ELECTRIC VEHICLES CHARGING
– *AN ULTRAFAST OVERVIEW* –

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Power Electronics Laboratory
Switzerland

BEFORE WE START...

Few Disclaimers

- All of the materials presented here is collected from various online sources
- All sources are acknowledged and links are provided
- The inclusion of products does not constitute an endorsement of any kind
- Most of the figures and circuits are redrawn
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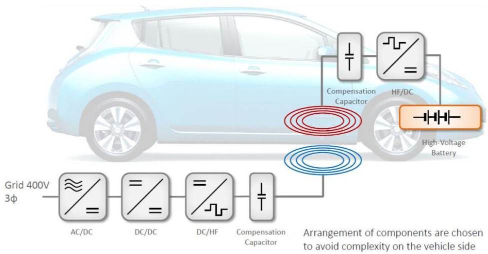
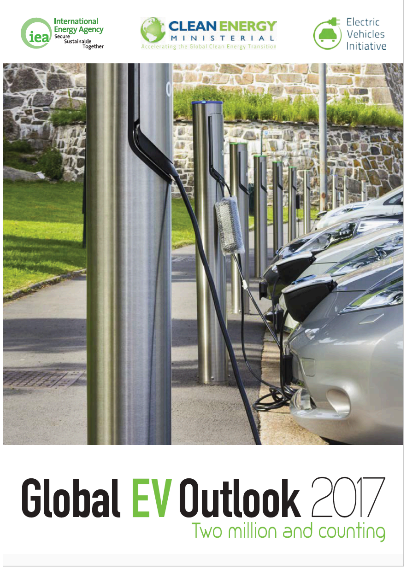


Arrangement of components are chosen to avoid complexity on the vehicle side

▲ General wireless charging scheme *(Source:* `https://insideevs.com/30-kw-wireless-charging-for-your-nissan-leaf-chademo-ev-anyone/`*)*



International Energy Agency
Secure Sustainable Together

CLEAN ENERGY MINISTERIAL
Accelerating the Global Clean Energy Transition

Electric Vehicles Initiative

Global EV Outlook 2017
Two million and counting

▲ *(Source:* `https://webstore.iea.org/global-ev-outlook-2017`*)*

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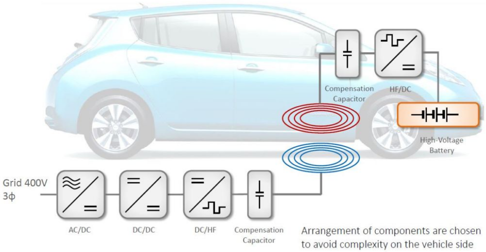

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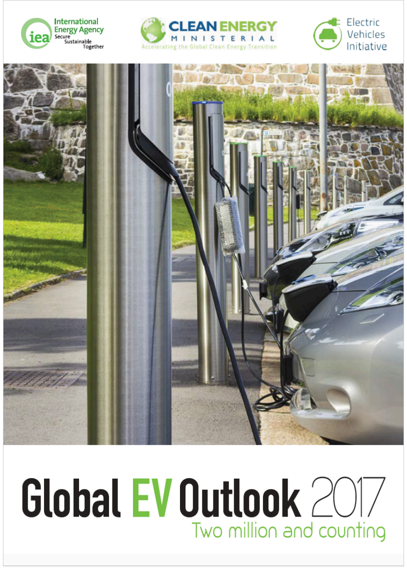

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⇒ Keynote pdf can be downloaded from: *(Source:* `https://pel.epfl.ch/publications_talks_en`*)*

INTRODUCTION

Into the electric future...

GRID CONNECTED ELECTRIC TRANSPORTATION

▲ Regional trains *(Source:* `www.sbb.ch`*)*

▲ City transport *(Source:* `www.stadlerrail.com`*)*

▲ Trolley buses *(Source:* `www.hess-ag.ch`*)*

▲ Electric trucks? *(Source:* `www.siemens.com`*)*

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▲ Electric trucks? *(Source: `www.siemens.com`)*

⇒ Provided existence of electrical infrastructure, electric transportation offers great benefits...

BATTERY POWERED ELECTRIC TRANSPORTATION - ON THE RISE...

▲ Electric hoverboards *(Source:* `www.razor.com`*)*

▲ Electric scooters *(Source:* `www.pinterest.ch`*)*

▲ Electric bicycles *(Source:* `www.stromerbike.com`*)*

▲ Electric trucks *(Source:* `www.daimler.com`*)*

▲ Electric buses *(Source:* `www.abb.com`*)*

▲ Electric motorbikes *(Source:* `www.supersoco.eu`*)*

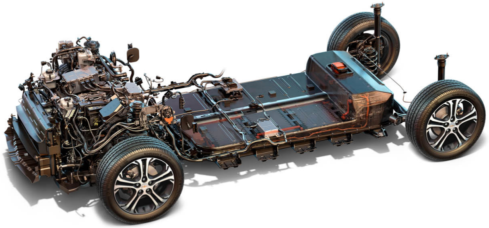
▲ Electric ferry boats *(Source:* `www.siemens.com`*)*

▲ Electric planes *(Source:* `www.pipistrel.si`*)*

▲ EVs *(Source:* `www.greenliving4live.com`*)*

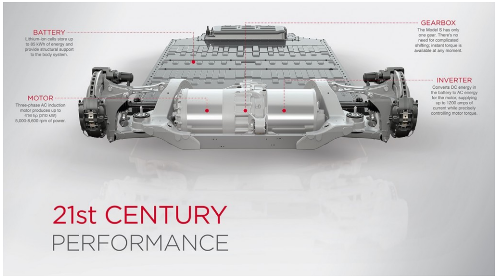
ELECTRIC VEHICLES ARCHITECTURE

▲ AUDI EV Drivertrain *(Source: `www.audi.de`)*



▲ GM Bolt EV Drivertrain *(Source: `www.gm.com`)*

▲ BMW i3 EV Drivertrain *(Source: `www.bmw.de`)*



BATTERY
Lithium-ion cells store up to 85 kWh of energy and provide structural support to the body system.

MOTOR
Three-phase AC induction motor produces up to 416 hp (310 kW) 5,000-8,600 rpm of power.

GEARBOX
The Model S has only one gear. There's no need for complicated shifting; instant torque is available at any moment.

INVERTER
Converts DC energy in the battery to AC energy for the motor, supplying up to 1200 amps of current while precisely controlling motor torque.

21st CENTURY
PERFORMANCE

▲ TESLA EV Drivertrain *(Source: `www.tesla.com`)*

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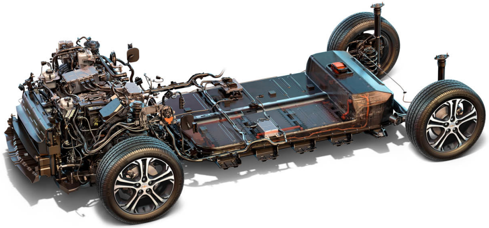

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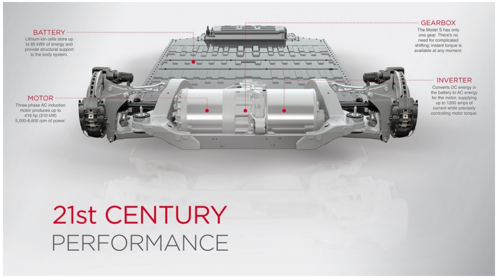


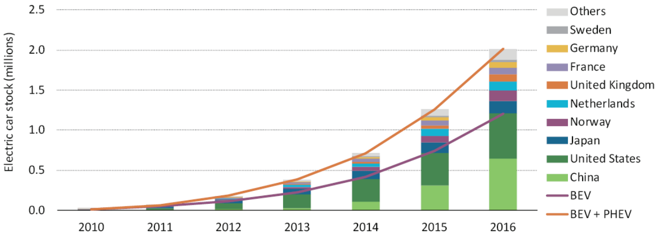
▲ TESLA EV Drivertrain *(Source: `www.tesla.com`)*

⇒ Simple power electronics application (Battery + 4Q Converter + Motor), but quite an advance integration is required...

NUMBERS OF EV WORLDWIDE

Table 1 Vehicles in use by fuel type (EU) - *(Source:* `http://www.acea.be/statistics/article/vehicles-in-use-europe-2017`*)*

Vehicle type	Fuel type					
	Petrol	Diesel	Electric (incl. plug-in)	Hybrids	LPG/Natural gas	Other
Passenger Cars	55.7%	41.2%	0.1%	0.4%	2.2%	0.4%
Light Commercial Vehicles	8.8%	87.8%	1.2%	0.01%	0.1%	1.1%
Medium and Heavy Commercial Vehicles	1.1%	95.5%	0.3%	0.04%	0.5%	2.5%



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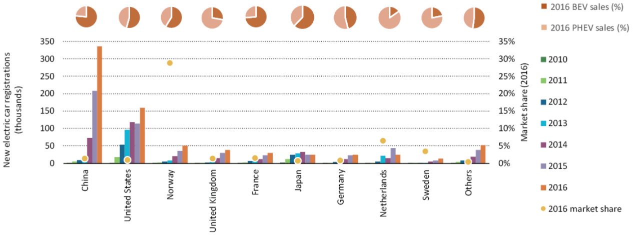

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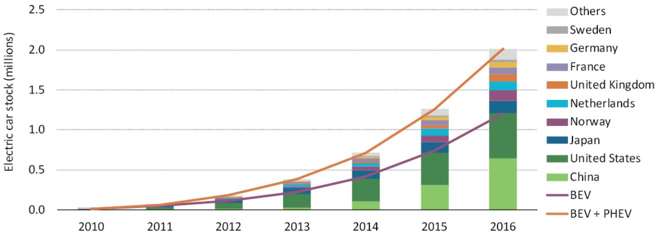
Light Commercial Vehicles	8.8%	87.8%	1.2%	0.01%	0.1%	1.1%
Medium and Heavy Commercial Vehicles	1.1%	95.5%	0.3%	0.04%	0.5%	2.5%



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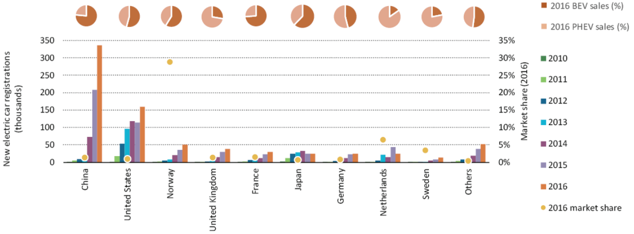

▲ EV sales, market share, and BEV and PHEV sales share in selected countries. 2010 - 2016, *(Source:* `https://webstore.iea.org/global-ev-outlook`*-2017)*

⇒ Despite very low absolute share, EV market growth rates are high, with China being The Leader of the EV deployment...

