Transport & Energy System Integration: the EV case

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Tutorial

- Goal:
  - understand the different EV charging technology concepts and business models to implement this
  - learn about the problems caused by and opportunities offered through a large fleet of EVs in the electricity system

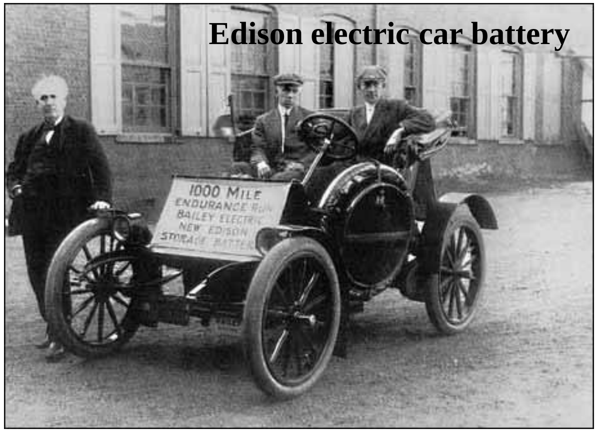
- Overview
  - EV overview: history, types, charging principles
  - Range Anxiety & solutions
  - Electricity system integration

Electric Vehicles overview

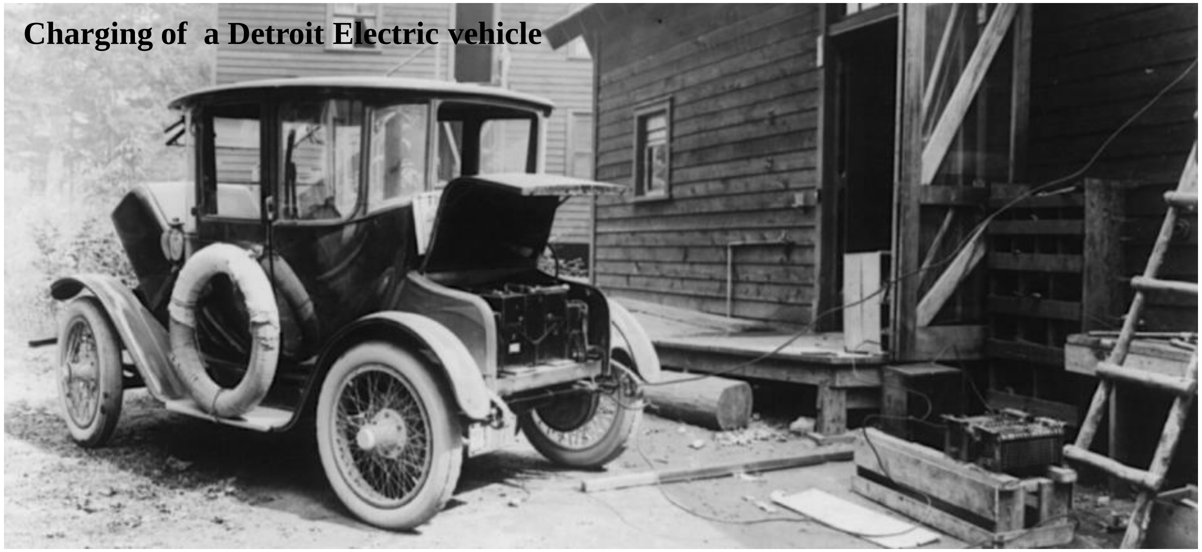
history, types, charging principles

History: 1895-1910

- electric vehicles were the most promising drive technology end 1800s: speed records, neater cars
- combustion engine took over in early 1900s: became more powerful, easy to take with cheap fuel



Edison electric car battery


Charging of a Detroit Electric vehicle

Early EVs

- Baker Inside Driven Coupe
  - 1.5 kW cont.
  - 4.5 kW peak
  - 40 km/h top speed
- 12 x 6V battery cells
  - 175 km range
  - Edison Nickel Iron Alkaline
- 2475 $ in 1915
  - Vs. 440 $ for 1915 Ford model T

Janetzy Jamais Contente

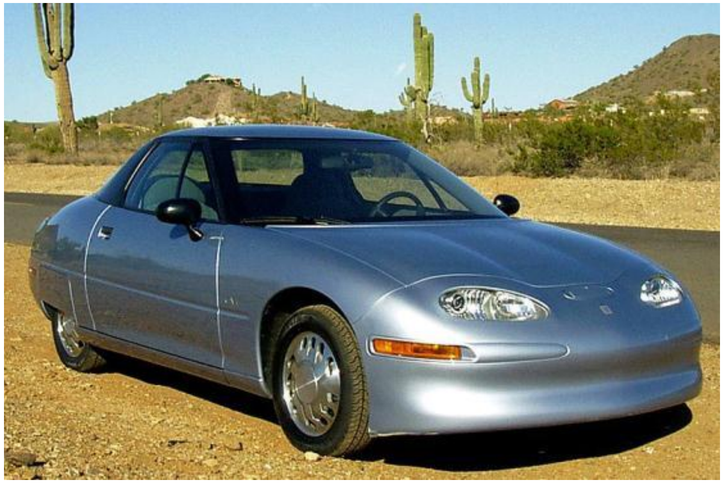
- first car ever to exceed 100 km/h
  - 24/04/1899
  - 105.882 km/h
  - 2 electric motors in ‘aerodynamic’ car
  - driven by Camille Janetzy (B.) in Achères (Fr.)
  - named “Jamais Contente”

History: 1905-1925

- gasoline vehicles take over completely: discovery of many oil wells drop fuel prices
- mass production techniques introduced by Ford
- comfort: electric starter motor
- 1900 US car production: 1575 electric cars vs. 936 gasoline cars down to 4% in 1925

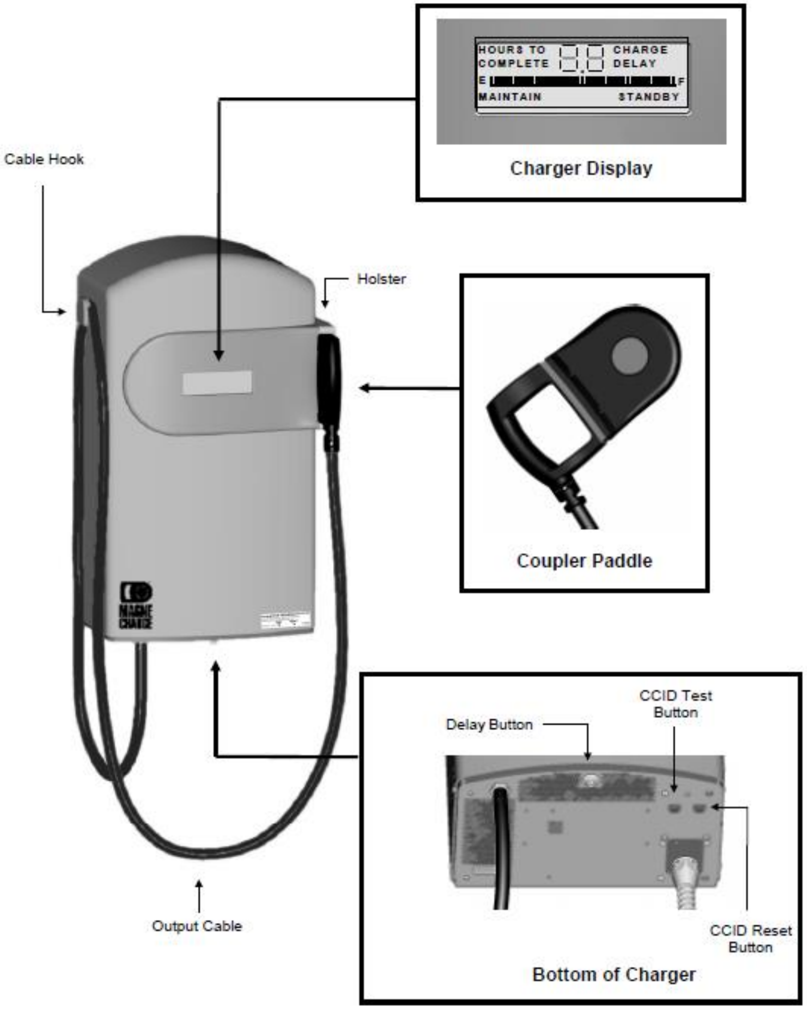
EV-1

- First 'modern' EV
  - 1996-1999
- AC induction motor
  - 102 kW @ 7000 rpm
  - 149 Nm @ 0-7000 rpm
- Lead-acid (gen1)
  - 26 Delco 12-volt/ 533 kg
  - 16.2 kWh/ 100-145 km range
  - 18.7 kWh/ 100-130 km Panasonic pack for initial gen 2
- NiMH batteries (gen 2)
  - Ovonics 26.4 kWh
  - 160-225 km range



EV-1

- Magne Charge
  - Inductive charging system
  - Safety reasons
- Small and large paddle
  - 6.6 and 50 kW
  - Both fit in the EV1
- Obsolete now



New EVs


Tesla Roadster
Tesla Model S

Smart ED


BYD E6


Nissan Leaf


Ford Focus EV


Honda Fit EV



Toyota RAV4 EV

Mitsubishi i-MiEV

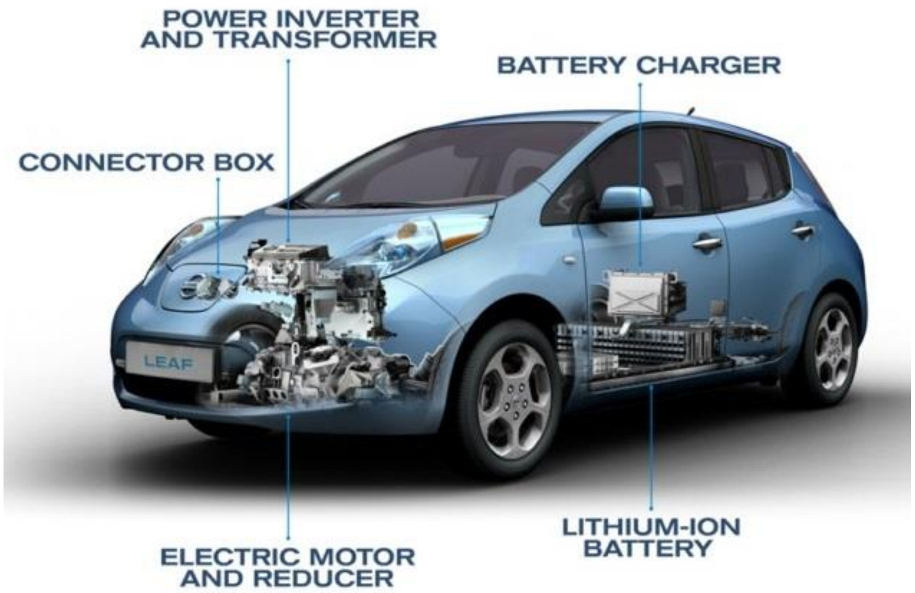


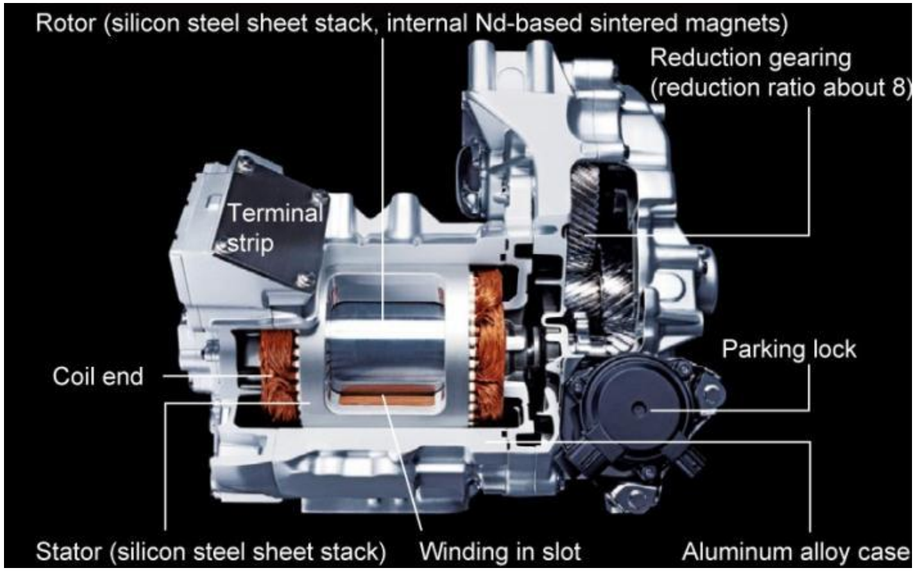
Coda Electric

Nissan Leaf

- MG: 80 kW_{peak}/280 Nm PMSM
- Battery: 24 kWh Li-on battery pack
  - 192 cells in parallel, 480 V
  - 300 kg
  - Air cooled
- Retaining 70-80 % of battery capacity over 10 years
- Single speed transmission
- Range: 117 km
- Charge at 16 A/230 V or DC (Chademo)
- Top: 150 km/h, 0-100 km/h in 10 s
- Mass: 1521 kg
- 2010

