Multi-port, 1+MW Charging System for Medium- and Heavy-Duty EVs: *What We Know and What Is on the Horizon*?

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DOE Clean Cities Program Introduction
MW+ Multiport MD/HD Vehicle Charging Resources

- Introductions
- Clean Cities related case studies on AFDC web page https://afdc.energy.gov/case

Search Results | 311 case studies

Date	Title
Nov. 22, 2019	Indiana Cleans up with Natural Gas Trucks
Nov. 15, 2019	Electric Vehicles Charge up the Police Force
Oct. 31, 2019	New Flyer Buses Go Electric
Sept. 19, 2019	Electric City, Utah
Aug. 27, 2019	SunLine Transit Demonstrates Excellence in Zero Emission Transit
July 2, 2019	Natural Gas Trains Make the Grade in Florida
June 27, 2019	EV Dollars and Sense
June 3, 2019	Colorado Energy Office: EV Fast Charging Corridors Grant Program
May 21, 2019	Multi-Unit Dwelling Procurement Case Study: Green Rock Apartments
April 27, 2019	Electric Vehicles Hit the Open Road

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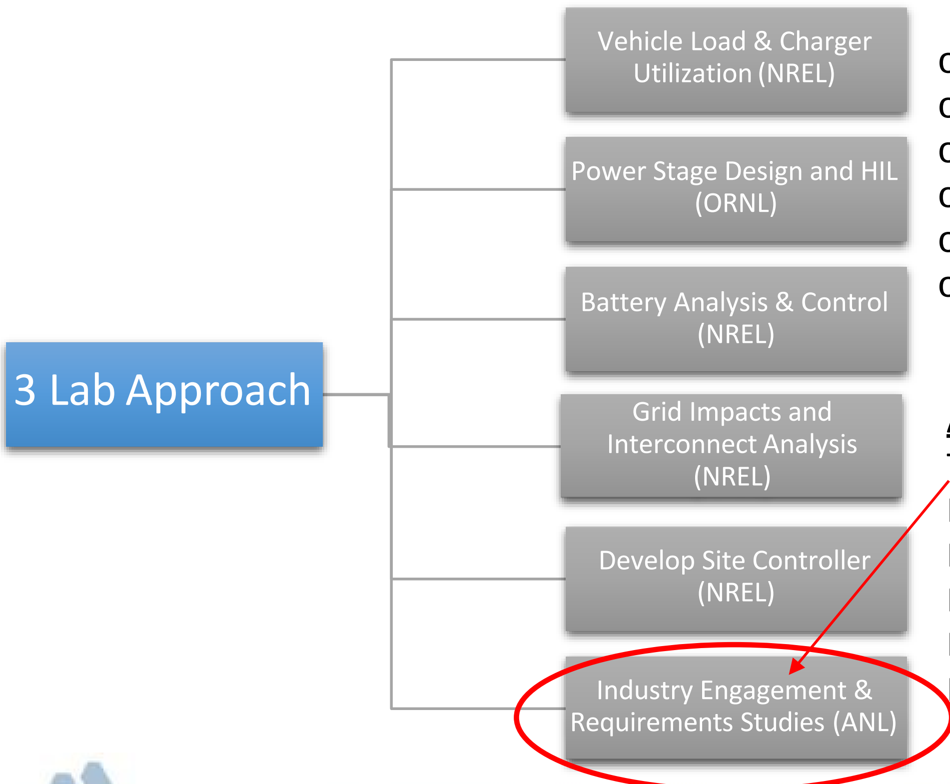

- **Task 1/2 – Topology Design** (ORNL)
- **Task 3 – Power Stage Design** (ORNL)
- **Task 4 – Assessment of Supply Equipment MD/HD** (ORNL)
- **Task 5 – Develop Host Controller** (ORNL)
- **Task 6 – Charger Utilization** (NREL)
- **Task 7 – Grid Impacts Analyses** (NREL)
- **Task 10 – Grid Interface** (NREL)
- **Task 8 – Battery Charge Control** (NREL)
- **Task 13/14/15 – Industry Engagement, MD/HD Truck, Bus, DCaaS Charging Requirements Report** (ANL)

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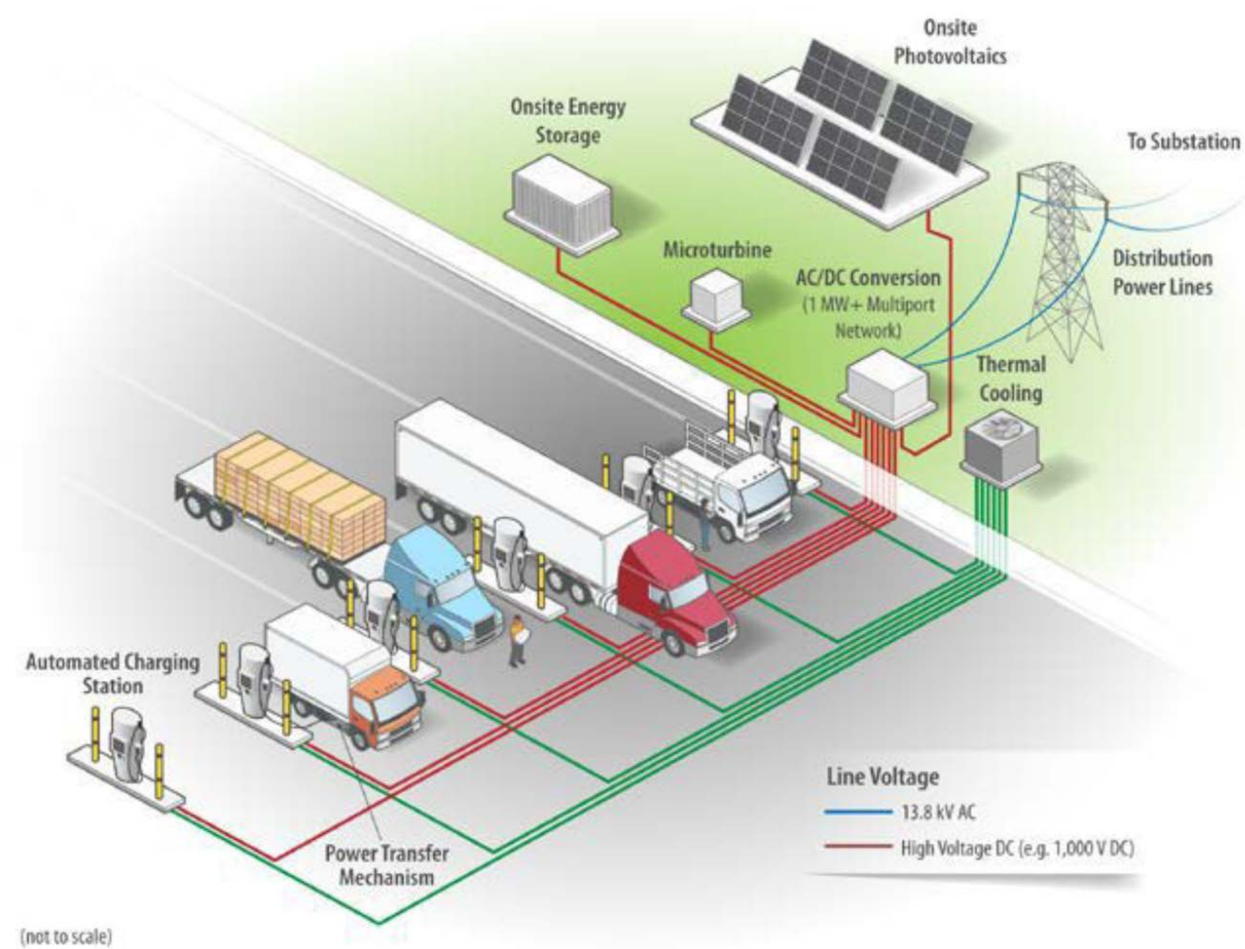
Overall Distributed Charging Perspective; Medium Voltage AC to 1000vdc to Dispensers to Batteries

- ANL focus in 2020 is on defining test cases, gaps in standards, identify data that can/should be collected for decision making



Diversity of Industry Stakeholders in MW+ Work Group; By Similar Functions/Concerns (200+)

- **Utilities(18), planning services(8), site operators (10)**
  Alliant, Black & Veatch, Burns & McDonnel, CTE, HDR Inc, AEP-Ohio, Duke Energy, EPRI, MG&E, PG&E, Seattle City Light, Southern Company, CTA-Chicago, Electrify America, EVgo, Loves/Trillium, TA Petro

- **EVSE/power electronics(14), couplers/cable systems(8), ESS vendors(8)**
  ABB, BTCPower, Chargepoint, Delta Products, Eaton, Efacec, Heliox, Siemens, Power Electronics Corp, Rhombus, Tritium, Marquette Univ., JMM Consulting, Huber-Suhner, ITT, Phoenix Contact, Power Hydrant, Rema, Schunk, Staubli, TE Connect.

- **Vehicle OEM/components(17), end users-customers(4)**
  Allison, Autocar Truck, BYD, Cummins, DTNA/Daimler, FCA, Ford, Gillig, MAN/VW Group, Navistar, New Flyer, Nova Bus, Orange EV, PACCAR/Peterbuilt, Proterra, Tesla, Xos, Transpower, Penske Leasing, Ruan Transportation, Zerology

- **DOE Funded/Lab coordination, contractors(11)**
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What is Argonne National Laboratory?

ANL was designated as the first National Laboratory in 1946, initially formed to support Enrico Fermi's work (Univ. of Chicago) on the Manhattan Project. (CP-1 reactor in 1942)

Bldg 300 Interoperability Research Center

Bldg 362 Center for Transportation Research

Some Statistics

Budget: $760M

Staff: 3350

Location: Lemont IL

Area: 1700 acres

Multidiscipline research including energy, materials, computing, nuclear, bio, etc

What is Argonne National Lab and the EV-Smart Grid Interoperability Center?