POLICY SUPPORT

Research support

- cost reduction
- performance improvements
- batteries
- semiconductors
- cables
- ...

Targets, mandates and regulation

- support policy making
- capacity building
- e.g. EV30@30 campaign
- ZEV - zero-emission vehicles
- low carbon technologies
- ...

Financial incentives

- reducing the purchase cost
- reducing the total cost of ownership
- direct rebates
- tax breaks
- exemptions
- ...

Other instruments

- limiting licence plates for ICE
- access to restricted urban areas
- road tolls
- parking places
- free charging infrastructure
- ...

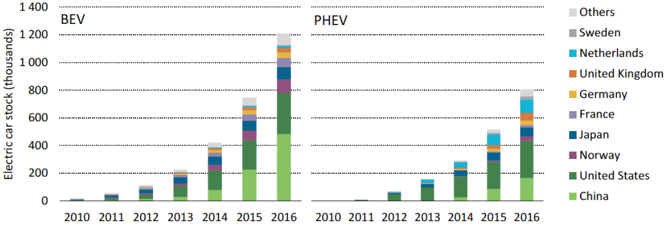

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Table 2 List of OEMs announcements on EV ambitions. *(Source:* `https://webstore.iea.org/global-ev-outlook`-2017*)*

OEM	Announcement	Source
BMW	0.1 mil. electric cars sales in 2017 and 15-25% of the BMW group's sales by 2025	Lambert (2017b)
Chevrolet (GM)	30 thousand annual electric car sales by 2017	Loveday (2016)
Chinese OEMs	4.52 mil. annual electric car sales by 2020	CNEV (2017)
Daimler	0.1 mil. annual electric car sales by 2020	Daimler (2016a)
Ford	13 new EV models by 2020	Ford (2017)
Honda	2/3 of the 2030 sales to be electrified vehicles (including hybrids, PHEVs , BEVs, FCEVs)	Honda (2016)
Renault - Nissan	1.5 mil. cumulative sales of electric cars by 2020	Cobb (2015b)
Tesla	0.5 mil. annual electric car sales by 2018 1 mil. annual electric car sales by 2020	Goliya and Sage (2016) Tesla (2017a)
Volkswagen	2-3 mil. annual electric car sales by 2025	Volkswagen (2016)
Volvo	1 mil. cumulative electric car sales by 2025	Volvo (2016)

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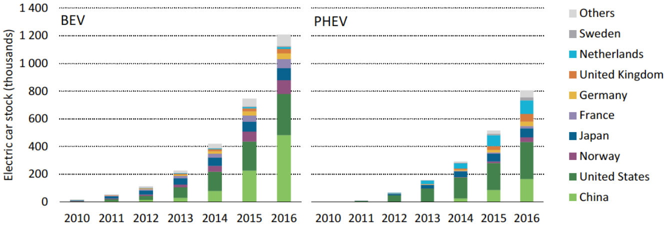

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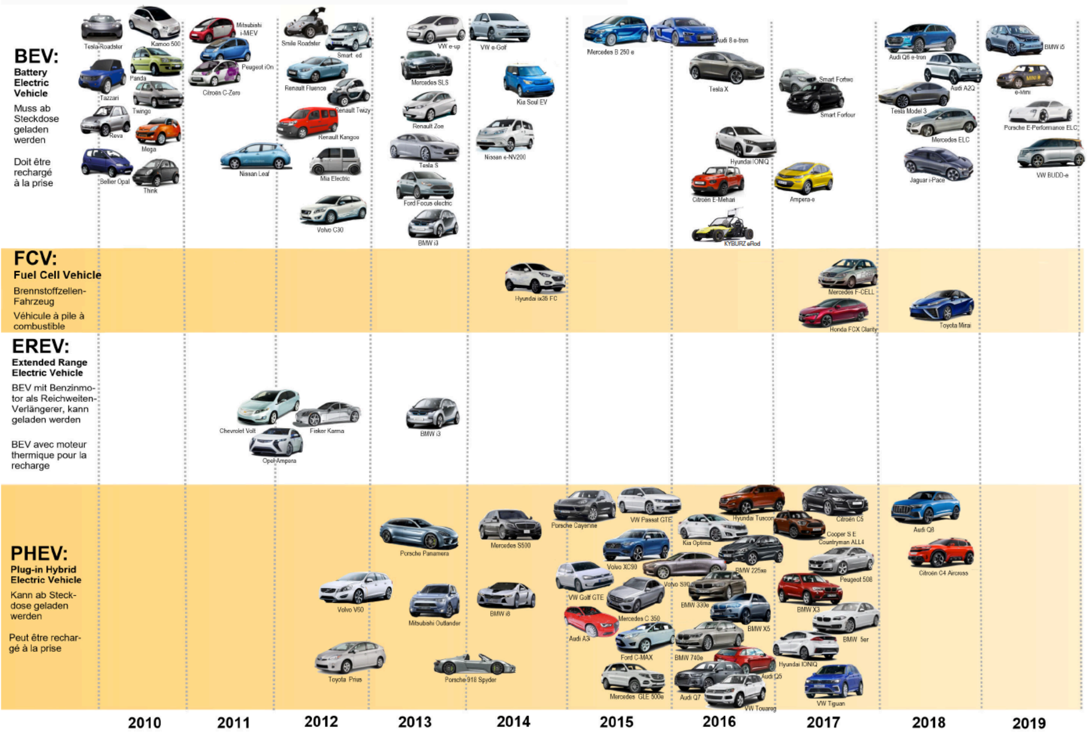
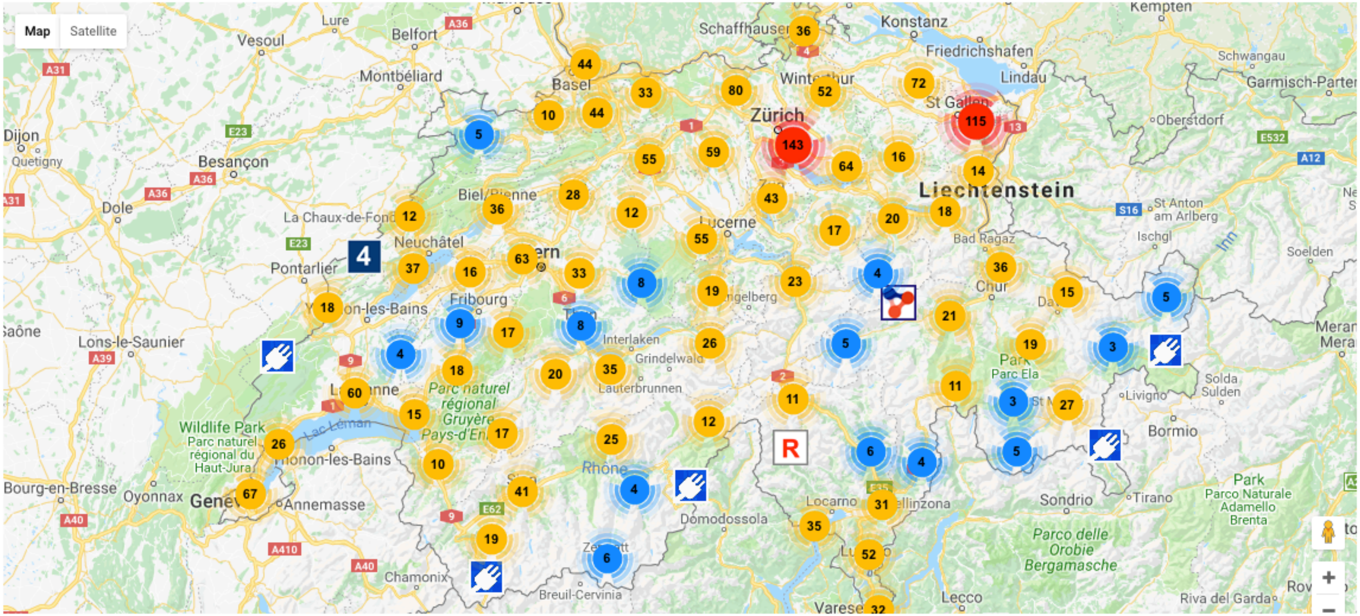
⇒ PHEV seems to be slowly losing the game against BEV...

CHOOSE WISELY...