Nissan Leaf

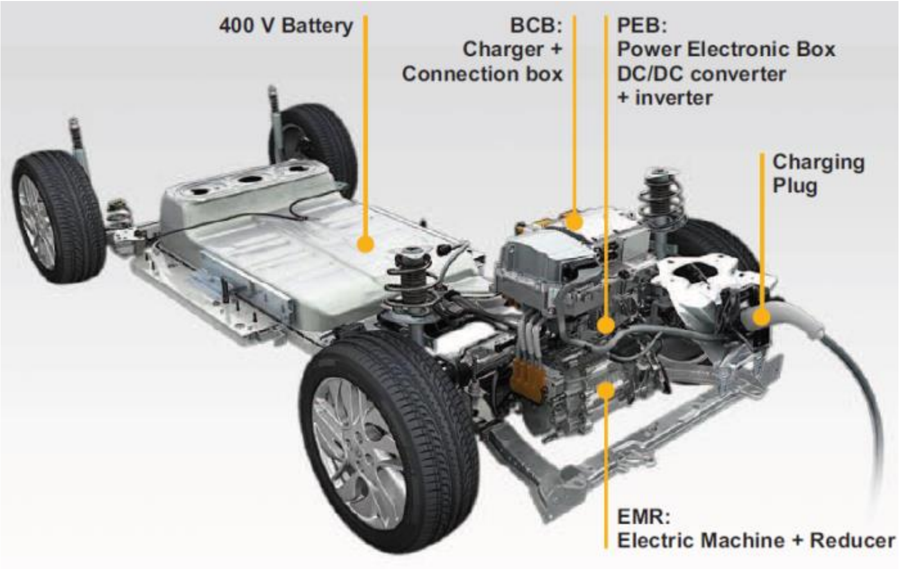

POWER INVERTER AND TRANSFORMER
BATTERY CHARGER
CONNECTOR BOX
LEAF
LITHIUM-ION BATTERY
ELECTRIC MOTOR AND REDUCER

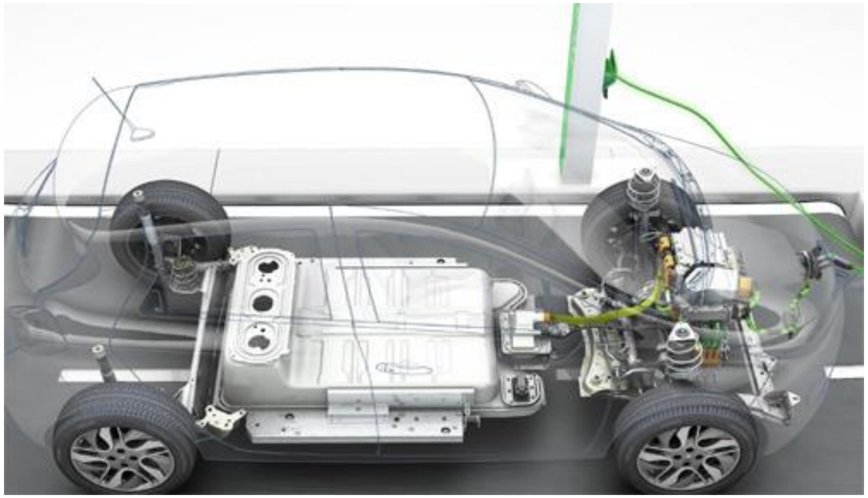

Rotor (silicon steel sheet stack, internal Nd-based sintered magnets)
Reduction gearing (reduction ratio about 8)
Terminal strip
Parking lock
Coil end
Stator (silicon steel sheet stack)
Winding in slot
Aluminum alloy case

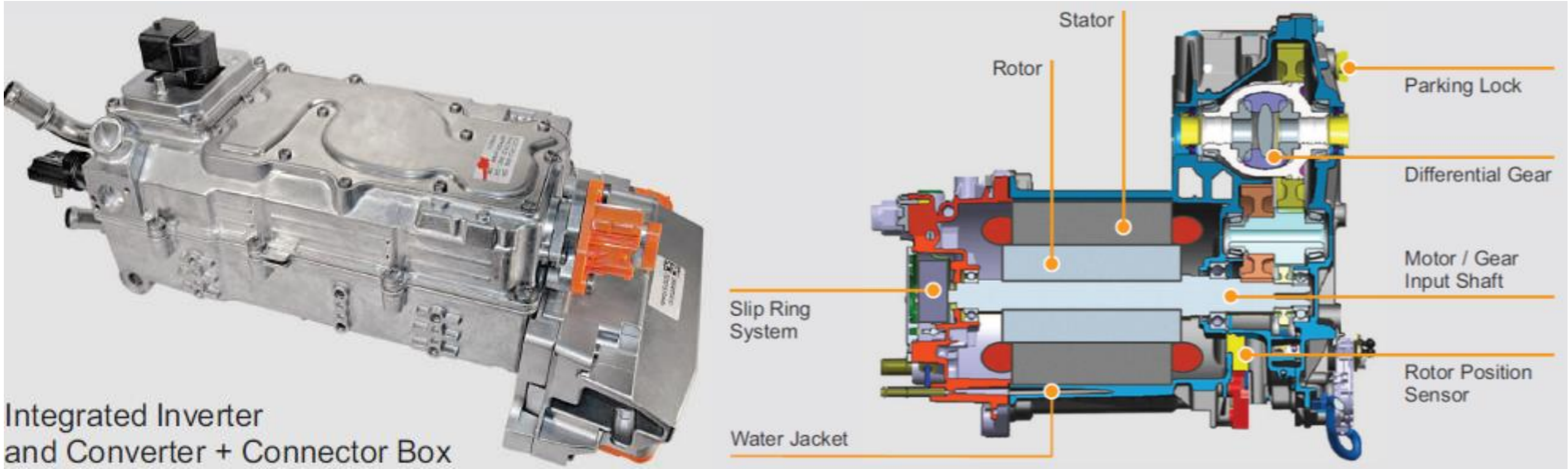
Renault ZOE

- MG: 66 kW_{peak}/220 Nm
- External excited synchronous motor
- Single speed transmission
- Battery: 220 kWh Li-on battery pack
  - 270-400 V
  - 300 kg
  - Air cooled
- Range: 210 km
- Charge at up to 63 A/400 V
  - Chameleon charger
  - Up to 43 kW
  - 0.03 m^3
  - Usage of powertrain PE components
- Top: 135 km/h, 0-100 km/h in 8.1 s
- Mass: 1392 kg
- 2012

Renault ZOE


400 V Battery
BCB:
Charger +
Connection box
PEB:
Power Electronic Box
DC/DC converter
+ inverter
Charging
Plug
EMR:
Electric Machine + Reducer

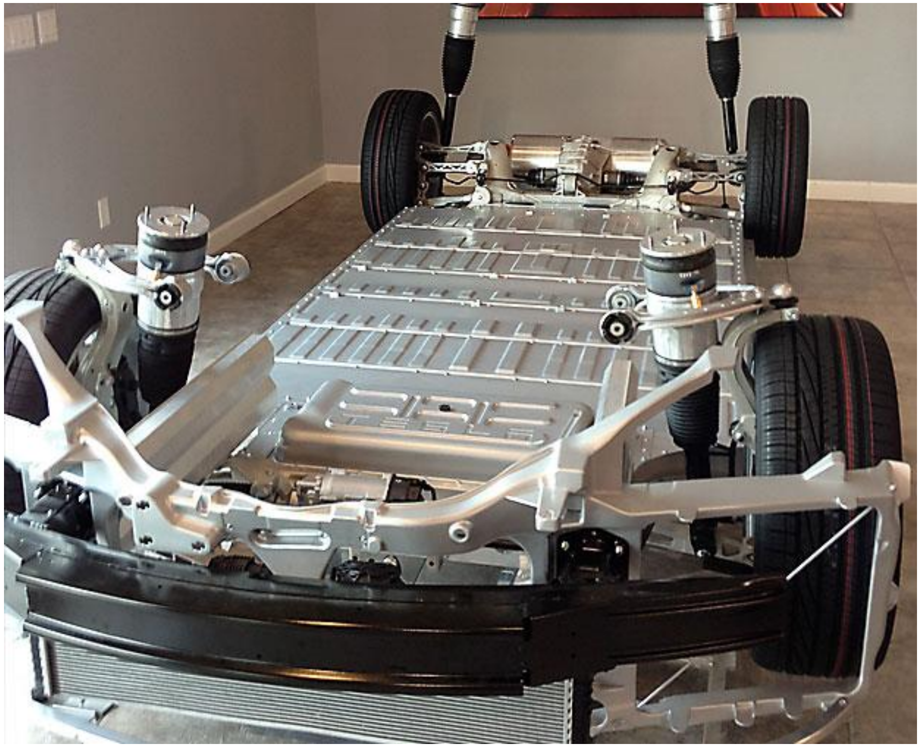


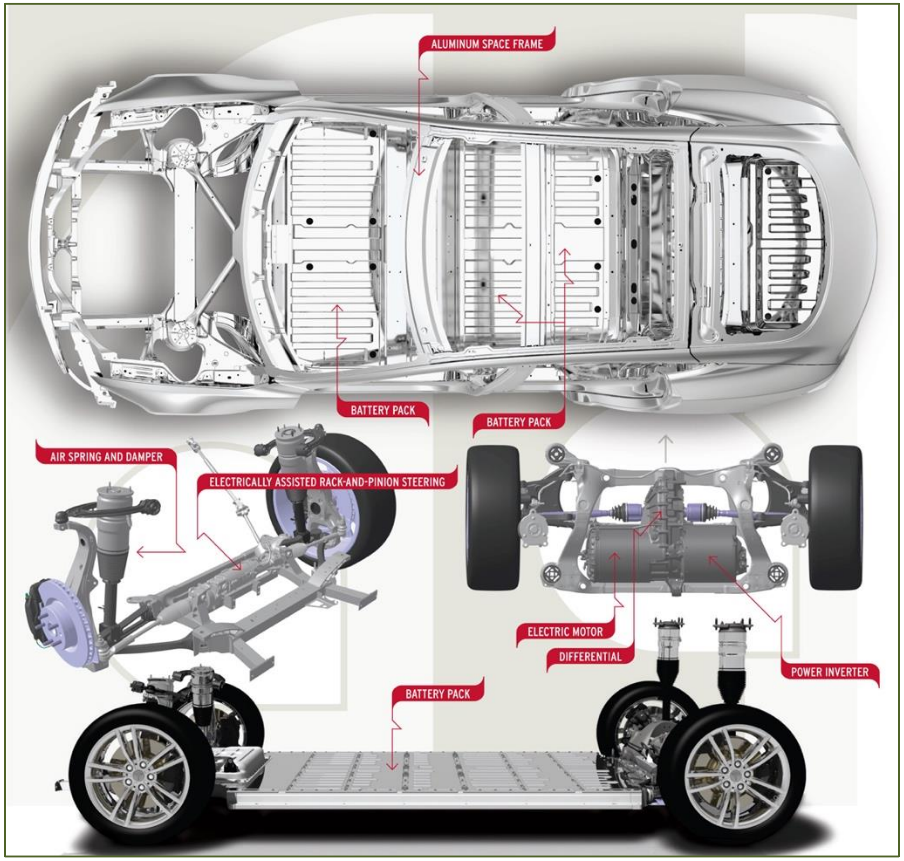

Integrated Inverter
and Converter + Connector Box
Stator
Rotor
Parking Lock
Differential Gear
Motor / Gear
Input Shaft
Slip Ring
System
Rotor Position
Sensor
Water Jacket

Tesla Model S (X)

- MG: 225/270/310 kW_{peak}
- 430/440/600 Nm
- Battery: 75-120 kWh Li-on battery
- Single speed transmission
- Range: 390/502 km
- 11/22 (10/20 in US) kW on-board charger
- fast charging up to 120 kW
- Top: 193/201/209 km/h
- 0-100 km/h in 6.2/5.6/4.4 s
- Mass: 2025/2108 kg

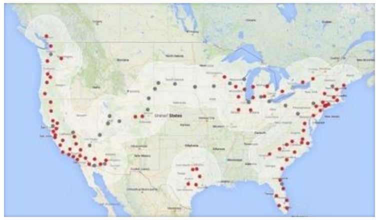
Tesla Model S (X)

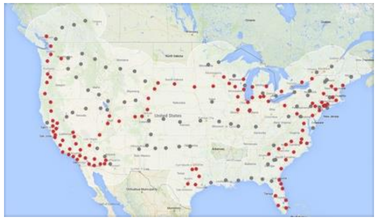


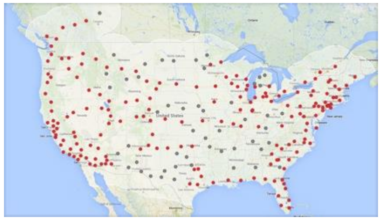


Tesla Supercharger

- 90-120 KW fast charging
  - ΔSOC of 50 % in 30-20 min
- Free for S/X, not for “3”
- Chademo compatible





