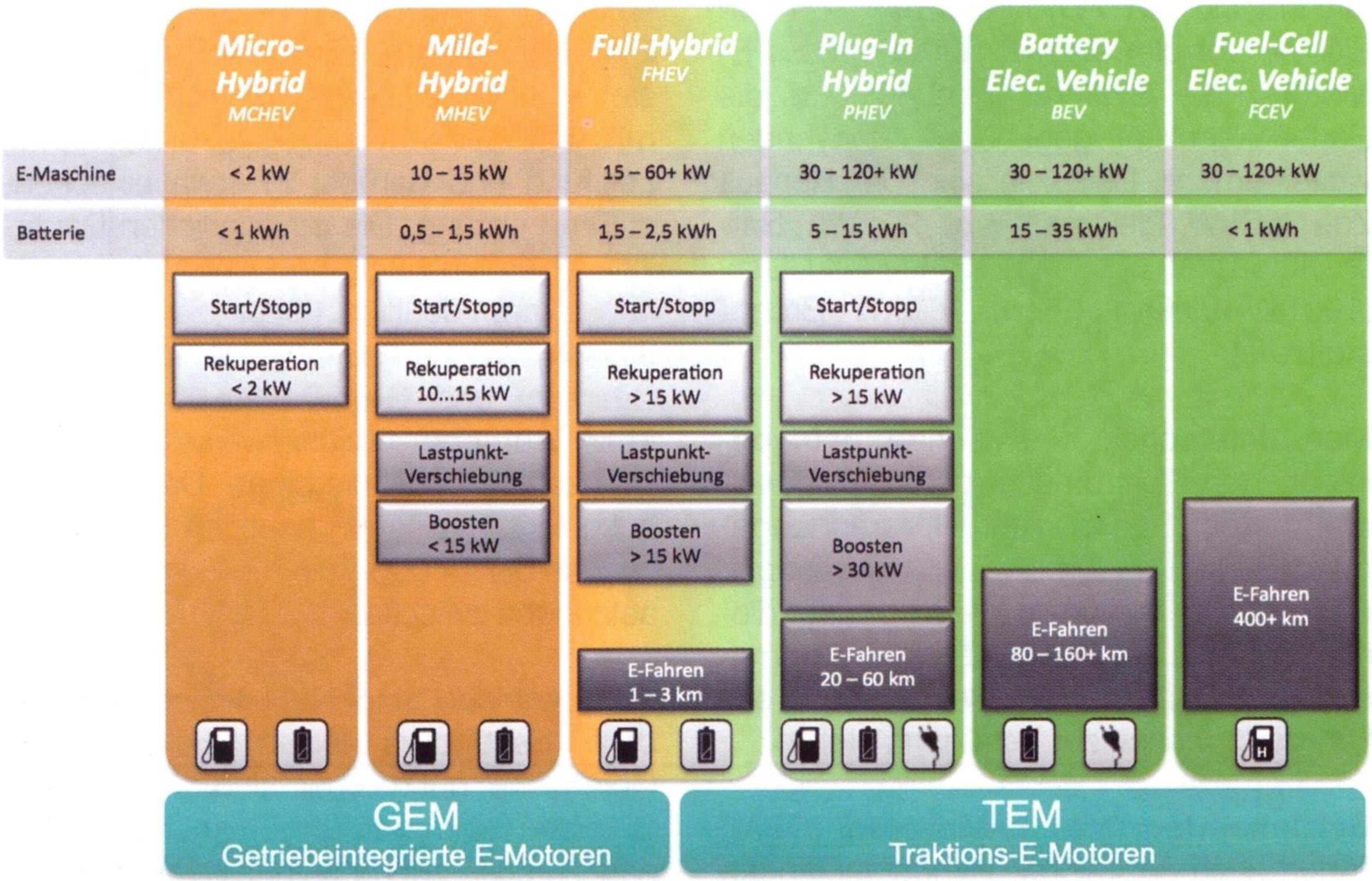
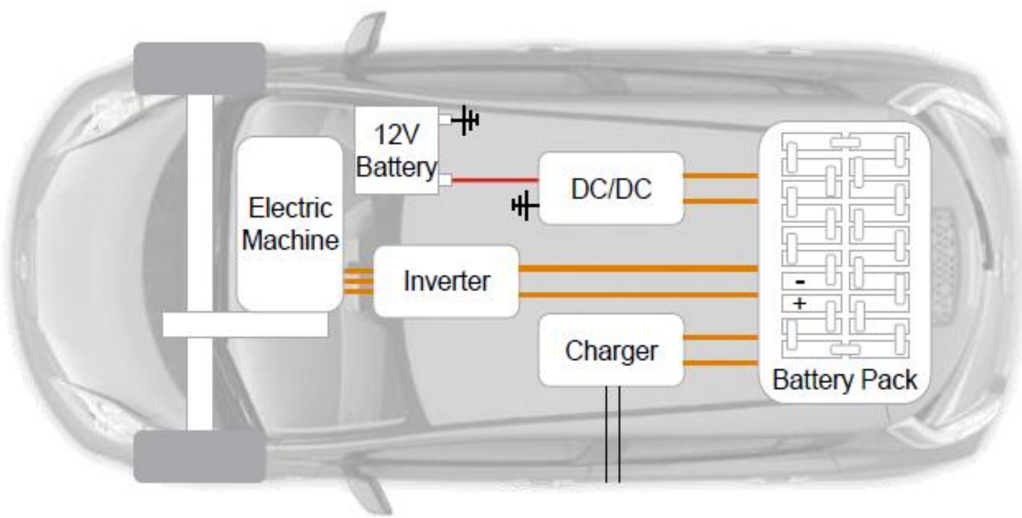


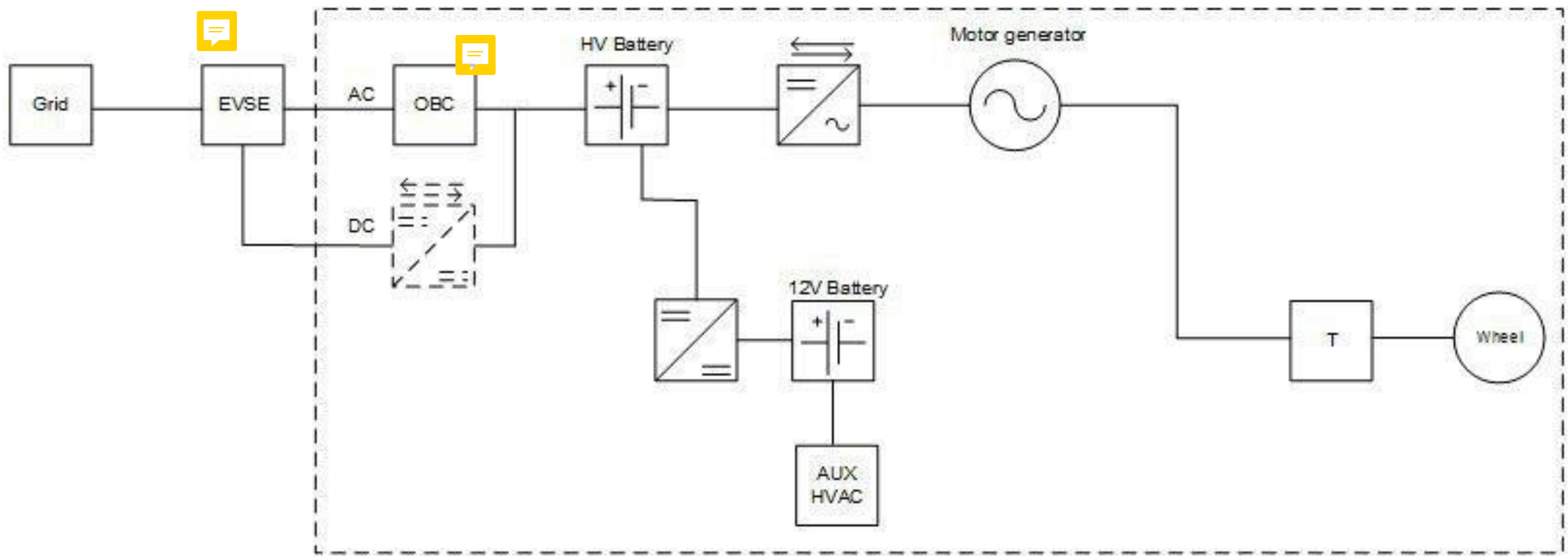
Bild 1: Hybridisierungsgrad und Anforderungen an den Elektroantrieb

Battery Electric Vehicles (BEVs)

- BEVs run exclusively on electricity provided by on-board HV batteries
- HV battery is charged by plugging into an EVSE, or charging station
- BEVs have no ICE (Internal Combustion Engine),
- Propulsion power is 100% supplied by Electric Motor
- BEV has zero tailpipe emissions
- Simple transmission system