▲ Electrosuisse *e'mobile* user guide. **e** stands for **Efficient** - not electric. Source: `https://e-mobile.ch/de/publikationen`

CHARGING STATIONS AVAILABILITY (SWISS EXAMPLE)



▲ Map of charging stations in Switzerland. Source: `https://e-mobile.ch/de/elektro-tankstelle-finden`

STANDARDS

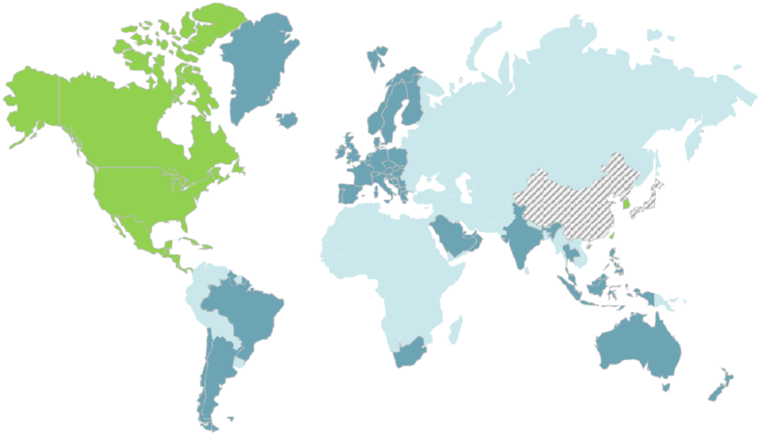
SAE J1772, IEC 62196, CCS, CHAdeMO, GB/T 20234 DC,...

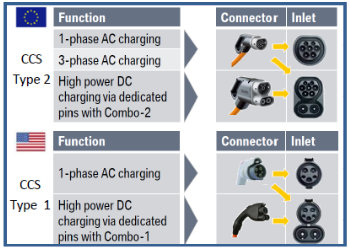
LEVEL OF CHARGING

Table 3 Overview of the level (power output) and type (socket and connector) of EVSE used in China, Europe, Japan and the USA.

Classification in use	Level	Current	Power	Type			
				China	Europe	Japan	North America
	Level 1	AC	$P \leq 3.7$kW	Devices installed in private households, the primary purpose of which is not recharging EV			SAE J1772 - Type 1
Slow Chargers	Level 2	AC	$3.7\text{kW} < P \leq 22$kW	GB/T 20234	IEC 62196 - Type 2	SAE J1772 - Type 1	SAE J1772 - Type 1
	Level 2	AC	$P \leq 22$kW	Tesla connector			
Fast Chargers	Level 3	AC - 3PH	$22\text{kW} < P \leq 43.5$kW		IEC 62196 - Type 2	SAE J3068 (Under development)	
	Level 3	DC	Currently $P < 200$kW	GB/T 20234 DC	CCS Combo2 connector (IEC 62196 - Type 2 & DC)	CHAdeMO	CCS Combo1 connector (SAE J1772 - Type 1 & DC)
	Level 3	DC	Currently $P < 150$kW	Tesla and CHAdeMO connectors			

INLET ADOPTION





CCS Type 2	Function	Connector	Inlet
	1-phase AC charging		
	3-phase AC charging		
	High power DC charging via dedicated pins with Combo-2		

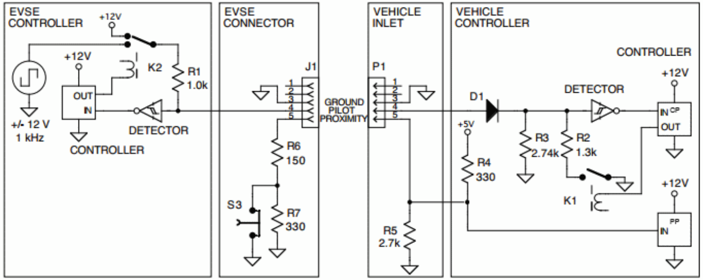
CCS Type 1	Function	Connector	Inlet
	1-phase AC charging		
	High power DC charging via dedicated pins with Combo-1		

▲ Inlet Adoption worldwide *(Source:* `https://insideevs.com/european-ccs-type-2-combo-2-conqueres-the-world/`*)*

COMMUNICATION

SAE J1772

- EVSE signal presence of AC input power
- plug detection via proximity plug (PP)
- control pilot (CP) functions between EVSE and EV
- EV instructs on energy requirements
- monitoring of continuity of safety ground
- no integrated circuits
- switches, diodes, resistors
- 1kHz square wave on control pilot (CP)
- PWM duty cycle indicates the maximum allowed mains current



▲ J1772 signaling circuit

P1901 power line communication

- IEEE 1901, IEEE 1905
- IP based communication

Table 4 SAE J1722 status modes

Base Status	Charging Status	Resistance, CP-PE	Resistance, R2	Voltage, CP-PE
Status A	Standby	Open, or ∞ Ω		+12V
Status B	Vehicle detected	2740 Ω		+9 ± 1V
Status C	Ready (charging)	882 Ω	1300 Ω	+6 ± 1V
Status D	With ventilation	246 Ω	270 Ω	+3 ± 1V
Status E	No power (shut off)			0V
Status F	Error			-12V

CHAdeMO

- CAN bus protocol

China

- CAN bus protocol

BATTERIES

One of the bottlenecks...

BATTERY PACKS

Since 2010 Lithium Ion dominates...

Cell formats:

- Button (not for EVs)
- Cylindrical (18650, 2170)
- Prismatic
- Pouch

Gravimetric Energy Density:

$$Cell\ (mAh/g) = \frac{1}{\frac{1}{C_A} + \frac{1}{C_C} + \frac{1}{Q_M}}$$

- C_A - specific capacity of the Anode
- C_C - specific capacity of the Cathode
- Q_M - specific mass of other parts

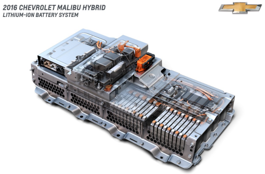
Continuous quest for:

- higher energy density
- high number of cycles
- longer lifetime
- lower cost

▲ Cylindrical 18650 cell *(Source:* `www.tesla.com`*)*

▲ Tesla battery pack *(Source:* `www.tesla.com`*)*

▲ Prismatic cell *(Source:* `www.hitachi-ve.co.jp`*)*



▲ Chevrolet battery pack *(Source:* `www.gm.com`*)*

▲ Pouch cell *(Source:* `www.nissan-global.com`*)*

▲ Nissan battery pack *(Source:* `www.nissan-global.com`*)*

BATTERY PACK INTEGRATION CHALLENGES

Cell voltage is typically 3.5V...

Configurations:

- number of parallel cell?
- number of series cells?
- operating voltage are normally below 500V
- 96 cells in series is typical number (not only)
- 1 to 5 cell strings in parallel
- Porsche - 800V ?

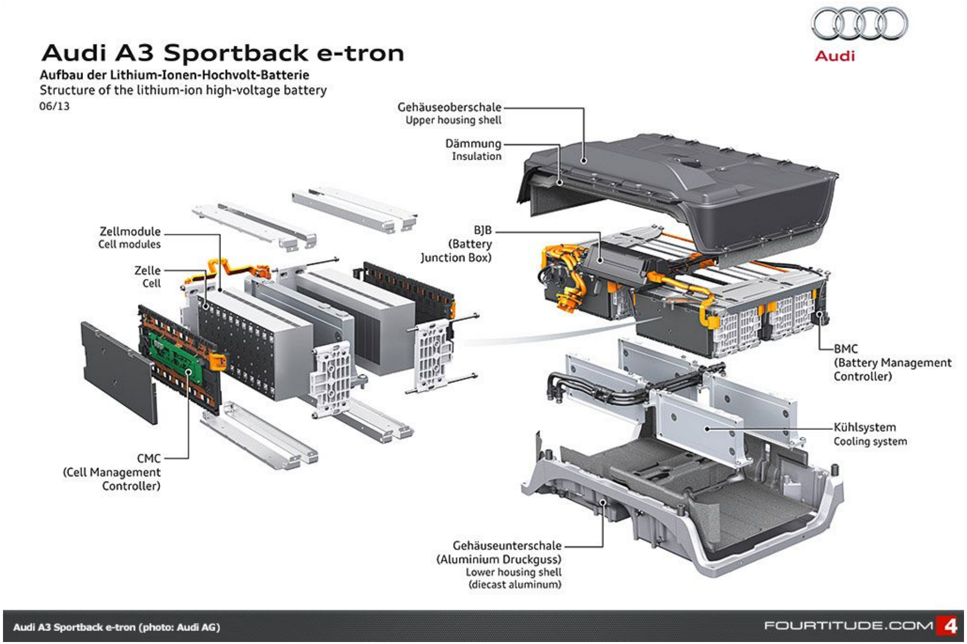
Thermal management:

- critical for cell performance
- affects the allowed charging speeds
- air passive
- air forced
- liquid cooling
- refrigerant

Mechanical:

- functional and structural support
- frame integration
- protection against elements
- collision integrity

Cost, Cost, Cost...