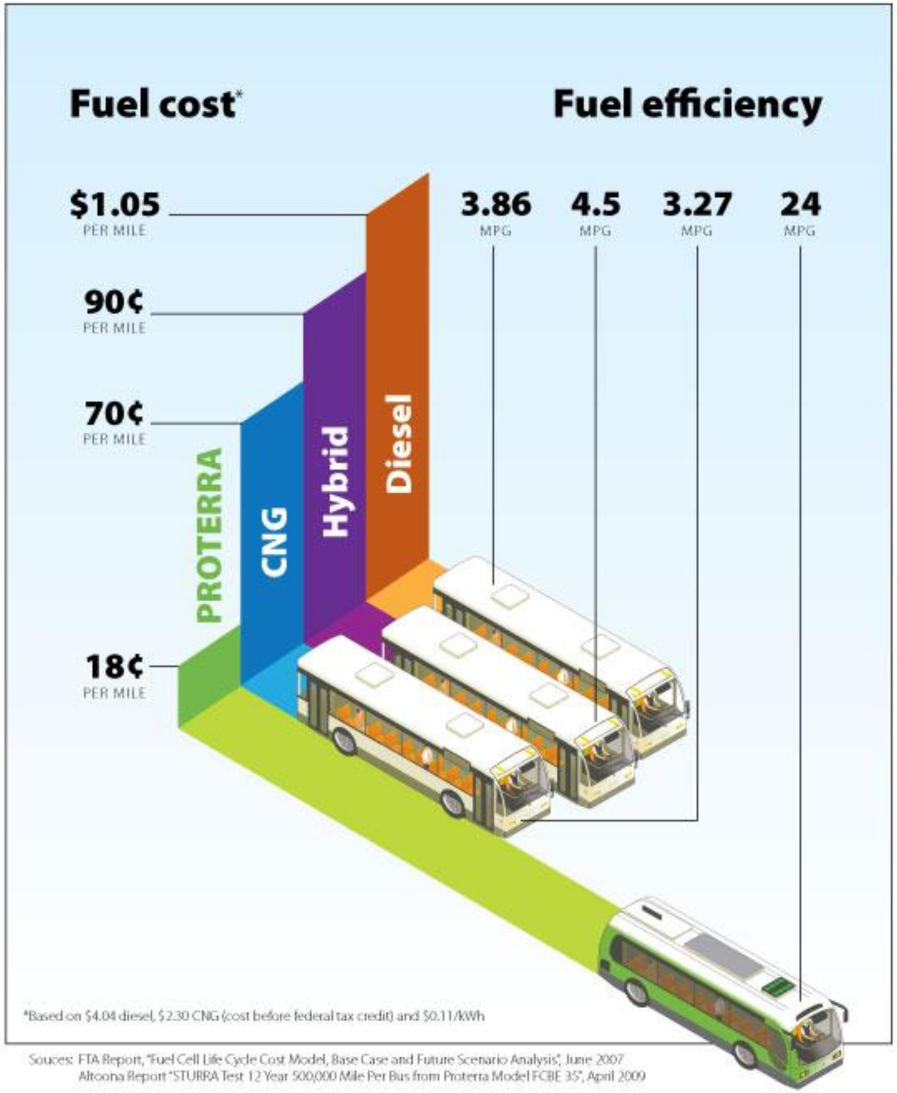


Battery Electric truck

- Delivery services
  - Scheduled routes
  - Limited distances
- Economical decision
  - Low total cost of ownership
- Less noise
- Low emission areas

Battery electric Heavy Duty

- High efficiency as main advantage
  - Stop and go traffic
  - Energy recuperation
- Using fast charging
  - During scheduled standstill
  - Smaller batteries needed



Souces: FTA Report, "Fuel Cell Life Cycle Cost Model, Base Case and Future Scenario Analysis", June 2007
Altoona Report "STURRA Test 12 Year 500,000 Mile Per Bus from Proterra Model FCBE 35", April 2009

Proterra Electric Bus

A look into the future

- Range Anxiety?
- Enough Li?
- Ethical issues with Co?
- Weight?
- Price?
- Safety?
- Shifted emissions?

Charging concepts and infrastructure

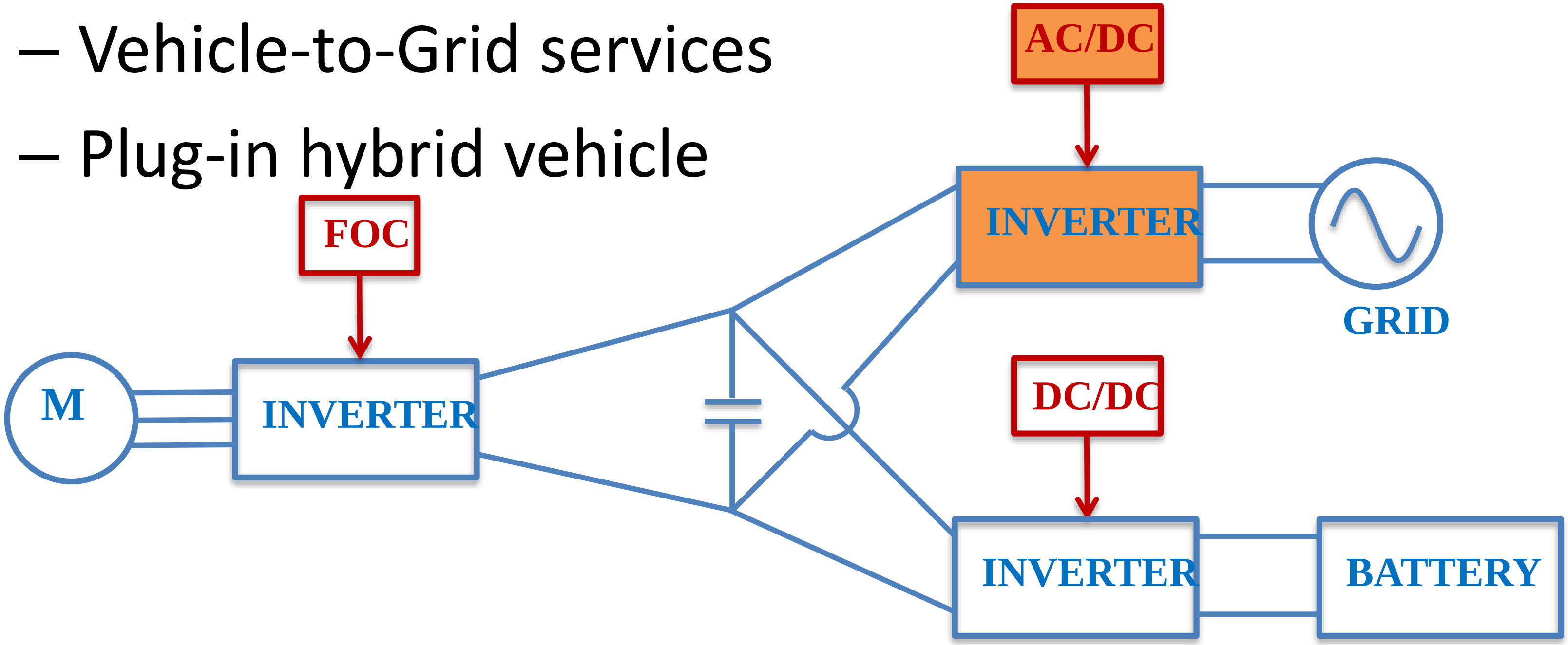
"An EV is pretty interesting when it is not driving"

Charging up

- filling up a classical car with gasoline is the equivalent of an MW energy transfer
- using an electrical cable: tens of kWh to transfer (need several hours?)
- 2 systems: conductive, inductive coupling

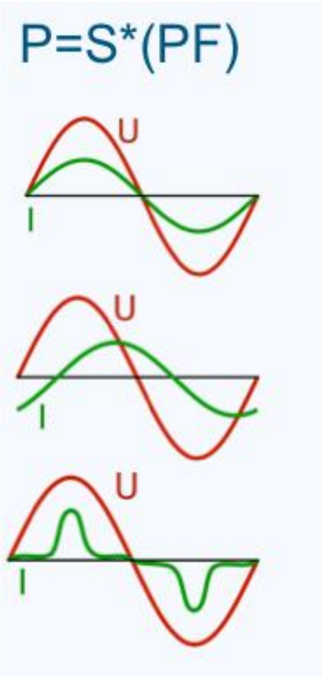
Concept
Grid coupling

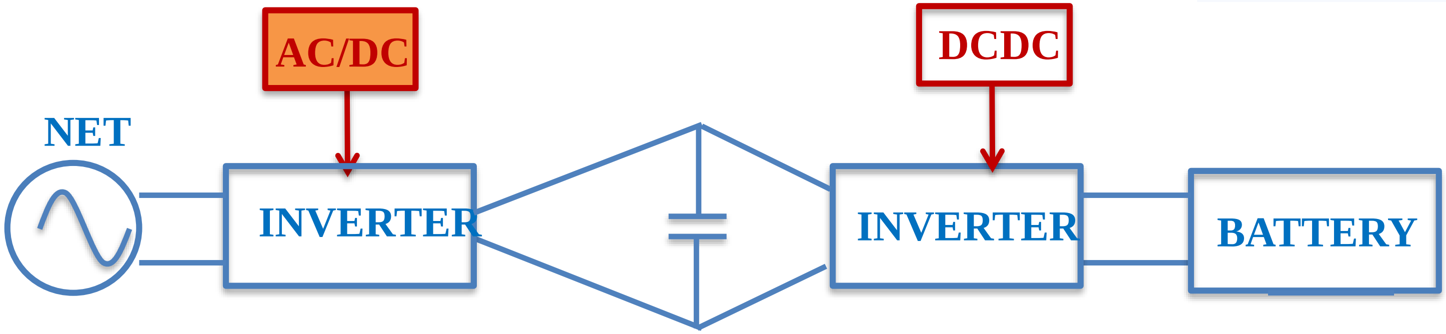
- Grid coupling : AC/DC converter
- Goal:
  - Charging batteries: Grid → DC-bus
  - Vehicle-to-Grid services
  - Plug-in hybrid vehicle



Concept
Grid coupling

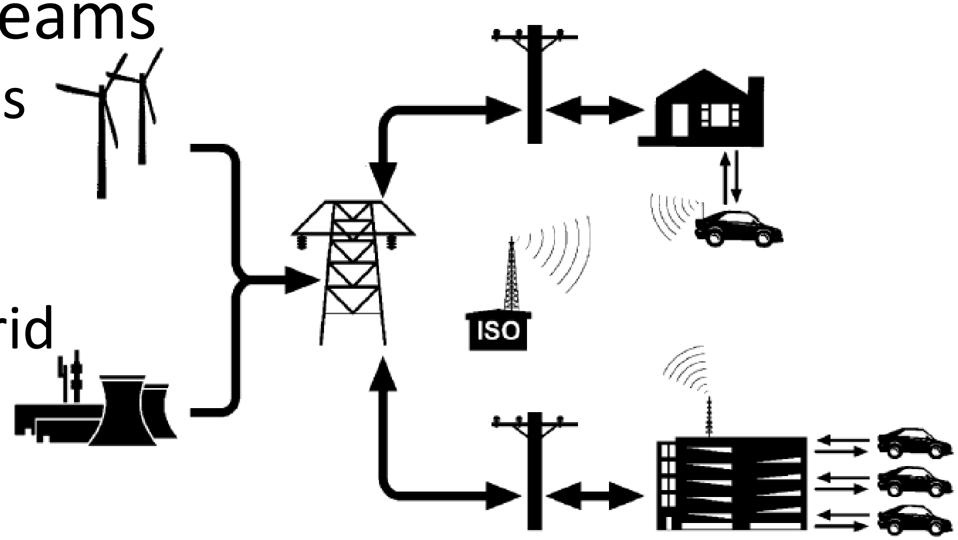
- Goal 1: charging battery
  - AC-grid → batteries
  - Power factor
    - Displacement Power Factor
    - Distortion

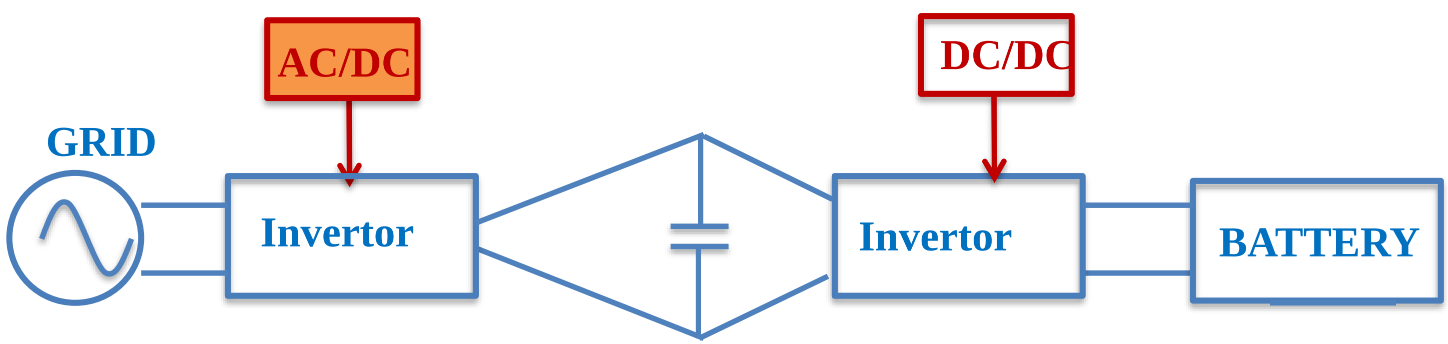




Concept
Grid coupling

- Goal 2: Vehicle-to-Grid (V2G)
  - Bidirectional current streams
    - Vehicles produce services to support the grid
    - Active en reactive streams deliver to the grid
      - PF ≤ 1
      - Distortion



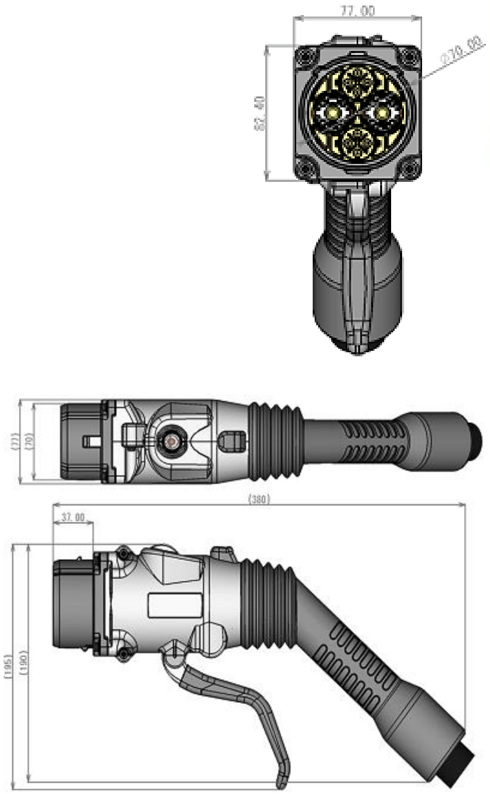


charging powers (1/2)