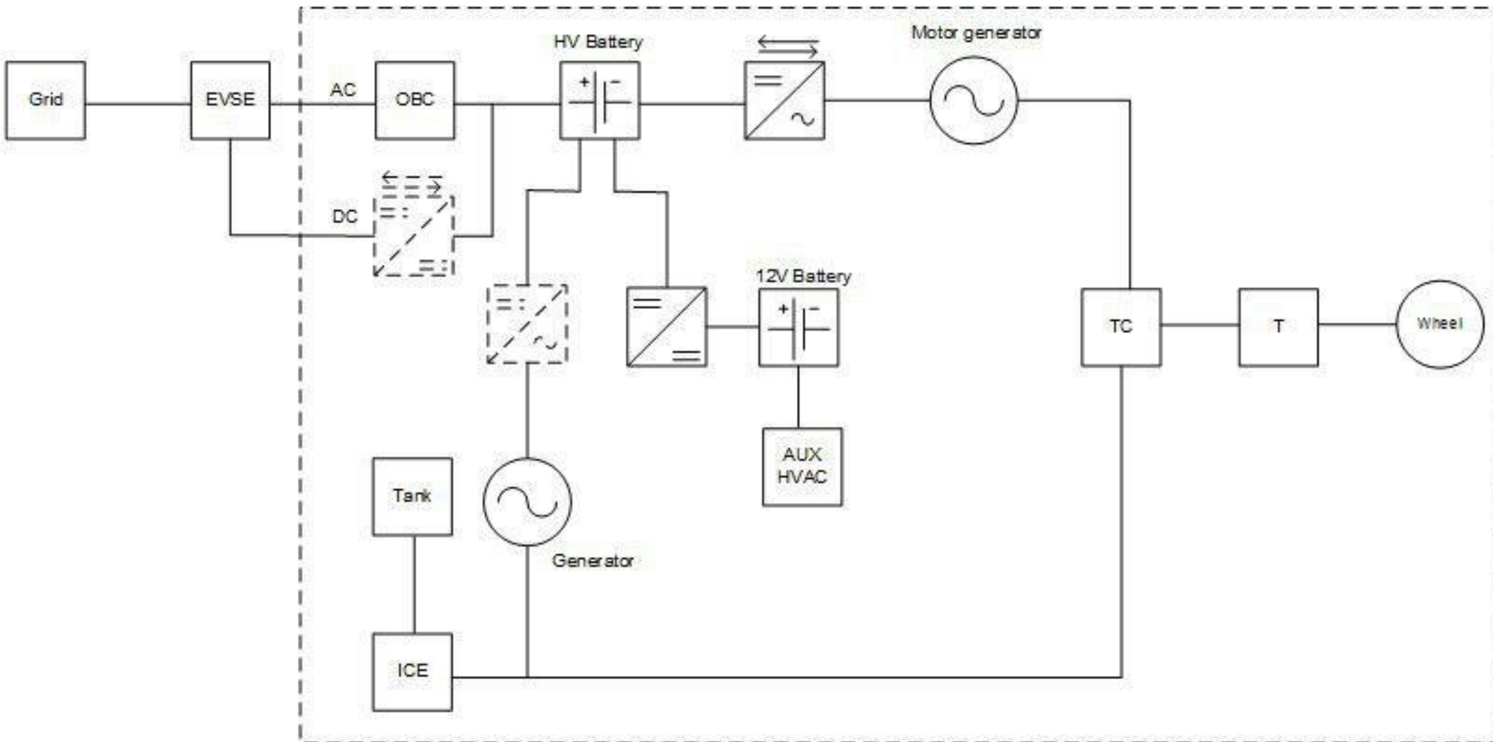


Battery Electric Vehicles (BEVs)



EVSE = EV Supply Equipment / AC Charging Station and DC Fast Charging
OBC = On Board Charger
T = Power Transmission
Aux HVAC = Auxiliary load, Heating, Ventilation, Air Conditioning

PHEV – Powertrain



A plug-in hybrid electric vehicle (PHEV) is an HEV that can be recharged from a Charging Station (EVSE in block diagram), since it is equipped with an On Board Charger (OBC)
PHEVs are provided with larger battery packs when compared to HEVs.
PHEVs can have any hybrid configuration.

HEV – Hybrid Electrical Vehicle

Hybrid electric vehicles (HEVs) have two different propulsion systems.

HEV’s Powertrain is formed by :

- **Conventional ICE** (Internal Combustion Engine)
- **Electric motor**, inverter and battery

They work together in order to improve performance and reduce emissions.

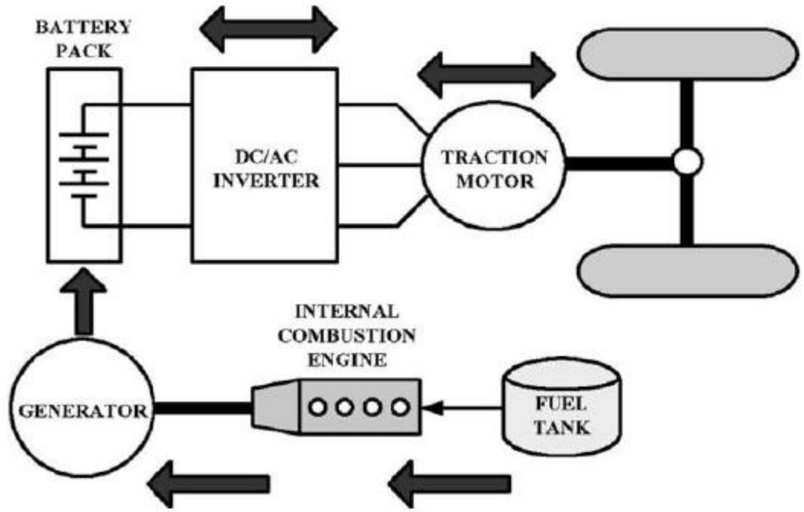
The market release of Toyota Prius at the beginning of 2000s started this trend.

Conventional hybrids, like Toyota Prius, cannot be plugged in and recharged.

Instead battery is charged by **regenerative braking** that converts kinetic energy into electricity. This energy is normally wasted in conventional vehicles.

Electric motor will work with the ICE to reduce fuel consumption, for example providing driving force during accelerations.

Series HEV – Powertrain



Series HEVs use an ICE to produce electricity by an EM generator which charges HV battery.

HV Battery feeds the electric motor that is responsible for traction through inverter.

The EM Traction Motor/Generator is also used to recharge the battery during deceleration and regenerative braking, since inverter is bi-directional.

Series HEV – Modes of Operation

The modes of operation of Series HEV are :

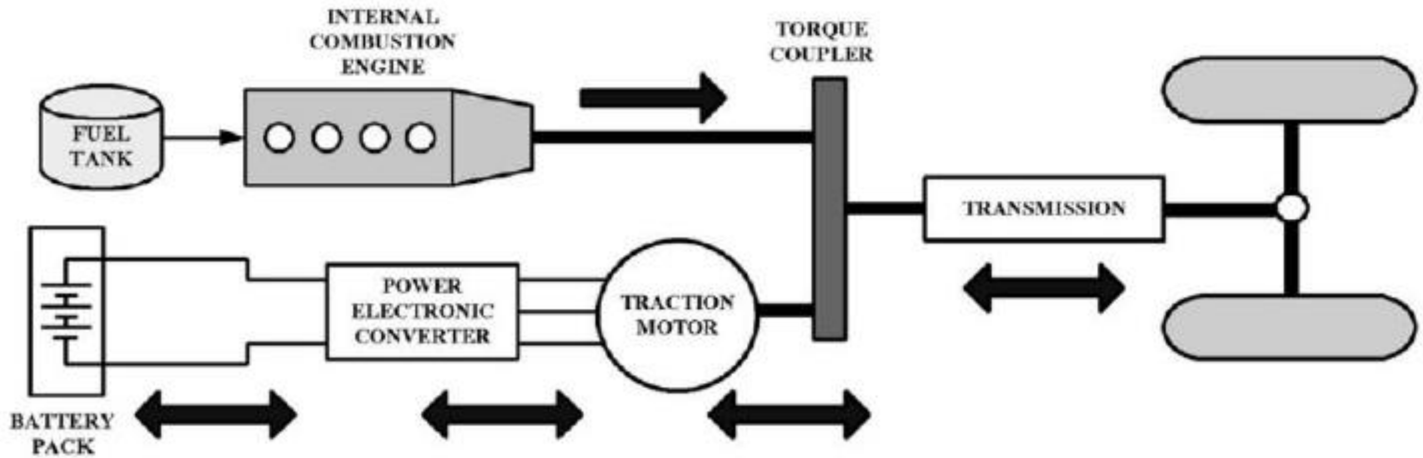
- Electric traction (only EM)
- Hybrid traction (ICE and EM)
- Battery Charging and No Traction
- Regenerative Braking

Drawbacks of Series HEV :

Two energy conversions

Both EMs have to be sized according to the maximum HEV power

Parallel HEV – Powertrain



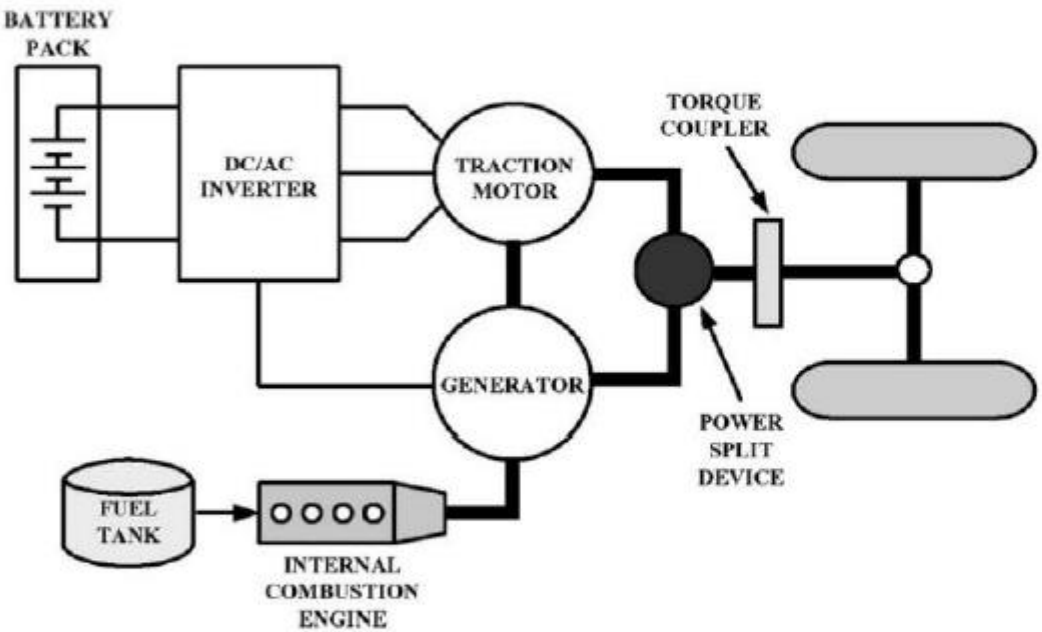
Parallel HEVs have two parallel propulsion systems to provide traction to vehicle.