▲ AUDI A3 Sportback e-tron battery pack integration *(Source:* `www.audi.de`*)*

BATTERY PACKS INSIDE VEHICLES

Table 5 Examples of some EV models and used battery packs

Manufacturer	Model	Power[kW]	Electric Machine Type	Battery Thermal Management Type	E_{bat} [kWh]	Cell Type	Range [km]
Audi	A3 e-Tron	110	PM	Liquid	8.8	Prismatic	50
BMW	i3	125	PM	Refrigerant	33.2/27.2	Prismatic	235-255
Cadillac	ELR	176.25	PM/PM	Liquid	17.1	Prismatic	63
Chevrolet	Volt	111	PM/PM	Liquid	18.4	Pouch	85
Chevrolet	Spark EV	97	PM	Liquid	19	Pouch	132
Chevrolet	Bolt EV	150	PM	Liquid	60	Pouch	380
Fiat	500e	83	IM	Liquid	24	Prismatic	140
Ford	Focus Electric	107	PM	Liquid	33.5	Pouch	185
Nissan	Leaf	110	PM	N/A	40	Pouch	241
Tesla	Model S	581	IM	Liquid	100	Cylindrical	520
Tesla	Model X	568	IM	Liquid	90	Cylindrical	400
Volvo	XC90 T8	65	PM/PM	Liquid	9.2	Pouch	43
VW	e-Golf	100	PM	Air	35.8	Prismatic	300
Toyota	Prius Prime	53	PM/PM	Air	8.8	Prismatic	35
Kia	Soul	82.5	PM	Air	30	Pouch	177

BATTERY PACK COST PREDICTIONS

Very active research field...

Cathode variations:

- manganese oxide spinel (LMO)
- nickel cobalt aluminum (NCA)
- nickel manganese cobalt (NMC)
- NMC-LMO blends

Anode variations:

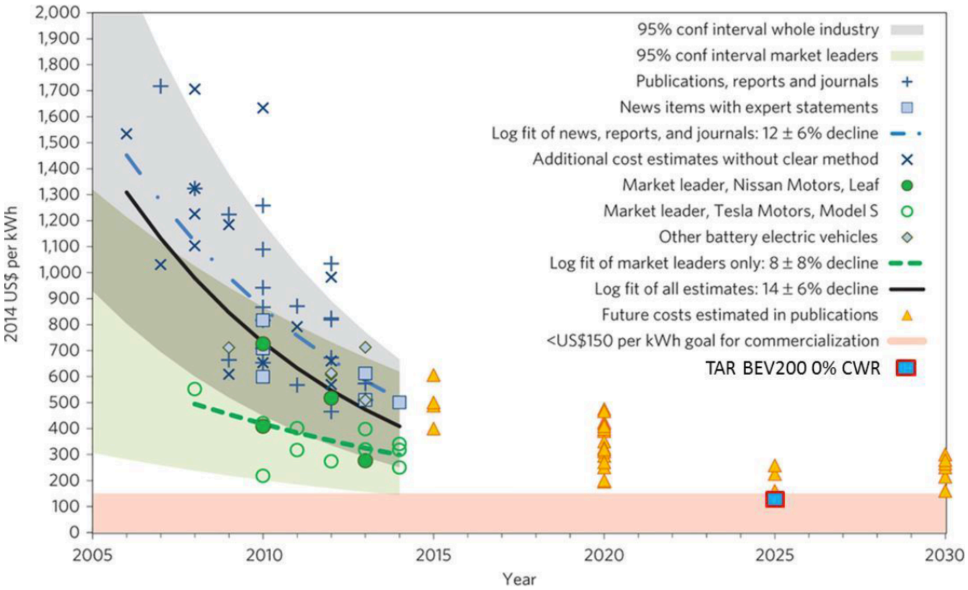
- graphite
- silicone (increasingly being added)

Research:

- lower cost materials
- cheaper manufacturing
- novel chemistry
- ...

Solid State Batteries

- Lithium Ion based
- solid material instead of electrolyte
- polymer or ceramic
- variety of anode and cathode options
- possibility of bipolar stacking (packaging)
- developments are not without troubles...



▲ Range of projected battery pack cost reduction, USD per kWh, *(Source:* `https://www.arb.ca.gov/msprog/acc/mtr/appendix_c.pdf`*)*

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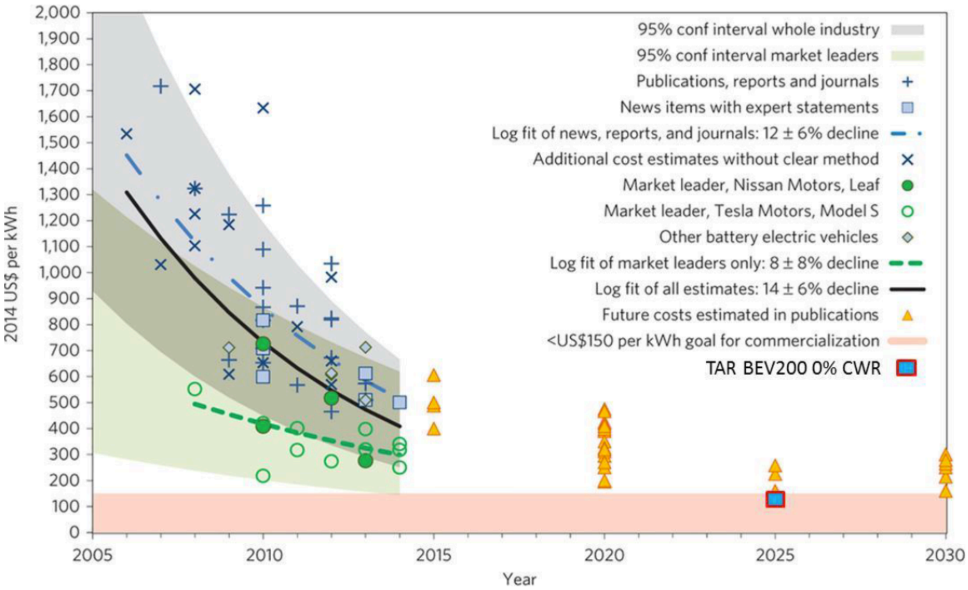

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⇒ Costs of battery packs are steadily declining...

SPEED OF CHARGING

How fast is enough?

SPEED OF CHARGING IN ICE WORLD

Slow charging

▲ Something you do not want to do

Numbers

- Re-fueling speed: 0.07 l/sec (measured)
- Re-fueling speed: 4.2 l/min
- Average consumption: 6 l/100km
- Charging range: 72 km/min

Normal charging

▲ Something you do every few weeks

Numbers

- Re-fueling speed: 0.7 l/sec (measured)
- Re-fueling speed: 42 l/min
- Average consumption: 6 l/100km
- Charging range: 700 km/min

Fast charging

▲ Something you likely never do

Numbers

- Re-fueling speed: 12 l/sec (limited)
- Re-fueling speed: 720 l/min
- Average consumption: 75 l/100km
- Charging range: 960 km/min (theory)

SPEED OF CHARGING IN ICE WORLD

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Numbers

- Re-fueling speed: 0.7 l/sec (measured)
- Re-fueling speed: 42 l/min
- Average consumption: 6 l/100km
- Charging range: 700 km/min

Fast charging

▲ Something you likely never do

Numbers

- Re-fueling speed: 12 l/sec (limited)
- Re-fueling speed: 720 l/min
- Average consumption: 75 l/100km
- Charging range: 960 km/min (theory)

⇒ You may get better with training in a slow charging game...

SPEED OF CHARGING IN EV WORLD

L1 charging

- AC only

Numbers

- Charging time: 7 - 17 hrs
- Supply line: 120/230 V, 1-phase AC
- Amps: 12 - 16 A
- Charge power: up to 3.7 kW
- Range added: 5 - 8 km/hour

L2 charging

- AC only

Numbers

- Charging time: 0.4 - 7 hrs
- Supply line: 208 - 240 V, 1-phase AC
- Amps: 12 - 80 A
- Charge power: 3.7 - 22 kW
- Range added: 16 - 32 km/hour

L3 charging

- AC or DC

Numbers

- Charging time: 0.1 - 0.4 hrs
- Supply line: 208 - 480 V, 3-phase AC
- Amps: max 400 A
- Charge power: 22 - 150 (350) kW
- Range added: 80% charge in (10)-20-30 minutes?

SPEED OF CHARGING IN EV WORLD

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- Supply line: 120/230 V, 1-phase AC
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L3 charging

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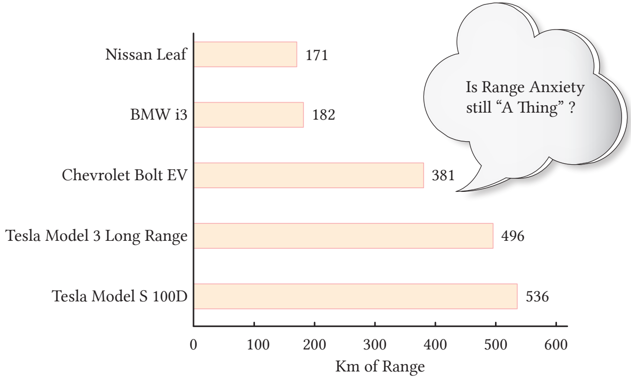
Numbers

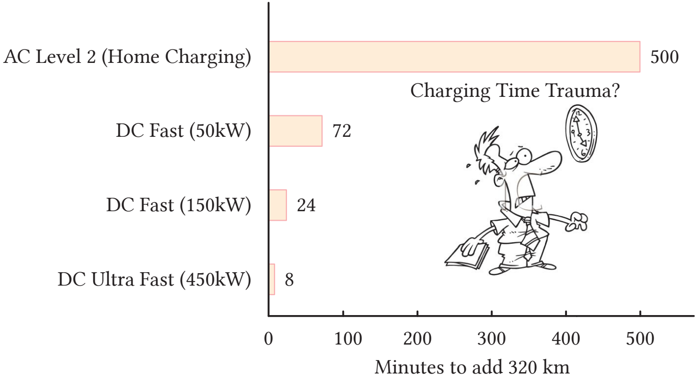
- Charging time: 0.1 - 0.4 hrs
- Supply line: 208 - 480 V, 3-phase AC
- Amps: max 400 A
- Charge power: 22 - 150 (350) kW
- Range added: 80% charge in (10)-20-30 minutes?