- Consumption EV: +/- 0,2 kWh/km
  - assume 1 kW charger
  - 1 hour charging adds 5 km range
  - "charging speed" of 5 km/h
- "Normal" charging
  - 1-phase: 16 A and 230 V=> maximal 3,68 kW
  - charging speed: 18,4 km/h
  - drawing 16 A for longer time from a socket not advisable?
- "Semi-fast" charging
  - 1-phase: 32 A and 230 V => 7,36 kW (36,8 km/h)
  - 3-phase: 16 A and 400 V => 11,09 kW (55,4 km/h)
  - 3-phase: 32 A and 400 V => 22,17 kW (110,9 km/h)

charging powers (2/2)

- fast charging
  - 50 kW and higher
  - >250 km/h charging speed
- special charging infrastructure
  - large part of converter electronics in the charging unit
  - large power grid connection
- Chademo standard
- Psychological effect
  - may help overcome range anxiety

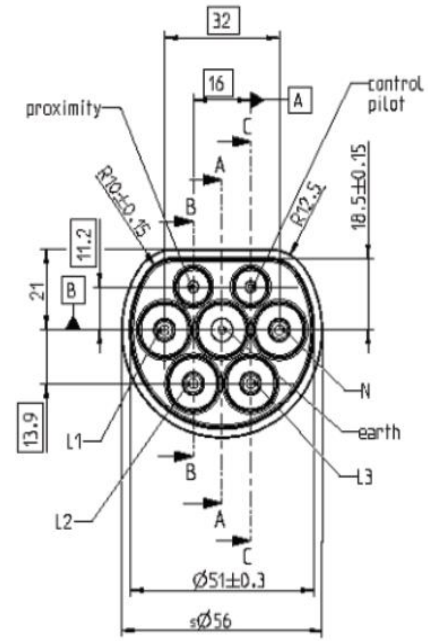


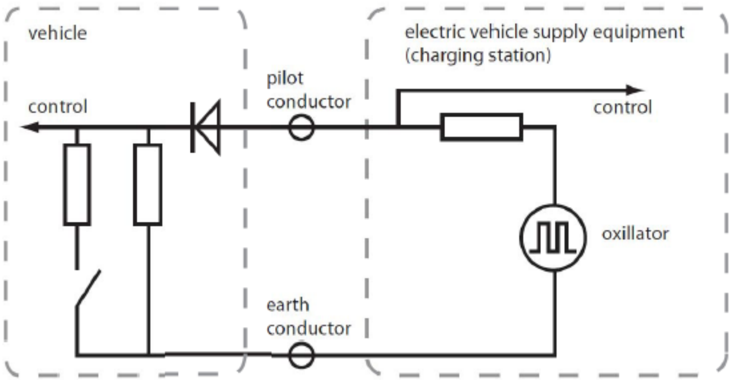
charging modi (1/2)

- defined in IEC 61851-1
- Mode 1
  - through standard sockets
  - applicable everywhere, simple and cheap
  - needs correct protection for single earth fault
    - earthing
    - differential protection
    - overcurrent protection (e.g. fuse)
  - mostly forbidden
- Mode 2
  - also through standard sockets
  - protection in the cable
  - protects the vehicle, not the plug

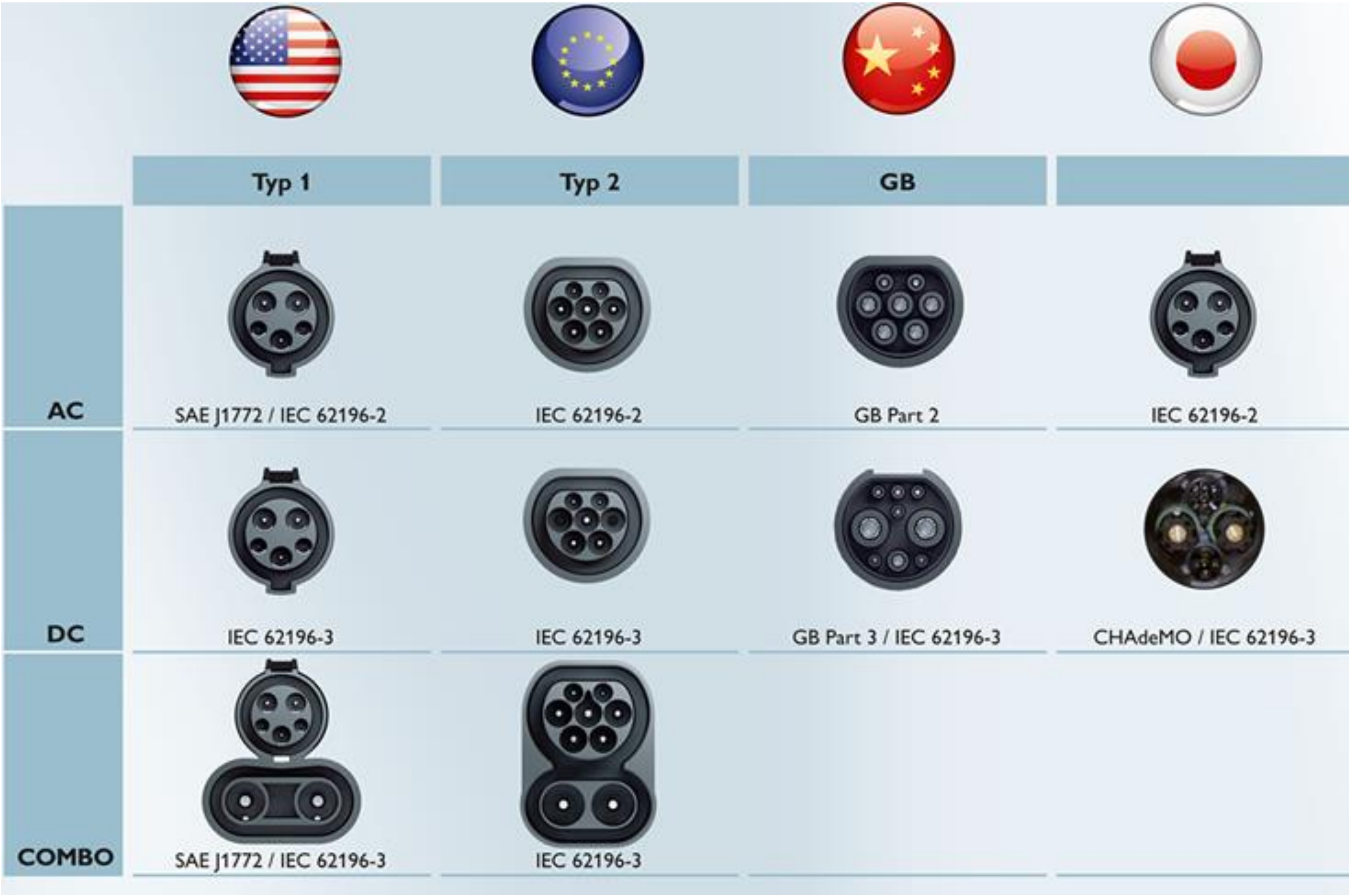
charging modi (2/2)

- Mode 3
  - specialized charging infrastructure
  - uses a control function
    - check correct connection
    - checks earthing
    - switches charging system on/off
    - selects charging current (duty-cycle)
  - Control signal through pilot wire or PowerLine Communication (PLC)
- Mode 4
  - for fast charging: external charger
  - also pilot wire
  - communication link for battery condition



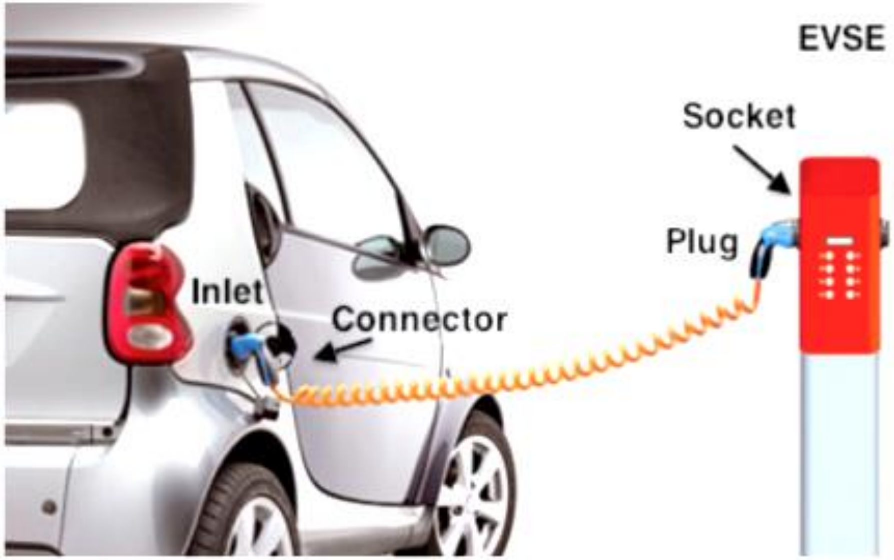


Connectors


Typ 1
Typ 2
GB
AC
SAE J1772 / IEC 62196-2
IEC 62196-2
GB Part 2
IEC 62196-2
DC
IEC 62196-3
IEC 62196-3
GB Part 3 / IEC 62196-3
CHAdeMO / IEC 62196-3
COMBO
SAE J1772 / IEC 62196-3
IEC 62196-3

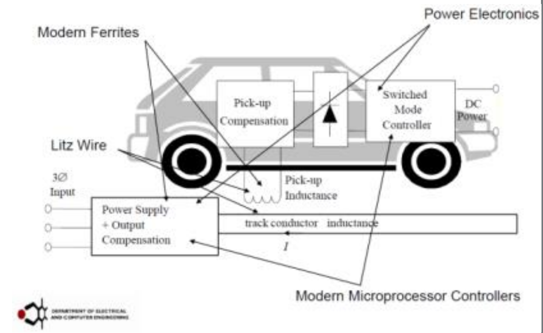
Charge cases: cables

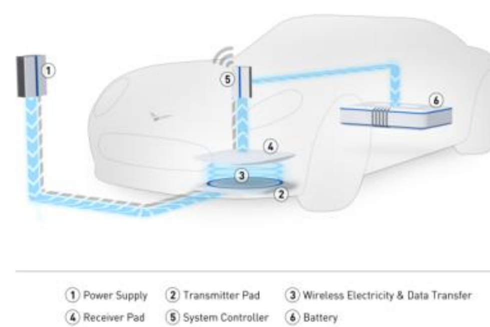
- IEC 61851-1 standard
- Case A: the charging cable is attached to the EV.
  - Small vehicles
  - Standard domestic socket.
- Case B: a loose cable is used
  - Connector at the EV side and a plug at the EVSE side
  - Most currently used configuration.
  - High degree of compatibility
- Case C: the cable is attached to the EVSE
  - Dedicated charging stations
  - The connector is chosen to be compatible with the EV inlet.

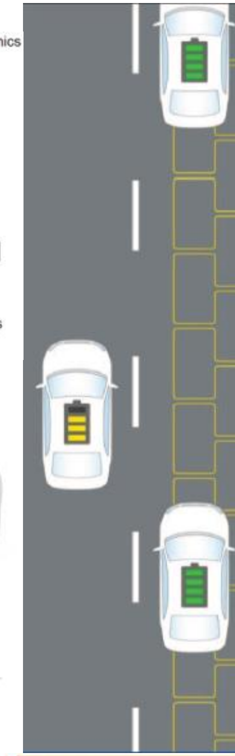


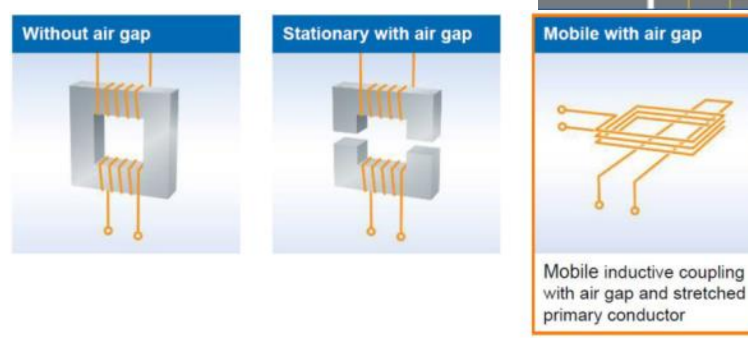
Inductive charging

- Contactless
  - Safety
  - No wear
  - Weather resistant
- Flexibility
  - Power ratings
  - Statis, continuous
- EMC
  - Within limits
  - Only field present if vehicle is charging
- Technology under development
  - Bombardier, Siemens, etc.
  - Halo IPT, Evatran, etc.
  - Volvo, Audi, etc.
  - …









Inductive charging

- Flanders Drive project (Lommel)
  - Busses and cars
  - Both static and continuous
  - EMC/EMF measurements
  - Efficiency measurements
  - System evaluation