ANL hosts the US EV-Smart Grid Interoperability Center, in conjunction with JRC in Ispra Italy, to develop and validate EV charging standards as well as research grid impacts

Smart Energy Plazas at bldgs 300 and 362

Some Statistics

50 AC EVSEs Site-wide
PV Fed Charging- 80kW
DC Fast Chargers: 25kW, 50kW, 200kW, 400kW
Wireless: 50kW

MW+ Multiport MD/HD Vehicle Charging Challenges to Address, Advantages to Leverage

- ***Space; the Final Frontier****….* Where to put all the 'stuff' needed to charge many vehicles at high power rate, in a space that is already full of vehicles/equipment? (bus depot, bus stop, truck warehouse/dock/depot, truck stop w/200+spaces…)

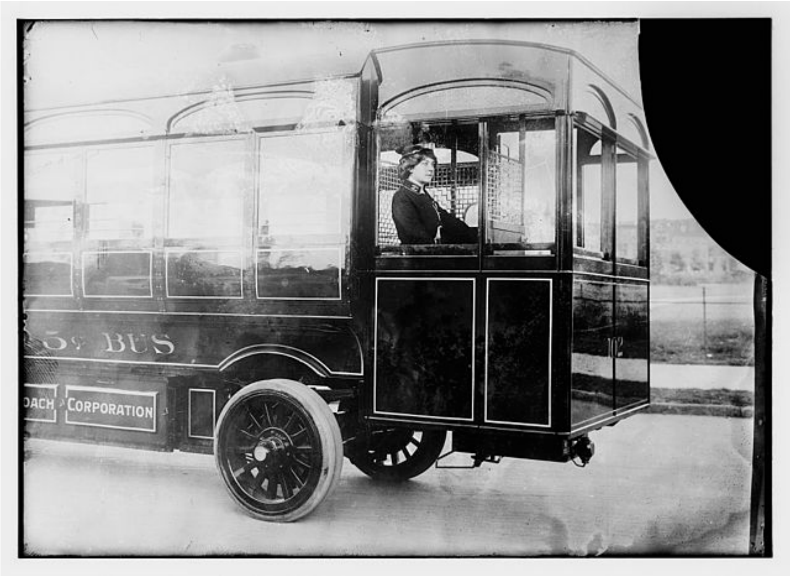
- ***Feeding the Beast….***Utility interconnection permits and capacity planning can be an expensive and long lead time process. One to two vehicles at 1MW each can typically be accommodated today by a single utility owned pad mounted 480vac transformer. Supplying tens to hundreds of trucks (10MW-100MW) is another story.

- ***Local Storage/DER to Manage Demand Will be the Norm….*** Load leveling, or averaging/aggregating multiple parallel charging sessions will require local energy storage to minimize transients and peaks during ramp up/ramp down of MW+ steps. This may be coupled to onsite generation (PV, natural gas engines/turbines, etc) and tied to dynamic market pricing that could take advantage of regulation services-SREC.

- ***Planning for the Today & Future- How Much Infrastructure is Needed Today/Later?*** Today we will review some pilot projects, ANL hosted work group activities and examples of coming deadlines (CARB 2040 zero emission bus fleets). Vehicles unable to charge don't make money; all MD/HD fleet vehicles need a full charge **EVERY** day.

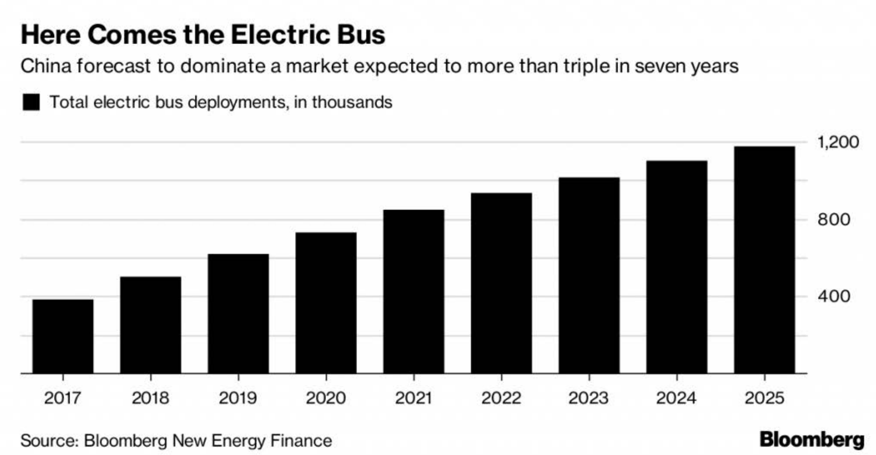
Electric Buses, Long Ago is Here Again….Like Light Duty EVs 100+ Years Ago; 1906, 1915… 16K in China

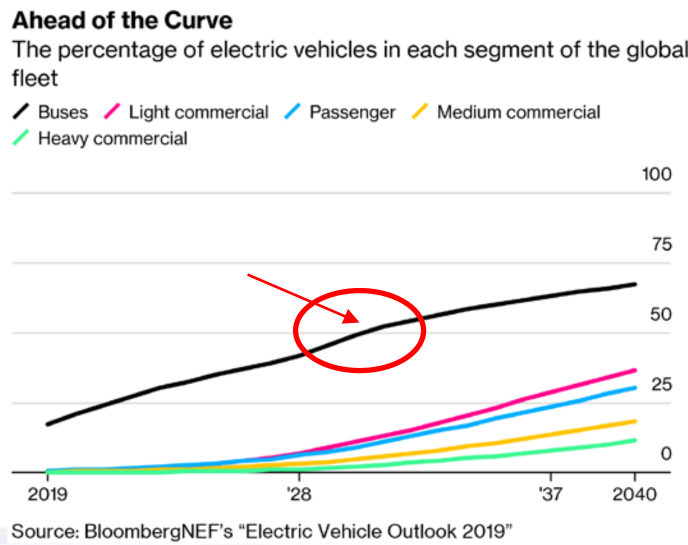
- Examples in Stamford CT 1906-1920 tour bus, 1915 Edison bus, Shenzhen-BYD…16k buses…as far as the eye can see



MD/HD Electric Vehicle Examples- Bus References; According to BNEF there were 300 US, 421K in China

- https://www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300
- https://www.cnbc.com/2019/09/28/electric-buses-are-taking-over-china-and-the-us-is-trying-to-catch-up.html
- Out of almost 425,000 e-buses worldwide at the end of 2018, 421,000 were in China.
- According to Interact Analysis, 80,000 electric buses were delivered globally in 2018, with 99% of those were in China
- The global e-bus fleet grew about 32% in 2018, according to a Bloomberg NEF report with the vast majority hitting the road in China.
- Europe had only 2,250 electric buses, by BNEF's count.
- Out of all the electric buses delivered in 2018, the US accounted for just 300.
- By 2030 e-buses should be cheaper upfront in most countries, according to BNEF





MD/HD Vehicle Examples- Available MD/HD Electric Trucks and eBuses

- https://www.metro-magazine.com/blogpost/736861/electrifying-transportation-a-holistic-approach
- *"There are 70 models of electric trucks and buses from 27 different manufacturers."*

- The California Air Resources Board will require transit agencies to have all zero-emission bus fleets by 2040. That regulation goes into effect with 100 percent of purchases starting in 2029. ***(Just 9 years to plan for all new buses being electric).***

- Select (i.e. arbitrary example models) Electric Bus Parameters:
  - Gillig; 3500 Nm (2,582 lbs.-ft.), battery capacity of 444 kWh, real-world range of 150 miles (2.3 kWh per mile); 210 miles at industry-advertised 1.7 kWh per mile.

  - Proterra Catalyst E2; battery capacity 220kWh to 660 kWh, consumption across model range (smallest XR) 1.58kWh/mile-~100 miles, 1.53-2.28kWh/mile-~290 miles

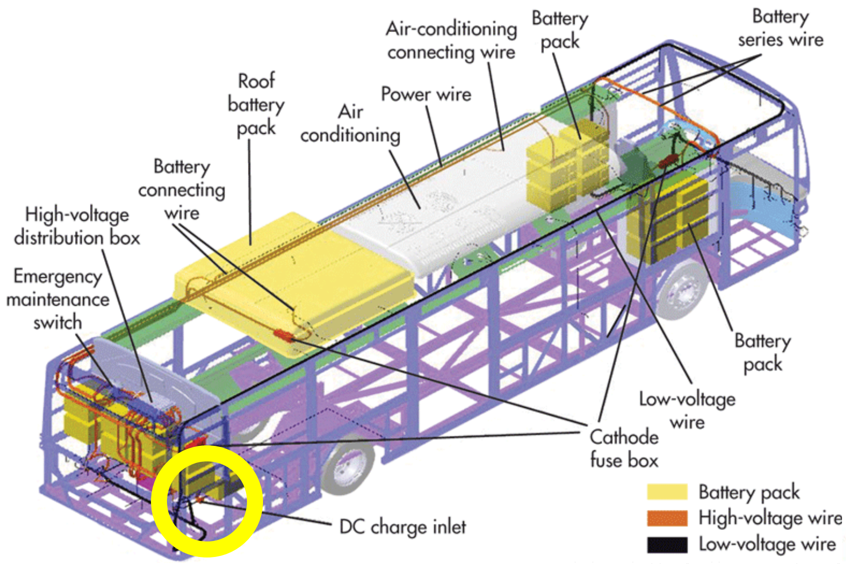
  - BYD K9; 23' to 60' models, single/double decker; 60' is ~55 seats, 50k lbs curb wt., 446kWhr, 200kW charging rate (2-2.5hrs recharge time)

