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TU Delft Department of Electrical Sustainable Energy

DC systems, Energy Conversion & Storage

Megawatt-level Charging Technology for Trucks

Keynote, 1300-1325

Power Electronics & Energy Storage 2026

Dr. Gautham Ram Chandra Mouli

Associate Professor

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TU Delft: https://research.tudelft.nl/en/persons/gr-chandra-mouli

Email: G.R.ChandraMouli@tudelft.nl

Research vision

Design and control of the battery and charging system of electric vehicles for charging from sustainable energy and massive grid integration

Research themes

- Power electronics for EV
- Battery modelling & ageing
- Smart charging, V2G & grid integration
- Electrification of Heavy-Duty vehicles

Gautham Ram
Associate professor

DC systems, Energy conversion & Storage

DCE&S
DC systems, Energy conversion & Storage

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Research Team


Wiljan Vermeer (Graduated)


Gautam Rituraj (Ex-Postdoc)


Darío Slaifstein


Yunhe Yu (Graduated)


Nikolaos Damianakis (Graduated)


Ibrahim Diab (Graduated)


Aditya Shekhar (Ex-Postdoc)

Power electronics for EV

Battery modelling & ageing

Smart charging, V2G & grid integration

Electrification of Heavy-Duty vehicles


Siddhesh Shinde


Carina Engström


Koen Linders


Nikolaos Damianakis (Postdoc)


Alvaro Agudin


Bagas Priambodo


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Leila Shams

Co + Promoter


Pavol Bauer


Laura Ramirez


Neil York Smith


Mathijs de Weerdt

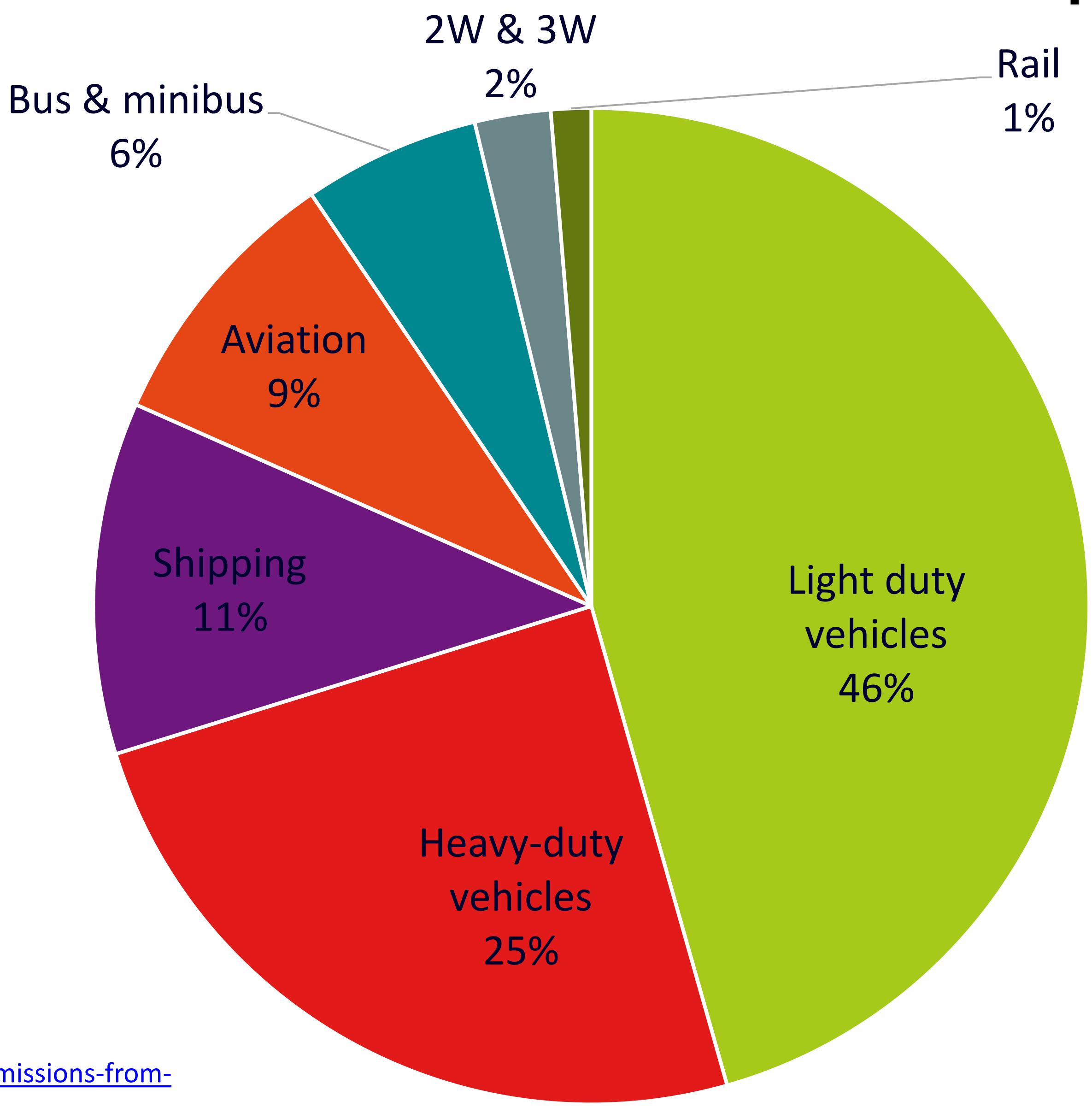

Chiara Falsetti


Wenli Shi


Vishnu Iyer (IISc, India)

Transport emissions

- Transport emissions in 2020 = 7.2 Gt CO_2
- Trucks & Bus are ~8% of 4W account for ~35% of CO_2 from road transport.



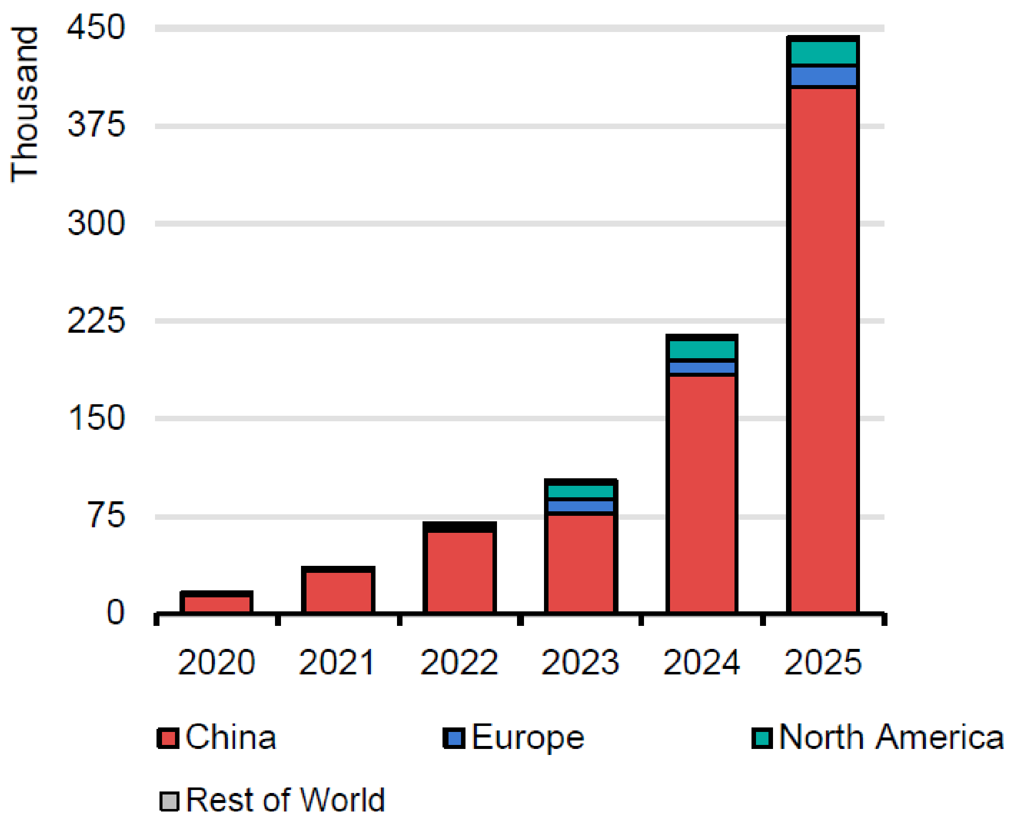
2020 Transport emissions (IEA)

Source: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-from-transport-by-subsector-2000-2030; https://energieinnederland.nl/cijfers/2023/broeikasgassen
Heavy duty vehicle includes trucks and road freight vehicles with a GVW<3.5t;

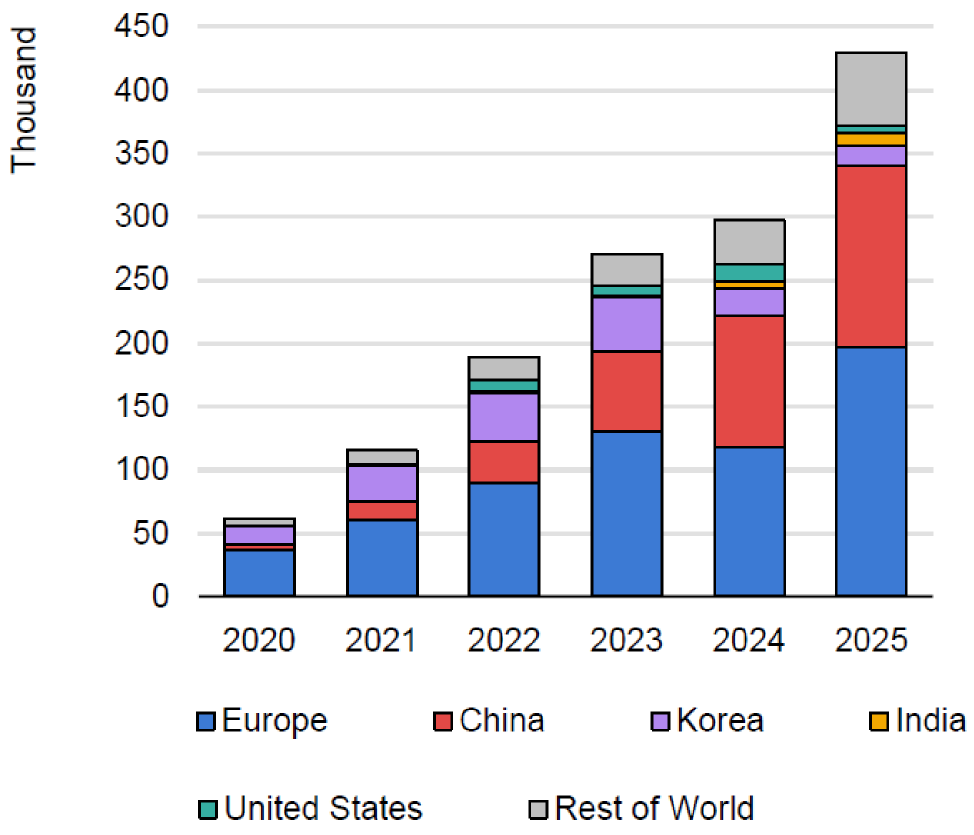
Trucks Sales 2025

- 9% of Medium & Heavy-duty trucks (>3.5t) sold globally were zero emission vehicles (ZEV) in 2025
- 97% of ZEV Trucks (>3.5t) are Battery Electric

Electric Medium and Heavy-duty truck sales



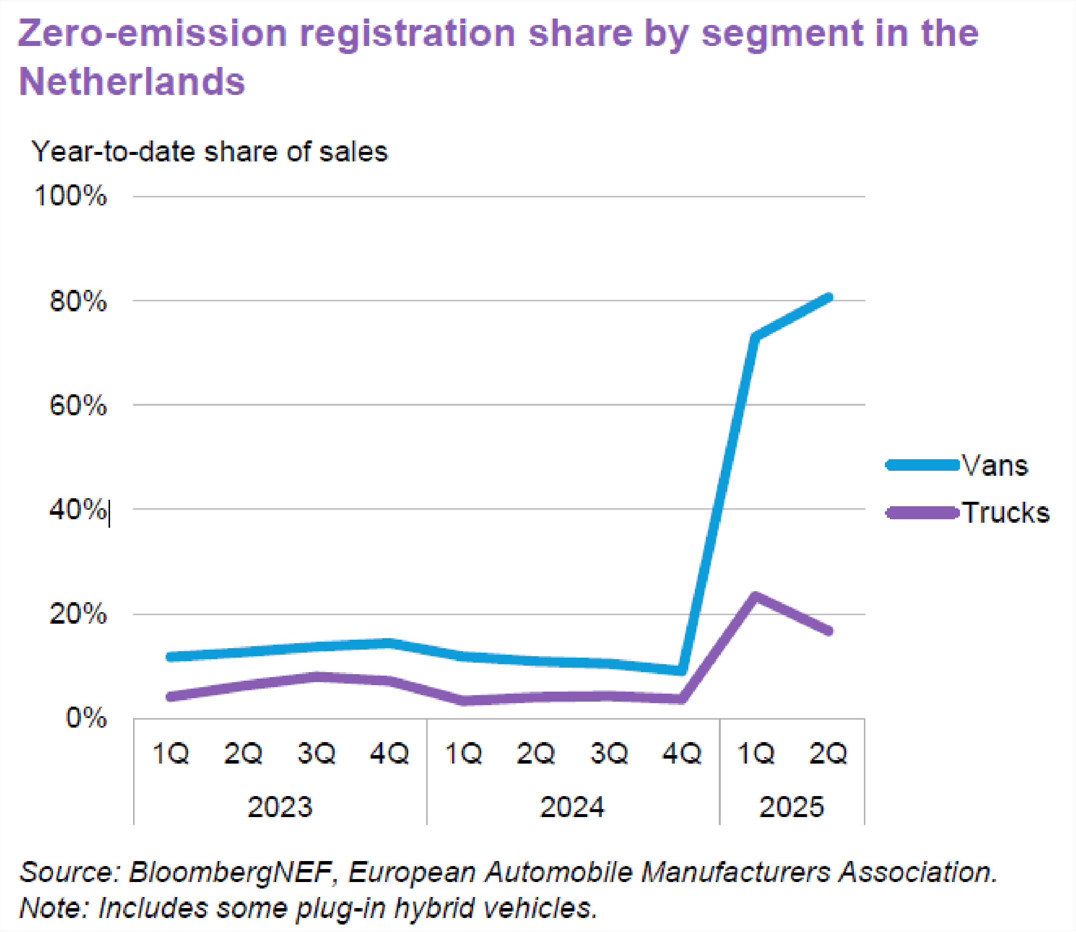
Electric Light Commercial Vehicle (<3.5t) sales



Reference - [Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025);](#) IEA Global EV outlook 2026