Inductive charging

- Contactless
  - Safety
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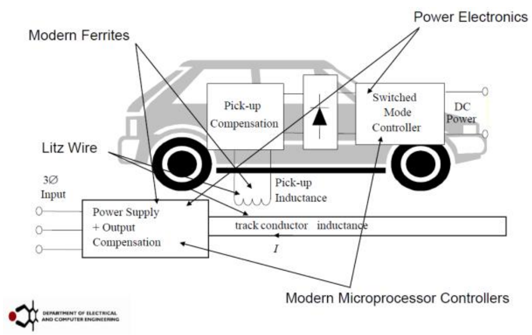
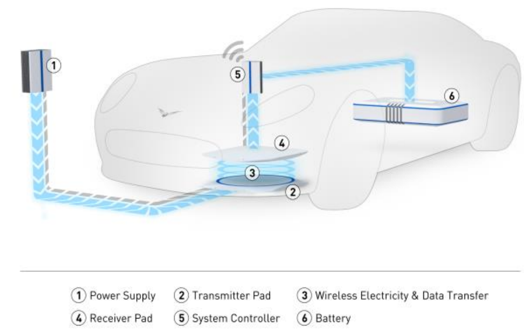
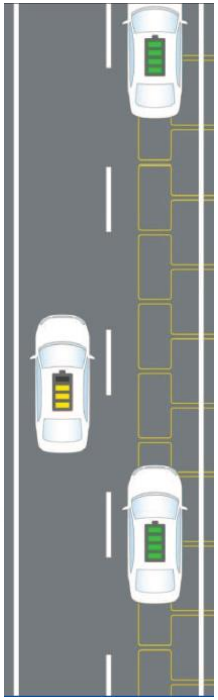
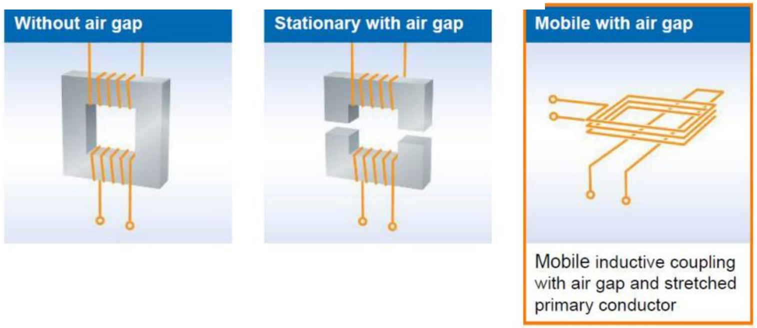
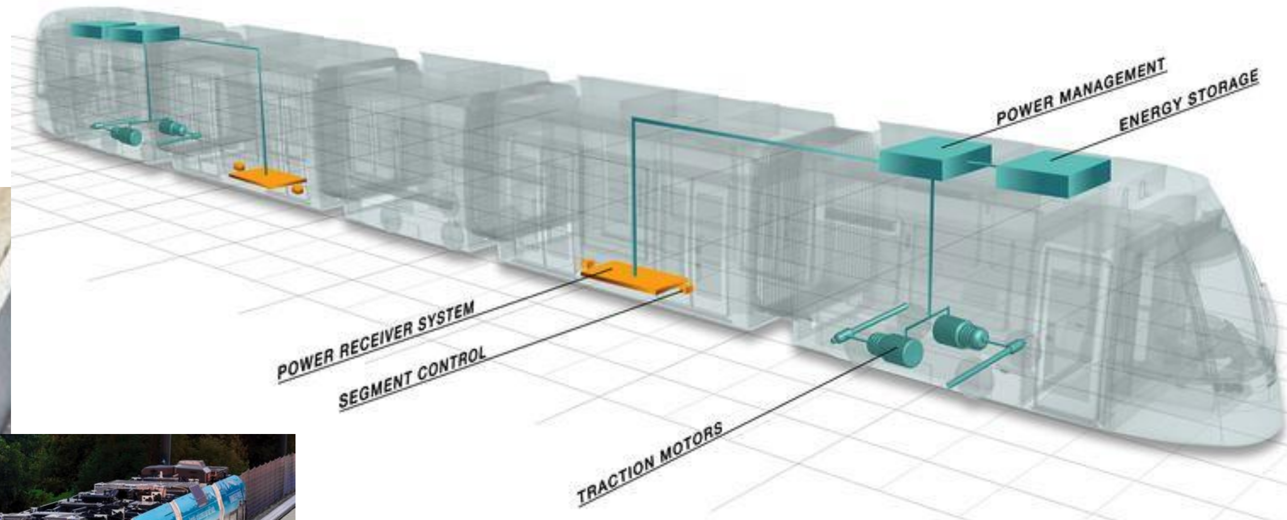




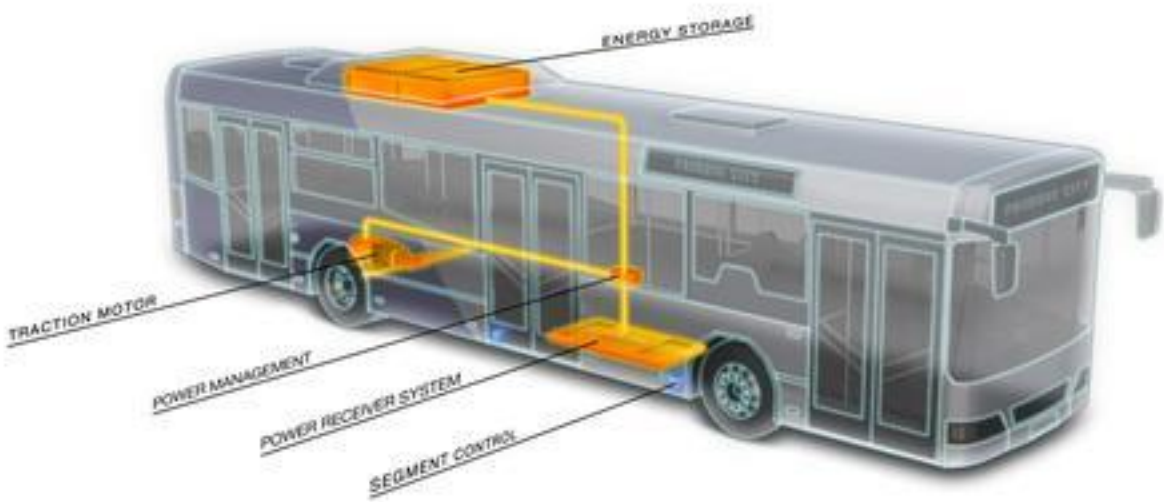


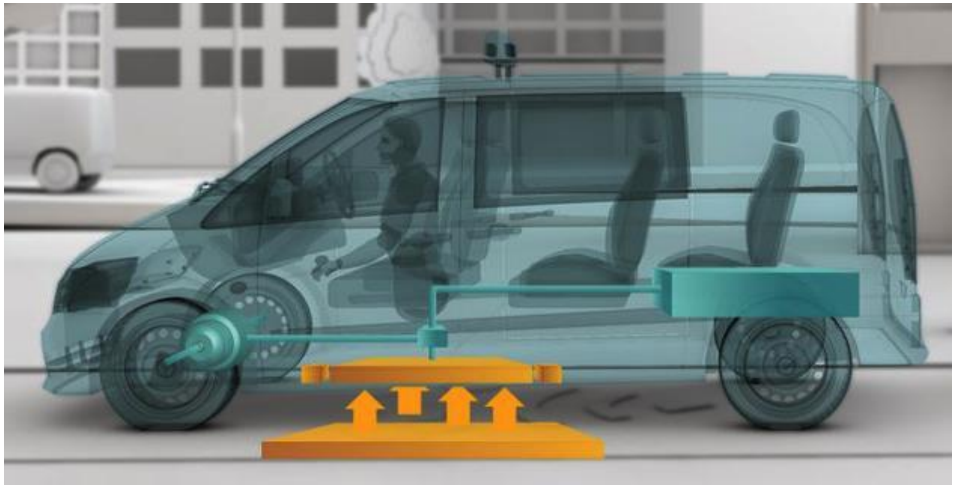


Bombardier Primove



Bombardier Primove





Range Anxiety

(and how to solve it)

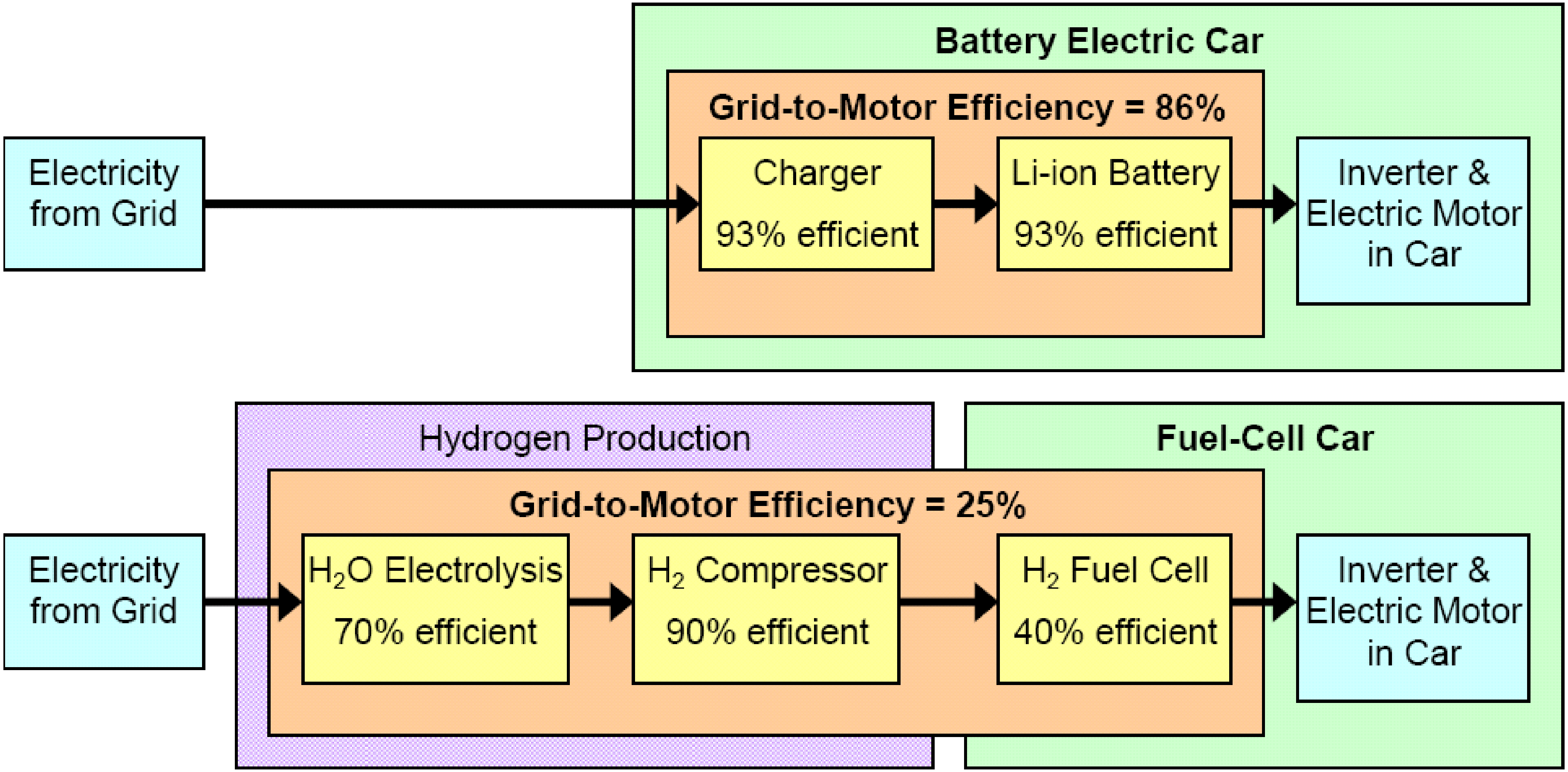
Range Anxiety

- #1 psychological barrier against switching to Evs (except for the price)
- Fear of
  - Getting stuck somewhere with an empty battery
  - Not finding a charge point
  - And if, getting stuck at the charge point for a long time
- Solutions: PHEV? Battery exchanging? Other fuels? More fast charging?

battery exchanging (swapping)

- alternative for fast charging
- similar principle as service station
- battery leased
- standardisation of batteries necessity
- needs more than1 battery per EV
- warehousing problem

BEV vs. Fuel cell car

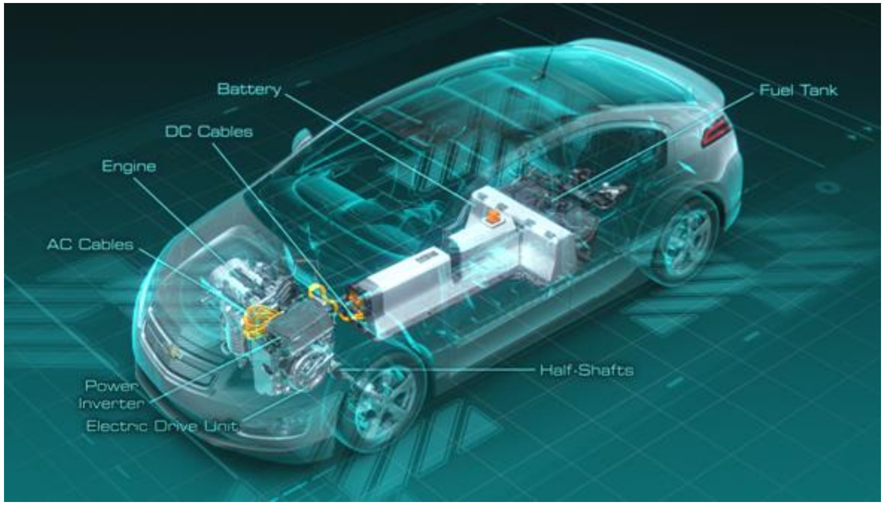


Plug-in hybrid electric vehicles

- HEVs which can be plugged in a standard outlet to charge the batteries: PHEV
- Same power train topologies as for full hybrids
  - Series
  - Parallel
  - Mixed