⇒ Numbers for charging times and range added are not exact, as many factors play the role...

USER NEEDS?



- Range Anxiety has been cured... [1]

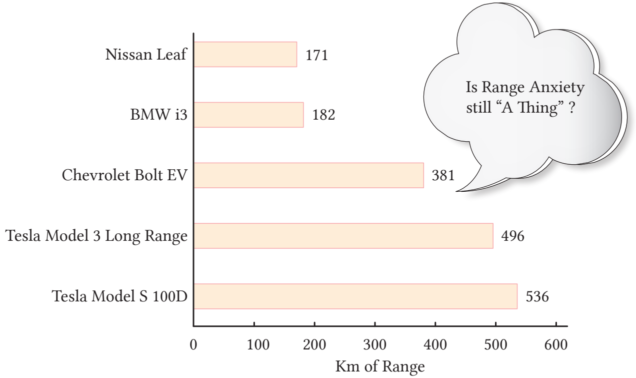


- Charging Time Trauma is, however, something to worry about now...

---

[1] Example borrowed from Prof. Srdjan Srdic presentation

USER NEEDS?



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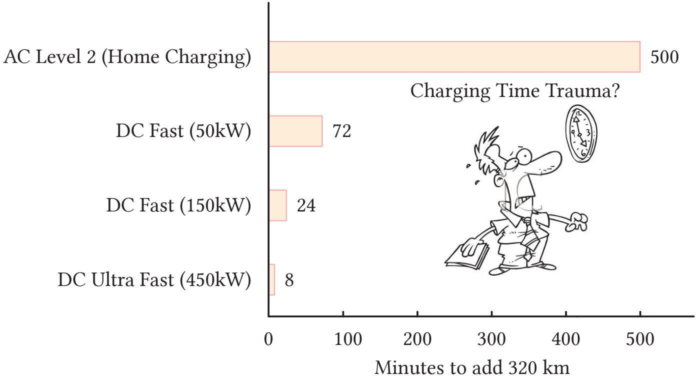
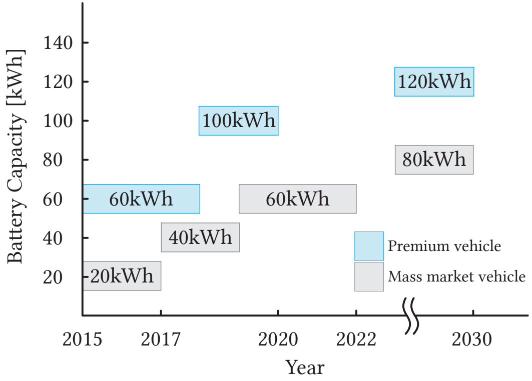


▲ Charging Time Trauma is, however, something to worry about now...

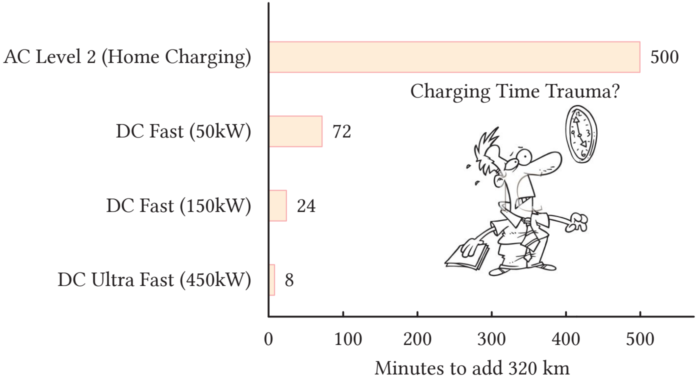
⇒ Several studies imply that users are increasingly more concerned with the speed of charging than with the actual range...

[1] Example borrowed from Prof. Srdjan Srdic presentation

FASTER MEANS MORE POWER IS NEEDED!



- ▲ Battery capacity increase expectations



- ▲ Will we be able to charge quickly, is what worries us now...

Small example [2]

- Charger efficiency = 90%
- Initial SoC = 10%
- Final SoC = 80%
- Δ SoC = 70%
- $E_{bat} \uparrow \Rightarrow t_{chg} \uparrow$

$$P_{chg} = \frac{E_{bat}\Delta SoC}{t_{chf}\eta_{chg}}$$

Table 6 Required charging power P_{chg} in kW depending on the battery capacity in kWh

		Ebat [kWh]						
		20	40	60	80	100	120	
t_{chg}	5 min	187	373	560	747	933	1120	P_{chg} [kW]
	10 min	93	187	280	373	467	560	
	15 min	62	124	187	249	311	373	

---

[2] Example borrowed from Dr. Marco Stieneker, IPEC 2018 ECCE ASIA paper

CONDUCTIVE CHARGING

L1, L2, L3

LEVEL 1 CHARGERS

Table 7 Level 1 Chargers Summary

Voltage	120 Vac (US) / 230 Vac (EU)
Power	$P_{max} \leq 3.7kW$
Connector	▶ IEC62196 - Type 1 (J1772) ▶ IEC62196 - Type 2 Mennekes Connector ▶ 3-Pin Connector ▶ Commando Connector

▲ Mitsubishi Level 1 cordset *(Source:* `http://www.activatedpower.com/index.php/products-services/products/`*)*

(a) 3-Pin – 3kW AC

(b) Commando – 3kW AC

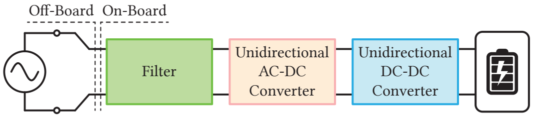
(c) Type 1 – 3kW AC

(d) Type 2 – 3kW AC

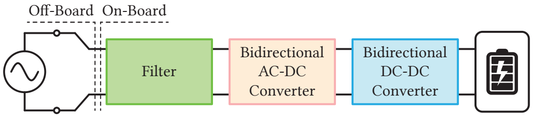
▲ Slow charging connectors *(Source:* `http://www.zap-map.com/charge-points/connectors-speeds/`*)*

▲ Greenmotion wall charger *(Source:* `https://www.greenmotion.ch/Product/PrivateOne`*)*

LEVEL 1 CHARGERS



▲ Unidirectional Charging - General Concept



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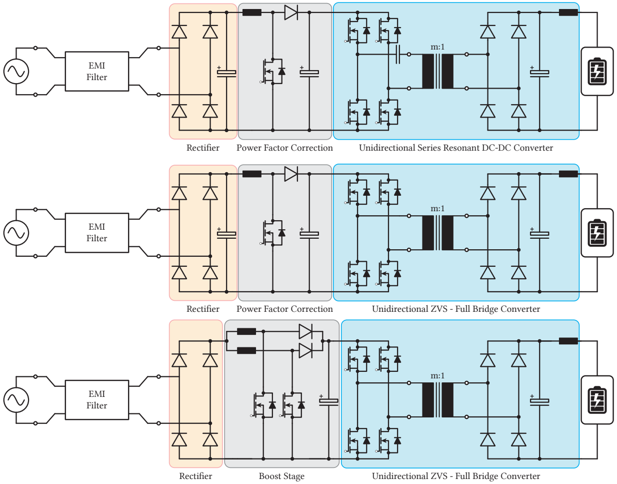
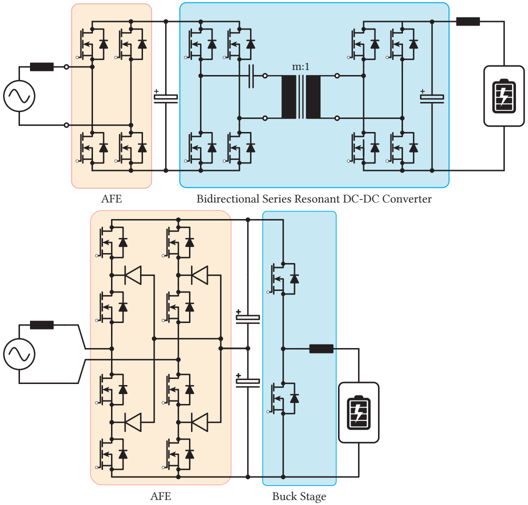


▲ Unidirectional topologies proposed within academia



▲ Bidirectional topologies proposed within academia

LEVEL 2 CHARGERS

Table 8 Level 2 Chargers Summary

Voltage	230 Vac (US) / 400 Vac (EU)
Power	3.7kW < $P_{max} \leq$ 22kW
Connector	▶ IEC62196 - Type 1 (J1772) ▶ IEC62196 - Type 2 Mennekes Connector ▶ Commando Connector

(a) Type 1 Connector

(b) Type 2 Connector

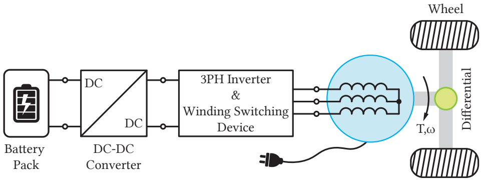
(c) Commando Connector

▲ Level 2 Connector Types

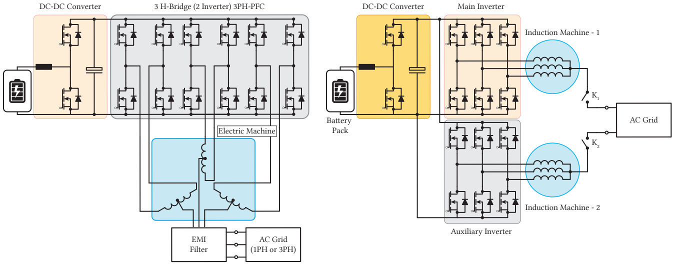
▲ Schneider Electric wall mounted charger *(Source:* `https://www.schneider-electric.us`*)*