Netherlands leads with eVan (N1, <3.5t)

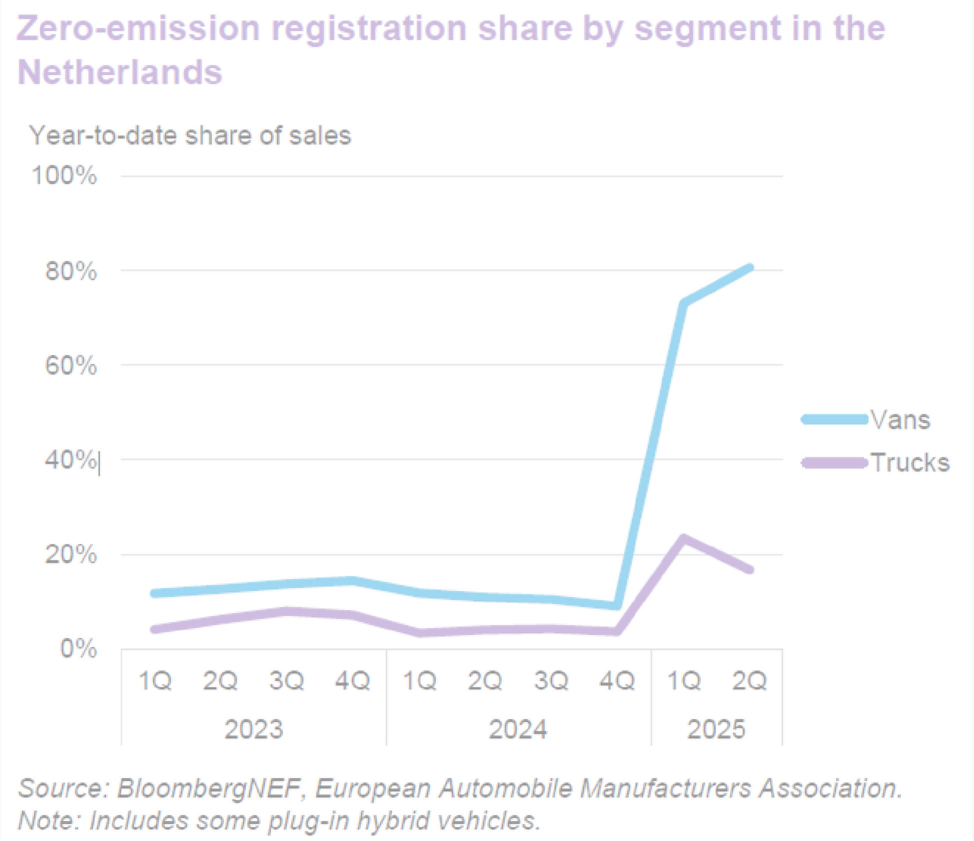
- 83.9% of total new vans registrations in NL were electric in 2025 - Highest globally



Reference - Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025); https://alternative-fuels-observatory.ec.europa.eu/general-information/news/netherlands-electric-vehicle-market-2025-overview-bev-phev; Early evidence from Dutch zero-emission zones for freight

Netherlands leads with eVan (N1, <3.5t)

- 83.9% of total new vans registrations in NL were electric in 2025 - Highest globally
- Driver: 1. New Zero-Emission Zones for Freight (ZEZ-F) in Dutch cities
- Driver: 2. NL has highest number of commercial EV chargers (~175k)



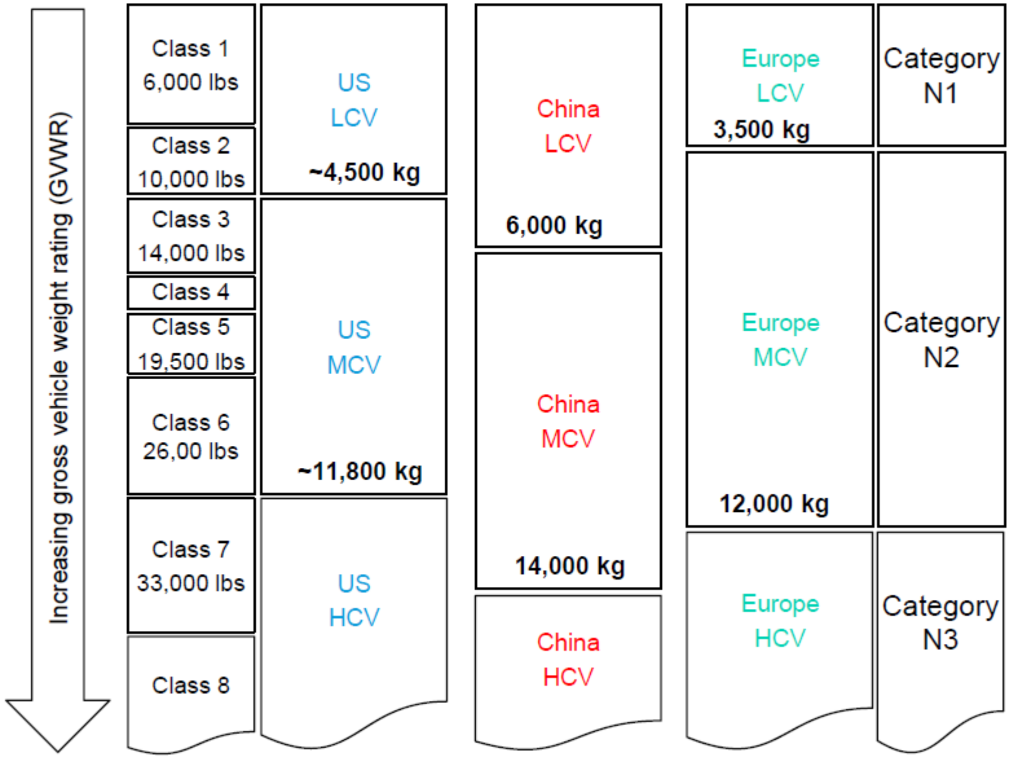
Zero-emission zones in Dutch cities

Reference - Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025); https://alternative-fuels-observatory.ec.europa.eu/general-information/news/netherlands-electric-vehicle-market-2025-overview-bev-phev; Early evidence from Dutch zero-emission zones for freight

Typical specs of eTrucks (N1-N3)

- Battery size (200-1000 kWh) and charging power (500-3000 kW)

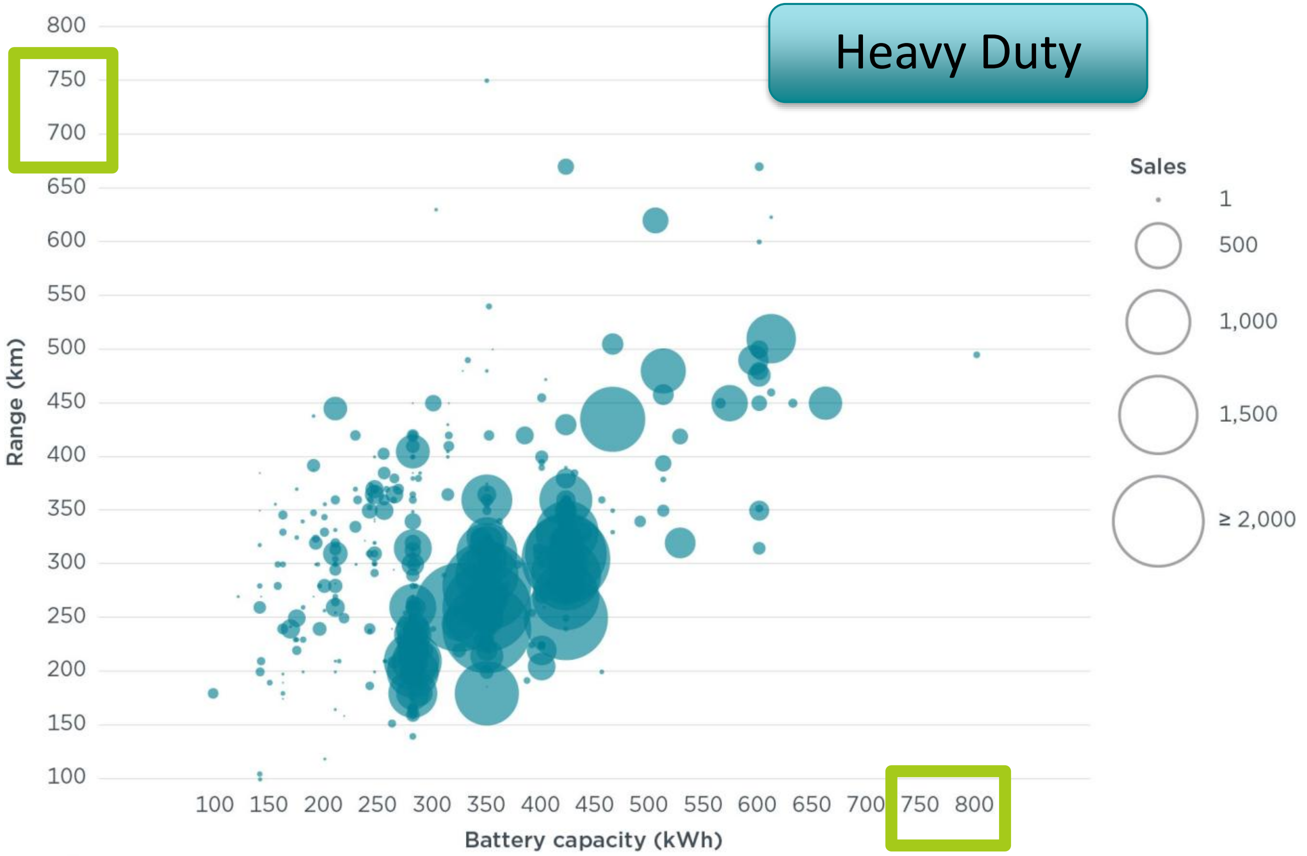
			
Category	N1 (<3.5t) Distribution	N2 (3.5-12t) Line Haul / Distribution	N3 (>12t) Long Haul
Distance per day (km)	150-300	300-600	600-1000
Yearly distance (km)	30k-50k	50k-100k	100-150k
Fuel economy (kWh/km)	0.3-0.75	0.5-1.5	1-2
Battery (kWh)	200-300	300-600	600-850
Charging power (kW) (80% in 15 min)	~800	~1500	~2000

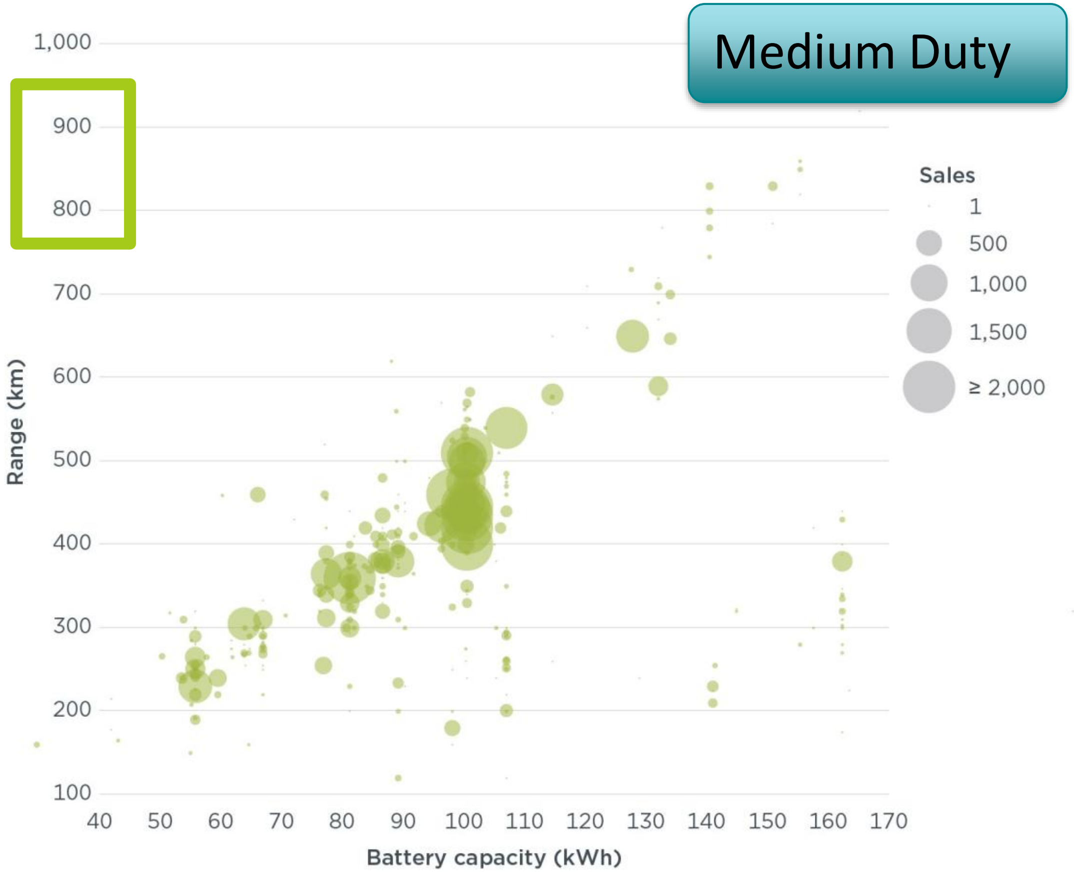


Reference – Battery-electric trucks on the rise - Truck Study 2024 (Strategy&); - Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025);

Range, Battery size & Fuel economy

- H1 2025 China Medium & Heavy-Duty Truck trend:
  - Range upto 800km and battery upto 800kWh
  - Fuel economy is 0.75-2 kWh/km





Reference - [Zero-emission medium- and heavy-duty vehicle market in China, H1 2025, ICCT]

Battery for Medium & Heavy Duty EV

Battery pack

- **3-4k cycles**
- **200-800 kWh**
- **Cell-to-pack ratio**
- **MW-level power**
- **Weight <5t**
- **Cost <100k**

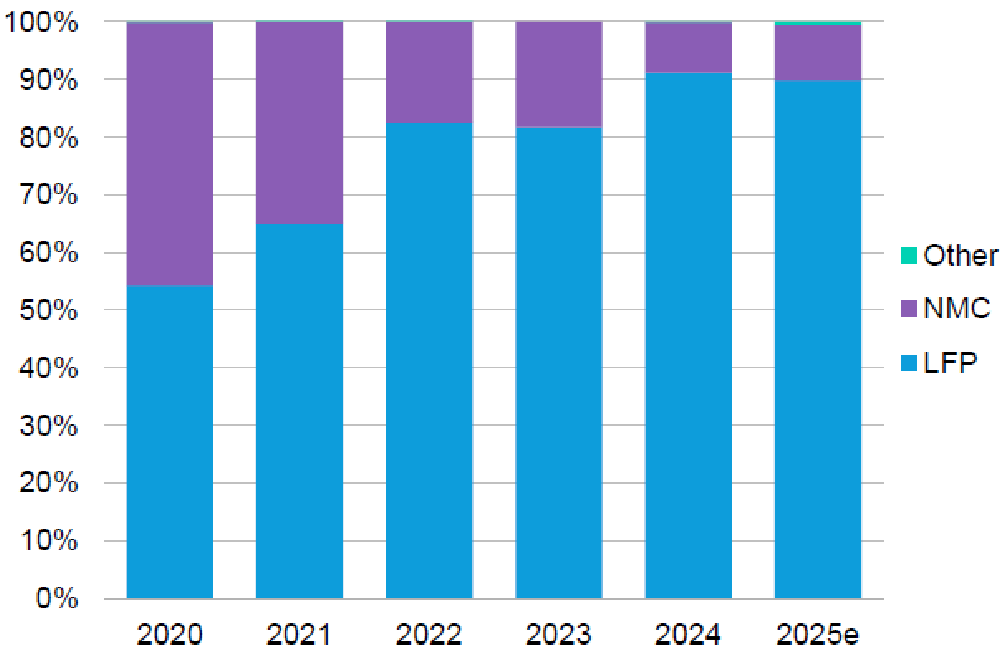
- "1 Million km" warranty
- 1-2 cycles per day → ~350-750 cycles per year → 3k-6k cycles total
- Multi-pack battery, 1000V architecture, Liquid cooled
- 80% SoC in 15-30min
- Ensure high payload capacity - Avg. battery pack energy desity is 200 Wh/kg in 2025 (LFP 200Wh/kg, NMC 250Wh/kg, LMFP in between)
- 2024 Commercial EVs volume-weighted average pack price $120/kWh $90/kWh (China) Vs $190/kWh (ex. China)

Reference - Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025)

Battery used in Medium & Heavy Duty EV

- LFP dominates due to low cost, safety characteristics, high cycle life but has lower energy density (Wh/kg)
- County & OEM: China (LFP), Daimler (LFP), Traton (NMC), Volvo (NCA), Tesla (NMC/LFP?)