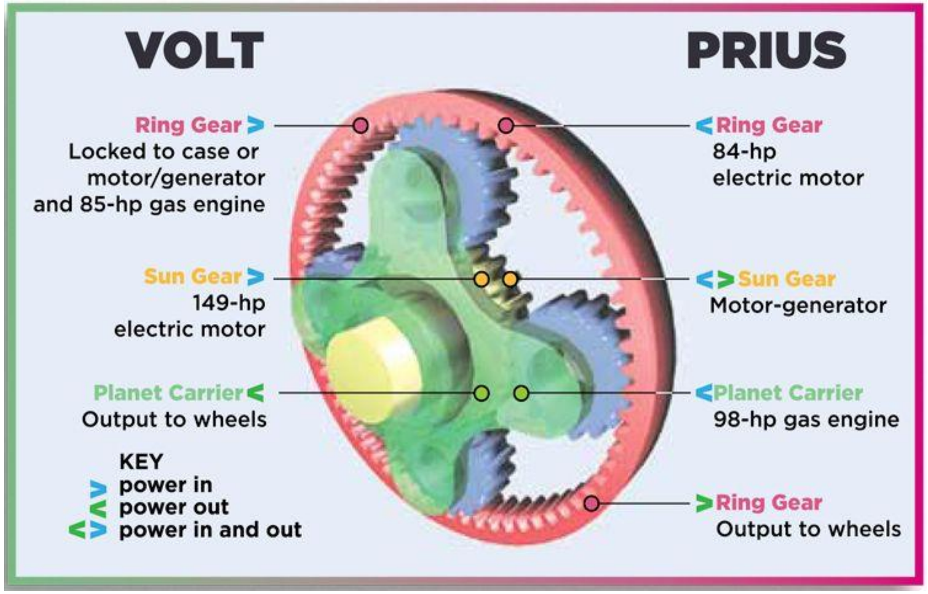
Chevrolet Volt

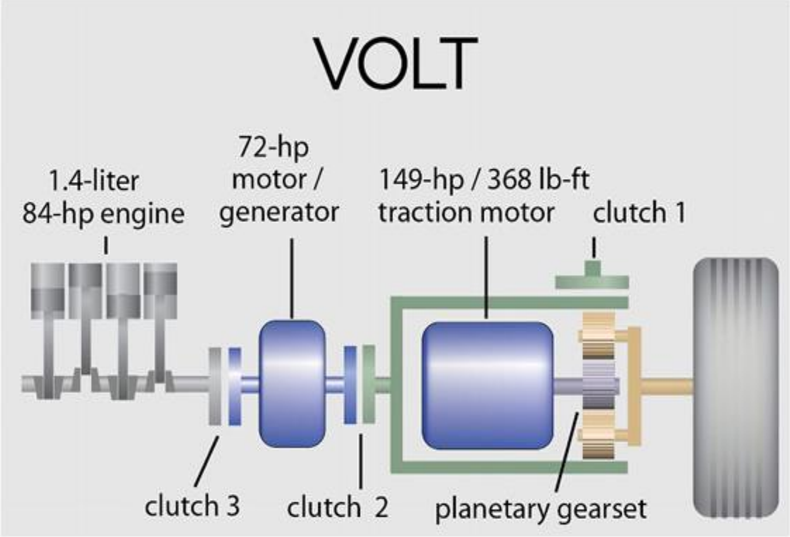
- Extended Range Electric Vehicle
- 1.4 l gasoline engine
  - 60 kW
- 2 electric motors
  - 111 kW traction motor
  - 55 kW generator
- Li-ion battery pack
  - 16.5 kWh
  - 10.8 kWh (30-85 %) used
  - 40-80 km electric range
- Hybrid if battery is depleted
- similar: Opel Ampera



Chevrolet Volt

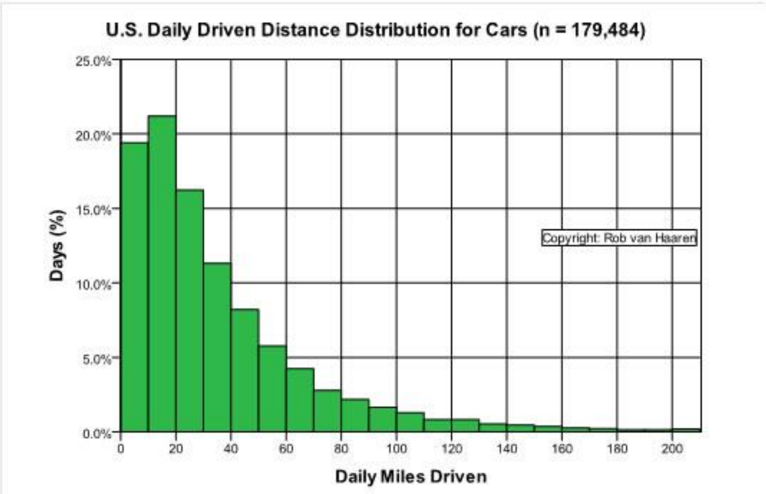
- Also planetary gearbox
  - But different configuration
- Reconfigurable hybrid
  - Through 3 clutches
  - ICE only active if battery is depleted





PHEVs

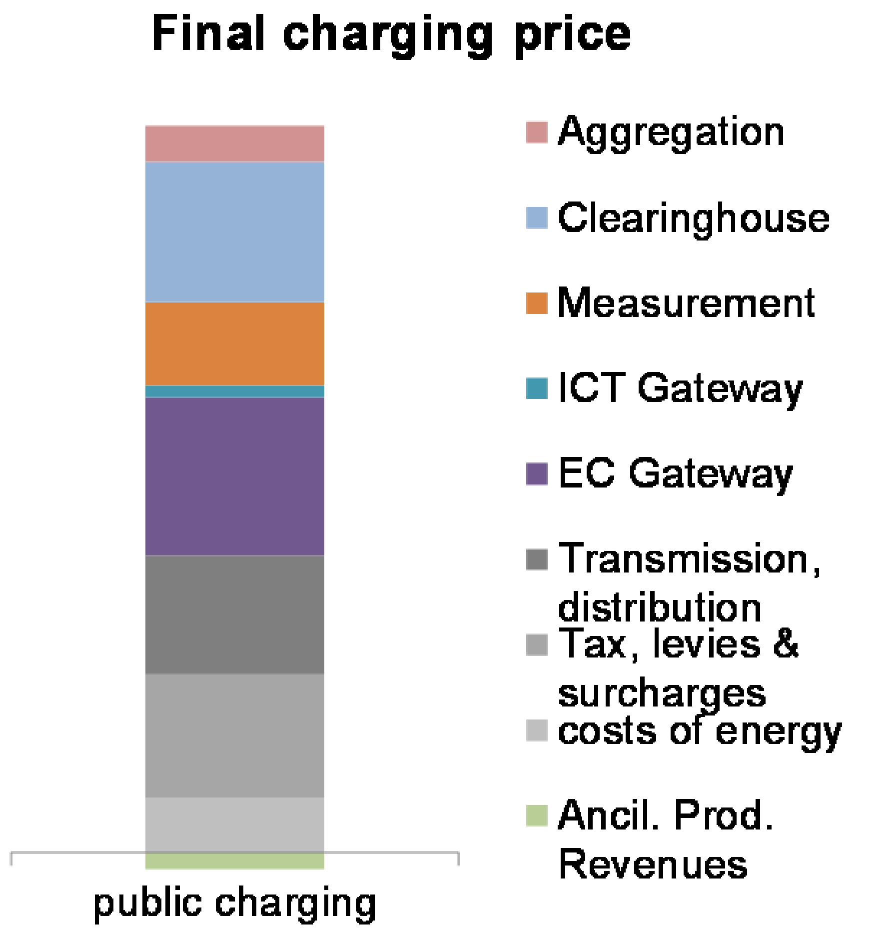
- Limited electric range
  - Typically low daily driven distance/ trip distance
- Charging infrastructure is available: standard sockets
- ICE for occasionally long trip
  - Reduced range anxiety
- Smaller battery pack than BEV
- More complex (heavy) architecture than pure BEV
  - Both ICE and electric motor(s)
- Transition technology?



Business models for charging

Exploitation cost of electric vehicles

- Electricity cost is the variable cost factor
- Public charging: opportunity charging
  - 20 % of the charging actions
  - Energy consumption: 2-10 kWh
- Consumption cost: 0,5-2,5 EUR/dag
  - Finale charging price will include more than this cost factor
  - Overhead cost must remain relatively low



Payment model

- Energy consumption measurement
  - Electronic smart meter: automated reading at a higher cost
- Time measurement
  - Simply measurable
  - Occupation of the infrastructure has a cost
  - Energy cost divided over time usage
- Flat fee system
  - No need for measuring infrastructure at every charging pole
  - Access via key or verification via tag
- Integration in the parking cost
  - Relatively high parking cost compared to charging
  - No need for additional high-end infrastructure

Payment procedure

- Low cost required
  - Low cost of charging action
- Different possibilities
  - 3G/4G/5G: simple and cheap
  - Modules for vehicles and infrastructure
  - Communication with the user (e.g. through text message, app)
- Charging procedure
  - Vehicle identification at arrival
  - Proposal of charging tariff
  - User confirmation, start of charging
  - Notification charging end to the EV driver and EVSE operator
- Settling of payment after finishing charging action

Considerations

- Authentication, privacy, anonymous payments
- Interoperability & “free roaming”
- Taxation (shift from taxes on gasoline)
- Use case for true smart metering?

Electricity System Interaction

Can the electricity system handle the EVs?

Questions

- Do we need extra power plants?
- Won't we increase or just shifts the emissions?
- Can the transmission system handle this?
- Can the distribution system handle this?
- Can we do more with those "distributed batteries"?

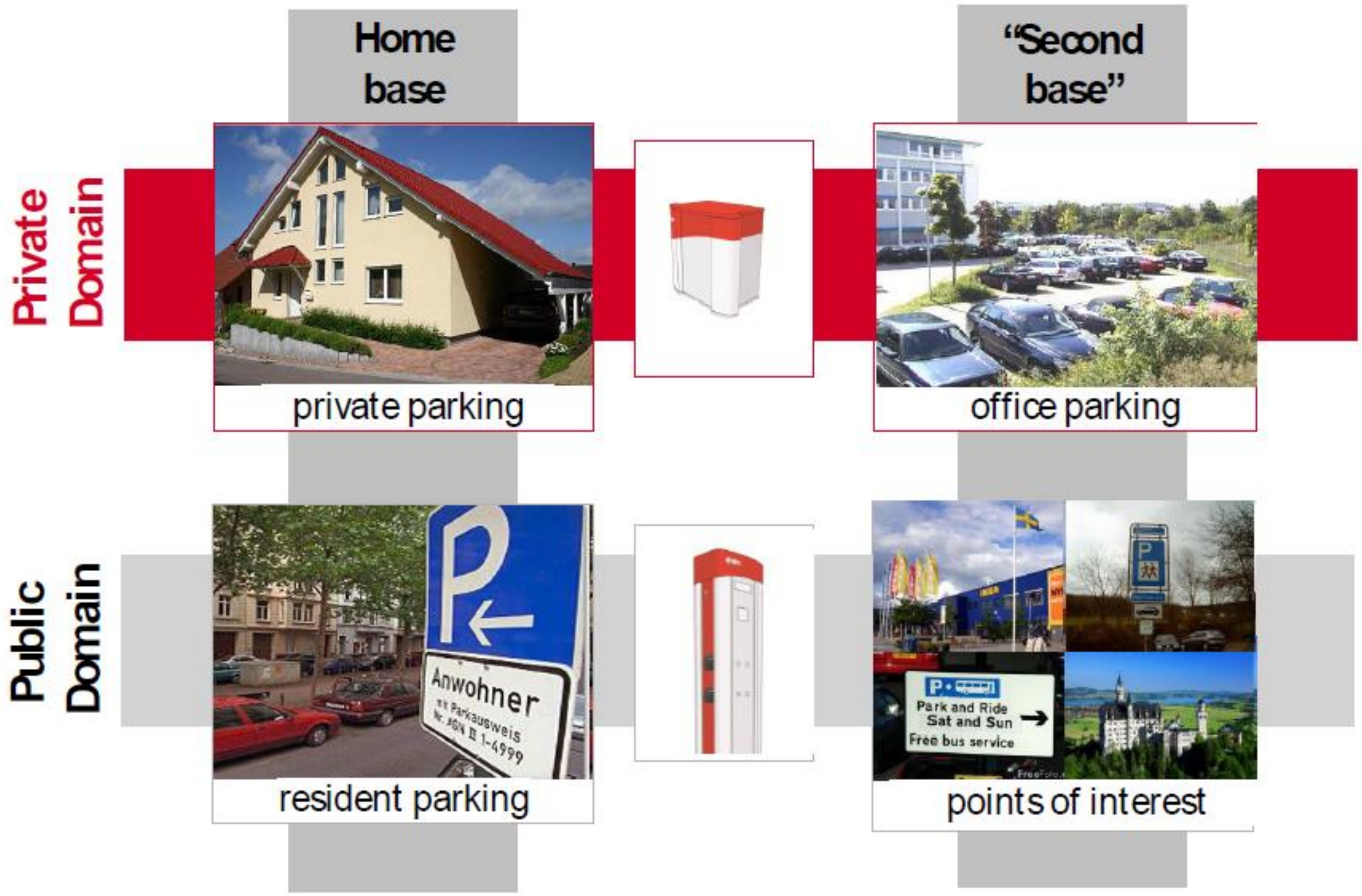
Energy consumption

- 1 car on average: +/- 3,300 kWh/year
  - 4-7 kWh/km, 90 % efficiency of charger
  - 15,000 km/year
- Significant increase in household electricity consumption
  - 3,500 kWh/year
  - Same order of magnitude
- Modest on national scale
  - 90 TWh (Belgium)
  - 3.3 TWh for 1 million vehicles
    - 3.7 % increase

Extra power plants needed?