Torque Coupler and Transmission couple EM motor/generator and ICE engine driving efforts to wheels.

Parallel Hybrid can operate in the following modes:

- ICE only traction
- Electric only traction
- Hybrid traction (ICE and EM)
- Regenerative Braking
- Battery charging from ICE

Series - Parallel HEV – Powertrain



This architecture is patented by Toyota.
A special transmission decouples the vehicle velocity from EM and ICE speeds.
ICE can be utilized simultaneously for vehicle propulsion and battery charging, and its operating point can be always optimized .
This HEV can also operate as a series or parallel vehicle only.

FCEV – Fuel Cell EV

Fuel Cell Electric Vehicles (FCEV) use an **electric motor** like a BEV, but store energy not recharging a battery.

FCEVs store hydrogen gas in a tank, at high pressure (up to 700bar).

The fuel cell in FCEVs combines hydrogen with oxygen from the air to produce electricity.

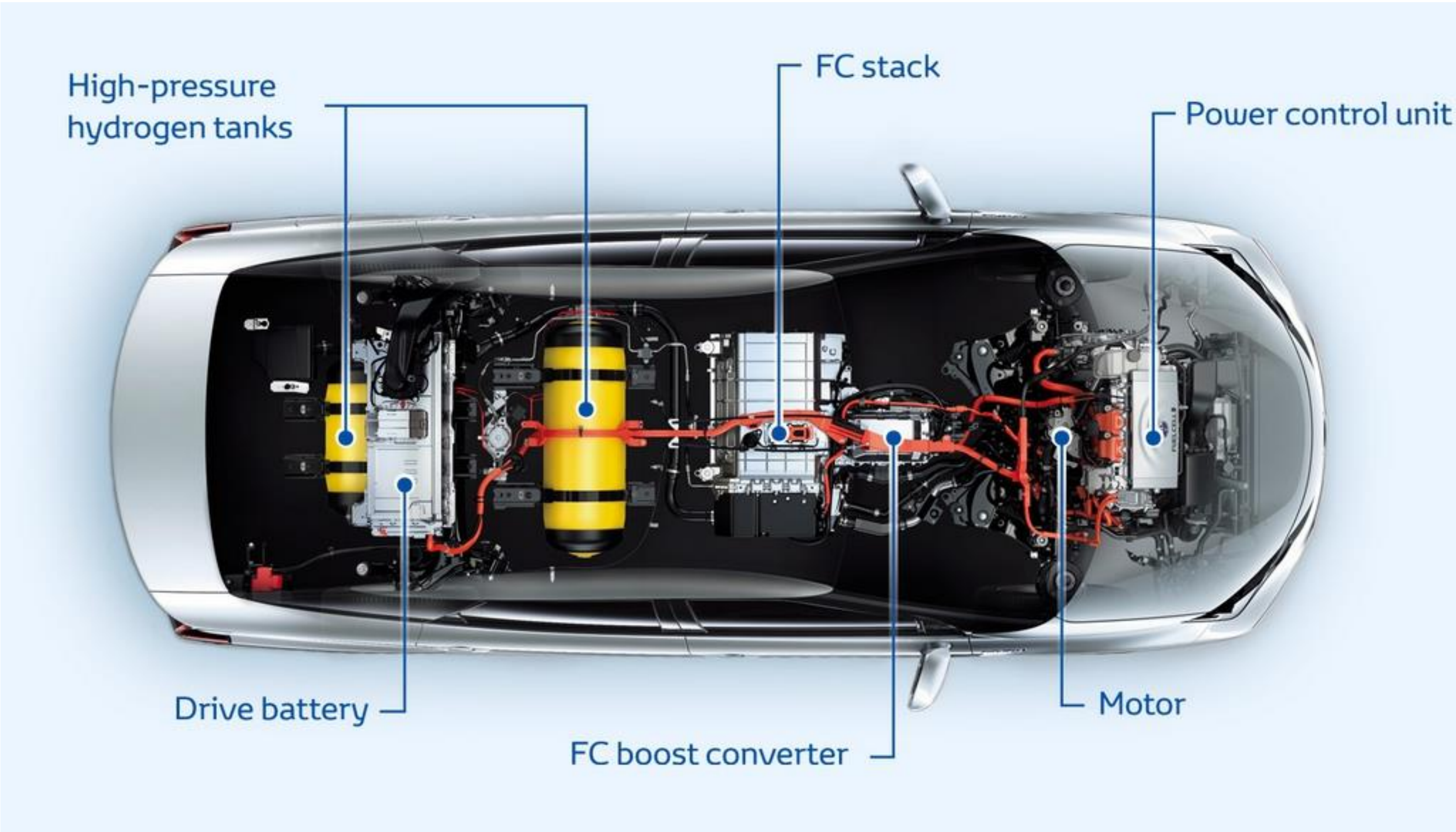
Powertrain of FCEV includes:

- High pressure Hydrogen Tank
- Fuel Cell Stack
- DC-dc Boost Converter, which steps up FC voltage to HV battery voltage
- HV Battery
- Bidirectional Traction Inverter
- Electric Motor/Generator

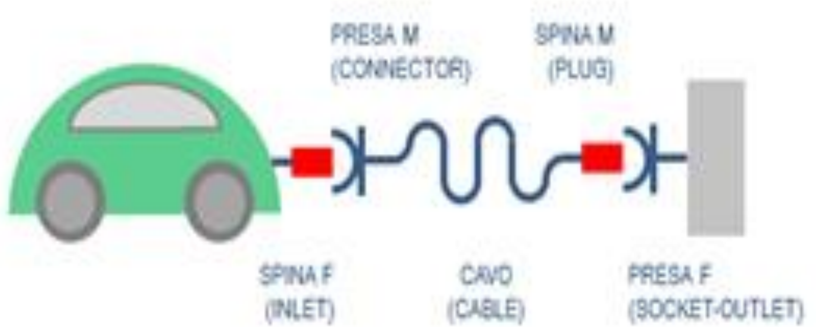
Advantages of FCEV :

- Range = more than 500km
- Short charging time = 5 minutes to refill tank with hydrogen
- Charging Infrastructure can be built on existing gas stations
- Fuel consumption = low, 3.6Liter/100km equivalent, on urban/highway cycle
- No gas/pollutants emission. From FCEVs tailpipe the only byproduct is water.

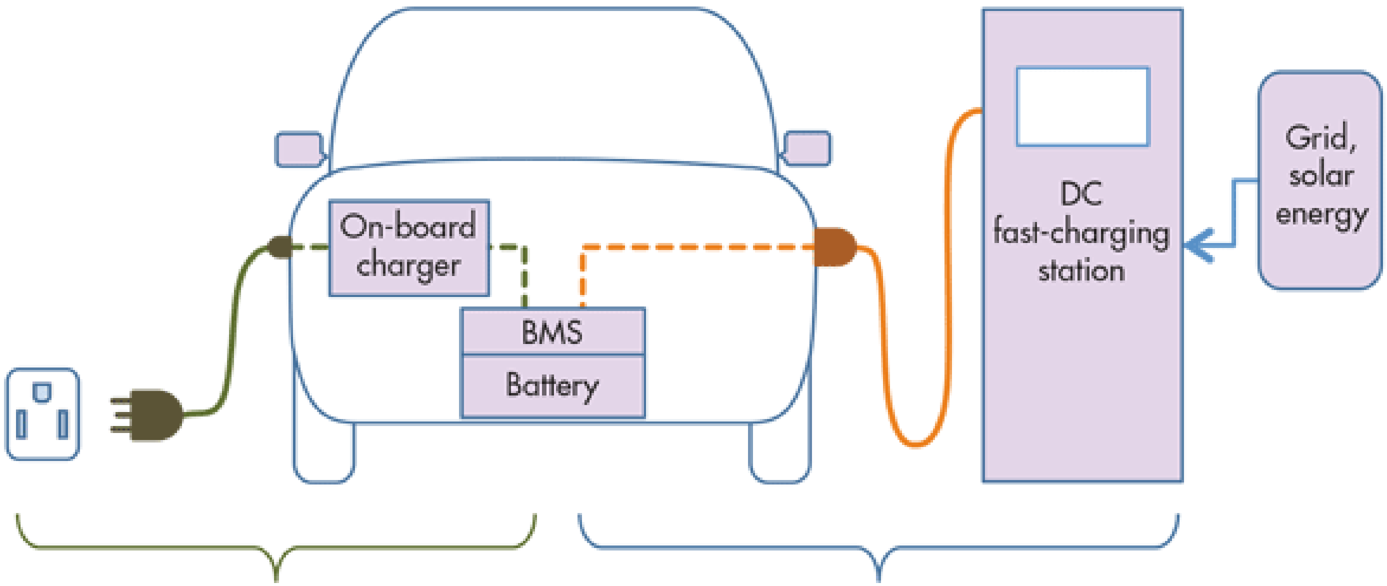
FCEV – Toyota MIRAI



BEV – Connection to Charging Station



EVSE – AC and DC Charging



AC charging

- Every vehicle has an on-board charger.
- Limited power, slow charging.

DC charging

- Infrastructure investment is shared among hundreds of users.
- Large power rating, fast charging.
- Capable of integration with renewable resources.