Battery chemistry of electric medium- and heavy-duty truck sales



Reference - Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025)

Battery used in Medium & Heavy Duty EV

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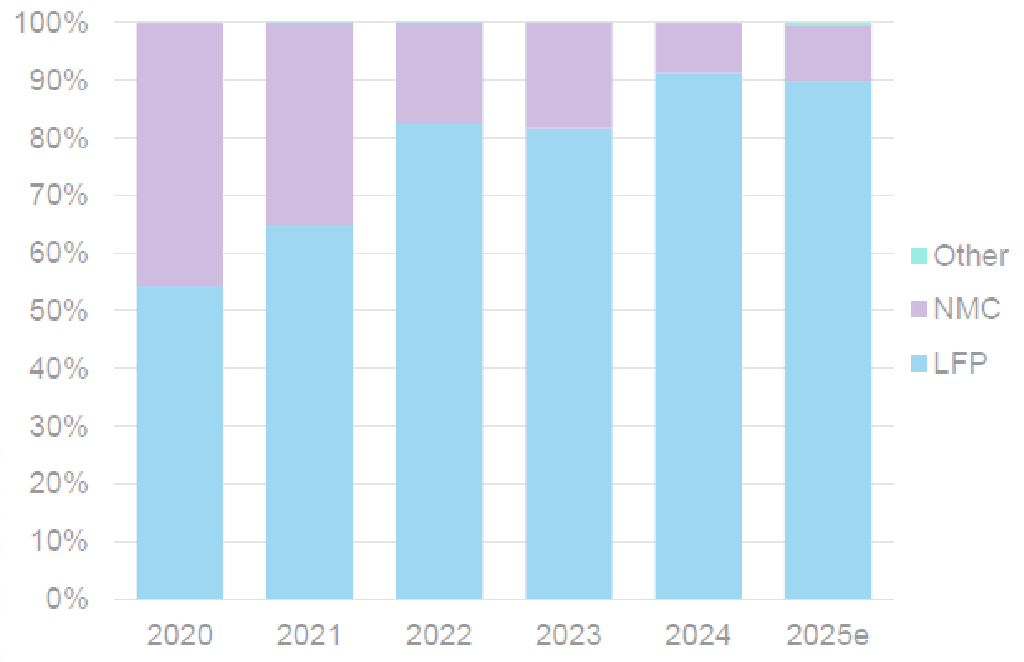
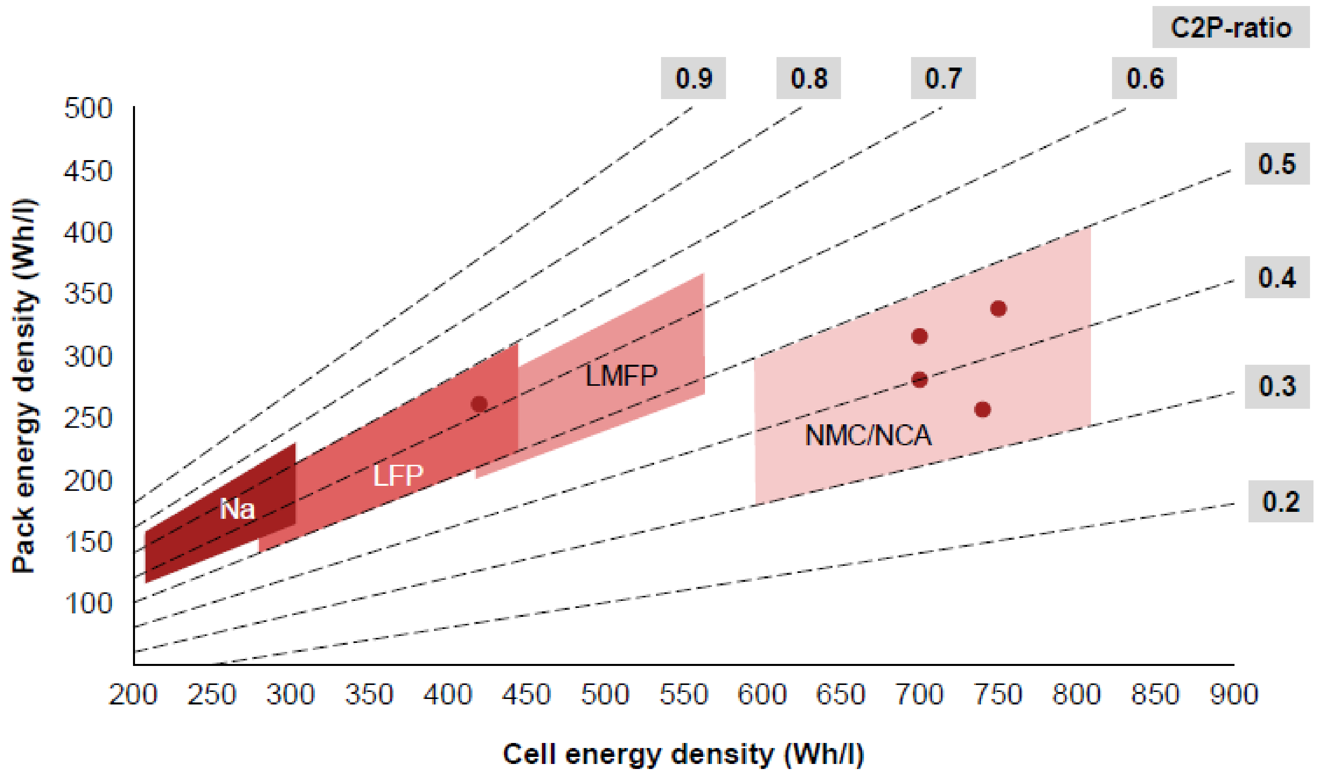
- County & OEM: China (LFP), Daimler (LFP), Traton (NMC), Volvo (NCA), Tesla (NMC/LFP?)
- Volumetric energy density of LFP and NMC/NCA are comparable to limit thermal propagation in NMC/NCA

Battery chemistry of electric medium- and heavy-duty truck sales





Reference - [Zero-Emission Commercial Vehicles - Accelerating the Transition (BNEF report 2025)]

Charging power evolution for Heavy Duty Vehicles

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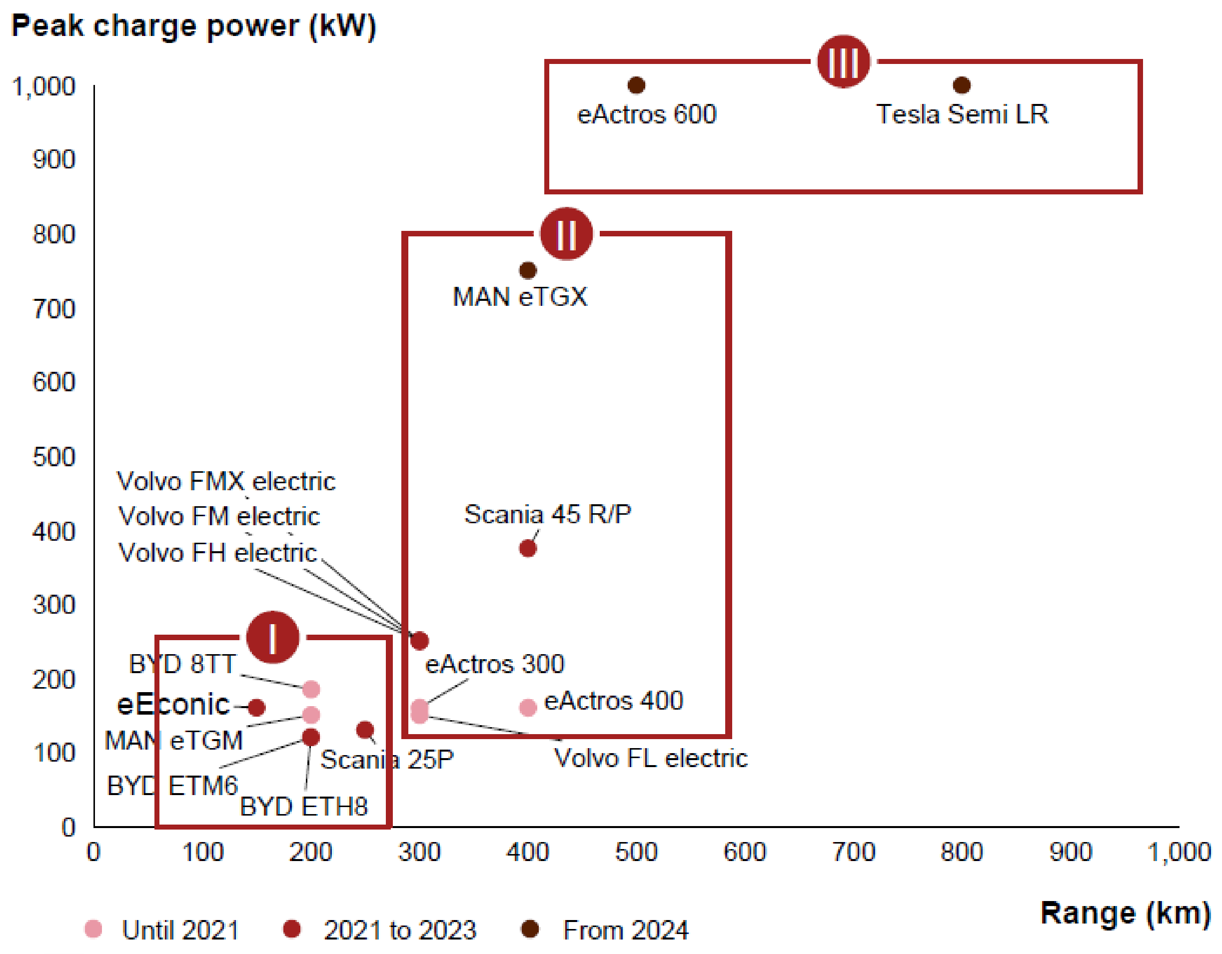
Charging power for N1 to N3 trucks