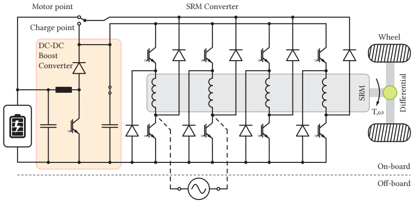
▲ Nissan Leaf fast home charger (7kW) *(Source:* `https://www.nissan.co.uk/vehicles/new-vehicles/leaf.html`*)*

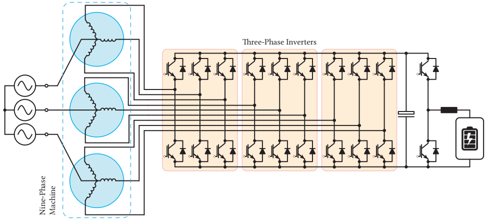
INTEGRATED ON-BOARD CHARGERS

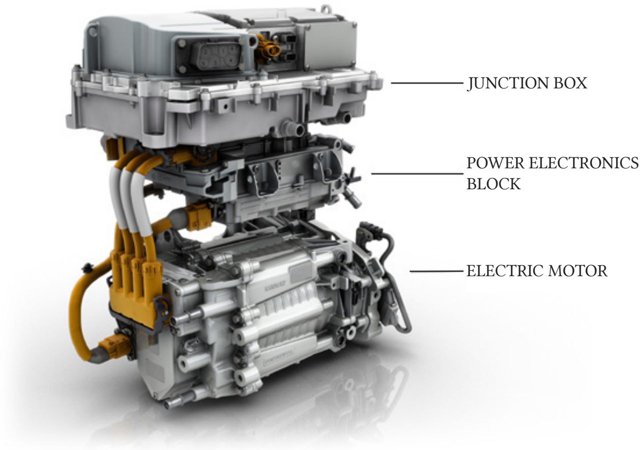


- General concept rely on the use of propulsion of drive train components









- Renault Zoe integrated system - Chameleon charger (43kW)
- Various proposals of integrated on-board chargers that use electrical machine's coils

LEVEL 3 CHARGERS

Table 9 Level 3 Chargers Summary

Voltage	200-600Vac or 200-800Vdc
Power	$P_{max} \geq 22kW$ (up to 350kW !)
Connector	▶ IEC62196 - Type 1 (J1772) ▶ IEC62196 - Type 2 Mennekes Connector ▶ Commando Connector

(a) CHAdeMO Connector

(b) CCS Combo Connector

(c) IEC 62916 - Type 2

(d) Tesla Connector

▲ Level 3 Connector Types

(a) (b)

▲ DC Fast Chargers; (a) ABB Terra 53CJG (50kW, CCS & Chademo); (b) Porsche DCFC CCS (350kW)

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(f) CCS Combo Connector

(g) IEC 62916 - Type 2

(h) Tesla Connector

▲ Level 3 Connector Types

(a)

(b)

▲ DC Fast Chargers; (a) ABB Terra 53CJG (50kW, CCS & Chademo); (b) Porsche DCFC CCS (350kW)

⇒ High power or ultrafast charging implies power levels of 150 - 350kW...

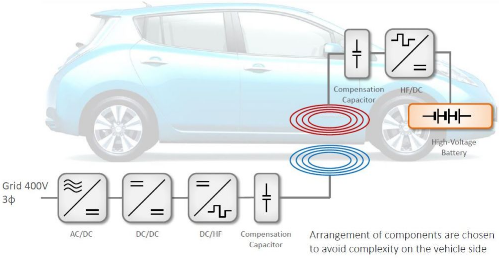
WIRELESS CHARGING

Cut the cord!

WIRELESS CHARGING

▲ BMW wireless charging pad *(Source: www.bmw.de)*

▲ TESLA plugless system *(Source: www.tesla.com)*



▲ General wireless charging scheme *(Source: https://insideevs.com/30-kw-wireless-charging-for-your-nissan-leaf-chademo-ev-anyone/)*

▲ WARTSILA wireless coastal ferry MW charger *(Source: www.wartsila.com)*

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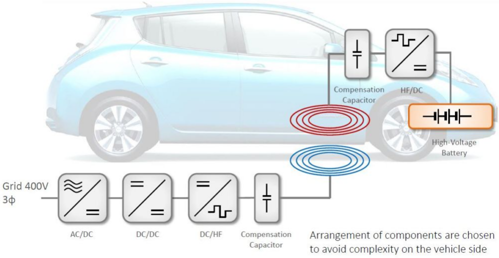


Arrangement of components are chosen to avoid complexity on the vehicle side

▲ General wireless charging scheme *(Source: `https://insideevs.com/30-kw-wireless-charging-for-your-nissan-leaf-chademo-ev-anyone/`)*

▲ WARTSILA wireless coastal ferry MW charger *(Source: `www.wartsila.com`)*

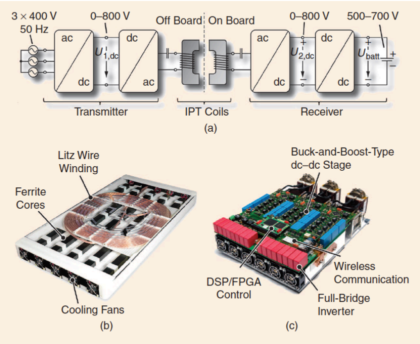
⇒ Wireless charging of privately owned EVs is driven mainly by the Convenience factor...

INDUCTIVE POWER TRANSFER

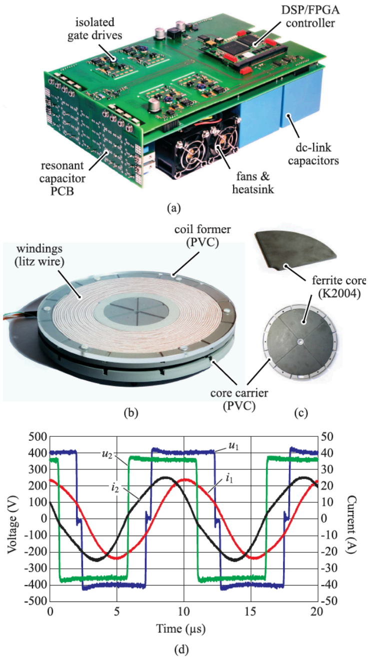
Design optimization:

- Coils form and shape
- High frequency converters
- Compensation and impedance matching
- Thermal design
- Interoperability (85kHz)
- Field exposure control
- Foreign object detection

Excellent tutorials on IPT at: `http://www.pes.ee.ethz.ch`



▲ (a) ETHZ PES prototype IPT system; (b) 50kW IPT coil with transmission efficiency of 98%; (c) All-SiC EV side converter with efficiency of 98.6%. [3]

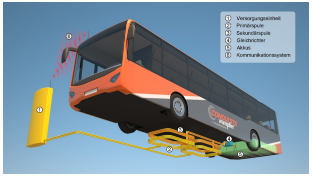


▲ (a) ETHZ PES prototype IPT system - 5kW at 100kHz accross 52mm; (a) All-SiC test inverter; (b) IPT coil; (c) Ferrite core; (d) Experimental results. [4]

[3] R.Bosshard, J.W.Kolar, "Inductive Power Transfer for Electric Vehicle Charging", IEEE Power Electronics Magazine, September 2016

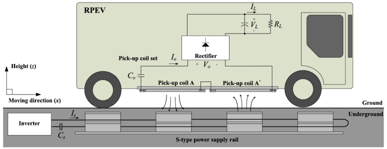
[4] R.Bosshard, J.W.Kolar et al, "Modeling and η-α-Pareto Optimization of Inductive Power Transfer Coils for Electric Vehicles", IEEE Journal of Emerging and Selected Topics in Power electronics, vol.3, no.1, March 2015

OPPORTUNITY (DYNAMIC) EV CHARGING



▲ IPT for buses *(Source: `www.conductix.com`)*

▲ Primove *(Source: `www.bombardier.com`)*



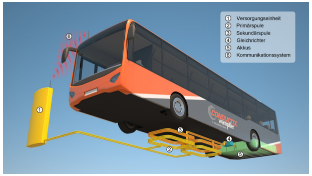
▲ Roadway power supply *(Source: `www.kaist.edu`)*

▲ IPT for buses *(Source: `http://wave-ipt.info`)*

Table 10 Some examples of inductive power supply systems related to EVs. There are many industrial solutions already in use.