- Studies show that deep penetration would lead to <5% extra consumption
  - Should be within reserves
  - Use flexibility to optimally integrate
- "Don't we just shift emissions?"
  - No, due to improved efficiencies in EV driving vs. combustions engines
  - Depends on generation mix, but even in worst case plant mix, there is a gain
  - + better pollution control: particles + NOx

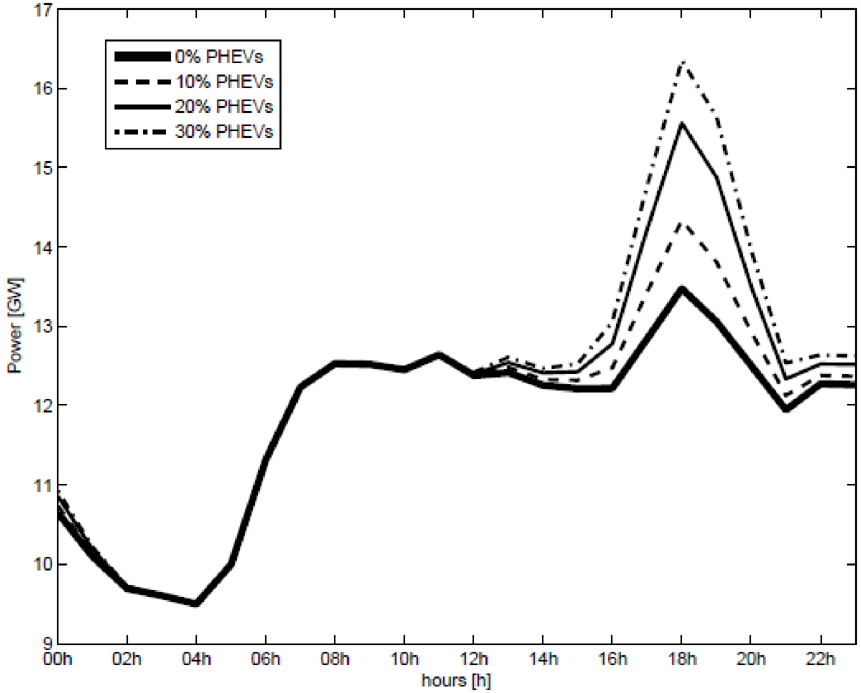
Not only home charging



Uncoordinated charging

Power production

- EV charging energy must be generated
- Power generation
  - Nuclear, gas, RE, pumped storage
  - Base, modulating, peak
- Simultaneity household and EV charging demand
  - High peak power
  - High ramp rate

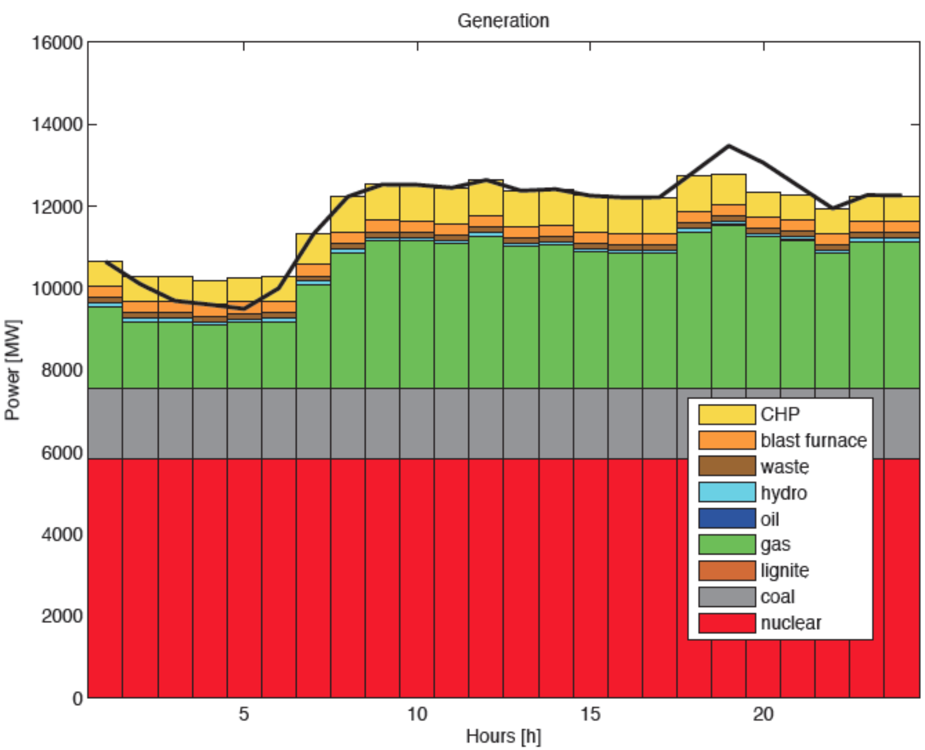


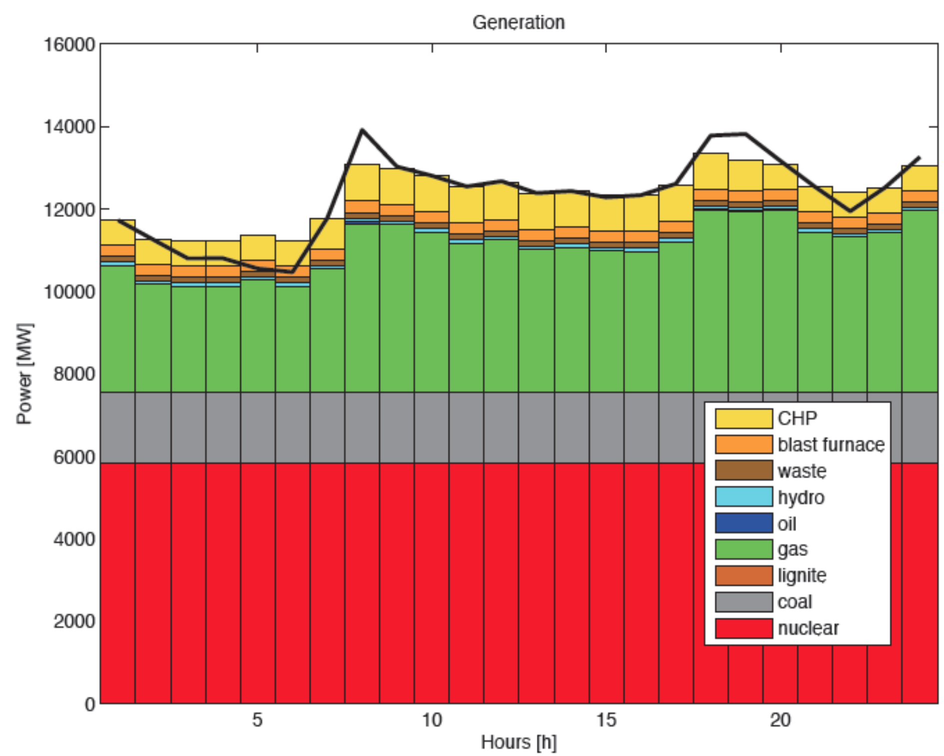
K. Clement, "Impact of Plug-in Hybrid Electric Vehicles on the Electricity system", PhD Thesis, K.U.Leuven, 2010

Uncoordinated charging

Power production

- Without expansion of the production plants
  - 30% EVs: with coordination
  - 10% EVs: without coordination

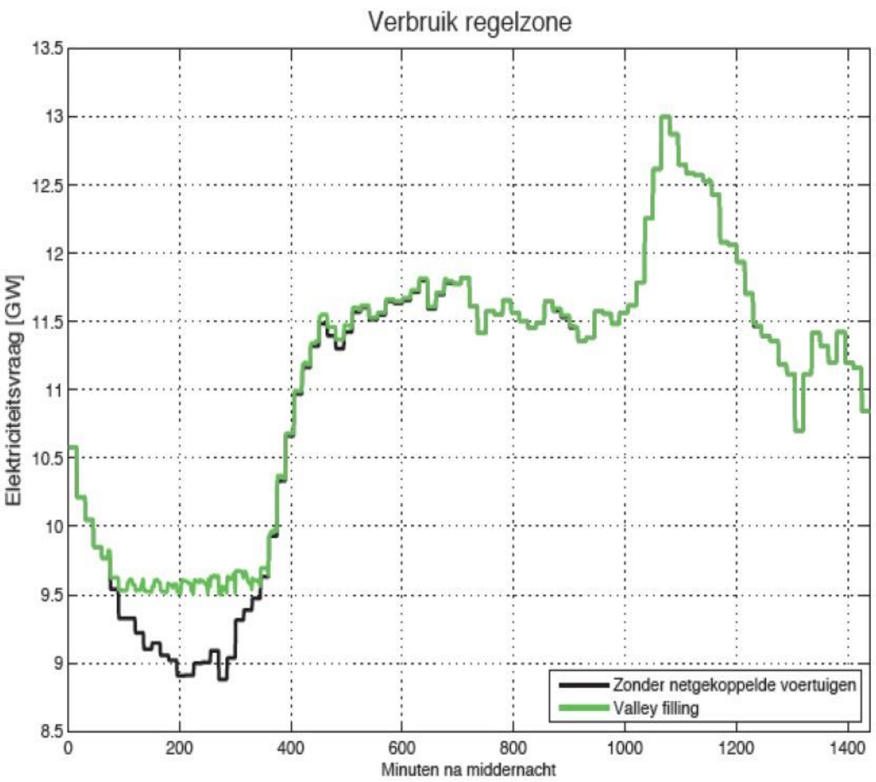




Coordinated charging

Transmission level

- Long distance, high volume transfer of electrical energy
  - Centralized power plants => LV/MV substations
  - National TSO: Elia in Belgium
- Enough available capacity?
  - Only limited increase in energy demand
  - No problem with coordinated charging
- Is stability guaranteed?
  - Shifting in load/generation patterns
  - Anticipating through grid planning
  - Gradual rise of EV penetration rate

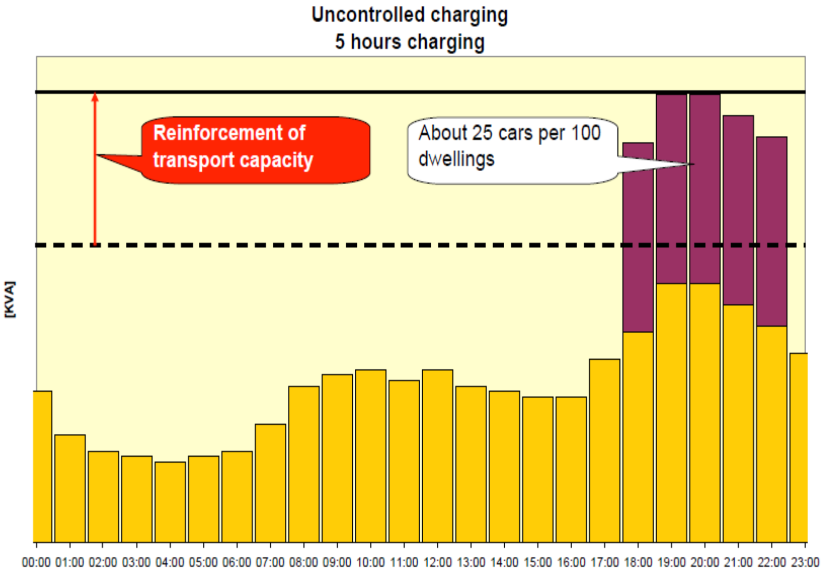


J. Van Roy, and K. Vogt. Analyse van verschillende batterijcapaciteiten voor plug-in hybride elektrische voertuigen, Master's thesis, KU Leuven, 2010.