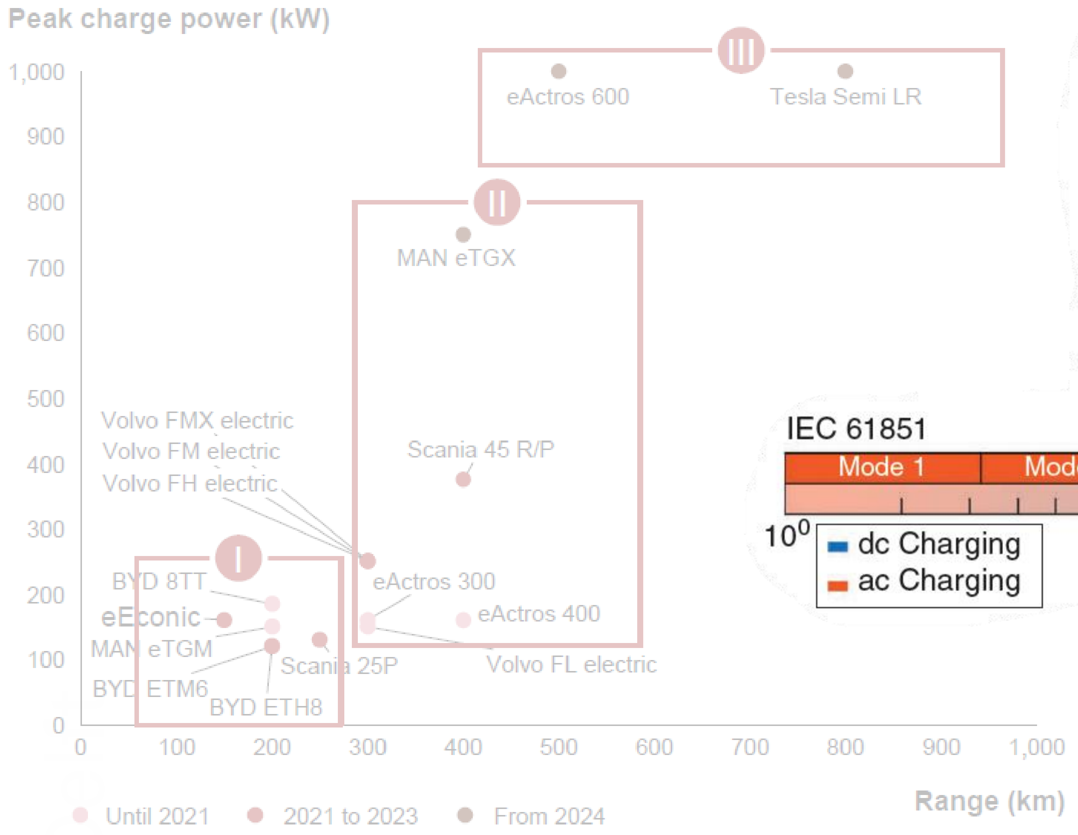


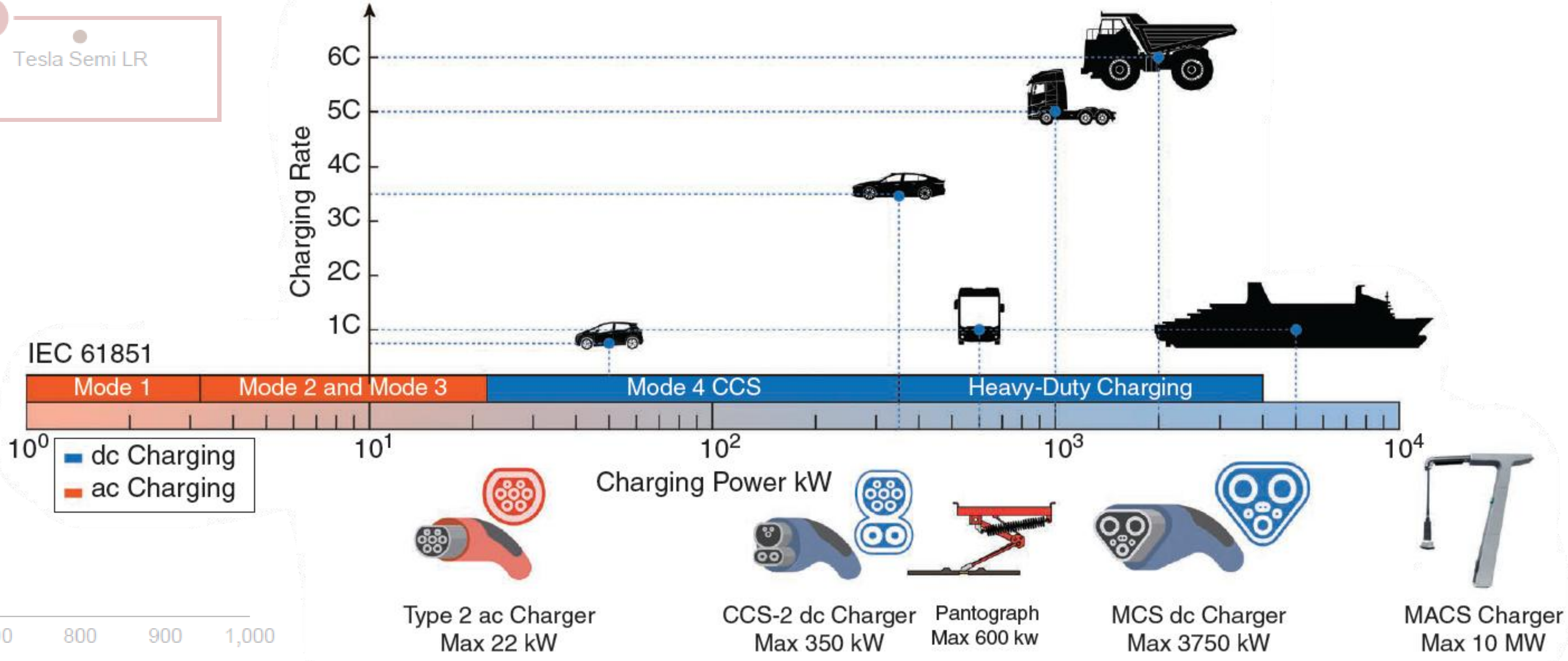
Reference – Battery-electric trucks on the rise - Truck Study 2024 (Strategy&); Z. Qin, S. Rivera, H. Yu and F. Blaabjerg, "Innovative electric vehicle charging infrastructure for european transportation electrification," in IEEE Electrification Magazine, vol. 13, no. 3, pp. 6-16, Sept. 2025, doi: 10.1109/MELE.2025.3597607.

Charging power evolution for Heavy Duty Vehicles

Charging power for N1 to N3 trucks

Charging power for trucks, mining, ships





Reference – Battery-electric trucks on the rise - Truck Study 2024 (Strategy&); Z. Qin, S. Rivera, H. Yu and F. Blaabjerg, "Innovative electric vehicle charging infrastructure for european transportation electrification," in IEEE Electrification Magazine, vol. 13, no. 3, pp. 6-16, Sept. 2025, doi: 10.1109/MELE.2025.3597607.

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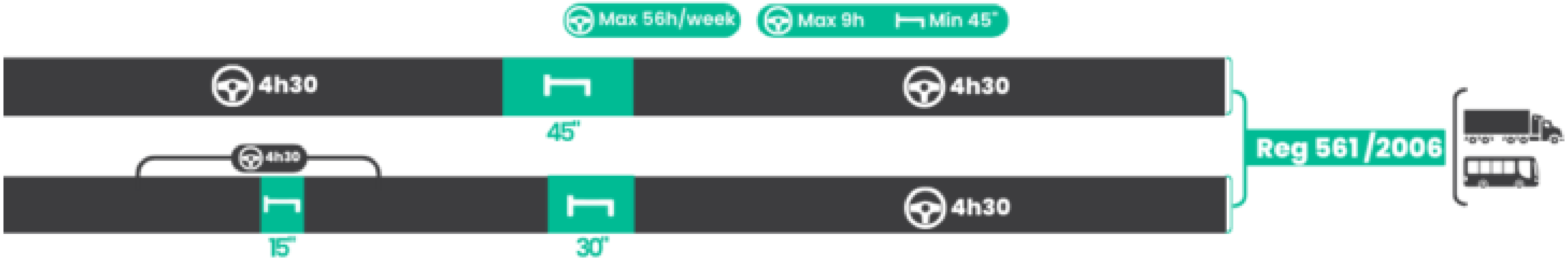
EU HDVs' driving rules

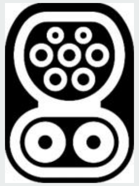
- European Regulation No 561/2006 on the harmonization of certain social legislation for road transport

- When driving 4.5h (80km/h*4.5=360km)
  - 45 min break
  - Or 15min + 30 min break



Source - https://1tacho.com/en/regulation-1258-2024-eu-what-changes-for-truck-drivers/

Plugs for EV charging (M1-M3, N1)

						
Connector inlet	CCS 2 62196 “FF” IEC61851	CCS 1 62196 “EE” IEC61851 SAEJ1772	NACS v3/v4 SAEJ3400 (For cars)	CHAdeMO 62196 “AA” IEC61851	GB/T 62196 “BB”	ChaoJi CHAdeMO 3.0 62196 “GG”
Rated voltage (V)	1000$^{\#}$	1000$^{\#}$	500/1000	1000	950$^{\#}$/1500*	1500$^{\#}$
Maximum current (A)	800$^{\#}$	800$^{\#}$	400/615	400	250$^{\#}$/800*	800$^{\#}$
Maximum power (kW)	800	800	250 (v3) 500 (v4)	350	237$^{\#}$/900*	900$^{\#}$
(High-level) Comm. HLC	PLC (ISO 15118)	PLC (ISO 15118)	PLC (ISO 15118)	CAN	CAN	CAN

Reference – Table 303 of IEC 62196-3:2026$^{\#}$, NACS & SAE J3400; CHAdeMO/Chaoji - https://www.chademo.com/technology/high-power; *GBT 20234.3-2023, https://www.tesla.com/supercharger-for-business

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Plugs for Heavy-Duty vehicles (N2,N3, >3.5t)

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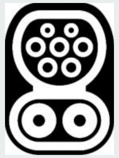
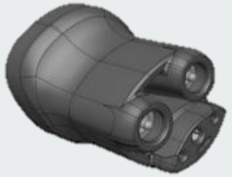
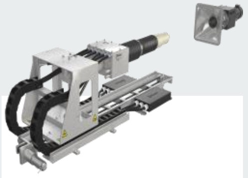
						
Connector inlet	CCS 2 62196 “FF” IEC61851	MCS SAE J3271	NACS v4 SAE J3400	ChaoJi	Pantograph SAE J3105	Pin&Socket SAE J3105/3
Rated voltage (V)	1000[#]	1250 (1500)	1000	1500	1000	1000
Maximum current (A)	800[#]	3000	615A ? (T<105C)	600	1200	2000
Maximum power (kW)	800	3750 (4500)	1200	900	1200	2000
(High-level) Communication HLC	CCS 2 62196 “FF” IEC61851	CAN FD/XL 10BaseT1S (ISO 15118)	CAN (J2411) PLC (ISO 15118)	CAN	PLC/Wi-Fi OppCharge (ISO 15118)	PLC
V2X function	Yes	Yes	No?	Yes	?	?

Reference –CharIN-MCS SAE J3271; Table 303 of IEC 62196-3:2026 [#]; NACS & SAE J3400; CHAdeMO/Chaoji - https://www.chademo.com/technology/high-power; SAE J3105;; https://www.phoenixcontact.com/en-in/technologies/high-power-charging; https://www.tesla.com/supercharger-for-business

Megawatt Charging System (MCS)

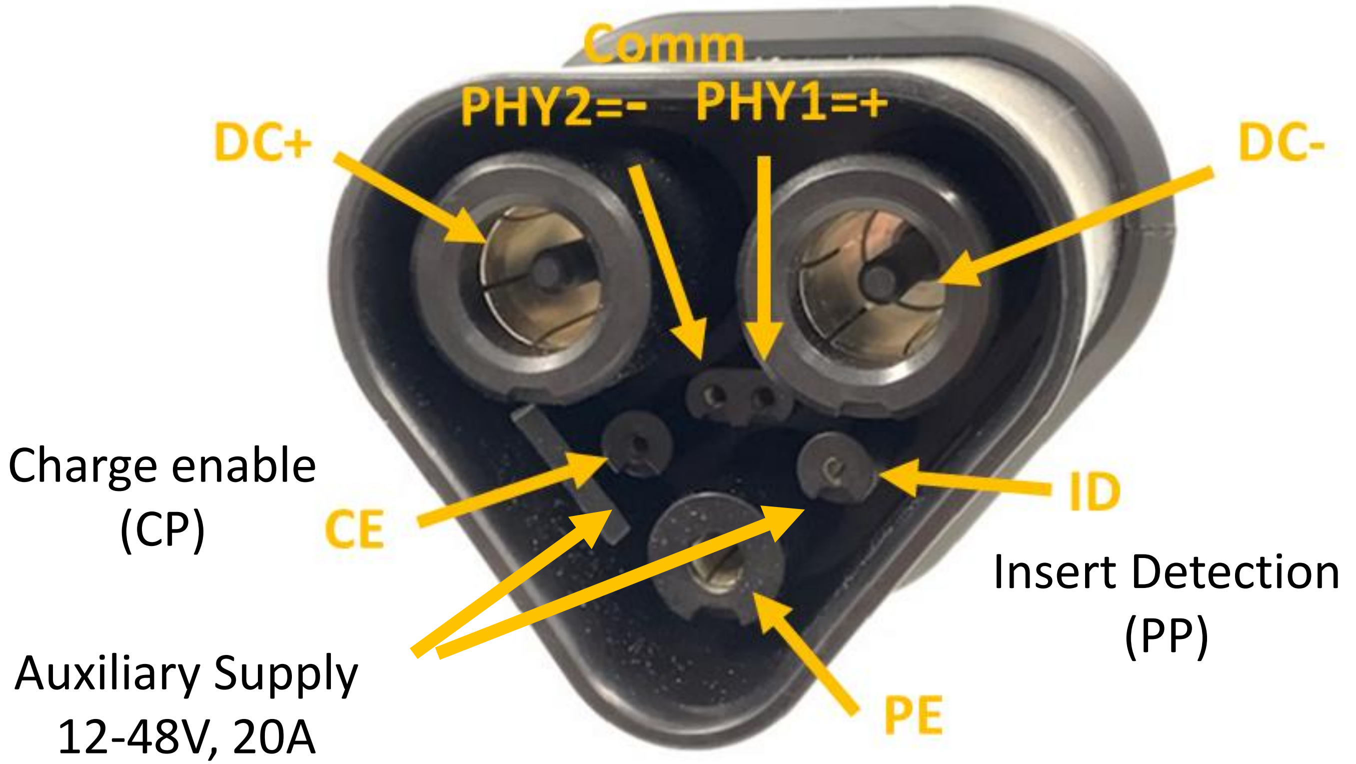
Ratings

- Voltage: 1250V/1500V
- Current 3000A
- Power: 3750kW/ 4500 kW

- SAE J2371

Pins

- PHY1, PHY2 - HLC using CAN, CAN FD, CAN XL or 10BaseT1s. Why not PLC as used in CCS?
- Charge enable CE
- Insertion detection ID



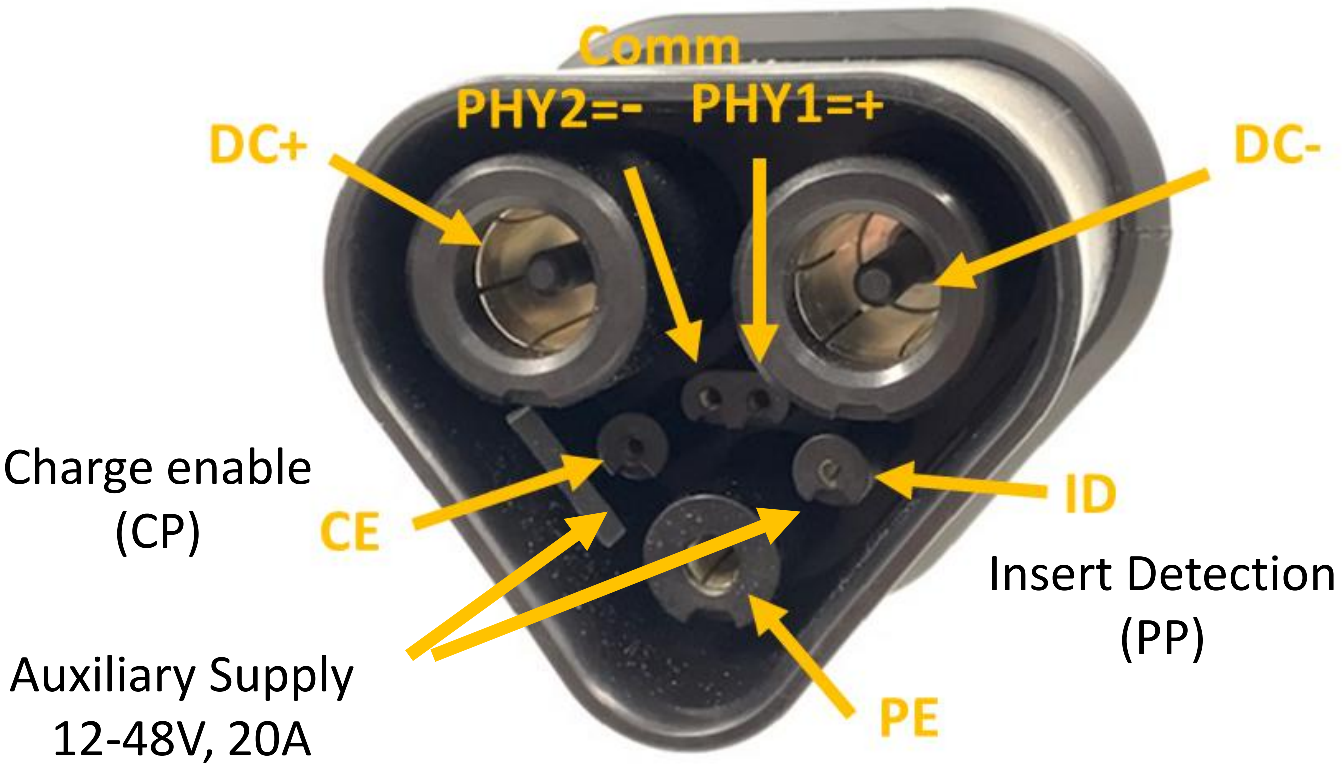
DC +	DC +	1
DC –	DC –	2
CE (CP)	Charge Enable	3
ID (PP)	Insertion detection	4
E	Protective earth	5
PHY1	Communication 1	6
PHY2	Communication 2	7

Reference – J3271 working group, https://www.charin.global/technology/mcs

MCS – SAE J2371

- Auxiliary supply over CE, ID: 12-48V, 20A
- Why is this needed?