Numeric Examples – Battery Energy Storage Systems

Energy capacity at BOL	kWh	100
Voltage	V	400
Capacity at BOL	Ah	250
Current @1C	A	**250**
N.cycles with DoD 80% to EOL	n.	2000
EnergyThroughput at BoL	MWh	**160**
RTE @ 1C	pu	0,94
Losses of one full cycle @ 1C	kWh	6
N of cycles with DoD 80%	n.	100
Losses on 100 cycles @DoD 80%	kWh	480
Time of slow charge C4	h	3,2
Energy to charge SoC 10-90%	kWh	80
Slow charge power	kW	25
Current in slow charge C4	A	62,5
C rate slow charge C4	pu	0,25
Time of fast charge 2C	h	0,3
Energy to charge SoC 20-80%	kWh	60
Fast charge power	kW	200
Current in fast charge 2C	A	500
C rate fast charge 2C	pu	2

The time required to charge the battery from 10% to 90%, with a **slow charge** at C4 and the charge current
Note: C4 means a C rate equal to one quarter of the nominal charging current

$$I_{C4} = 250A \cdot 0,25 = 62,5A$$

$$P_{C4} = 400V \cdot 62,5A = 25kW$$

$$T_{C4} = 100kWh \cdot (0,9 - 0,1) / 25kW = 3,2h$$

The time required to charge the battery from 20% to 80%, with a **fast charge** at 2C and the charge current

$$I_{2C} = 250A \cdot 2 = 500A$$

$$P_{2C} = 400V \cdot 500A = 200kW$$

$$T_{2C} = 100kWh \cdot (0,8 - 0,2) / 200kW = 0,3h$$

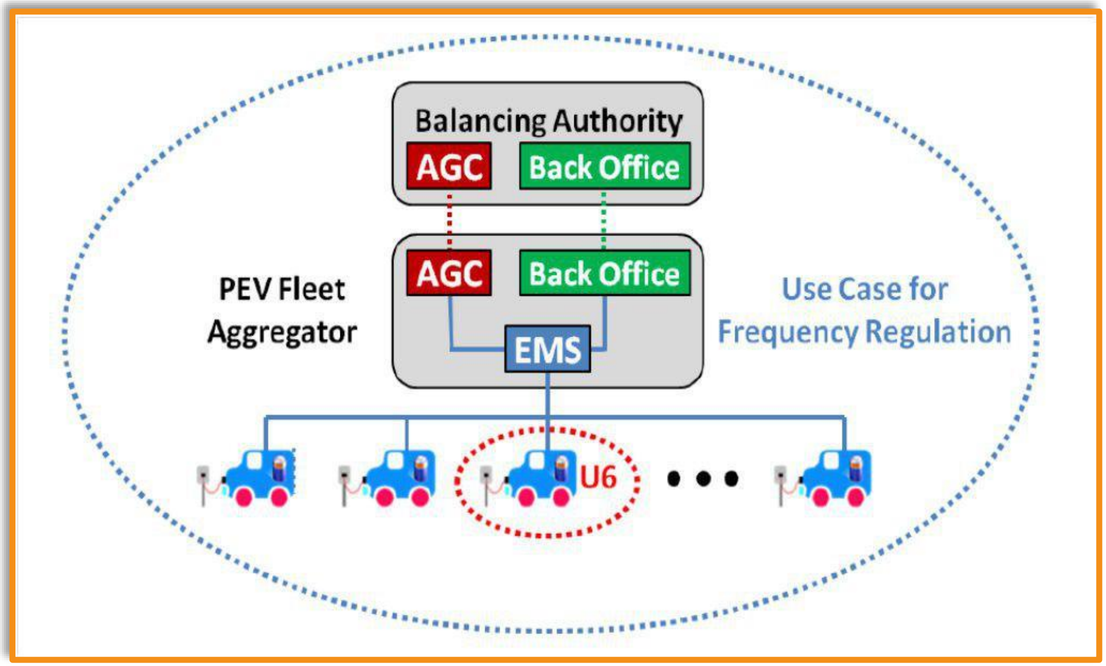
Smart Charging and V2G. Multi charging port stations

Multi charging port stations.

EV Fleets
Large Facilities:

- parking lots,
- shopping centers,
- corporate campuses,
- hotels and resorts
- public buildings

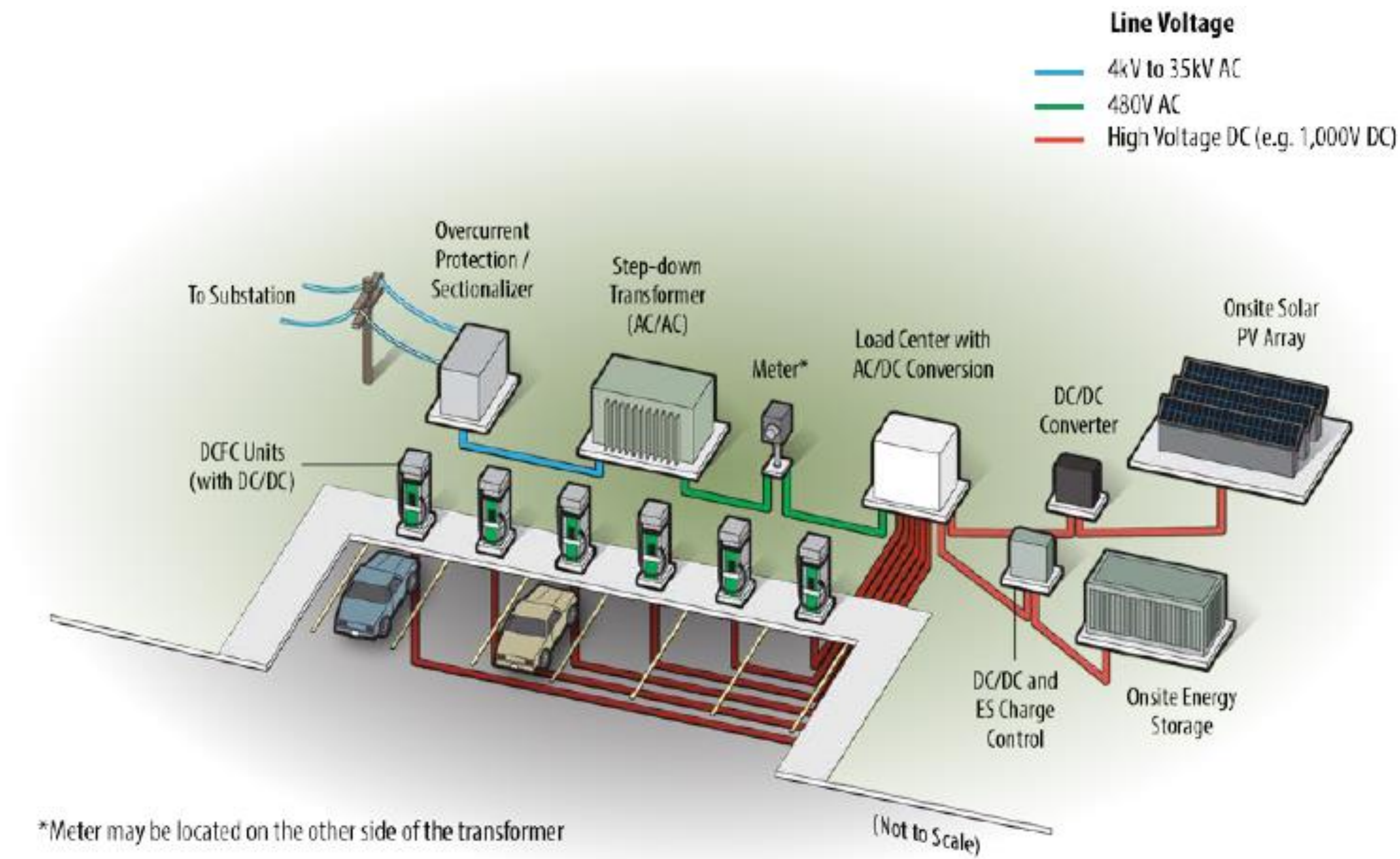
(hospitals, schools, military, government)



Service petrol stations
Multi dwelling units,
Large residential buildings
Residential houses

Multi Charging Point Station

Multi charging station. With Energy Storage, several DC-DC EVSEs connected to a DC bus



BEV – Advantages and Challenges

Advantages of BEV

- Zero emissions
- Silent driving
- High Torque at very low speed
- Simple transmission system (commercial BEVs have one speed transmission)
- O&M cost lower than gasoline cars
- EM is more efficient than ICE
- Better Tank-to-wheel and Well-to-wheel ratios

BEV Technology Challenges. Performance improvements are expected in these areas :

- Battery Lifetime (8-10 years, 100.000-150.000km)
- BEV Cost
- Recharge time (8hours by 3kW AC charger at home, 30min by 50kW DC fast charging)
- Mileage (200km with 30kWh battery)
- Battery Energy Density (more energy for the same weight)

Reference is made to an average commercial BEV, similar to Nissan Leaf, the most sold EV worldwide or Fiat 500e

Mileage - Comparison between ICE and BEV

The energy storage capability of vehicle fuel or battery can be measured by :

Energy Density (Wh/liter) and/or Specific Energy (Wh/kg)

Energy Density is the amount of energy stored by volume.
Specific Energy is the amount of energy stored by mass (weight)

Fossil fuel, gasoline = 12,9 kWh/kg and 9.5 kWh/liter
Battery pack = 30kWh/300kg = 0.1kWh/kg (lithium ion, Nissan Leaf)

Mileage depends on driving cycle, it can be assumed on average:
Gasoline car = 15 km/liter = 0.63 kWh/km → 20.4 km/kg
BEV = 0.15-0.20 kWh/km; 0.18 kWh/km → 1.8 km/kg

Gasoline has higher specific energy, but BEV has better efficiency (3-4 times) when compared on mileage

Battery Aging

Battery aging process depends on **calendar aging** and **cycle aging**.
Consequence of aging is reduction of capacity (Q) and increase of resistance

Main aging influence factors are:

- Time (t)
- Temperature (T)
- State of Charge (SoC)
- Depth of Discharge (DoD)
- Charge/discharge current (C-rate)
- Charge (or Energy) Throughput (Ah or kWh)