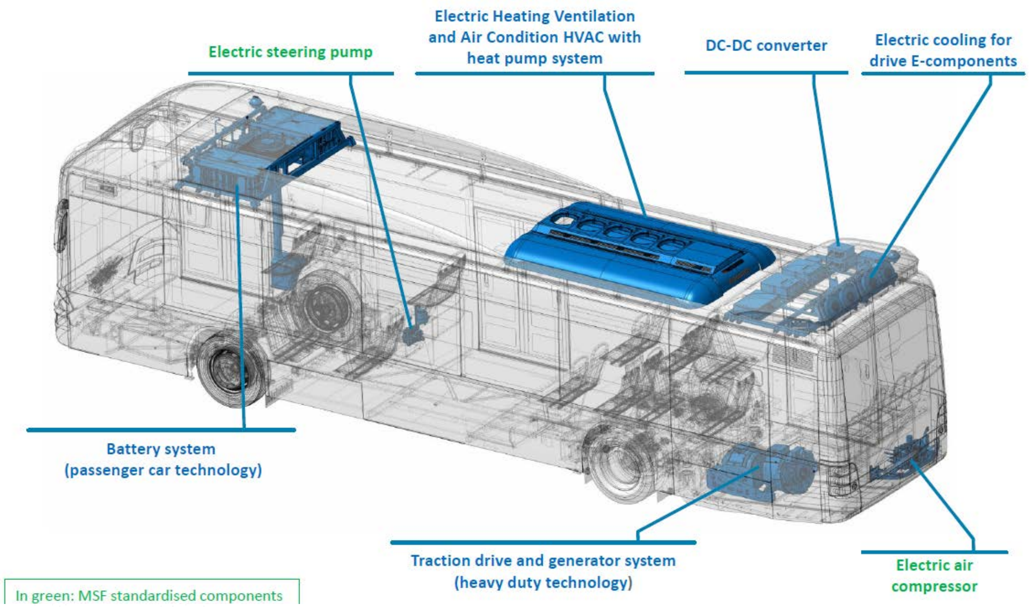
  - New Flyer Xcelsior; 35' to 60' models, 160-446kWhr, 225 miles range; 450kW (J3015)

  - **Nova Bus;** 40', 41 seats, 75 total, 230kW/1700Nm electric motor, 5 min. fast charge

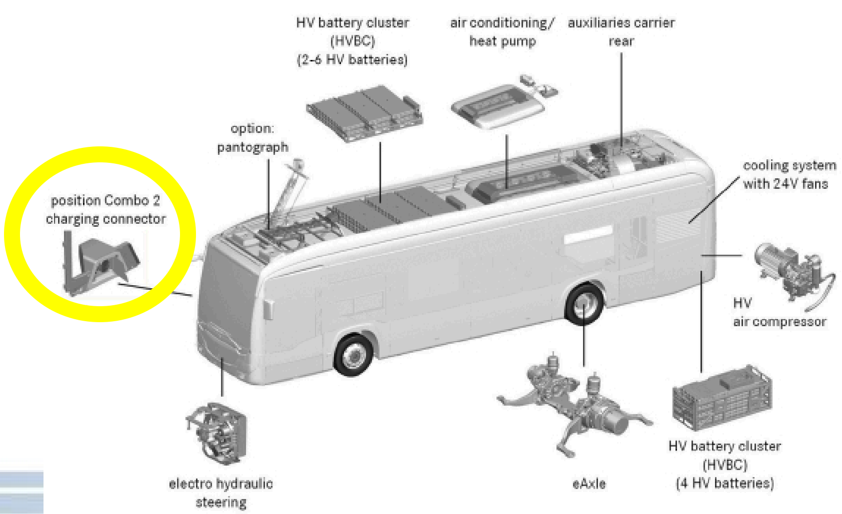
Electric Bus Component Placement Examples

Batteries on roof, in rear/front storage areas, etc

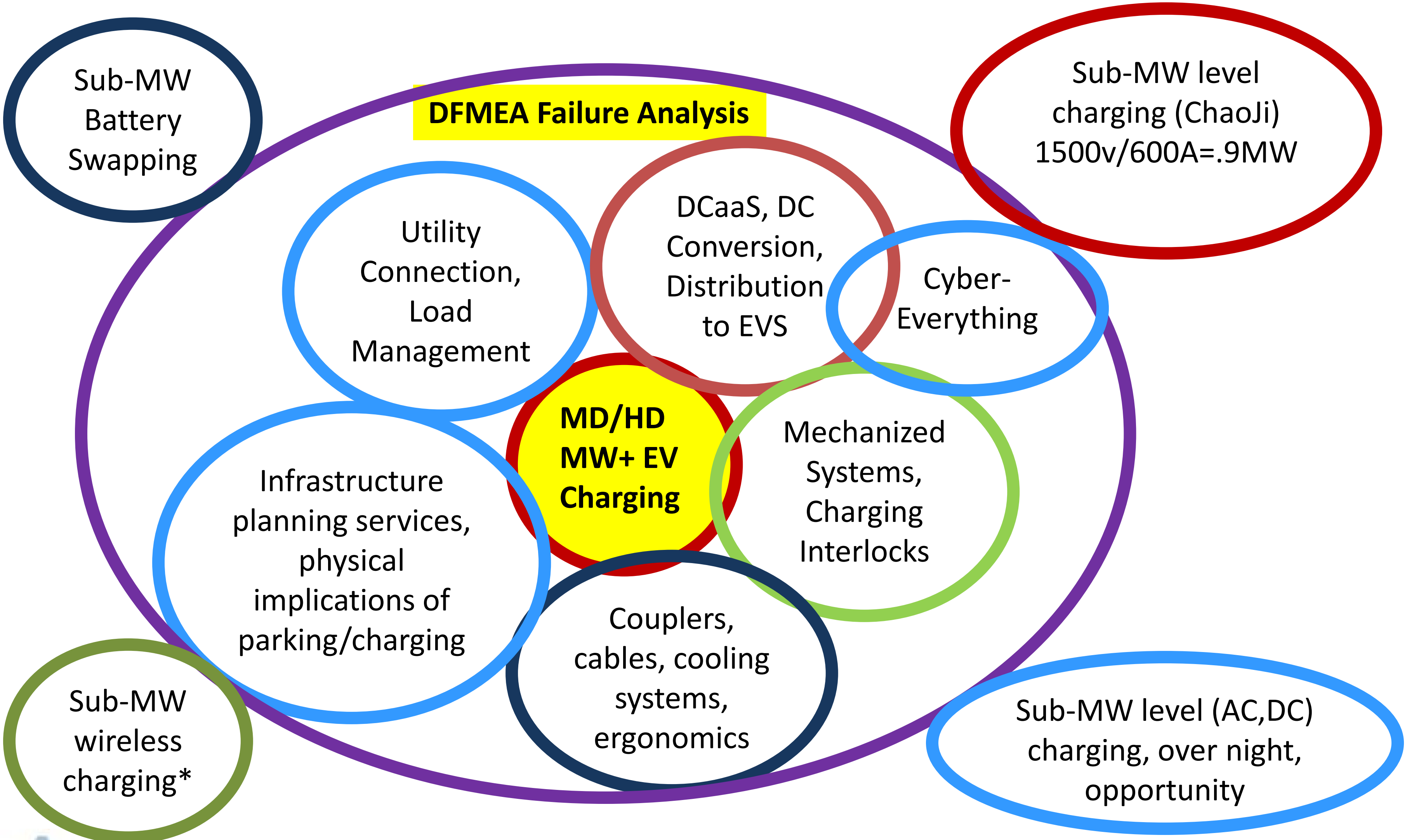




Electric Citaro with intelligent module concept



Overlapping Areas: MD/HD Electric Vehicle Charging Processes (≥MW and other levels)



Spectrum of Charging Levels in Standards; Only Two Are Presently Rated For 1+ MW

~ 1.9kW	(J1772) L1-AC
~ 3.3kW-~20kW	(J1772) L2-AC
~ 20kW-100kW	(J3068) AC (208/230/480vac three phase, w/onboard chargers)
~ 4kW-40kW	(J1772-CCS) L1-DC (50-500v/80A limit)
~ 20kW-~150kW	(J1772-CCS) L2-DC (basic, 50-500v/350A limit)
~ 150kW-350kW	(J1772-CCS) L2-DC (XFC, 200-1000v/350A limit {850A/1000A TBD})
3.3kW-22kW	(J2954) WPT1-4 wireless
60kW-590kW	(J2954/2) WPT5-8 heavy duty wireless
~150kW-**1200kW**	(J3105) L1-L2 DC mechanized coupler 3 formats (250-1000v/600A, 1200A limit)
~150kW-**4500kW**	(HPCVC) DC (work in progress) (1500v/3000A limit)

Example: High Power CCS Coupler Approaching 1MW Capability; Brugg 850-1000A 1000v (Swiss)

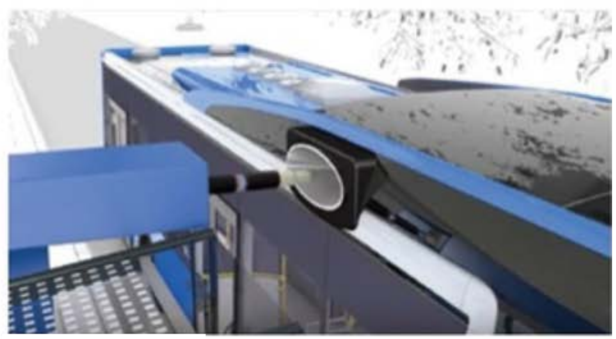
The cable’s core is a strand arrangement in which finely-layered hollow structures allow the flow of coolant. The water-based cooling fluid is non-toxic and largely biodegradable. Utilizing a newly-developed CCS2 connector, the coolant can be routed directly to the contacts. The cooling system allows cable lengths of up to 7 meters. *“…the Alligator-HPC was able to manage currents of up to 1,000 amps under laboratory conditions at an ambient temperature of 40° C.”*

ANL **4000A**, 1000vdc power supplies

Mechanized Commercial EV Charging Systems (1MW) SAE J3105 (3 versions of pantograph/side plug)

Fig. 1 - J3105-1 Infrastructure-Mounted Pantograph (Cross Rail).

J3105-2 Vehicle-Mounted Pantograph (Bus-up).