- Power flow:
  - from EVSE to EV over CE/ID
  - or EV to EVSE for V2X possible
- Why both ways?



DC +	DC +	1
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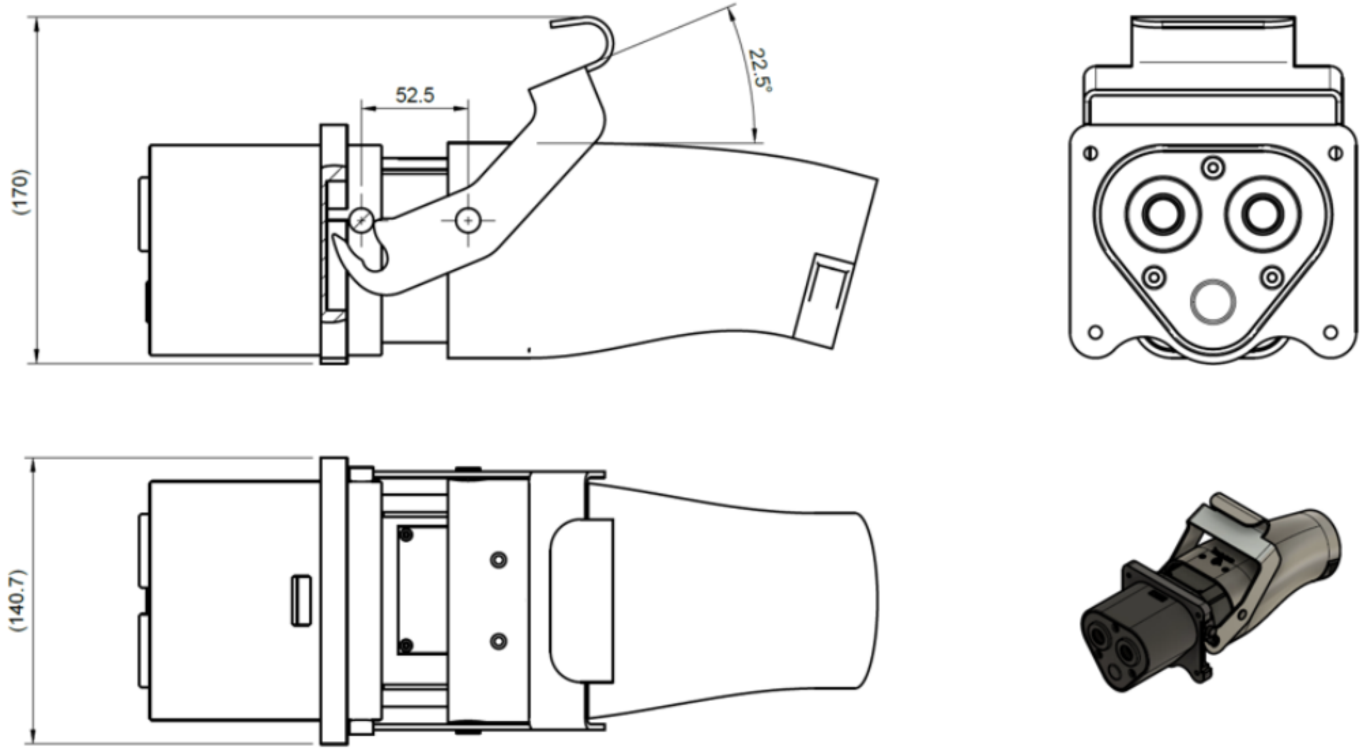
ID (PP)	Insertion detection	4
E	Protective earth	5
PHY1	Communication 1	6
PHY2	Communication 2	7

Reference – J3271 working group, https://www.charin.global/technology/mcs

Ruggedized MCS (rMCS) – Mining

Adapt the existing MCS connector to meet the **Mining requirements**

- Increase voltage from 1250 to 1500 V, current from 3000 to upto 4000A
- Improve chemical compatibility and ruggedization (IP 64 and IK 11 rating), Ingress Protection as per IEC 63379 and IEC 60529
- Lever for coupler retention
- 20,000 mating cycles
- Cable length upto 15m. Why?



Heavy Duty Charging station – Conventional

- Integrated unit with Power cabinets + Charing plugs
- Modular Power units with high frequency isolation
- 1 Charger per parking spot

Benefits:

- Easier installation

Challenge:

- Size not scalable for >1MW
- Limited flexibility for power sharing
- More parking spots/vehicles = More chargers

ABB A400 charger

200-400 kW in 50kW steps

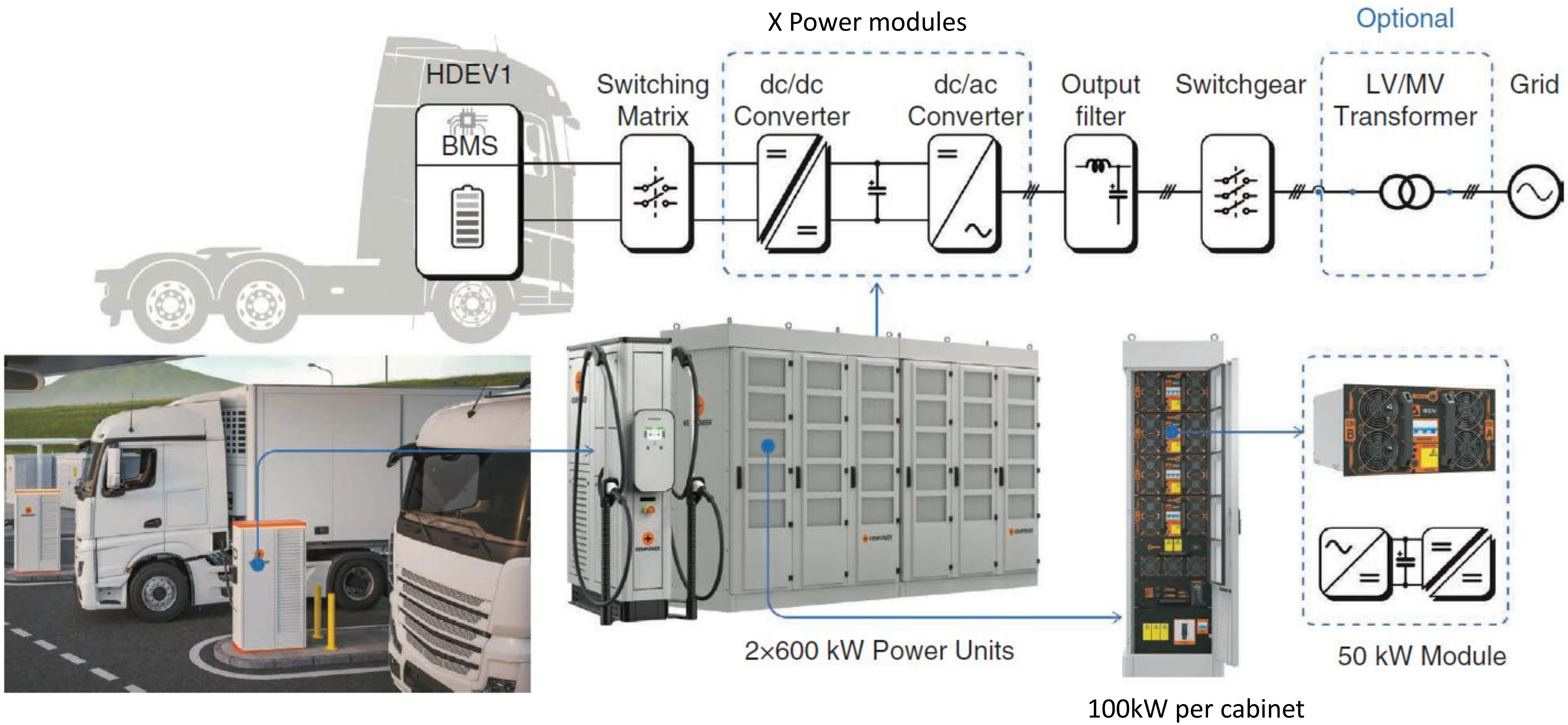
2x 600 A plugs

97% efficiency

Reference – ABB

Heavy Duty Charging station – MW Architecture

- Power cabinets upto 1MW made of Modular Power Modules of 50-125kW
- Separate charging dispenser connected via a switching matrix



Reference – Z. Qin, S. Rivera, H. Yu and F. Blaabjerg, "Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration.," in IEEE Electrification Magazine, vol. 13, no. 3, pp. 6-16, Sept. 2025,

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Tesla v4 Supercharger

TU Delft

Separated Supercharger Cabinet and Posts

V4 Supercharger Post
- 1.2MW for Semitruck,
- 500 kW for Cybertruck,
- 615 A, 1000 VDC

V4 Supercharger Cabinet
- Up to 1200 kW, shared by 8 posts
- 180–1000 VDC, Efficiency >96%
- Input: 380-480V 3ph AC, 1200-1500A!

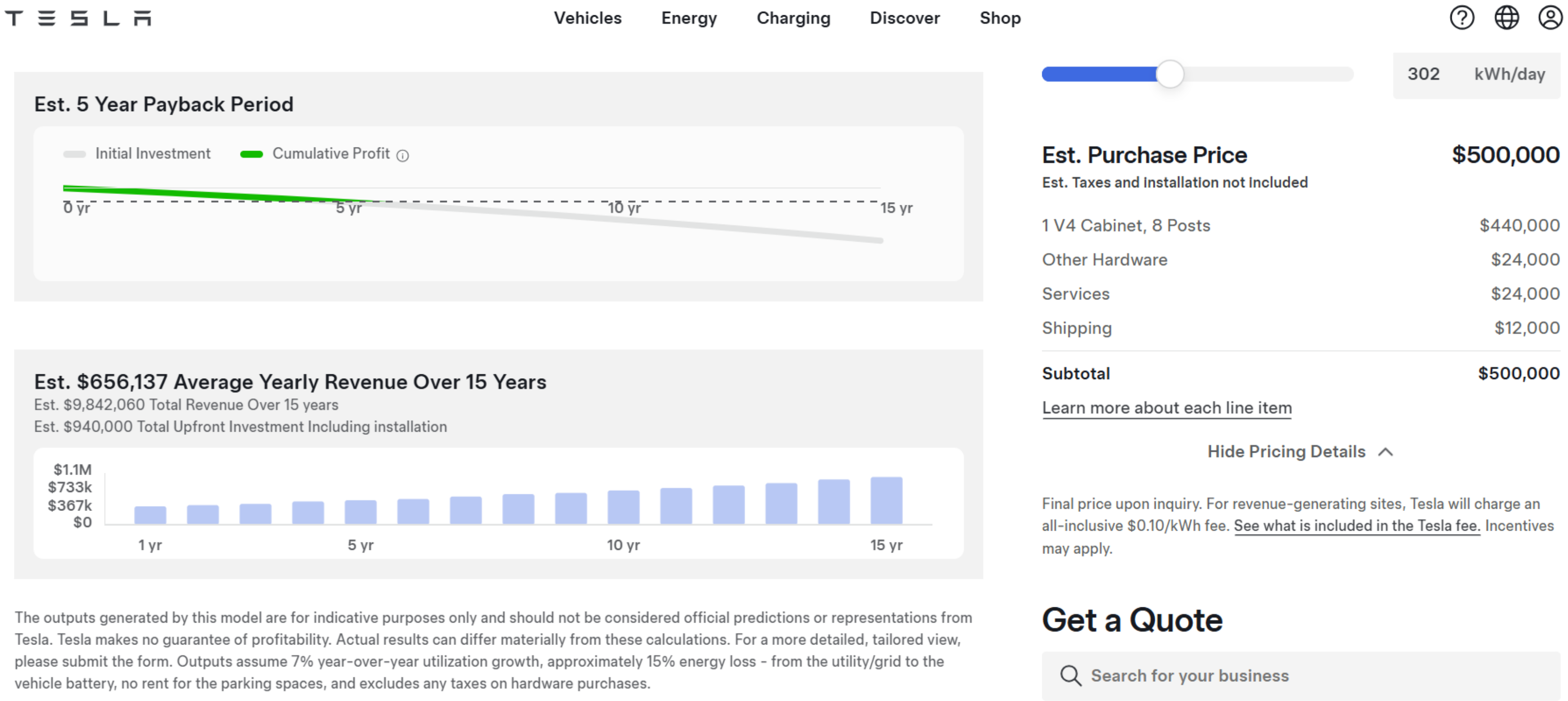
https://www.tesla.com/supercharger-for-business; Phoenix contact https://www.phoenixcontact.com/en-in/industries/e-mobility/charging-infrastructure/nacs-charging-cables;

Tesla v4 Supercharger

- Charger cost including services + shipping (excluding. Taxes + Installation)