Cycling

$$Q_{loss\%} = B(SOC, T, C-rate)e^{-\frac{E_a(SOC,T,C-rate)}{RT}} Ah^z$$

Calendar

$$Q_{loss\%} = A(SOC, T)e^{-\frac{E_a(SOC,T)}{RT}} t^z$$

Numeric Examples – Battery Energy Storage Systems

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Current in fast charge 2C	A	500
C rate fast charge 2C	pu	2

Energy Throughput available at the beginning of life (in MWh)

$$E_{thr} = 0{,}8 \cdot 2000 \cdot 100kWh = 160MWh$$

The charge and discharge current at 1C

$$I = 100000 / 400 = 250A$$

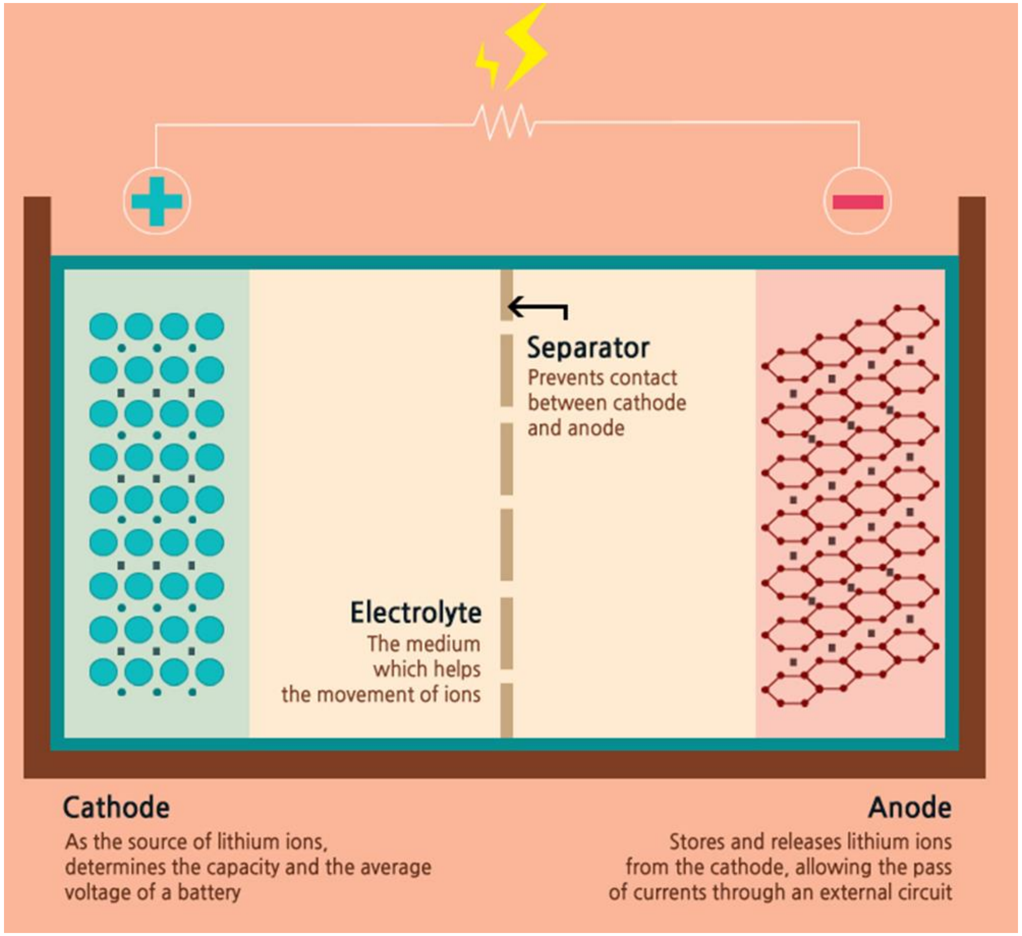
The energy losses during a full cycle from SoC = 0% to SoC = 100% and back to zero, at 1C speed

$$P_L = 100kWh \cdot (1 - 0{,}94) = 6kWh$$

The energy losses during 100 charge and discharge cycles (it is assumed that the battery capacity does not degrade during these cycles), going from SoC = 10% to SoC = 90% and back, again at 1C

$$E_L = 100kWh \cdot (0{,}9 - 0{,}1) \cdot (1 - 0{,}94) \cdot 100 = 480kWh$$

Lithium Ion Battery (LIB) - Schematic



State of the art
Liquid electrolyte LIBs
State of the art LIBs use

Oxide Cathodes
(particularly NMC and NCA),

Liquid electrolytes
with additives
to improve coulombic efficiency

Carbon Anodes
with 3-5% silicon added
to improve energy density

Current LIB achieve a gravimetric energy density of 200-260 Wh/kg
By improving same technology it can reach up to 400 Wh/kg

Future Trends in Lithium Battery Technology Development

Objectives

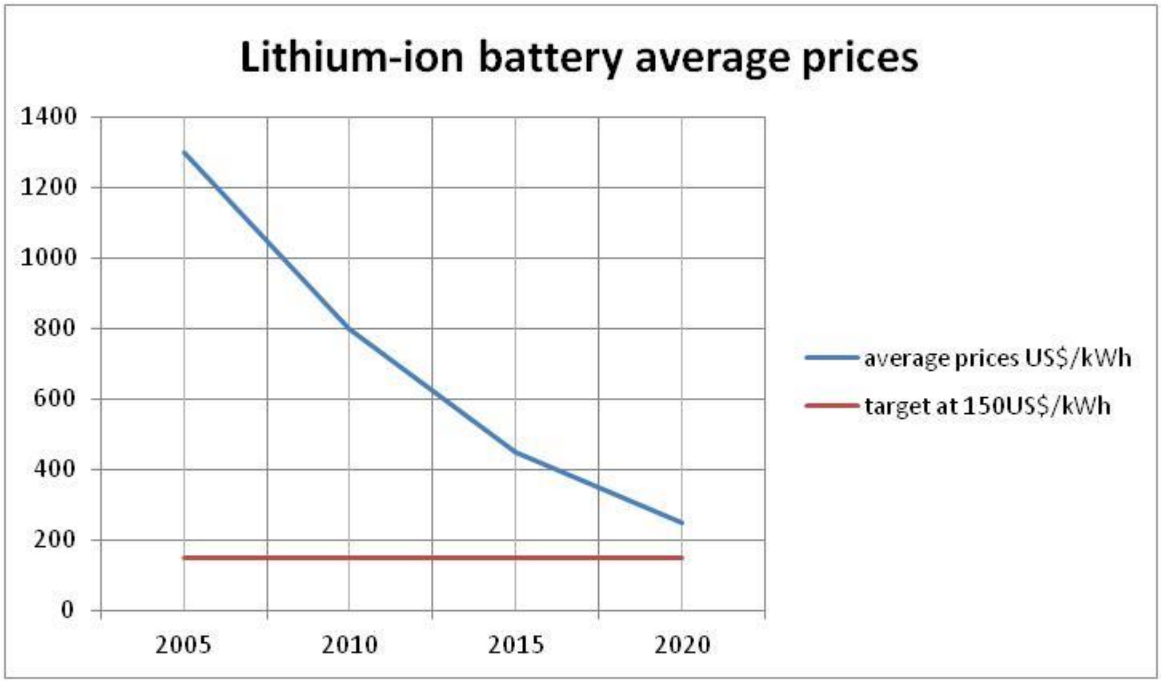
- Increase the energy density of battery cell (from 200 to >500Wh/kg)
- Improve the energy conversion efficiency
- Improve safety (reduce and eliminate fire hazard)
- Extend battery lifetime (number of cycles, energy throughput)
- Extend Electrical Vehicle range (from 200km up to 700km)
- Reduce manufacturing cost (at 100 US$/kWh EV in parity with ICE car)

Technology Steps

- **State of art** : Li-Oxide cathode (NMC), liquid electrolyte, Carbon anode
- From 100% Carbon Anode to **Silicon-Carbon Anode**
- From Liquid to **Solid State Electrolyte**, with all lithium anode
  (no fire hazard)
- Lithium-Sulphur Cathode
- Lithium air (Li-O2)

BESS – Lithium–ion Battery Price Decline

Lithium-ion battery prices are declining faster than expected, probably due to high production growth by electric car manufacturers.
A cost of 200 US$/kWh has been achieved in 2018 by market leaders.

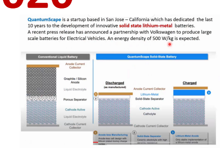


Automotive market.
EV Battery Price decline

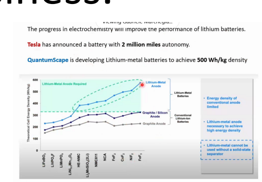
Lowest prices in 2014
300 US$ per kWh

Time interval :
2005 – 2020.