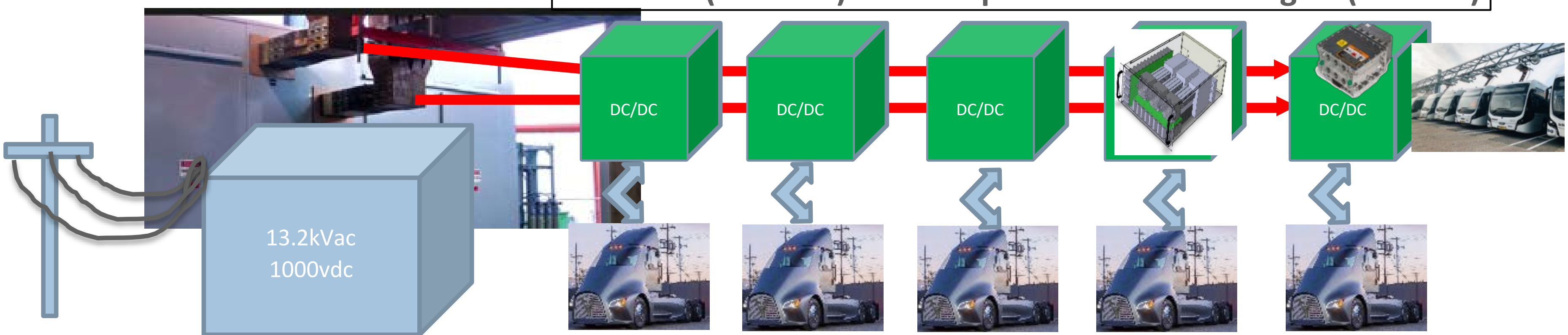


J3105-3 Enclosed Pin and Socket.

Modular/Scalable Approach to Space Constrained MW+ Multiport Charging Installations; DC Busway

- Depiction of AC and DC power distribution segments; Four regions of pathway
  - Medium voltage AC feed to charging installation (overhead, buried cables)
  - DC output of medium voltage-to-~1000vdc to dispensers (bus bars/busway)
  - DC flexible cable from dispenser to PEV (passive/active cooled), robotized?
  - Vehicle inlet to battery terminals (w/safety systems); vibration-cooling issues
- Access to the vehicle from EVSE determines length/pathway of charging cable

Multi-drop DC bus, dispenser-coupler challenges
Modular (250kW?) 'Field Replaceable Power Stages' (4x each)

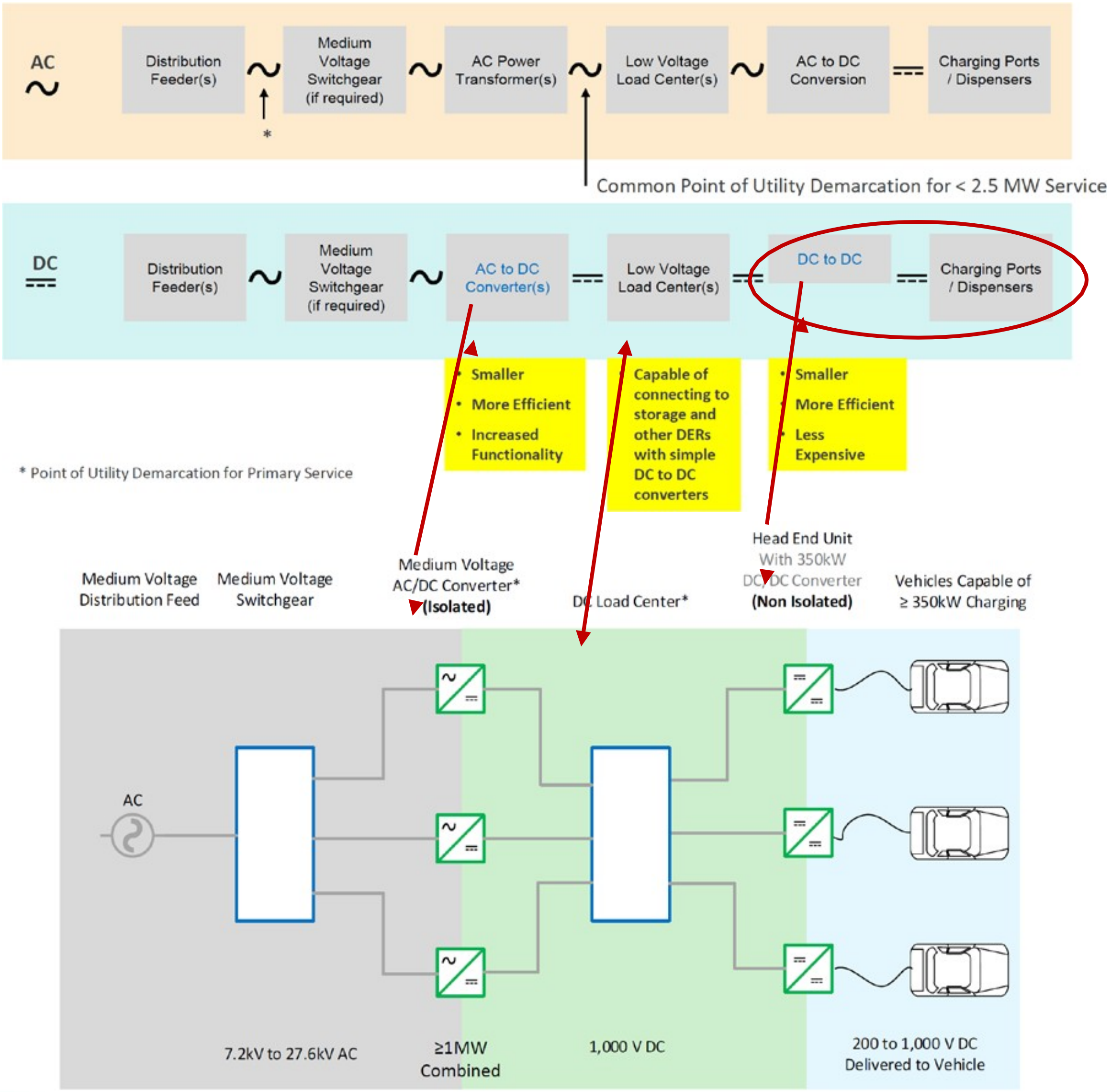


DC as a service- Utility challenges

Depot charging- vehicle inlet/control challenges

DC as a Service; Summary of Previous Discussions

(Watson Collins-EPRI graphics); Limitations on 2.5MW AC Utility Service



Example Charging Equipment Site Layout (350kW max per port, w/local AC coupled storage) 6 x 350kW=2.1MW (Someday all this will charge 1 truck)

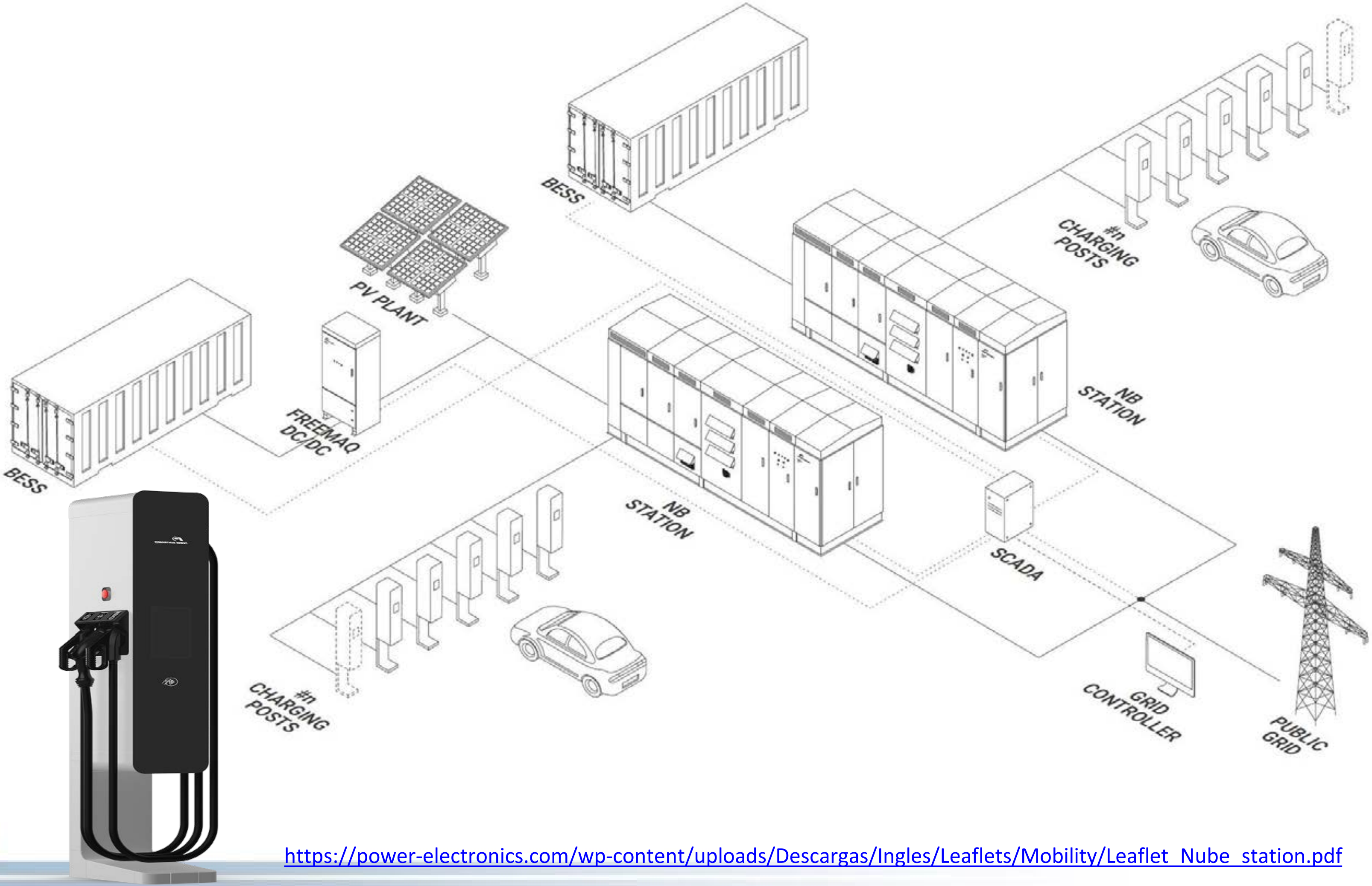
Single and dual output dispensers at curb

480vac to DC power converter cabinets in back

480vac switchgear and local peak shaving energy storage

DC as a Service/Integrated PV-Storage w/SCADA Example
Power Electronics Corp NB1400: 1.4MW, 6*350kW CCS

NBSHV1400S at 1.4MW (1000vdc/1400A total?), 4x600kW pantographs; 6x 350kW CCS1
Solar + storage coupled to the 1.4MW charging station skid, including the MV switchgear.