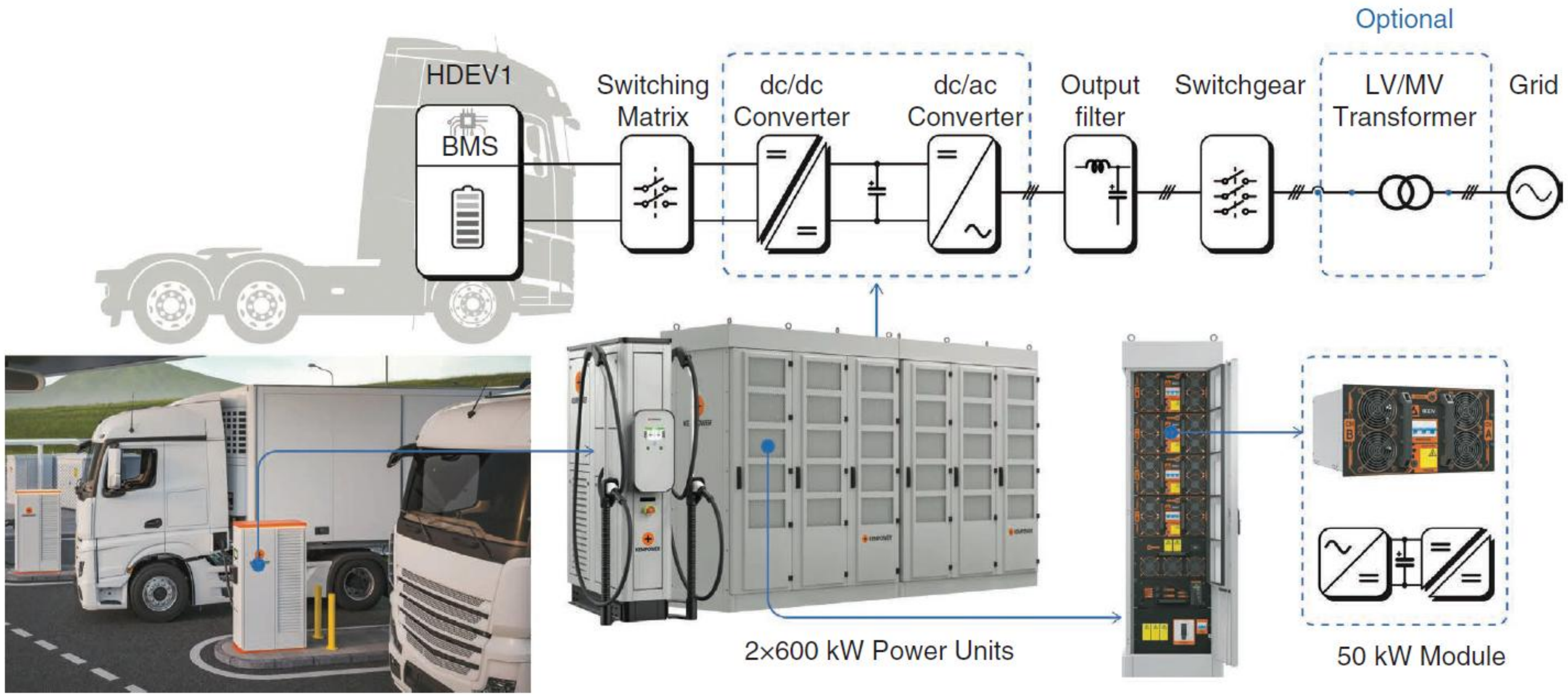
https://www.tesla.com/supercharger-for-business/get

- ➢ V4 1MW Cabinet + 4 posts = 250k USD
- ➢ V4 1MW Cabinet + 8 posts = 500k USD



What are the challenges?

- Efficiency (Losses 3%*1MW), thermal challenges, magnetics design?
- How to make the installation of the modular system faster?
- How to reduce the high currents at LVAC side?
- Grid impact of the MW chargers is significant!



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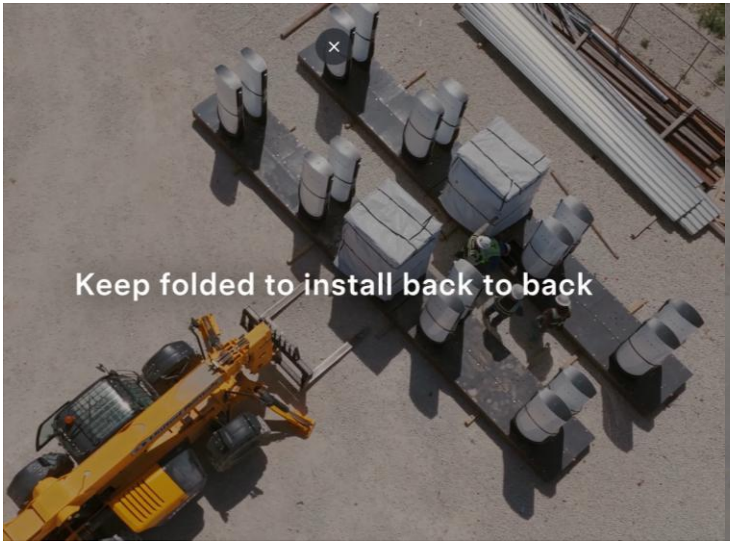
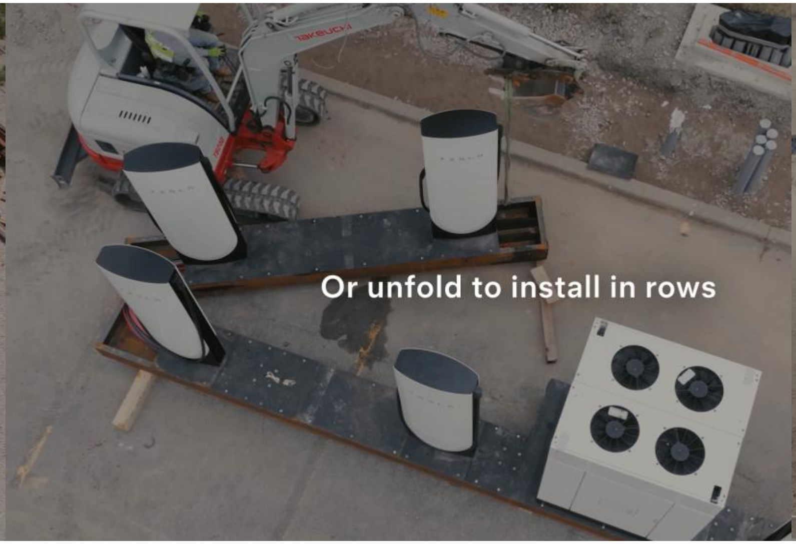
Tesla v4 Supercharger

To reduce installation time of MW chargers, Tesla introduced Prefab and Prewired “Folding unit” Supercharger

- with 1x 500kW Cabinet and 8 Posts
- 2 units per trucks
- Flexile installation: folded, unfolded
- Claim: 2x fast installation, 20% lower cost





References - https://x.com/TeslaCharging/status/2036951111798505517

MCS charger – Architecture based on SST

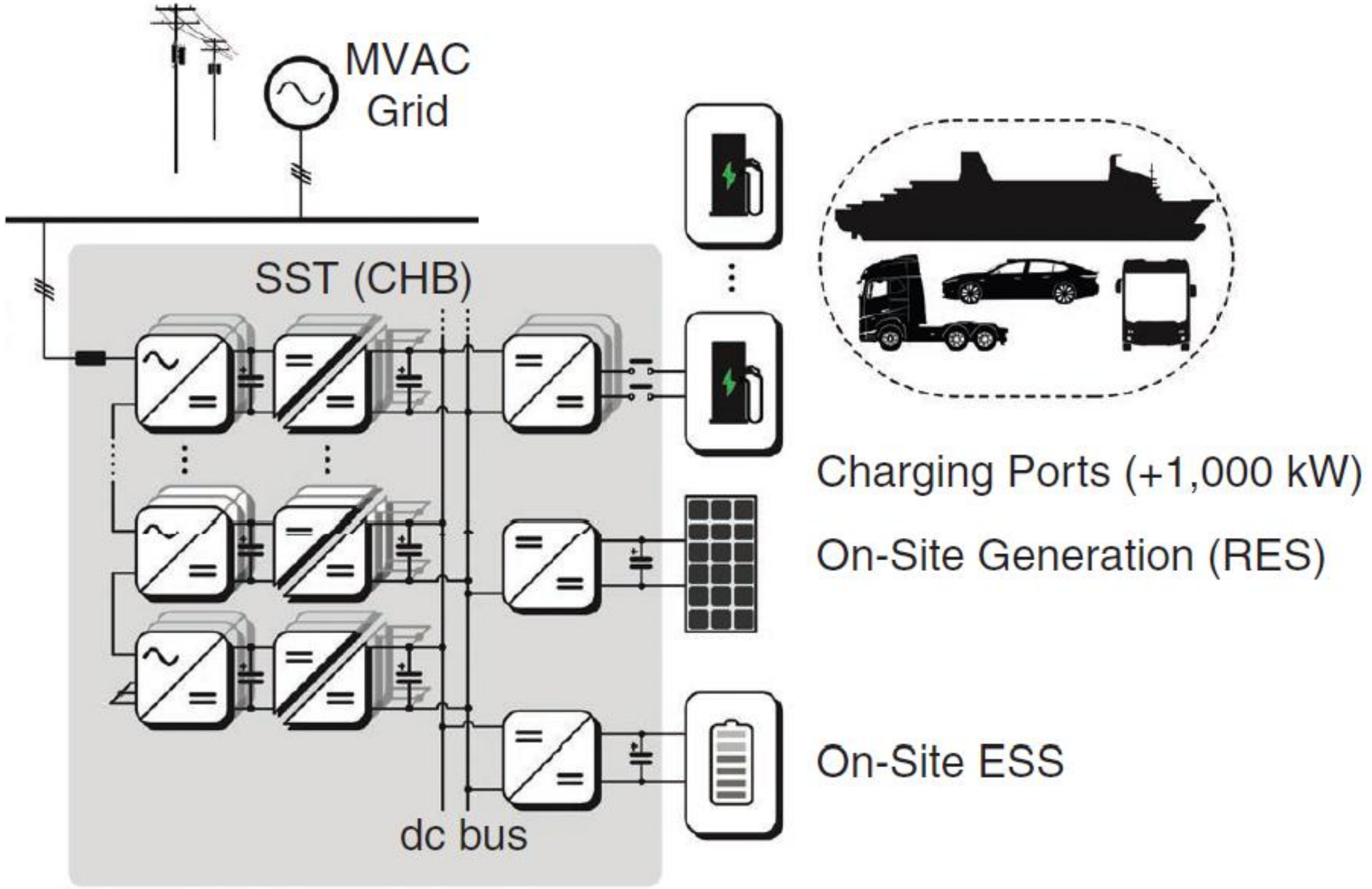
Solid state transformer (SST)

Advantage

- Direct MV connection
- Integrate LV-MV conversion, medium frequency isolation and PEBB in one unit
- Flexible, Reconfigurable Power routing
- Direct integration of RES, BESS

Disadvantage

- Higher (initial) cost
- Developing standards
- Themrla management
- Complex design than 50Hz



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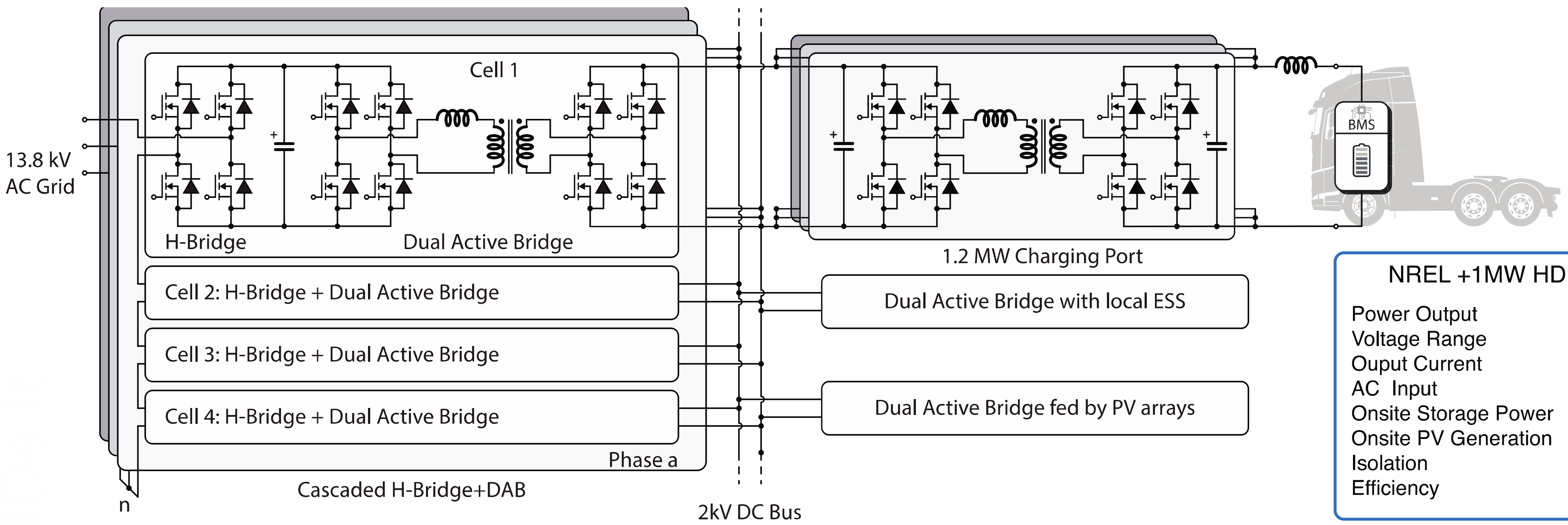
MCS charger – 3.6MW SST Architecture (NREL)

- Input: 4x Series connected Cells of 300kW, 1.2MW per phase: Cascaded H-bridge + DAB
- 13.8kV MVAC input → 2kV DC bus
- Output: 3x 400kW DAB connected in parallel, 1.2MW, 220-1500V
- Direct integration of 400kW each of PV, BESS on 2kV DC bus