Projection :
150 US$/kWh by 2020



Battery price reduction will transfer from automotive to stationary energy sector.
Economy of scale and Learing Rate will push cost down as it happened in solar business.
Utility scale PV power plant CAPEX dropped in 15 years to less than 0,5€/Wp



A Li-ion battery system cost can be split in battery pack, inverter, BoS (balance of System)
Based on BNEF reports, Vartiainen_et_all estimate a CAPEX of 275 €/MWh for a utility scale storage system, 80MWh/20MW, in year 2019.
Battery pack: 140 €/kWh, inverter: 16 €/kWh, BoS: 119 €/kWh

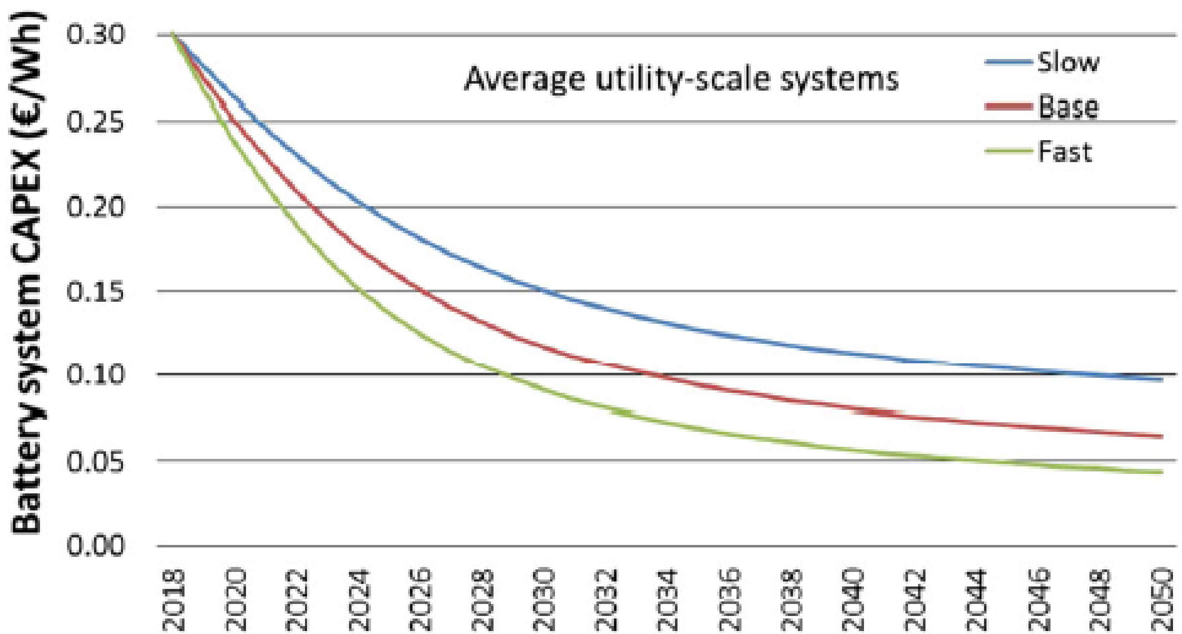


FIGURE 7 Li-ion battery system capital expenditure (CAPEX) price development projection for the years 2018 to 2050 for different growth scenarios, prices in 2019 real money without value added tax

EV Power train – Battery, Inverter and Traction Electrical Machine

CONTENTS

- Racing cars Power train / Formula E
- Power Semiconductor Devices (IGBT, MOSFET, Si and SiC)
- Power Semiconductor Devices. Power Losses
- Power Conversion Systems - PCS Configurations (2-level and 3-level inverter)
- Heat Transfer
- Power Density – PCS and Electrical Machines
- EM drive control
- EM Motor/Generator (types, formulas, graphs)

Formula E Power train / Battery

	Gen1	Gen2
Lithium ion – NMC / Nickel Manganese Cobalt electrochemistry	NMC	NMC
Stored energy	32 kWh	
Available energy	28 kWh	54 kWh
number of battery cells	165	209
Battery weight	320 kg	385 kg
Min weight of car (including driver)	880 kg	900 kg
Energy density, available energy/weight Wh/kg	87,5	140,3
Cooling method	liquid cooled	liquid cooled
Dc Voltage nominal	610 Vdc	
Peak permitted regenerative power	150 kW	250 KW
Peak permitted power (race mode)	170 kW	200 kW
Peak permitted power (qualifying mode)	200 kW	250 kW

Battery Gen1 was supplied by Williams Advanced Engineering to all Formula E racing teams
Battery Gen2 is supplied by McLaren dvanced Engineering to all Formula E racing teams

Power Semiconductor Devices
(Trade off conduction / switching losses)

Trade-off between conduction losses and switching losses.

The improvement of technology aims at total loss optimization, which in turn means :

IGBTs : to minimize the product **Vcesat x Eoff,**

since the two factors are respectively proportional to conduction and switching losses

MOSFETs : to minimize the product **Rds on x Q gd,**

since the drain-source on resistance is proportional to conduction losses and Qgd gate-drain charge, is proportional to switching losses.

Formula E / Gen1 Battery

165 Lithium Pouch Cells held in 5 modules
Cell maker : XALT / Lithium ion NMC cells, (3.7V, 53Ah, 196 Wh)
165 x 3.7V = 610V / 196Wh x 165 = 32kWh
Indirect battery cell liquid cooling, by dielectric fluid
15 CMUs individually monitor Voltage, Cell Temp, Current and other operating parameters

Power Semiconductor Devices (Material : Si and SiC)

Most semiconductor power devices are currently made by Si, while SiC is emerging as a new and promising technical alternative, especially because of the very low power losses.

But the advantages of SiC devices with respect to Si are several.

SiC has a **very high dielectric strength** and the breakdown voltage is consequently high, up to 10 times that of Si.

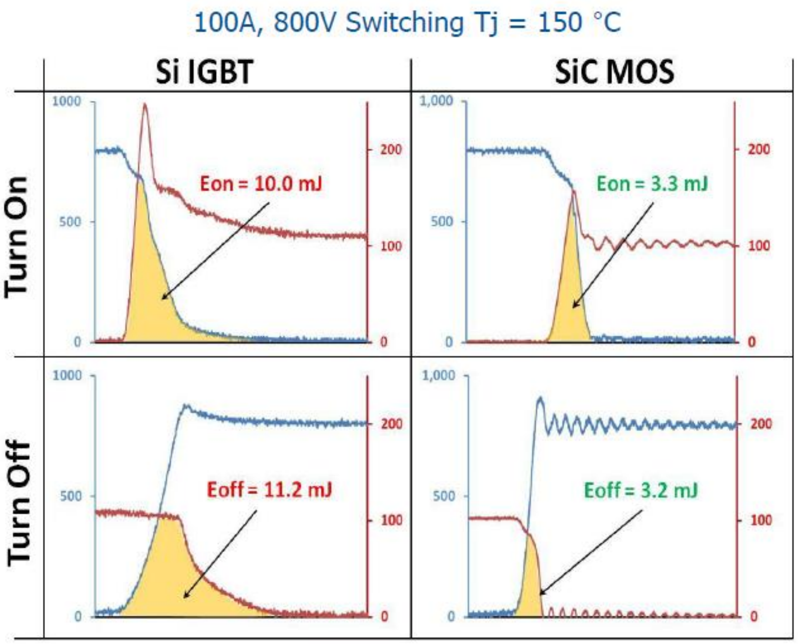
This feature allows to use chips with low specific on-resistance and faster switching properties at the same voltage level.

The **thermal conductivity is higher than Si** (about 3 times), which allows to operate at higher current densities.

Since SiC has not minority carriers it presents almost zero Reverse Recovery Charge (Qrr), which results in very low switching losses of the SiC diodes.

Conduction losses of SiC MOSFET are lower than in Si IGBT.

Power Semiconductor Devices (Material : Si and SiC)



PCS - Power Density (W/dm3)

Liquid Cooling , SiC MOSFET
Power density = 200kW / 1,4 dm3 = 143 kW / dm3

PCS - Power Density (W/dm3)

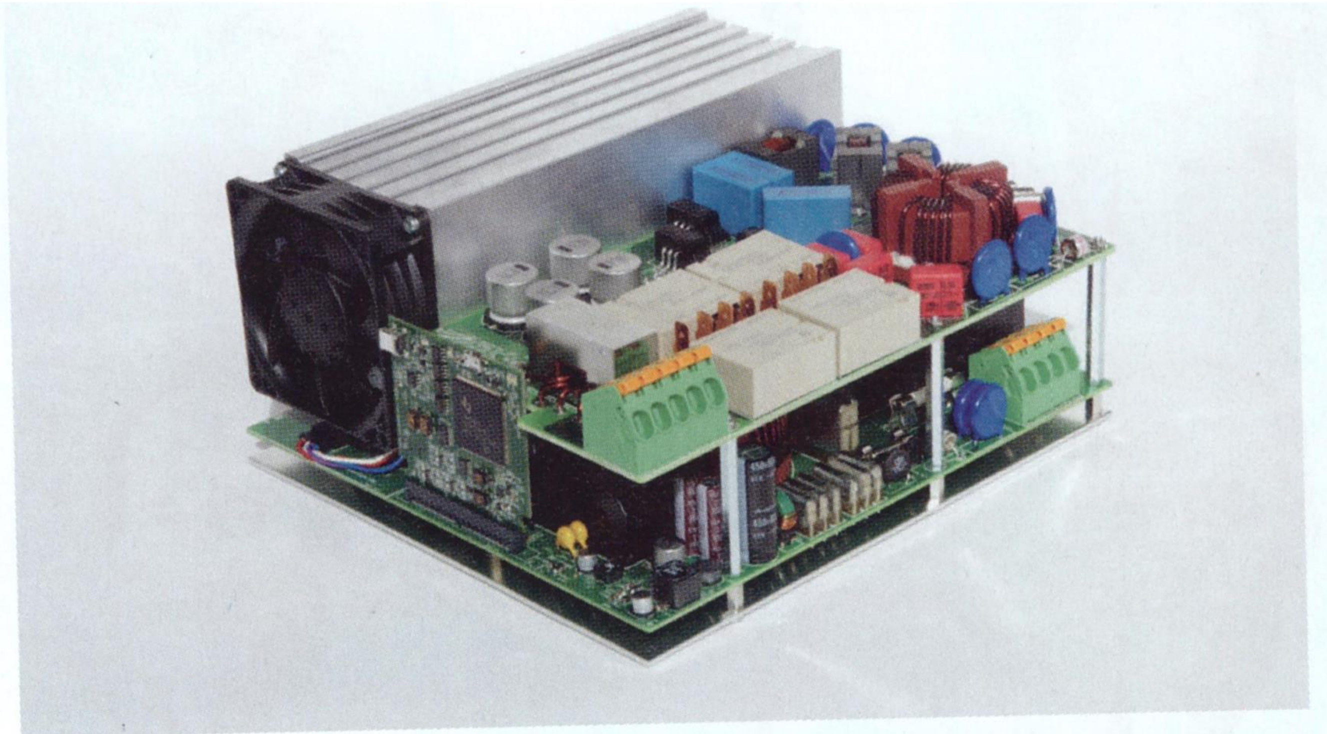


Figure 4: 10kW UPS Inverter with size of 23 cm x 21 cm x 10 cm and a weight of 4,5 kg