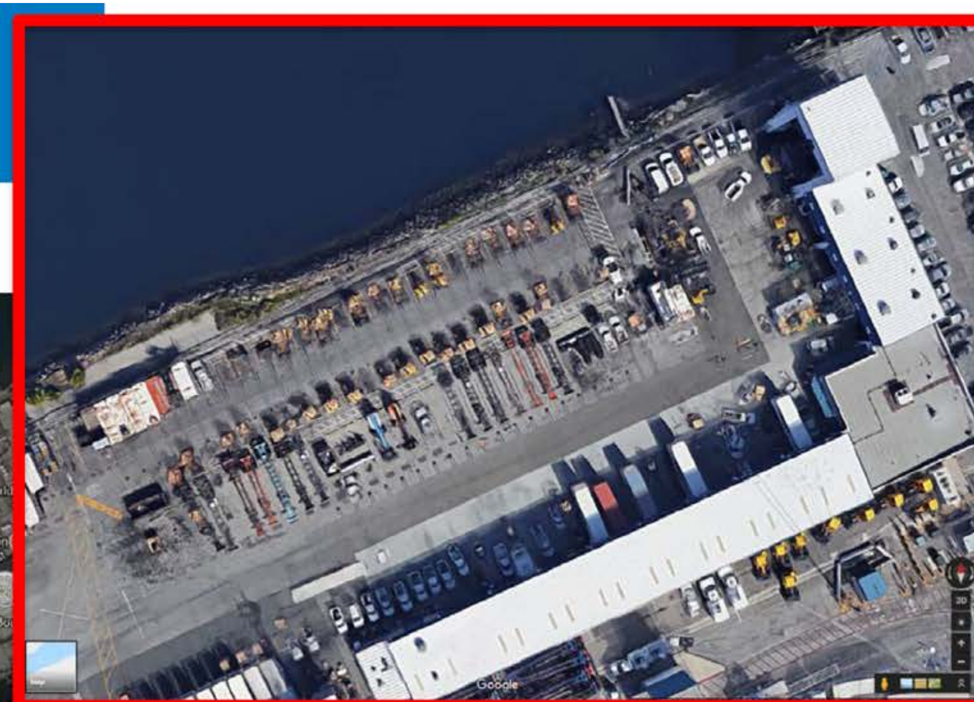
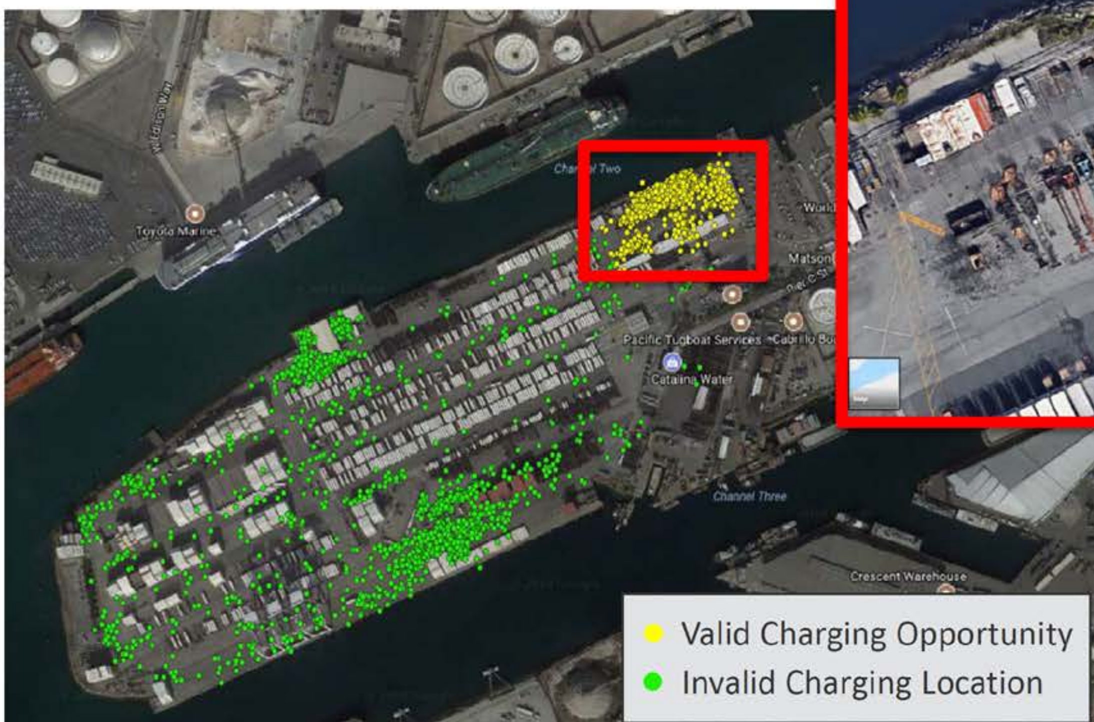


https://power-electronics.com/wp-content/uploads/Descargas/Ingles/Leaflets/Mobility/Leaflet_Nube_station.pdf

Case Study/Example: Port of Long Beach Charging Installation, 33 yard trucks x 175kW=5.5MW grid load

- NREL Study of Terminal C; (Excerpts from March 2019 summary presentation)
- Trucks operate on two 8 hour shifts, 1 hr charging between, and over night

Assumed Charging Opportunities

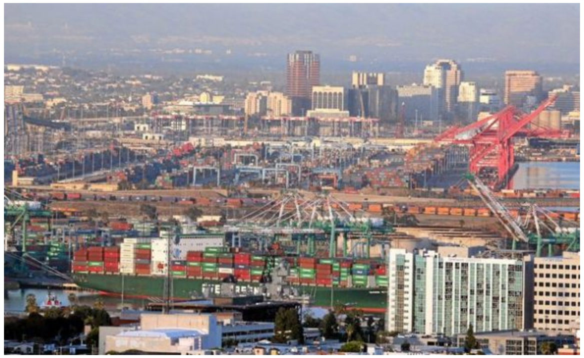



- Simulations assume charging opportunities only exist when equipment is parked at/near garage

NREL | 14

Case Study/Example: Port of Long Beach/Los Angeles Top Handlers and Yard Trucks

- Electric top handlers can operate up to 18 hours between charges and can load containers weighing as much as 75,000 pounds onto trucks..
- There are 16,000 big rigs that service the port, plus dozens of cranes, forklifts and other diesel-powered cargo-moving machines along the dock.
- Both ports have made it their goal to fully transition from diesel to zero-emission cargo-handling equipment by 2030.

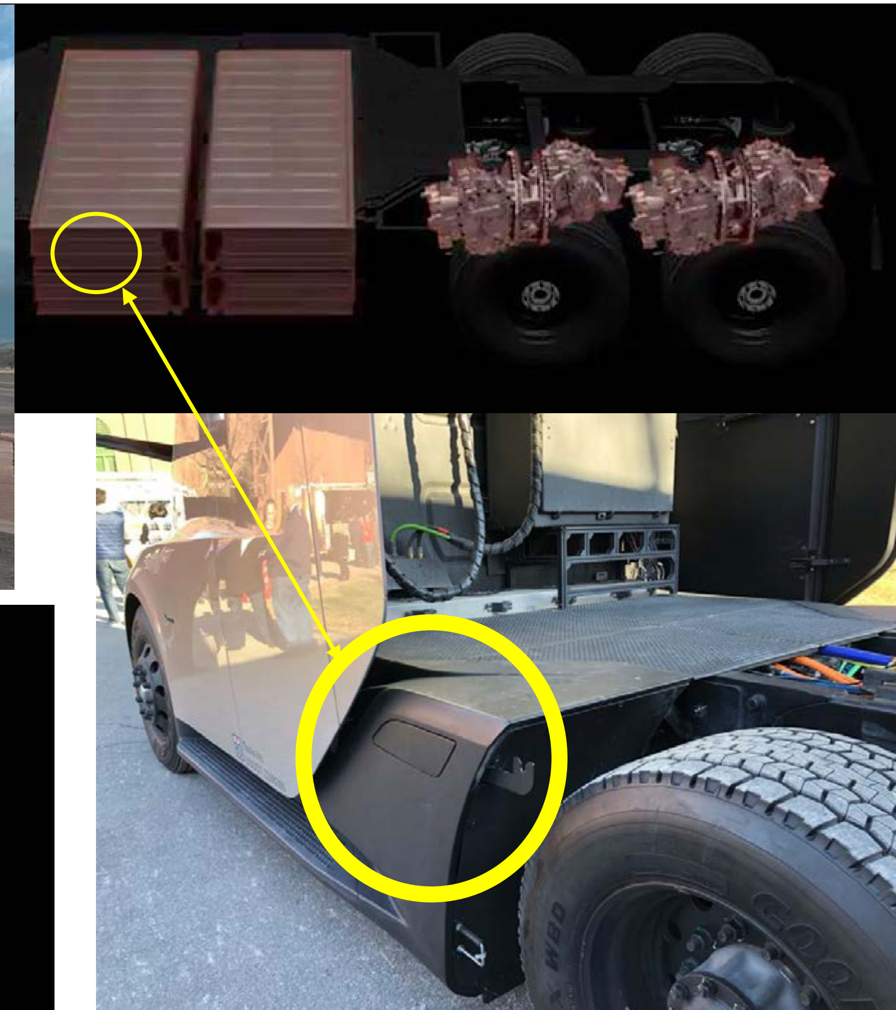


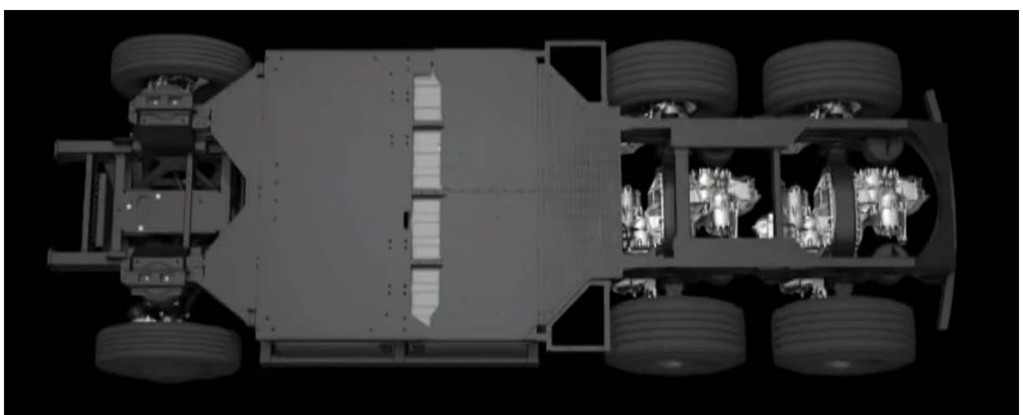
Class 8 Electric Truck Example: Peterbilt Model 579 w/Meritor-TransPower EPC Powertrain (8x44kWhr)