3kV DC bus



NREL +1MW HD EV Charger

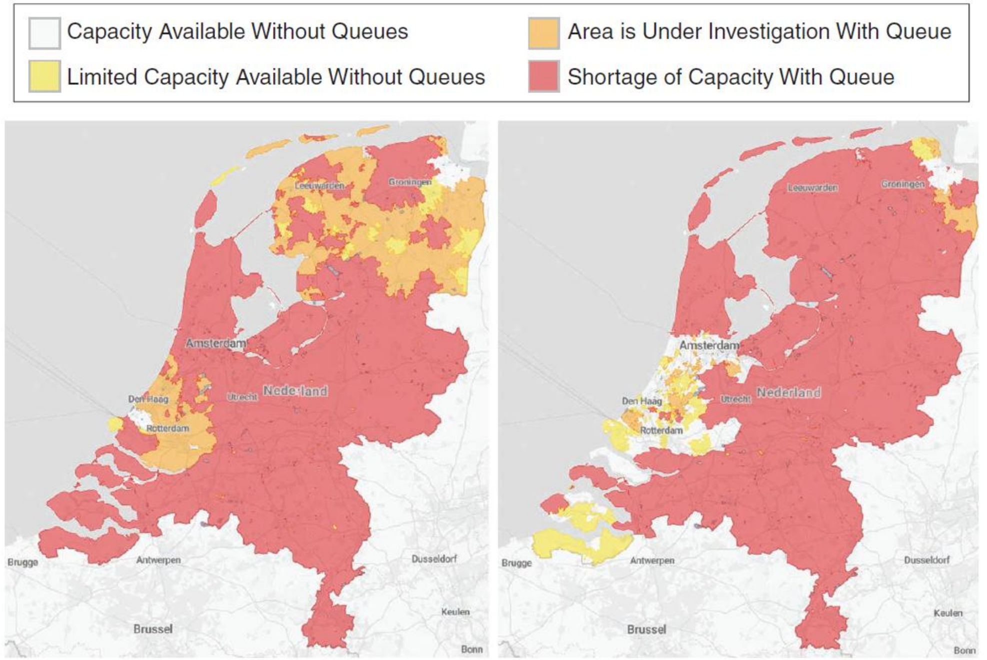
Power Output	400kW -1.2 MW
Voltage Range	220 - 1500 V
Ouput Current	800 A
AC Input	13.8 kV
Onsite Storage Power	400 kW
Onsite PV Generation	400 kW
Isolation	HF
Efficiency	98%

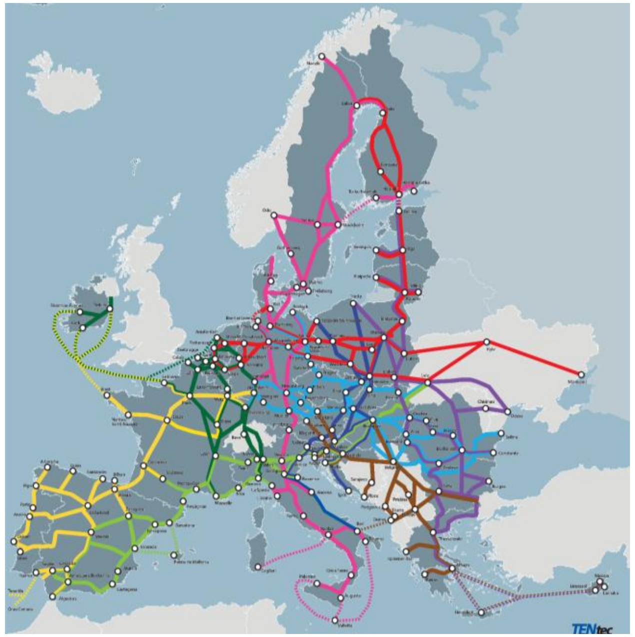
Reference – S. Rivera et al., "Charging Infrastructure and Grid Integration for Electromobility," in Proceedings of the IEEE, vol. 111, no. 4, pp. 371-396, April 2023, doi: 10.1109/JPROC.2022.3216362; Charging Infrastructure Technologies: Development of a Multiport, >1 MW Charging System for Medium- and Heavy-Duty Electric Vehicles - Andrew Meintz National Renewable Energy Lab - https://docs.nrel.gov/docs/fy20osti/76707.pdf

MW Charging Energy Hubs

Key challenges

- Investment for 100’s of locations
  - Power converters for chargers & BESS onsite
  - Commissioning costs
- Peak power levels (5-10MW) per location
  - Grid congestion
  - Grid connection costs



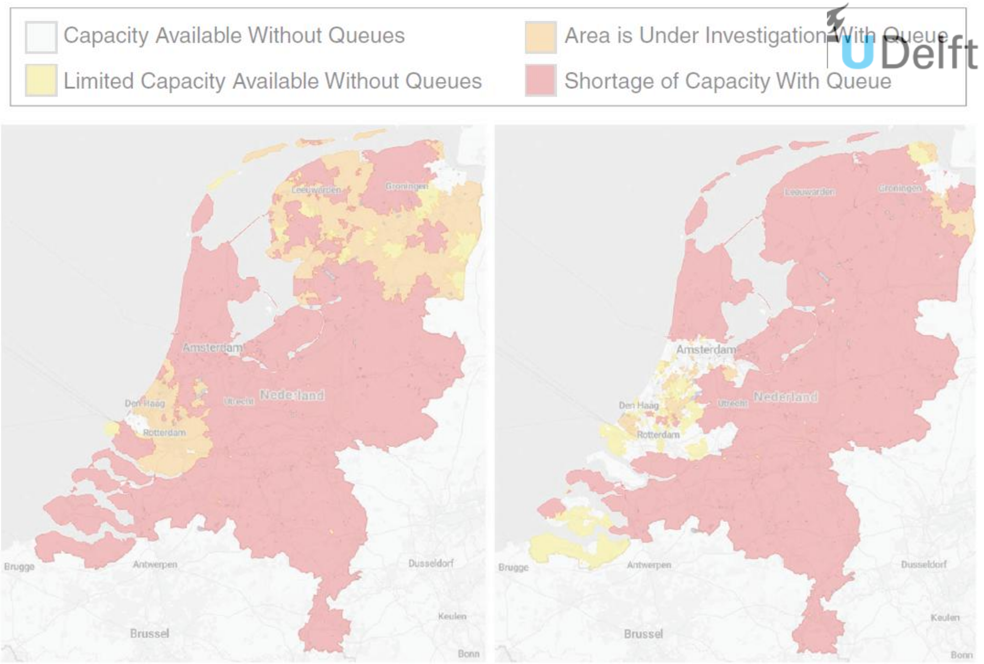


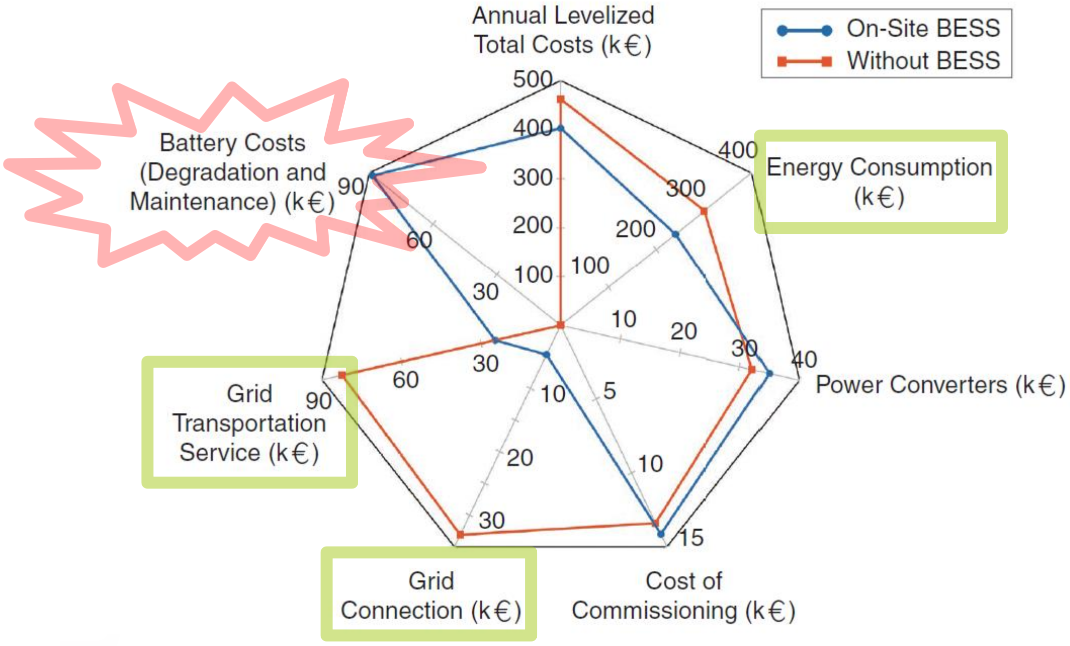
Reference – Z. Qin, S. Rivera, H. Yu and F. Blaabjerg, "Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration.," in IEEE Electrification Magazine; Tesla megapack

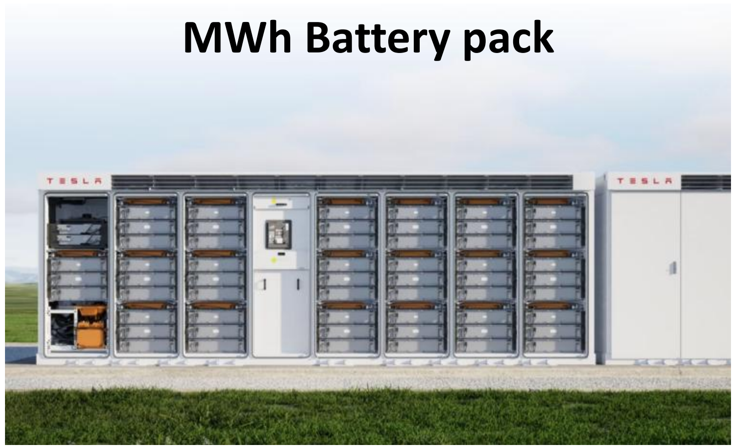
MW Charging Energy Hubs

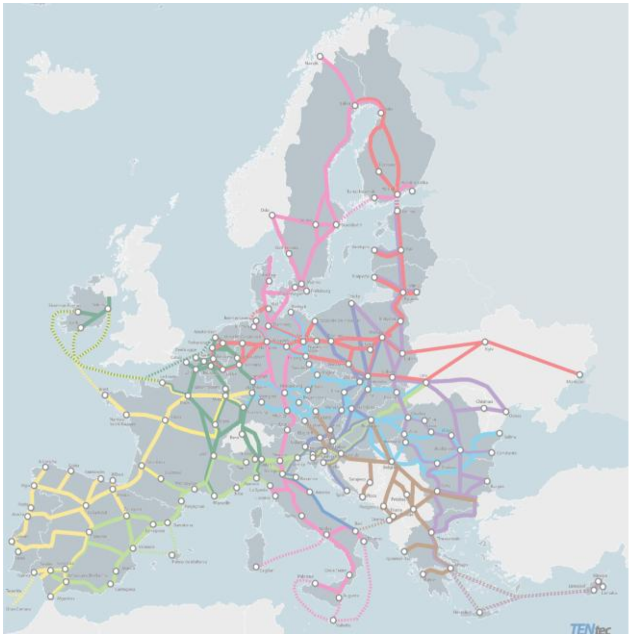
Key challenges

- Investment for 100’s of locations
  - Power converters for chargers & BESS onsite
  - Commissioning costs
- Peak power levels (5-10MW) per location
  - Grid congestion
  - Grid connection costs









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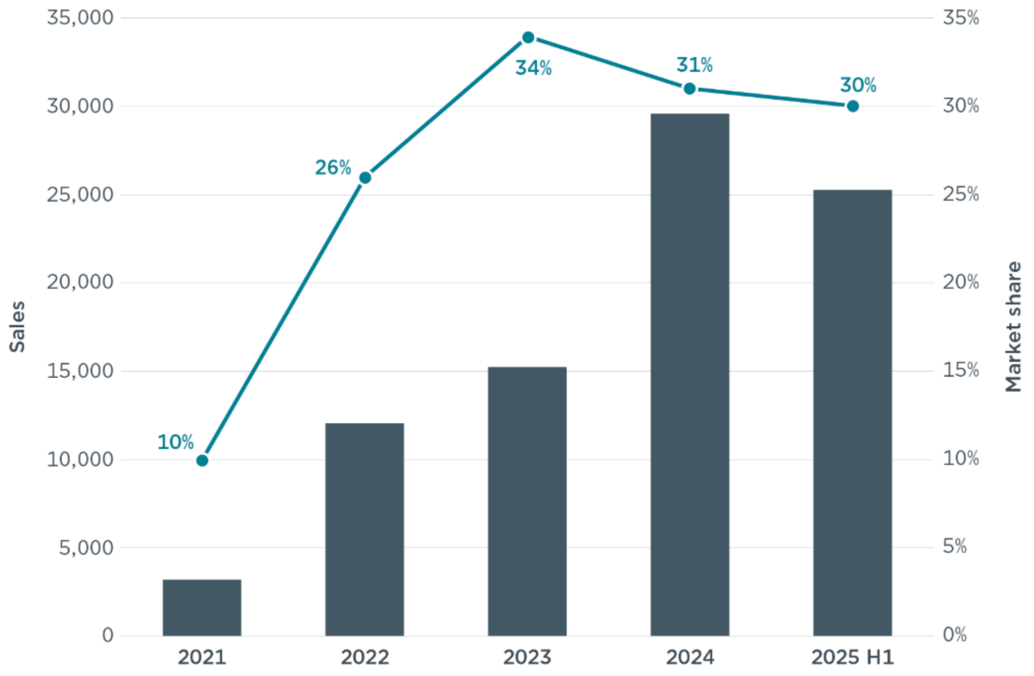
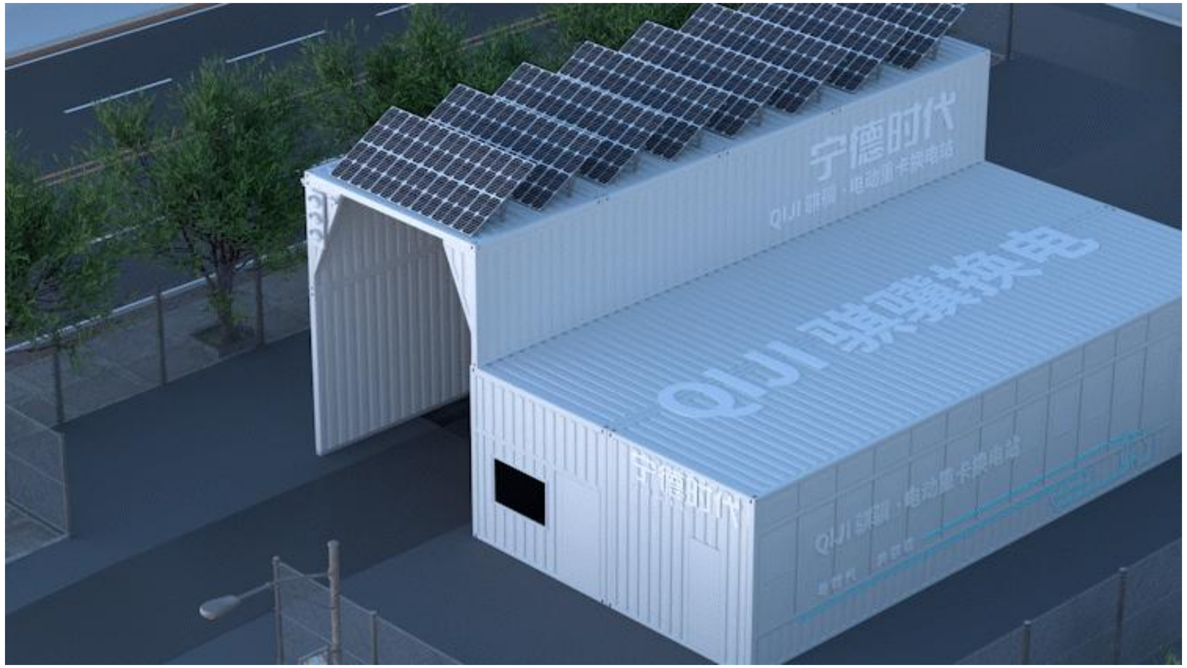
Battery swap for trucks