Cooling = forced air convection
Power density = 10kW / (2.3 x 2.1 x 1) = 2.3 kW / dm3

Vehicle / Torque vs speed / ICE and EM

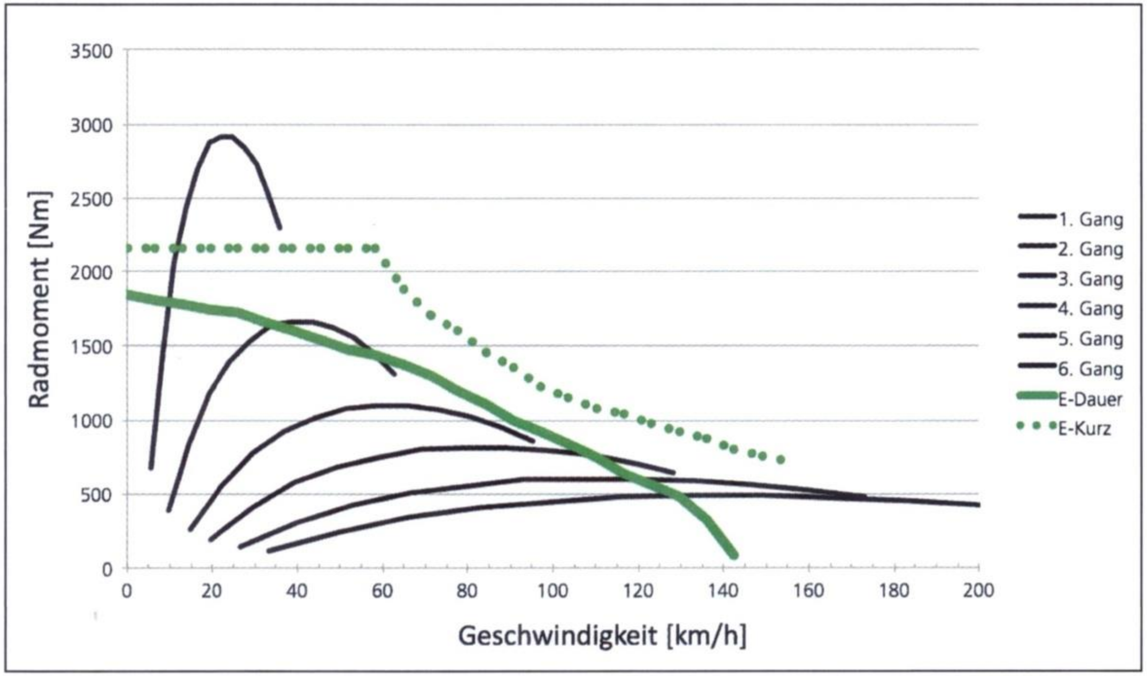
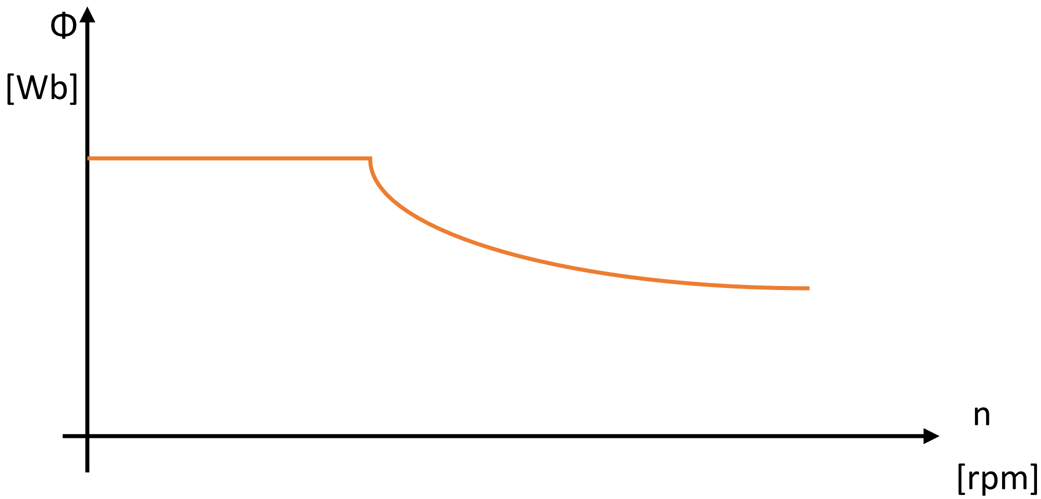
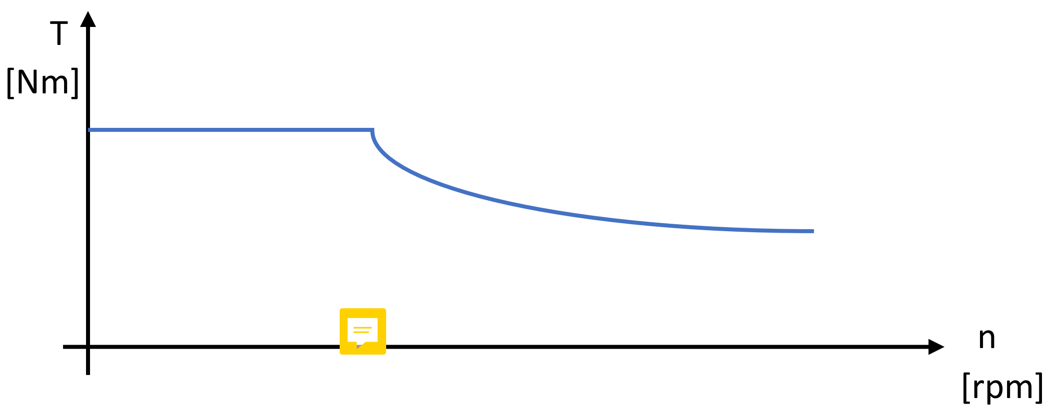


Bild 3: Verlauf des Raddrehmoments eines Verbrennungsmotors (schwarz) und eines Elektromotors (grün)

X axis : vehicle speed (km/h)
Y axis : Torque (Nm)
Black lines : ICE engine curves, 6 speed transmission
Green lines : EV curves, ideal /continuous ____ and peak/short duration - - - - -

EM Motor / EV Drive Control (1)





EV Traction Motor Drive Control

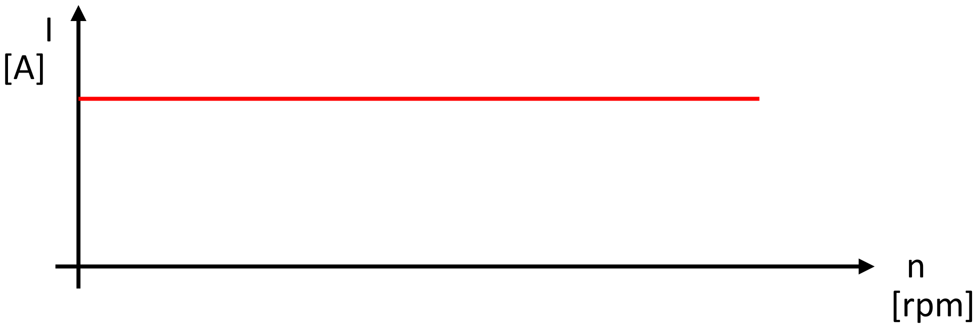
Torque (Nm) is held constant up to a vehicle speed of 40 – 60 km/h

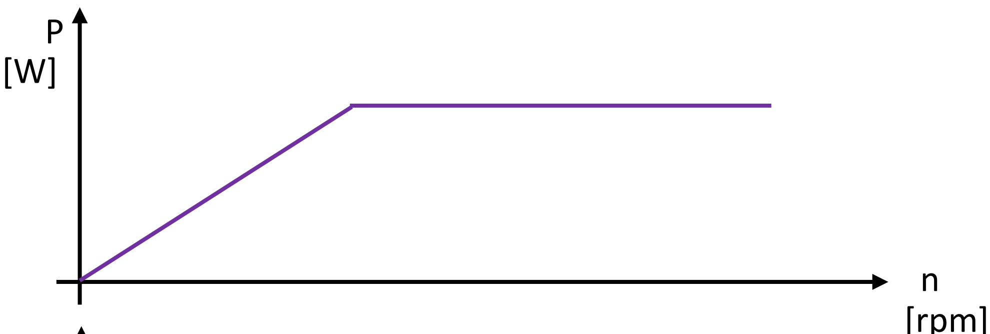
Magnetic flux ϕ is controlled in the same way.