	Conductix - Wamper	**Bombardier**	**Kaist-OLEV**		**WAVE**
Type	Static	Static / Dynamic	Static / Dynamic		Static
Application	Bus / Tram	Bus	Bus	Tram Train	Bus
Power [kW]	60/120/180	200	100	180	50
Frequency [kHz]	20	20	20	60	23.4
Max. Distance [cm]	5	6.5	20	10	17.8
Efficiency [%]	90	92	85	74	90
Missalignment [cm]	–	–	30	–	15
Comp. Topology (Primary/Secondary)	Series/Series	Series/Series	Series/Series	Series/Series	LCL-T/Parallel
Coil Type	Circular	Meander	Monorail		Circular
Converter Type	–	Full Bridge	Full-Bridge		Full-Bridge

OPPORTUNITY (DYNAMIC) EV CHARGING



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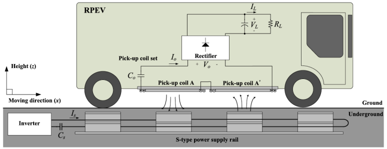

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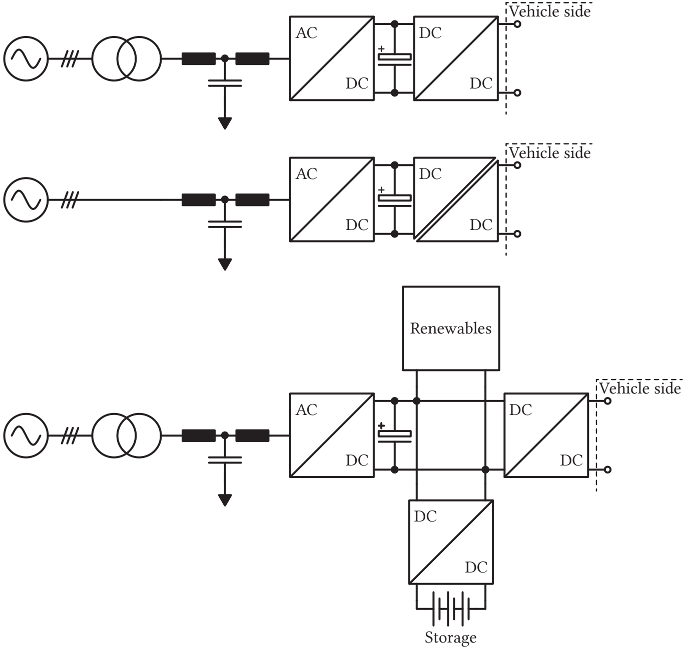
Coil Type	Circular	Meander	Monorail		Circular
Converter Type	–	Full Bridge	Full-Bridge		Full-Bridge

⇒ Dynamic IPT charging systems make a lot of sense if the routes and patterns are well known in advance...

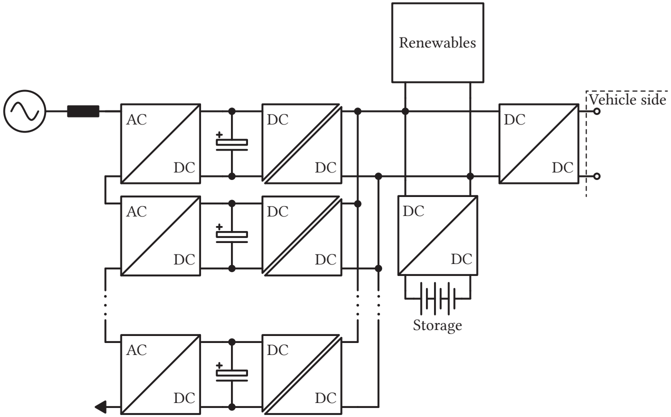
INFRASTRUCTURE
VS.
ULTRA FAST CHARGING

Let the battle begin...

ULTRAFAST CHARGING

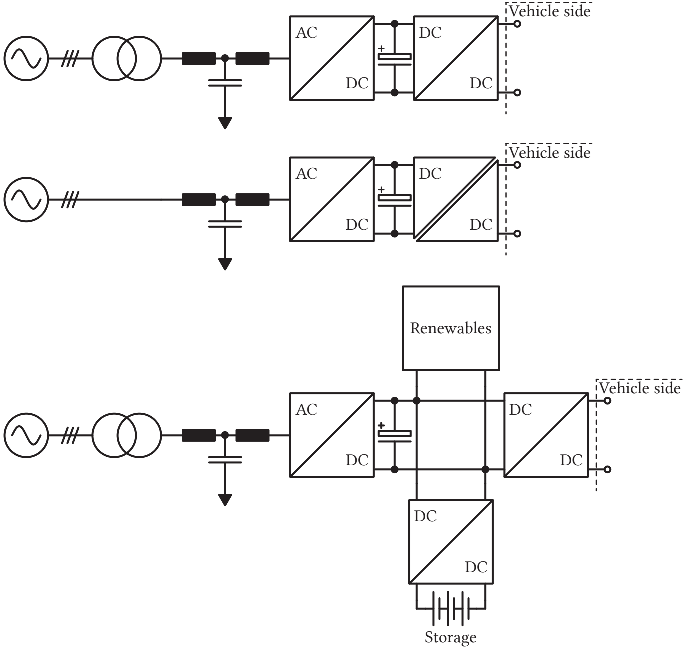


- Ultrafast charging requires certain decoupling from the grid



- Employment of multilevel topologies allows for connections to MV grid levels

ULTRAFAST CHARGING



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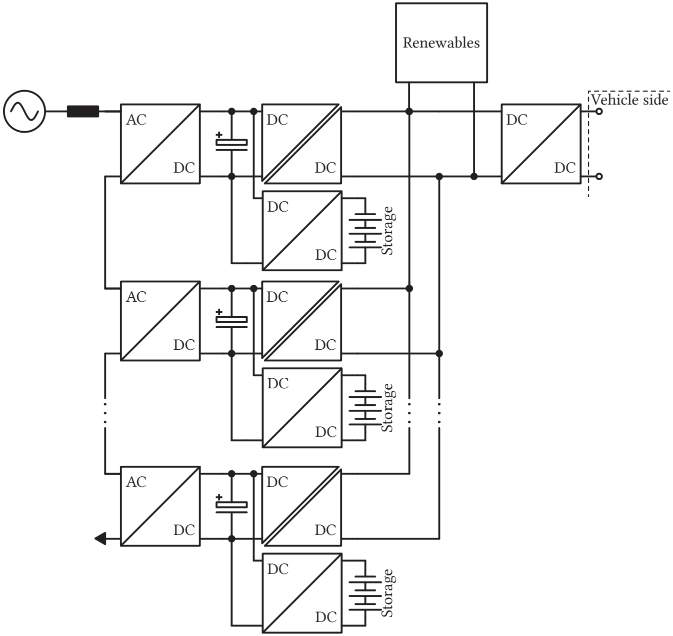


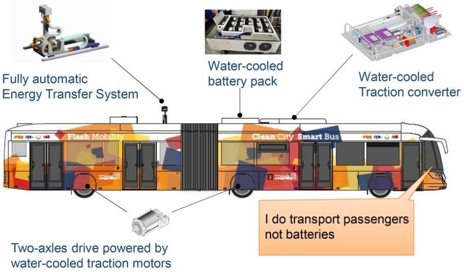
- Employment of multilevel topologies allows for connections to MV grid levels

FLASH CHARGING

▲ TOSA flash charging e-bus *(Source:* `https://new.abb.com/substations/references-selector/tosa-flash-charging-e-bus-geneva-switzerland`*)*

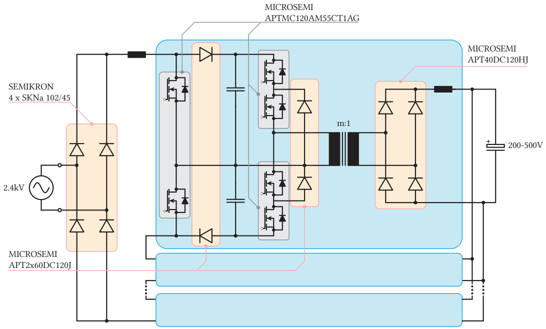
TOSA e-bus:

- 13 Flash-charging stations: 20s, 600kW, 600Vdc
- 3 Terminus feeding stations: 3-5min, 400kW, 600Vdc
- 4 Depot feeding stations: 30min, 45kW, 500Vdc
- water cooled battery pack
- battery on bus
- **battery at station**



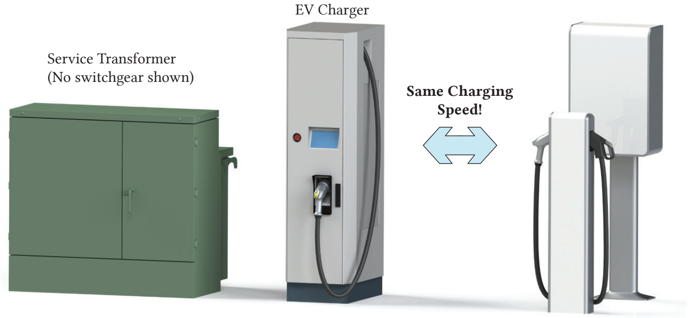
▲ ABB TOSA e-bus system *(Source:* `www.abb.com`*)*

MEDIUM VOLTAGE SOLID STATE CHARGER



▲ Concept proposed by FREEDM, North Carolina, USA

▲ Power Electronics Building Block (PEBB)



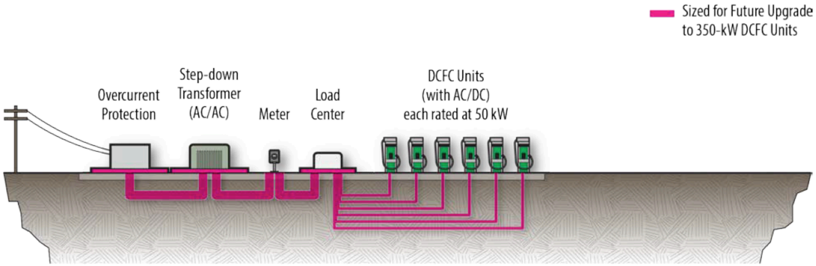
▲ System size reduction owing to the LFT omitting