- Twelve Class 8 Electric Peterbilt 579's being built for Port of Long Beach
- Recent DOE FOA award to PACCAR/Peterbuilt for 1MW wireless charging version, with subcontract to WAVE/Utah State University
- 490 HP, ~250 mile range, 350-440 kWh, recharges in less than five hours
- Uses the first five gears of an Eaton AutoShift 10-speed transmission

Tesla Semi (battery placement, inlet location, power pathways); 300-500 mile range; $150k-$180k

Batteries under cab, inlet just ahead of first rear axle, street side

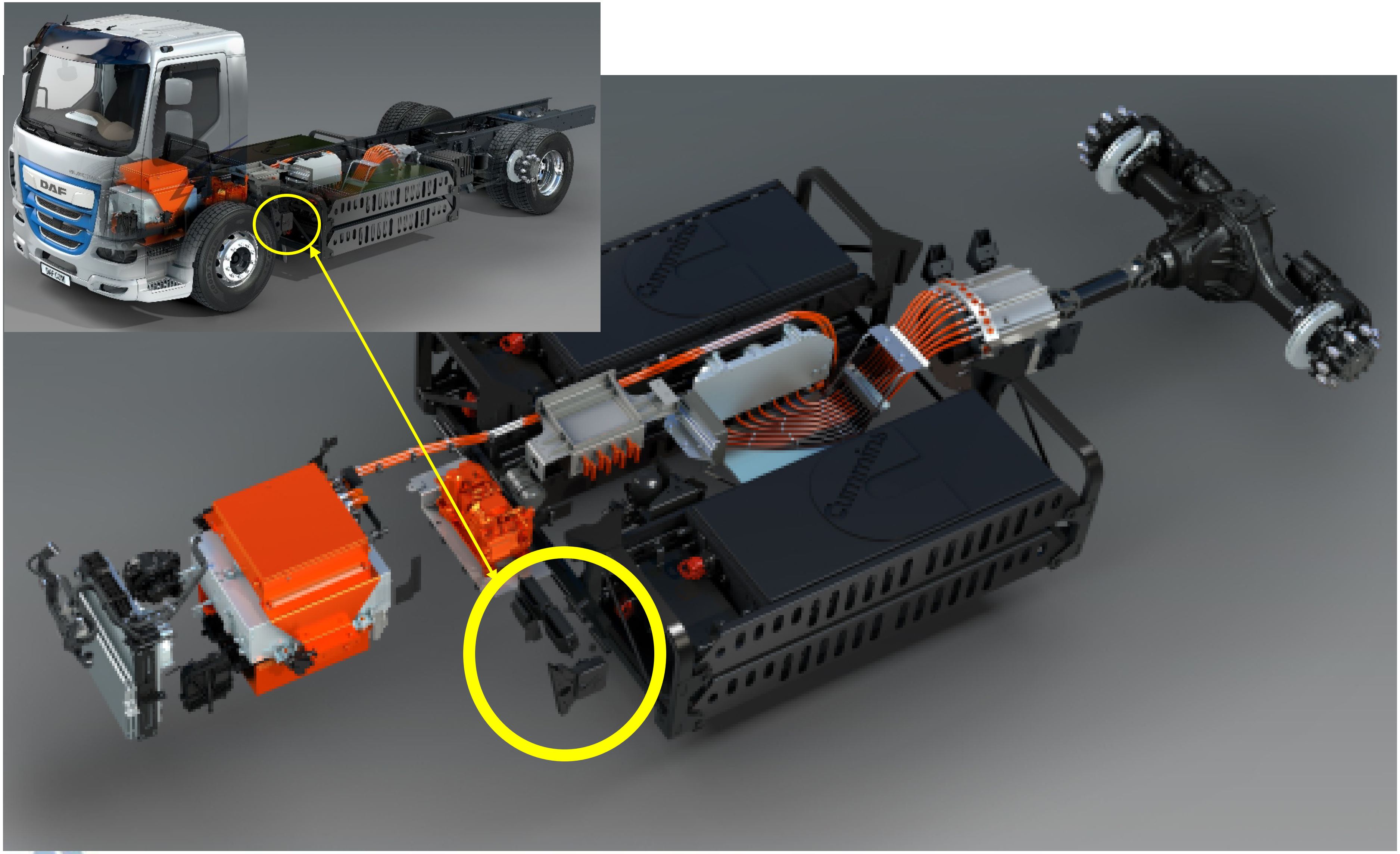




Daimler eCascadia Class 8; Pilot fleet w/Penske

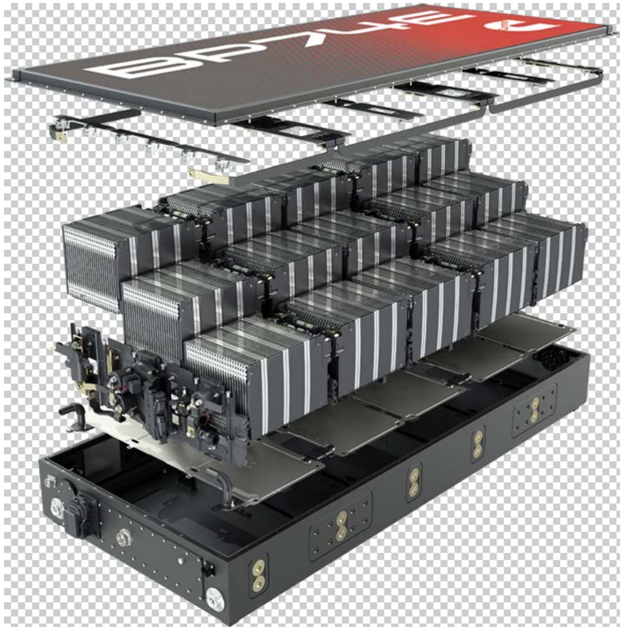
DAF-Paccar Straight Truck

Batteries between front/rear axles, inlet behind front wheels



Cummins EOS Concept Urban Tractor

- Class 7; 18,000lb tractor weight
- 140kWhr, 100 mile range



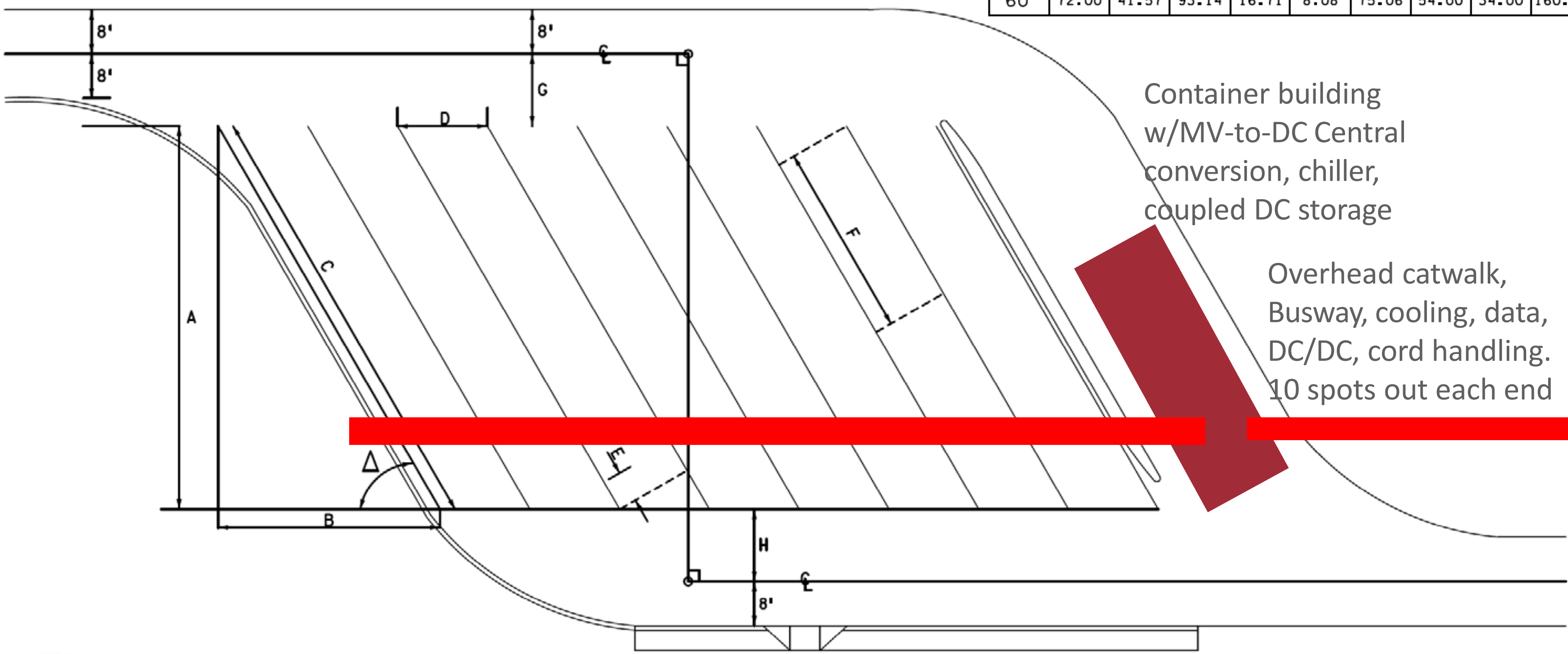
Neuron Prototype Class 8 Tractor

Example: MN-DOT Parking Stall Layouts, Truck Page (14’w x 75’ minimum stall size)-10 stalls =140’