- ~30% (2022-H1 2025), 15% (2025) of trucks sold in China are with battery swap
- Examples: CAMC, Foton, XCMG in China; Sun mobility in India; Mitubishi & Ample in Japan
- Benefits
  - Smaller battery
  - 2 min charge! 30C!
  - New business models
- Challenges
  - High costs of swapping stations
  - Battery standardization

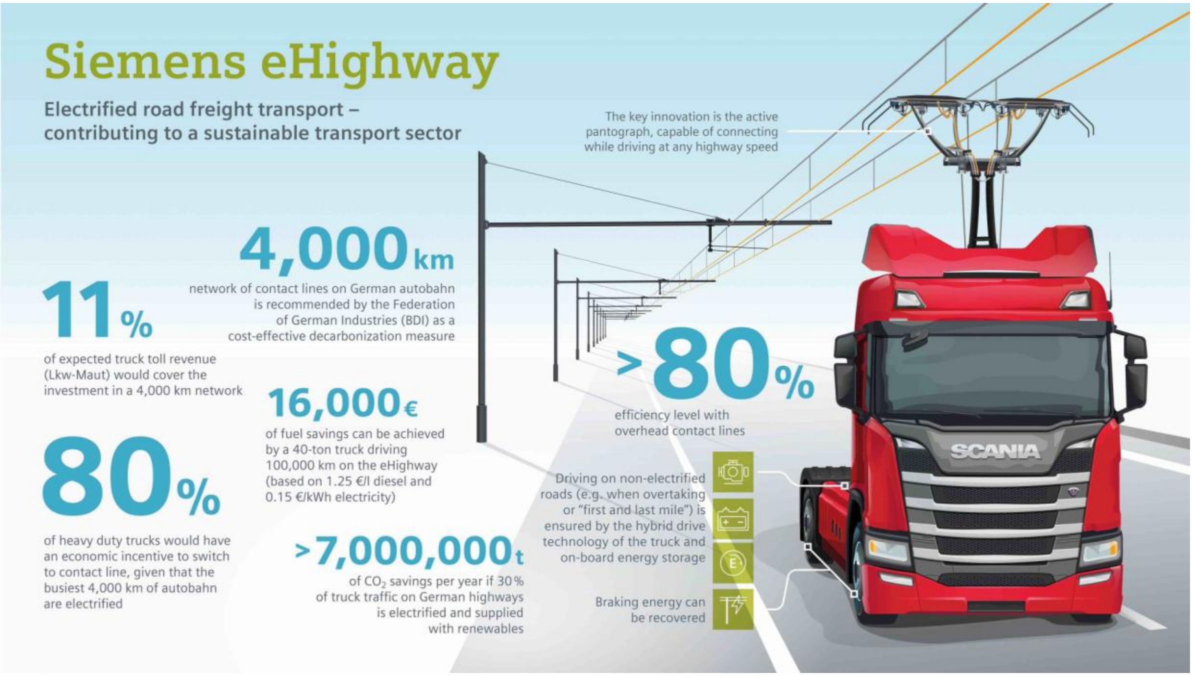




Reference - [Zero-emission medium- and heavy-duty vehicle market in China, H1 2025, ICCT], Qiji-CATL

Electric Road Systems / eHighway

- In-motion Truck charging via pantograph using overhead catenary along corridors
- Example is Siemens eHighway: 670V DC overhead catenary and upto 200kW power

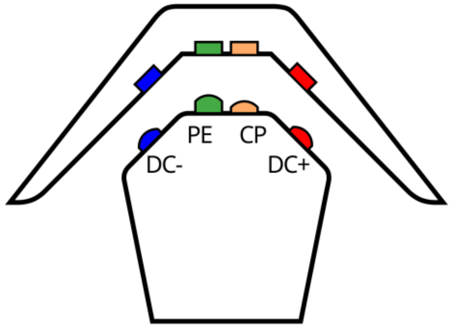


Reference – Siemens eHighway Sustainable road freight transport

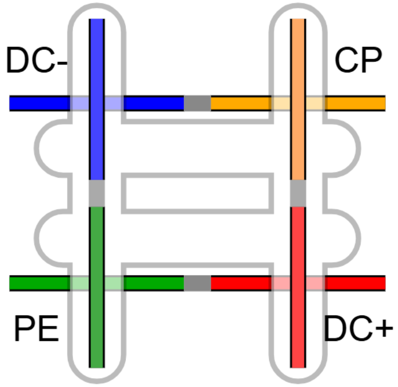
Pantograph (up/down) charging

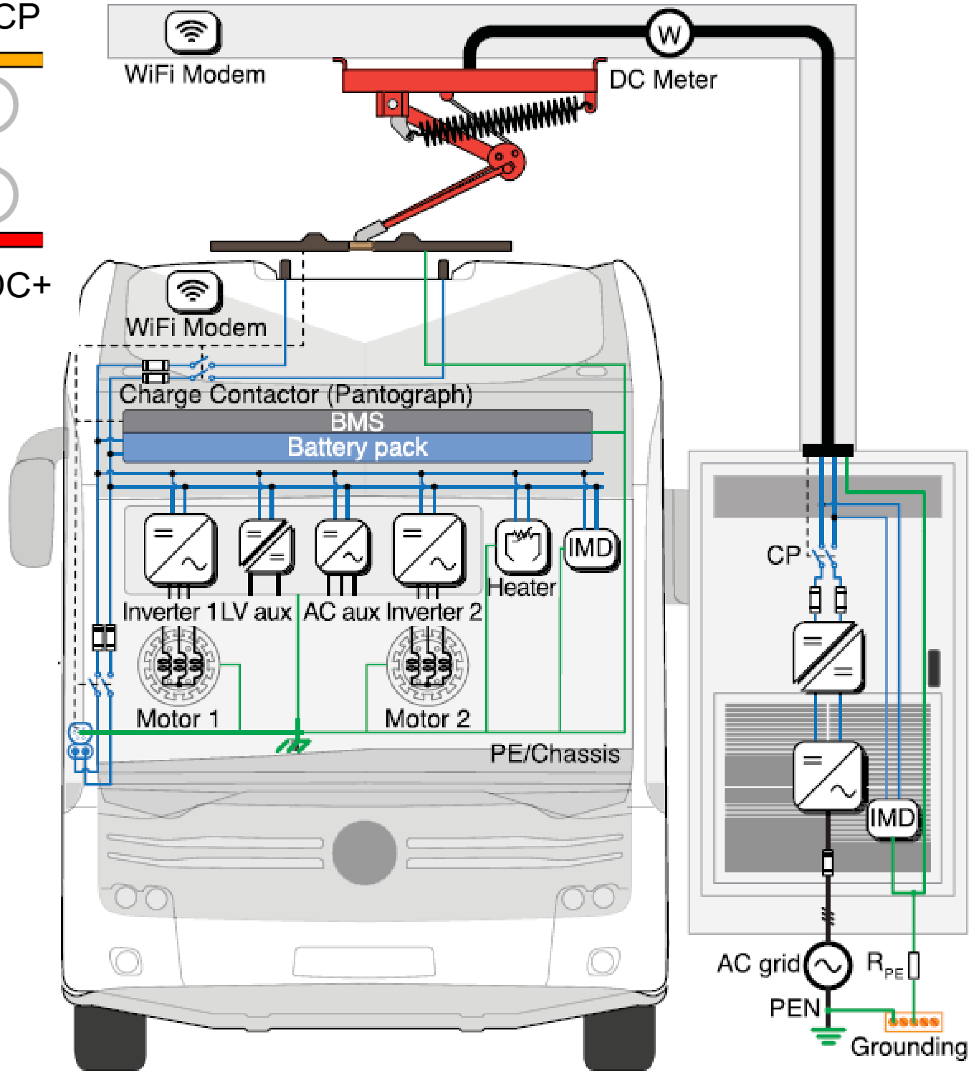
- SAE J105 Automatic connection device
- Rated for 1000V, 600/1200A, 1200kW
- DC+, DC-, PE, Control pilot CP
- J3105-1 "Infrastructure-Mounted Cross Rail Connection" Pantograph down
- J3105-2 "Vehicle-Mounted Pantograph Connection“ Pantograph up

Pantograph up SAE J3105-1



Pantograph down (Cross rail) SAE J3105-1





Reference – S. Rivera et al., "Charging Infrastructure and Grid Integration for Electromobility," in Proceedings of the IEEE, vol. 111, no. 4, pp. 371-396, April 2023, doi: 10.1109/JPROC.2022.3216362; https://en.wikipedia.org/wiki/SAE_J3105

Electric Road Systems / eHighway

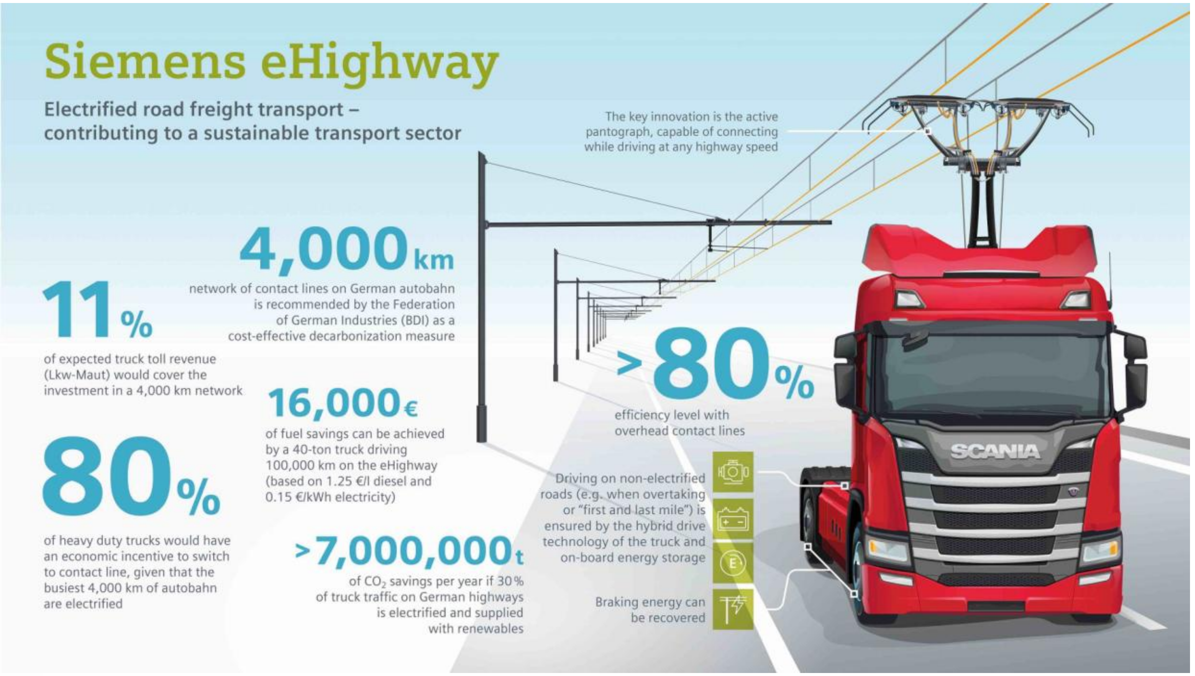
- In-motion Truck charging via pantograph using overhead catenary along corridors
- Example is Siemens eHighway: 670V DC overhead catenary and upto 200kW power

Advantages

- Smaller battery
- Better for grid congestion
- Continuous operation

Challenges

- Battery for first/last mile
- High infra costs (e.g., 4000km in DE at 2.26MEUR/km)
- Vehicle standardization



Reference – Siemens eHighway Sustainable road freight transport

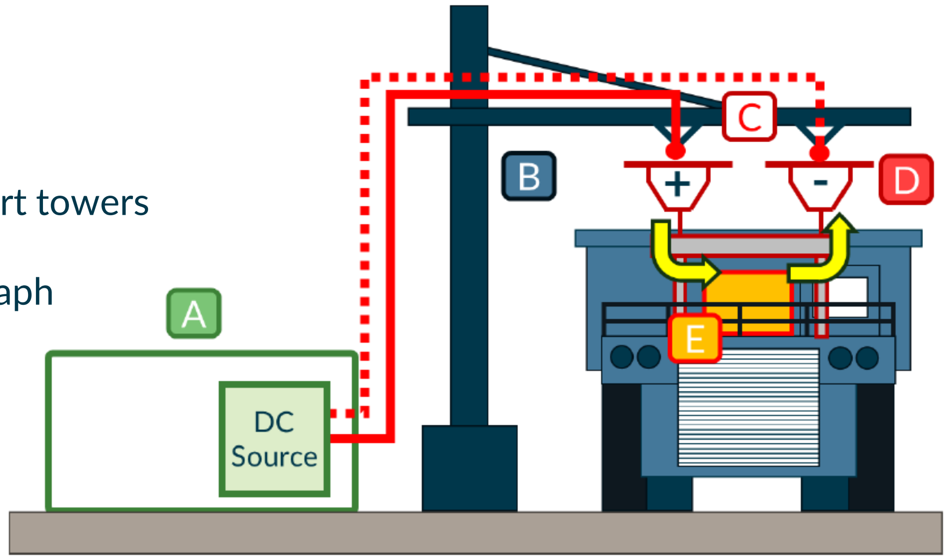
Dynamic Charging Interface

- Provide in-motion power via catenary or third rail (IP 69K)
- On-Boarding Power Module: DC+, DC-, PE, Communication

Voltage and Power levels

- 2.6kV DC traction with 1.6-3.9kA current, 4.5-8.5MW power
- 1.8kV DC traction with 2-5kA current,   4-8MW power

A. Rectifier substation
B. Roadside infrastructure, such as support towers
C. Contact wires or side rails
D. Power connector, such as the pantograph
E. Power On-Boarding Module, connects to truck’s electrical system (via DC/DC converter with/out isolation)



Reference – White Paper Dynamic Charging Interface (DCI) -Recommendations and requirements for Dynamic Charging Interface v1.0

Multi-inlet Multi-Pack charging

- Damen RSD Tug 2513 Electric
- Tug boat with 3.7bMW power and upto 2.782MWh battery
- 2h Charging via 4x CCS connector via Special charging arm (upto 4x350kW=1.4MW)

Reference – https://www.damen.com/vessels/tugs/electric-tugs/rsd-tug-2513-electric