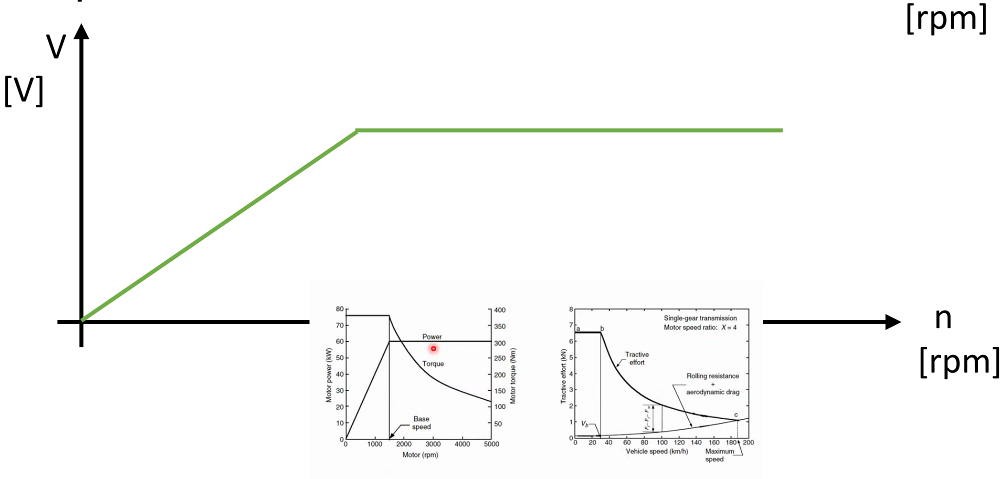
Above that transition speed, when motor power achieves max value, Power is kept constant, while Torque and Flux decrease according to law :

P = T x n (rpm) = constant

EM Motor / Drive Control (2)







EV Traction Motor Drive Control

Up to a vehicle speed of 40-60 kph inverter feeds power to motor with increasing output power and keeps the ratio

$$V/f = \text{constant} \approx \Phi$$

Voltage and frequency increase in proportion with speed n (rpm)

Above the transition speed , power and voltage are kept constant.

Motor current I is kept constant
Torque T and Flux ϕ follow the law :

$$T = k\,\phi\,I$$

EM motor/generator types utilized on EV

- PMSM – Permanent Magnet Synchronous Machine
- ASM – Asynchronous Machine
- SRM – Switched Reluctance Machine

High power EM are often PMSM type, with outer diameter up to 350mm and speed up to 20.000rpm

Construction (typical) of an EM – PMSM, with high power and high speed

- Distributed stator windings, copper wire
- Stator core made by non oriented silicon iron steel, with 0.1mm strip thickness
- Liquid cooling
- Rotor core made by laminated core segments, retaining RE magnets (NdFeB or SmCo)
- Weight/power ratio less than 1.0 kg/kW, referred to continuous power

Type of EM	Rotor surface speed	Rotational speed
PMSM	70 – 90 m/s	12.000 – 14.000 rpm
ASM	140 – 160 m/s	20.000 rpm
RSM	200 – 240 m/s	30.000 rpm

EM / Motor and Generator / Construction

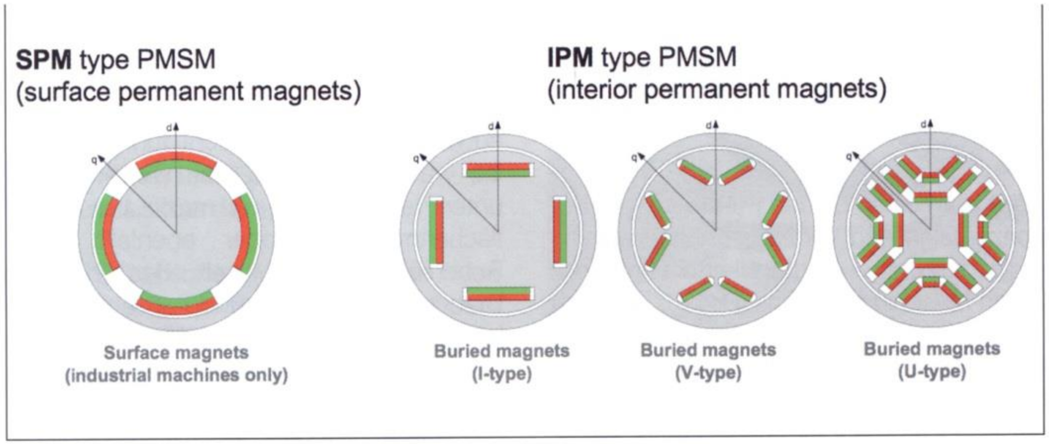


Bild 7: Rotorvarianten von PM-Synchronmaschinen

Bild 6: Verteilte Wicklung (oben) und konzentrierte Wicklung

PMSM can be built according to different design
Rotor construction varies with position of PMs

SPM = Surface Permanent Magnets
IPM = Interior Permanent Magnets

Stator windings can be made :

Distributed, for high speed
Concentrated, low cost

EM / Basic Design Formulas

Design Formulas defining EM Rated Power and Torque

$T = k1 \cdot (B \cdot A) \cdot (d^2 \cdot l) = k1 \cdot (B \cdot A) \cdot \text{EM Volume}$; **Torque = (Nm)**

The product (B·A) represent the utilization intensity of the magnetic and conductor materials . A is the linear current density (A/m) in the EM motor windings.
To obtain a high Torque-to-Volume ratio (= Nm/dm3) the EM design requires high B and A, which in turn determine higher power losses.

$P = T \cdot 2\pi \cdot n = T \cdot 2\pi \cdot f/p \approx k2 \cdot T \cdot f \approx k1 \cdot k2 \cdot (B \cdot A) \cdot \text{EM Volume} \cdot f$; **Power (VA)**

$P / \text{EM Volume} \approx k3 \cdot (B \cdot A) \cdot f$ **Power-to-volume = (VA/m3)**

The rated power of EM is the product of Torque by frequency (or rotational speed)
The Power-to-Volume (VA/m3) and the Power-to-Weight (VA/kg) of EM is proportional to the product of frequency by the utilization intensity of materials (B·A)

EM / Iron Power Losses

In a rotating EM machine the iron power losses for electrical steel can be calculated

$$\mathbf{Pfe = Kh \cdot (B^2 \cdot f) + Kc \cdot (B \cdot f)^2 + Ke \cdot (B \cdot f)^{3/2}}$$

Where

- Pfe = W/kg is specific iron loss
- B (Wb/m2) is peak magnetic flux density
- f (Hz) is frequency
- Kh is coefficient of hysteresis losses
- Kc is coefficient of classical eddy current losses
- Ke is coefficient of excess eddy current losses

An increase of operating **frequency or flux density** determine a higher specific iron loss.

Electric Machine - Motor and Generator Weight/Power Ratio

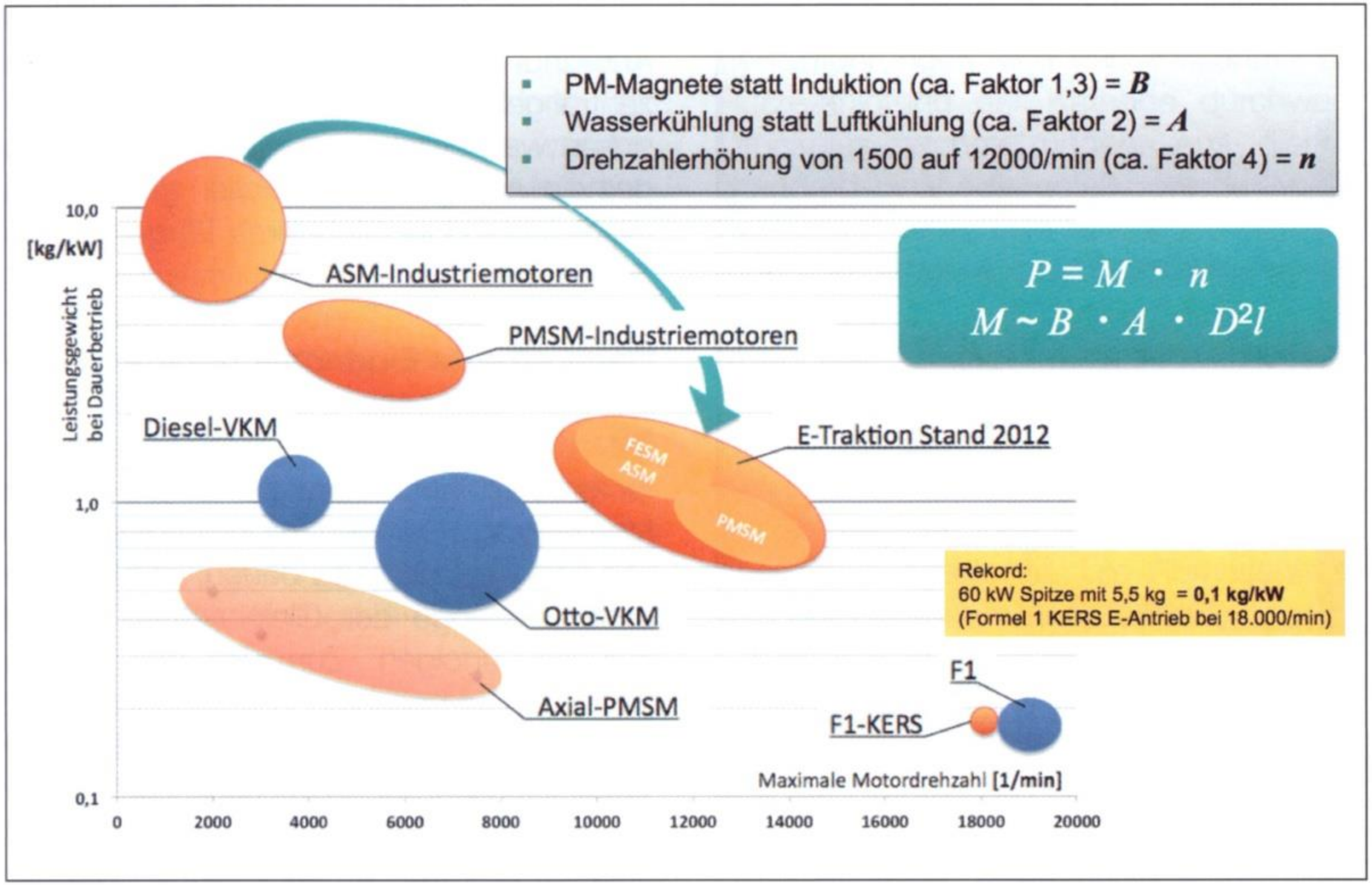


Bild 12: Entwicklung des Dauerleistungsgewichtes von Industrie- und Traktionsmaschinen