Parking Space data
(based on 14ft x 75ft minimum stall length)
(ALL DIMENSIONS ARE IN FEET OR FRACTIONS OF FEET)

Δ	A	B	C	D	E	F	G	H	℄-℄
30°	50.00	86.60	100.00	28.00	24.25	75.75	14.00	15.00	79.00
35°	55.00	78.55	95.89	24.41	20.00	75.90	19.00	18.00	92.00
40°	59.00	70.31	91.79	21.78	16.69	75.10	26.00	21.00	106.00
45°	63.00	63.00	89.10	19.80	14.00	75.10	32.00	25.00	120.00
50	67.00	56.22	87.46	18.28	11.75	75.72	40.00	28.00	135.00
55	70.00	49.01	85.45	17.09	9.80	75.65	46.00	31.00	147.00
60	72.00	41.57	93.14	16.71	8.08	75.06	54.00	34.00	160.00

TRUCK PARKING STALL



DC Charging Electronics Power Density Comparison Pad mounted equipment space may not be available; leading to overhead mounted solutions

- DC EVSE in the ~500-600kW net system comparison of volume/mass; some are ~53W/lb.
- High frequency/WBG topologies can help (Marquette-U, Rhombus, John Deere examples). Solid state transformers as part of DC as a Service (DCaaS) with integrated storage and energy management can distribute sections of the electronics with just isolated dispensers at vehicle.
- Distributing DC power via bus bar connection to point-of-use electronics can lead to a short flexible output cable.
- Non-cooled 1000A conductors could be a bundle of 4/0 cables, or 770MCM{~1"} fire hose size.

  JD PD400 dual inverter; 700v/280kVA=30kg, 21.1L; 4x extrapolated to 4*280kW=**~1MW, 120kg**

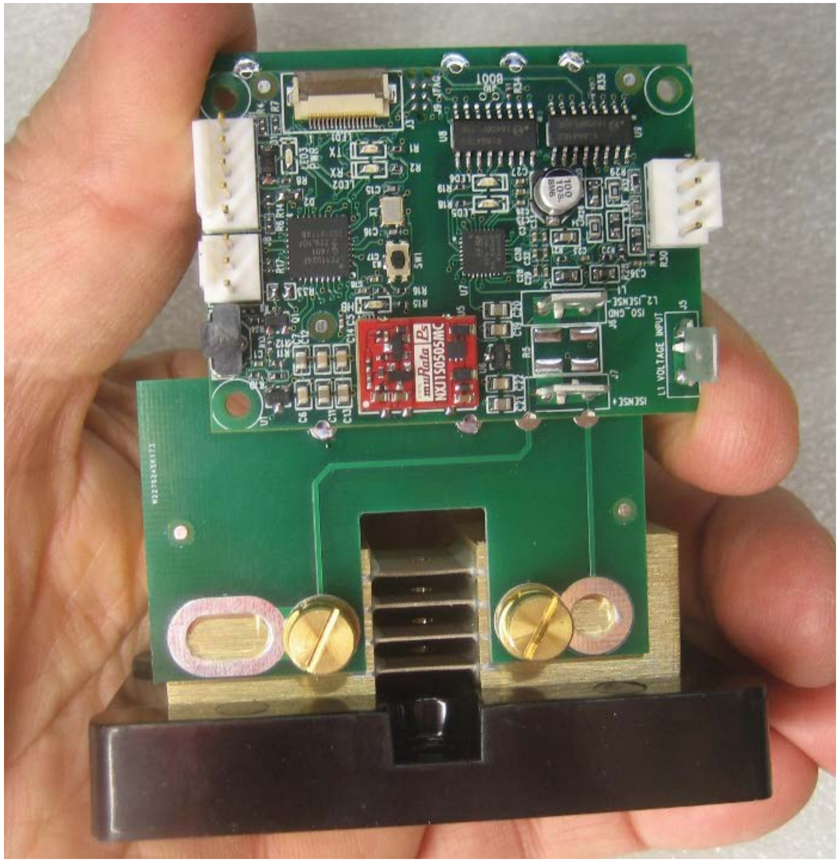
5.5MW SMA PV Inverter 36'x10'x8'H, **58,000lbs**

Daimler Bus Mezzanine; 4x ports

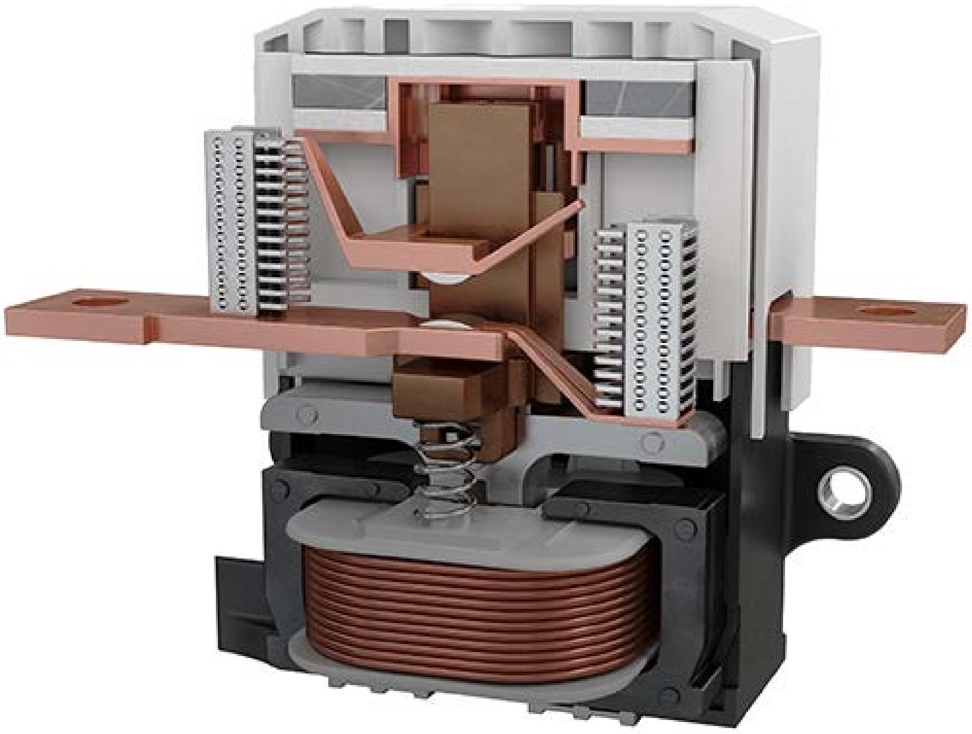
600kW Heliox 16'x2.6'x7.5'H **11.2klbs**

Safety Related Technologies: ANL DC Metering, Eaton ‘Breaktor’ 350A/1000vdc, 10kA interrupt

- 5 millisecond actuation
- Self triggering
- Combines functions of
  - fuses
  - pyro switch
  - contactor



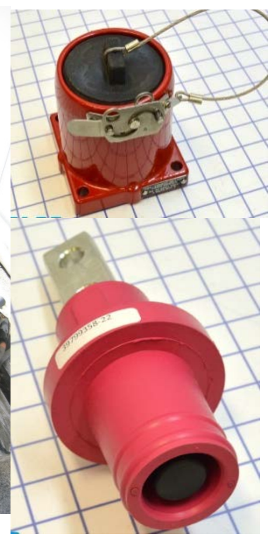
ANL 500A-1000vdc Submeter TCF
Commercial product in 2020(?)

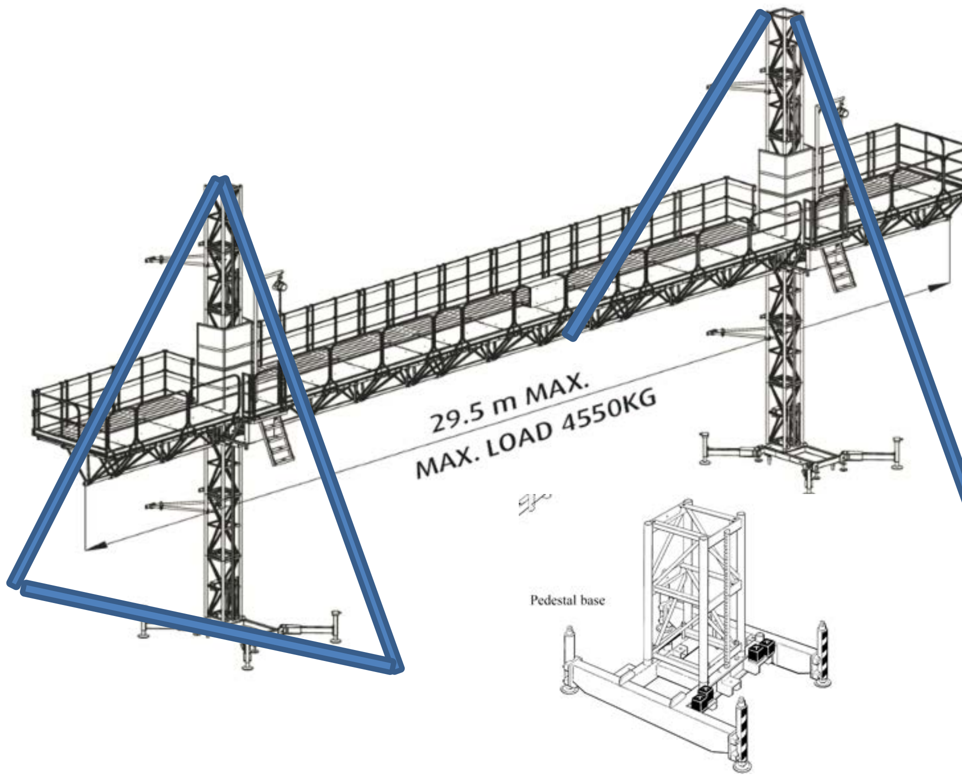


Develop Test Cases and Cost Estimates for MW Charging Test Bed-Mast Climbing Work Platform