TESLA SUPERCHARGER
- Power: 675 kW
- Efficiency: 92.6%
- Total cost: $250k

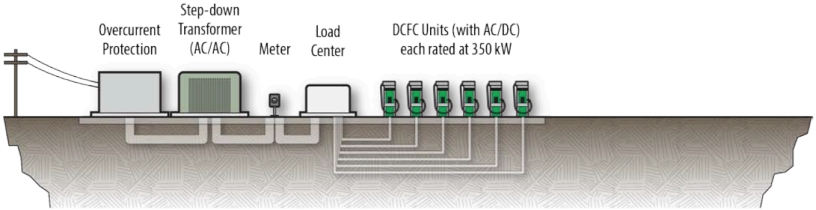
FREEDM SOLUTION
- Power: 900 kW
- Efficiency: 97.6%
- Total cost: $200k

▲ Comparative system evaluation (reducing the cost of installation)

INFRASTRUCTURE REINFORCEMENTS



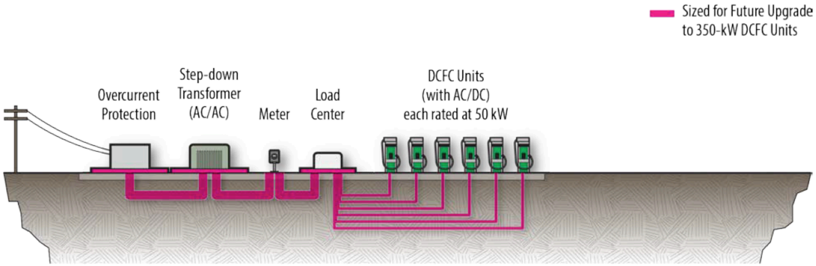
A) DCFC complex with 50-kW chargers and no ES and PV systems



B) DCFC complex with 350-kW chargers and no ES and PV systems

- Idaho National Laboratory study for DOE. Source: `https://avt.inl.gov/sites/default/files/pdf/reports/DCFCChargingComplexSystemDesign.pdf`

INFRASTRUCTURE REINFORCEMENTS



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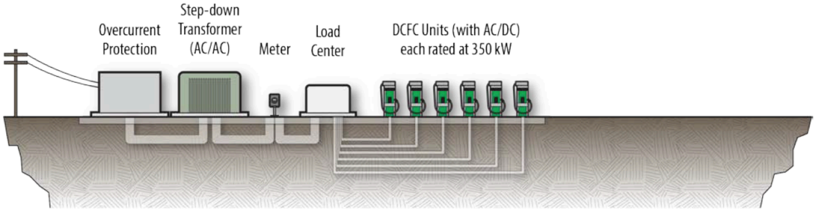
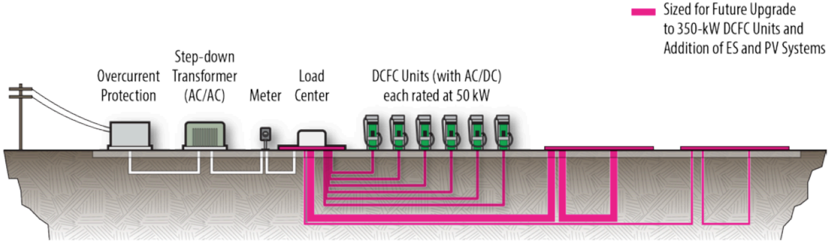


B) DCFC complex with 350-kW chargers and no ES and PV systems

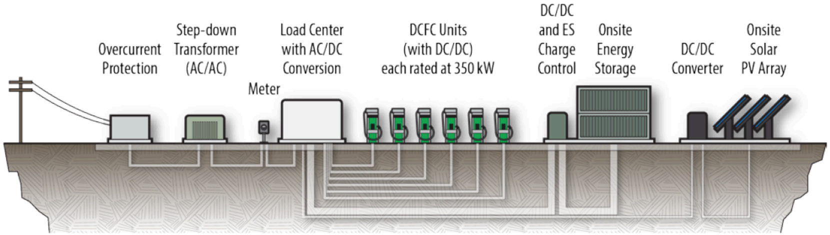
▲ Idaho National Laboratory study for DOE. Source: `https://avt.inl.gov/sites/default/files/pdf/reports/DCFCChargingComplexSystemDesign.pdf`

Future systematic upgrades require long term planning and commitment of all parties...

INFRASTRUCTURE REINFORCEMENTS



A) DCFC complex with 50-kW chargers and no ES and PV systems at initial installation



B) DCFC complex with 350-kW chargers and ES and PV systems

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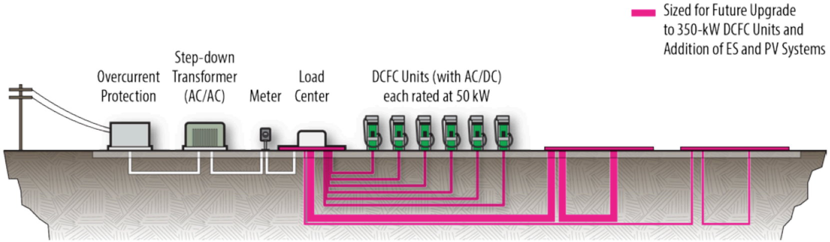
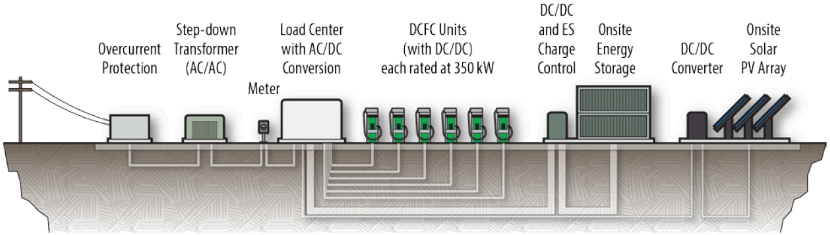
INFRASTRUCTURE REINFORCEMENTS



A) DCFC complex with 50-kW chargers and no ES and PV systems at initial installation



B) DCFC complex with 350-kW chargers and ES and PV systems

▲ Idaho National Laboratory study for DOE. Source: `https://avt.inl.gov/sites/default/files/pdf/reports/DCFCChargingComplexSystemDesign.pdf`

Upgrading or extending the existing utility infrastructure is another possibility...

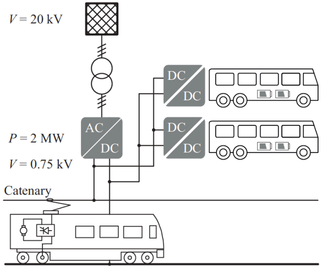
REDUCING THE GRID STRESS

V2X - Vehicle-to-X concepts?

- V2G - Vehicle to Grid
- V2B - Vehicle to Building
- V2H - Vehicle to Home
- V2L - Vehicle to Load
- ...

Business case issue?

- Utility interest?
- Charging infrastructure owner interest?
- Battery owner interest? (Battery is an asset?)



▲ Using the existing railway infrastructure *(Source:* `www.rwth-aachen.de`*)*

▲ Power Booster *(Source:* `www.ads-tec.de`)

▲ Using PV to charge EVs *(Source:* `www.tudelft.nl`*)*

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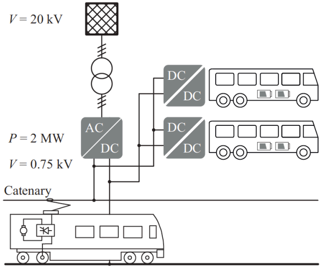

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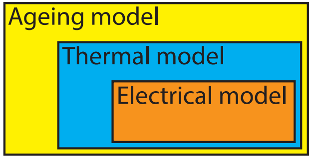
Bidirectional EV on-board chargers are still not widespread technology to enable large scale V2X...Business case?

SUMMARY

Flexible and efficient power electronics conversion will play important role...

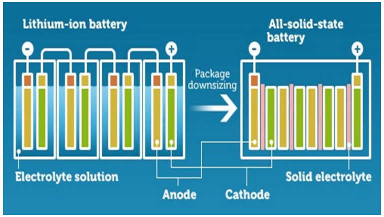
TRENDS AND CHALLENGES



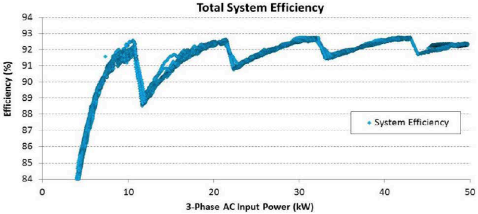
- Battery Modeling and Optimization

- SiC Semiconductors

- Interoperability

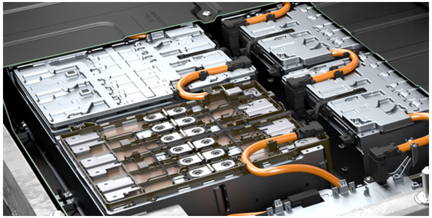


- Solid State Battery



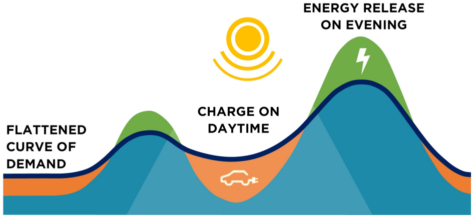
- Charger Efficiency

- Vehicle-to-Grid



- Integration Technologies

- Power Electronics Integration



- Power System Integration

THANK YOU FOR YOUR ATTENTION

Keynote pdf can be downloaded from:

- `https://pel.epfl.ch/publications_talks_en`

- Special thanks to Mr. Stefan Milovanovic for support with preparation of the keynote material