Uncoordinated charging

Distribution level

- HV/MV substation => households (400/230 V)
  - Extensive infrastructure
  - High variety of topologies
- Charging typically at LV level
  - Relative high R/X ratio
  - Voltages strongly influenced by loads
  - Unbalanced situations
- Local high penetration grades

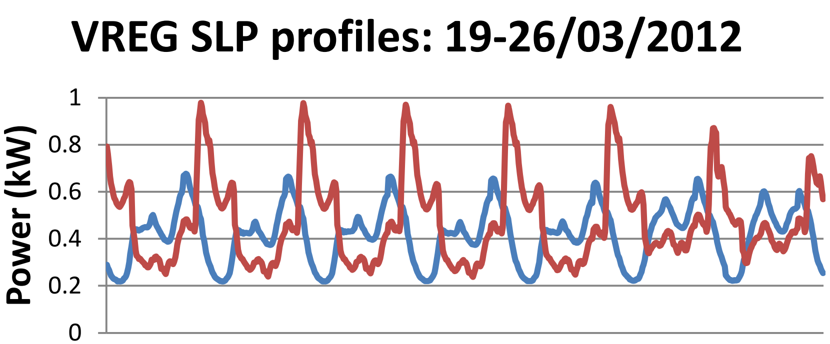


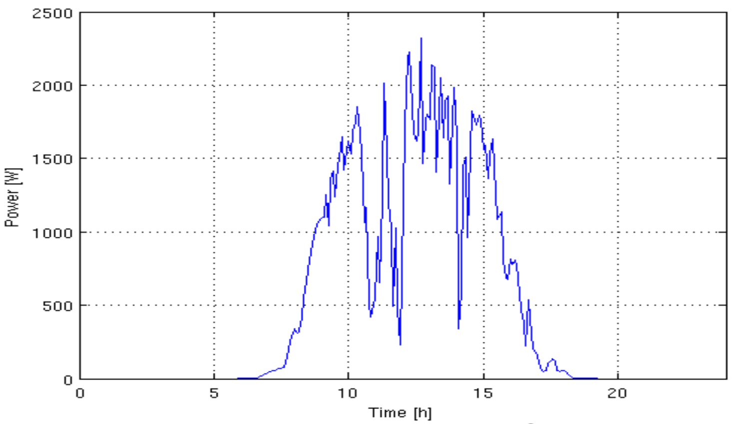
K. Kok, M. Venekamp, "Market based control in decentralized electric power systems", ECN, 2010

Uncoordinated charging

Distribution level

- Highly stochastic loads
    - lack of aggregation
    - Inaccurate predictions
    - Strong voltage variations
- Voltages should stay within limits
- Interaction with PV not straightforward
    - Unbalanced situation
    - Both can worsen each other





Source: KU Leuven

Coordinated charging

Distribution level: losses?

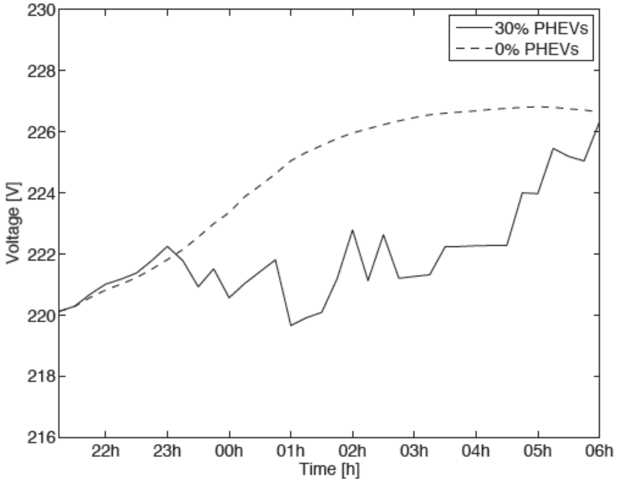
- Uncoordinated charging
  - Increased peak: need for new investments
  - Higher load→ higher currents→ higher losses?
    - Higher losses→ influence electricity price

	Uncoordinated	Coordinated		
PHEVs [%]		double tariff	voltage deviations	power losses
0	2.2	2.2	2.2	2.2
10	2.4	2.2	2.2	2.2
20	2.7	2.4	2.4	2.2
30	2.9	2.6	2.5	2.3

Coordinated charging

Distribution level: voltage deviations

- Uncoordinated
  - Higher load→ higher currents→ higher voltage deviations: standard EN 50160
    - 230 V ± 10 % for 95 % of time
    - VUF < 2% for 95 % of time (ratio of inverse/forward component of voltage)



	Uncoordinated	Coordinated		
PHEVs [%]		double tariff	voltage deviations	power losses
0	9.9	9.9	9.9	9.9
10	10.4	9.9	9.9	9.9
20	11.4	9.9	9.9	9.9
30	12.3	9.9	9.9	9.9

Spanningsafwijkingen

Coordinated charging

Stakeholders perspective

- Grid operators
  - Optimal usage of infrastructure
  - Limiting the losses
  - Limiting voltage deviations

Minimizing investments

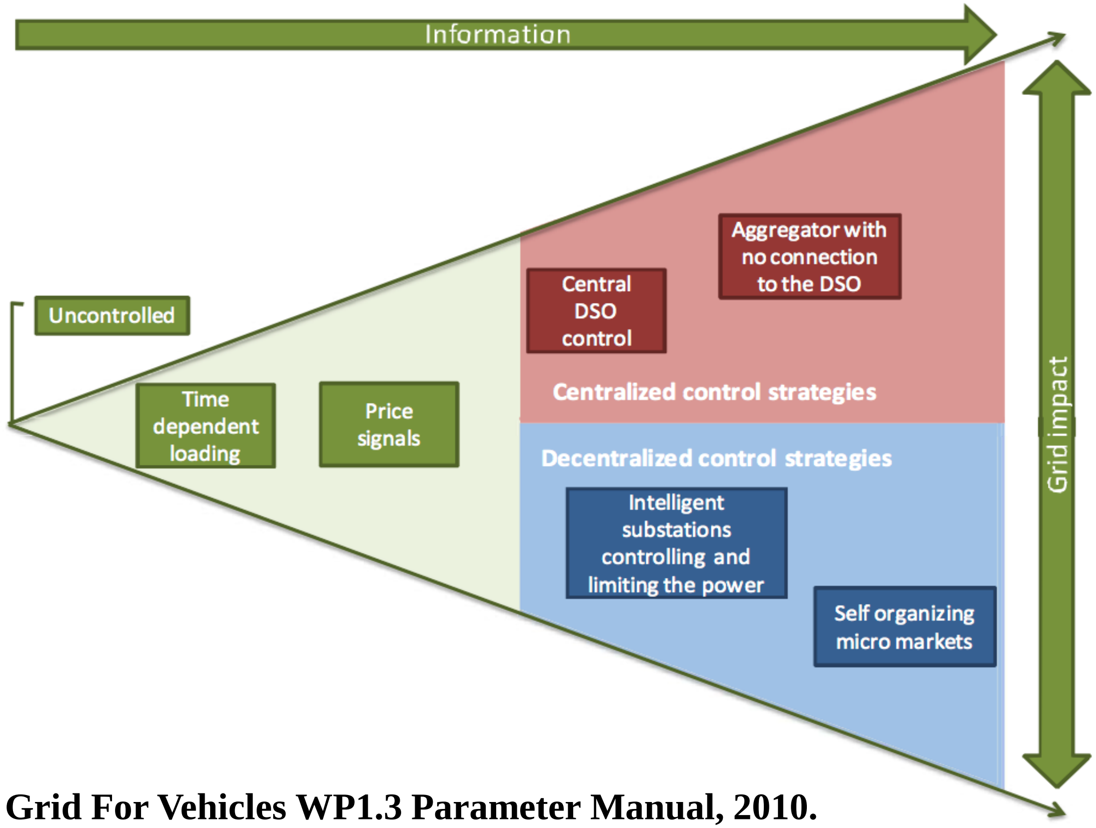
- Users
  - Minimizing charging costs
- Combination of objectives for general optimum
- Coördination methods to address flexibility
  - Central
  - Distributed
  - Hiërarchical

Controllability

- Charging
  - Delay
  - On/off
  - Continuously variable

  Note: not all car brands allow this

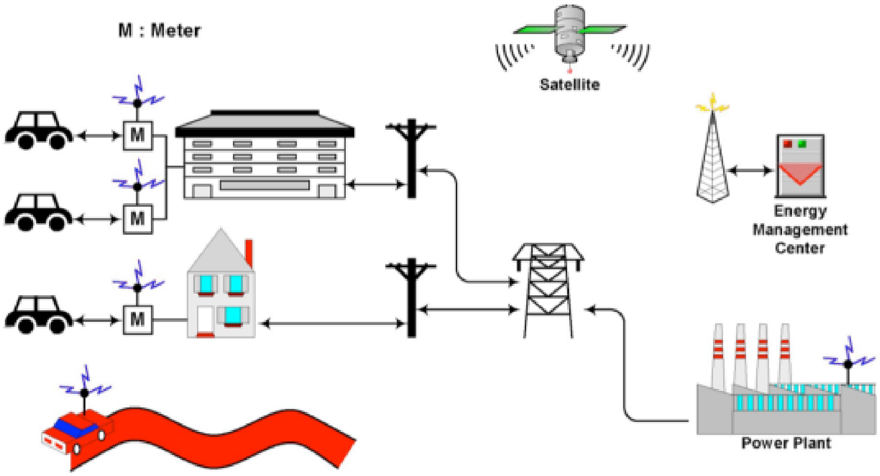
- Discharging?
- Vehicle-to-grid, vehicle-to-home, vehicle-to-building



Grid For Vehicles WP1.3 Parameter Manual, 2010.

Vehicle-to-Grid (V2G)

- Vehicle-to-Grid intelligent charging
  - Adaptation of charging power
  - Injecting power into the grid
- Bidirectional power flows
  - Active and reactive
- Limited storage in the grid
  - E.g. pumped storage
  - High flexibility required
  - Increasing amount of intermittend sources
- Potential flexibility of vehicle charging
  - Long standstill times
  - Average short daily driven distance



Electric vehicles availability

- 15 - 50 kWh per vehicle
- > 90 % of the time at standstill
- Large flexibility potential when being plugged in sufficiently
- Grid support
  - Controlled charging
    - Bidirectional / unidirectional / Q?
  - V2G / V2H
- Expensive due to degradation of battery
- Note: not standard available in EV (yet)

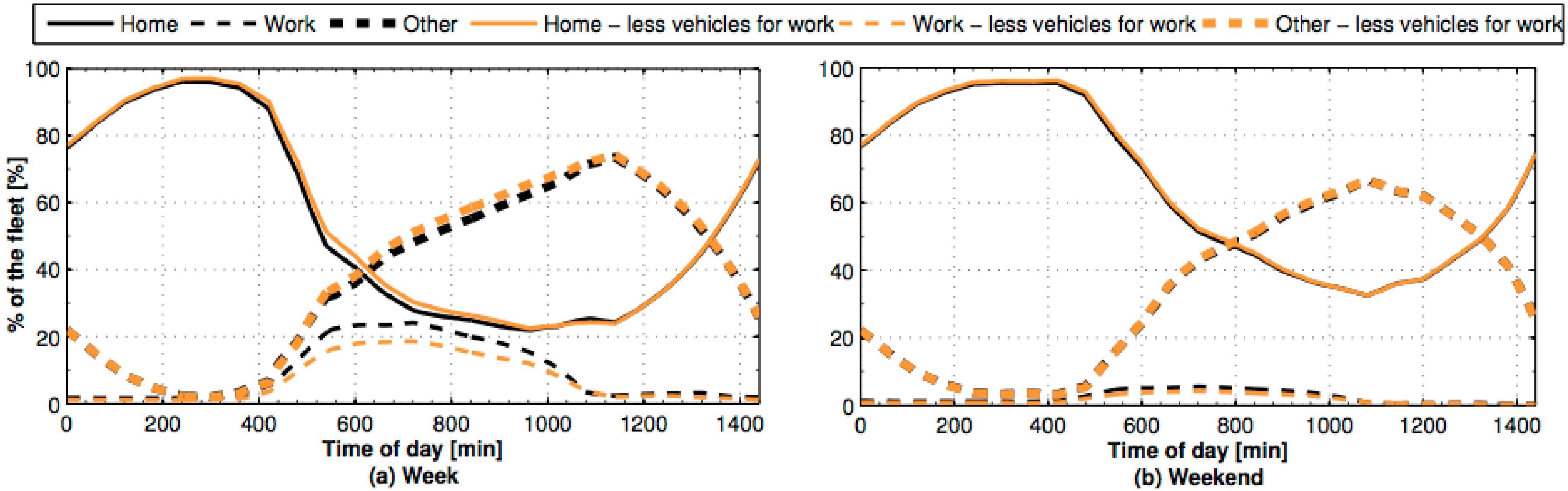
Potential of EV fleet?

Electric utility generation compared with the light vehicle fleet (for the US)

Metric	Electric generation system	Current light vehicle fleet (mechanical power)	Hypothetical fleet with 25% EDVs
Number of units	9351[a]	176,000,000[f]	44,000,000
Average unit power (kW)	64,000	111[g]	15[k]
Total system power (GW)	602[b]	19,500[h]	660
In-use	57%[c]	4%[i]	4%
Response time (off to full power)	Minutes to hours[d]	Seconds	Milliseconds to seconds[l]
Design lifetime (h)	80,000–200,000[o]	3000	>3000
Capital cost (per kW)	US$ 1000+	US$ 60[j]	US$ 10–200[m]
Cost of electricity (US$/kWh)	.02–.09 average, .05–.80 peak[e]	n.a.	.05–.50[n]

W. Kempton and J. Tomic, Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy, Journal of Power Sources, vol. 144, no. 1, pp. 280-294, Jun. 2005.

Vehicles at home



J. Van Roy, N. Leemput, S. De Breucker, F. Geth, P. Tant, and J. Driesen, An Availability Analysis and Energy Consumption Model for a Flemish Fleet of Electric Vehicles, in European Electric Vehicle Congress (EEVC), 2011, pp. 1-12.

V2G pros and cons

- Pro
  - Delivering grid support in peak situations
  - Increasing amount of renewables to be integrated in the grid
  - Could be activated very fast: power electronic interface
  - Large fleet of Evs = large power and energy buffer
- Con
  - Battery wear?
  - Total cost covered?
  - Needs substantial coordination
  - Vehicle manufacturers need to allow it (is foreseen in standards)

Grid impact

Conclusions

- EVs will impact the power system, mainly at distribution level
- Uncoordinated charging will increase peak power demand
- Potential for coordinated charging
  - Shifting charging to off-peak moments
  - Flexibility within the mobility objective
- Challenges first on the local level
  - High local penetration grade
  - Highly stochastic behavior
  - Grid constraints on the LV grid
  - Goes side by side with problems caused by PV integration

Thank you!