- FY21 Testing Symposium Testbed, using Alimak configurable width 'mast climbing work platform' as a safety certified (10,000lb payload) motorized fixture to mount equipment at ground level and elevate the fixture above truck/bus height, avoiding use of ladder or scissors lift safety plan
- Propose minimum of three couplers: J3105, robotic HPCVC coupler/cable, manual HPCVC with cord retriever evaluation capacity

Piles of 4/0 'extension cords' at ANL (test setups), 770MCM 1135A Camloks

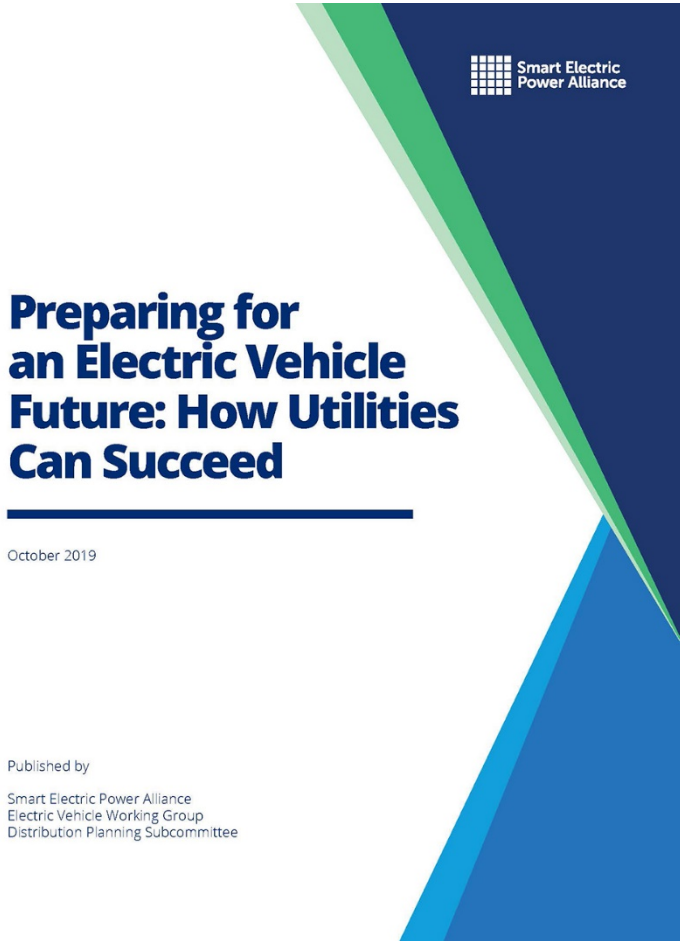




Backup- Reference Slides

MW+ Multiport MD/HD Vehicle Charging References: SEPA survey/public document

- https://sepapower.org/resource/preparing-for-an-electric-vehicle-future-how-utilities-can-succeed/



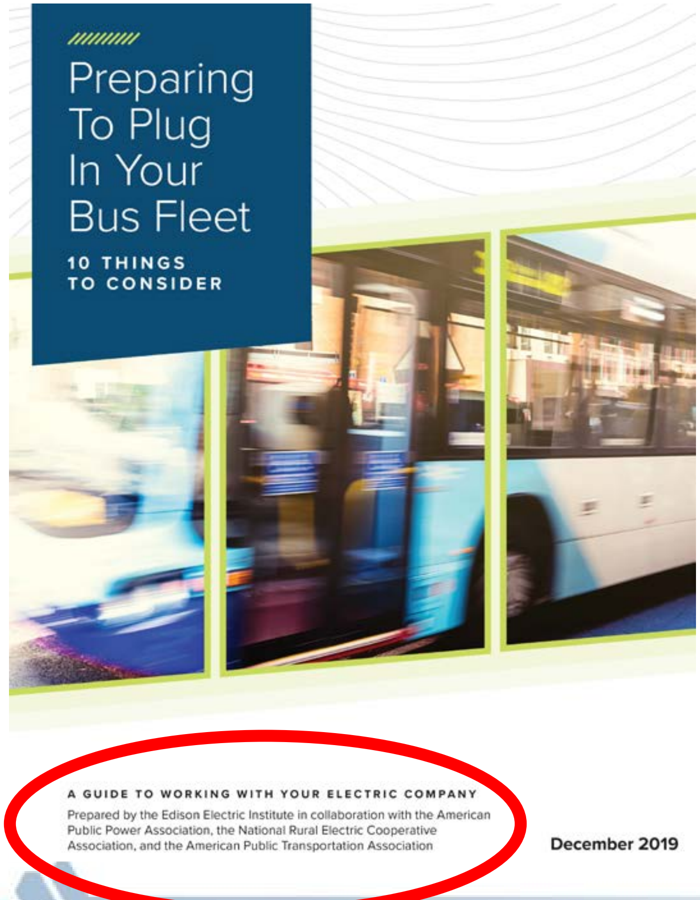
Combining results from an industry survey with personal insights of utility industry experts, the paper delivers recommendations and best practices for improving how utilities should support, plan and deploy EV charging infrastructure.

With similar time horizons for realizing large EV deployments and utility infrastructure deployments, the message is clear: all utilities should be preparing today for significant EV penetration.

This report was written by members of the Distribution Planning Subcommittee from SEPA's Electric Vehicle Working Group.

References, Guides/Documents: eStorage, Bus Prep.

- Behind the Meter Storage: "*KPI-Based guarantees will unlock 300MW of Commercial Storage-as-a-Service*" (AC coupled; Honeywell/NRStor C&I) https://www.greentechmedia.com/articles/read/kpi-based-guarantees-will-unlock-300mw-of-commercial-storage-as-a-service
- https://www.eei.org/issuesandpolicy/electrictransportation/Documents/PreparingToPlugInYourFleet_FINAL_2019.pdf



For the project with NRStor C&I, Honeywell will use two remote operations centers that deploy artificial intelligence peak prediction and value stack optimization algorithms in order to optimize the operation of the energy storage systems. Hajabed projects that customers will save 20 to 30 percent on their electricity bills.

*The two companies are offering performance guarantees customized to the specific objectives of corporate customers….involves collaboratively identifying and quantifying specific key performance indicators (KPIs). If NRStor and Honeywell achieve and exceed those KPIs, **there's a financial incentive for those two companies — and there are consequences if they fall short.***

MW+ Multiport MD/HD Vehicle Charging Infrastructure Upgrade of Service Lead Time (Location Dependent)

- https://sepapower.org/resource/preparing-for-an-electric-vehicle-future-how-

Table 3: Power Delivery Schedules

Potential Power Delivery Upgrades	What is Involved	Typical Ranges (Months)
No Distribution Circuit Upgrades (up to 1 MW)	Often, site loads below 1 MW can be supported with a new service transformer connected to the local distribution grid.	0-2
Supply Conductor Upgrade, No Grid Upgrades (up to 1 MW)	The supply conductor upgrade may require replacement to serve the increased load. The service transformer may also be replaced with a larger size.	0-2
Medium Voltage Service, No Grid Upgrade (up to 2 MW)	The manager may have to take primary service at medium voltage to allow for multiple service transformers (customer-owned) behind the meter if the site load exceeds standard service transformer and low voltage switchboard ratings (typically around 3,000 A).	0-5
Grid Upgrade Deployment: Re-conductor or New Line Equipment (over 1 MW)	The overhead or underground wire may require upsizing to increase the load capacity and improve voltage regulation on the feeder if the charging load overloads the distribution circuit.	6-36
Substation Upgrade: New Transformer Bank (over 10 MW)	An overloaded transformer bank is either replaced by a larger bank in the substation or an additional bank is added.	18-36
New Substation (over 20 MW)	A new utility or dedicated high voltage substation may be required for very large installations.	24-48

Source: Black & Veatch. 2019. Electric Fleets: 8 Steps to Medium and Heavy-Duty Fleet Electrification.[28]

Note: Example ranges—all power delivery scenarios are specific to a location, feeder access, existing, in queue projects and utility operating/ power provisioning standards, and available land/ right of ways.

Modular Power Electronics Approach- Scalability Extrapolating Traction Drive Inverter Power Density to Future WBG/Liquid Cooled DC/DC Converters

John Deere Electronic Systems- PD400 Dual

700vdc, 450A each continuous output, 280kVA; **30kg**

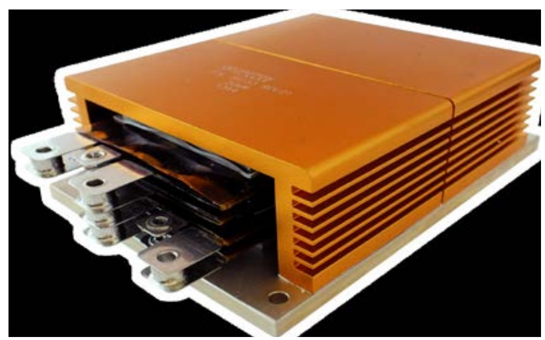
395 x 330 x 185mm; (17x14.5x8.2”); 1300 cm^2, 24.1L volume

Hypothetical 4x280kW=1.12MW, 120kg, ~100L

- Target: 250kW rack mount DC/DC converter module (4x=1MW); 5U high/50kg?

UPS/Rectifier Chassis-like blind mate power racks

Payton Planar Transformer
20kW (100kHz), 3kg

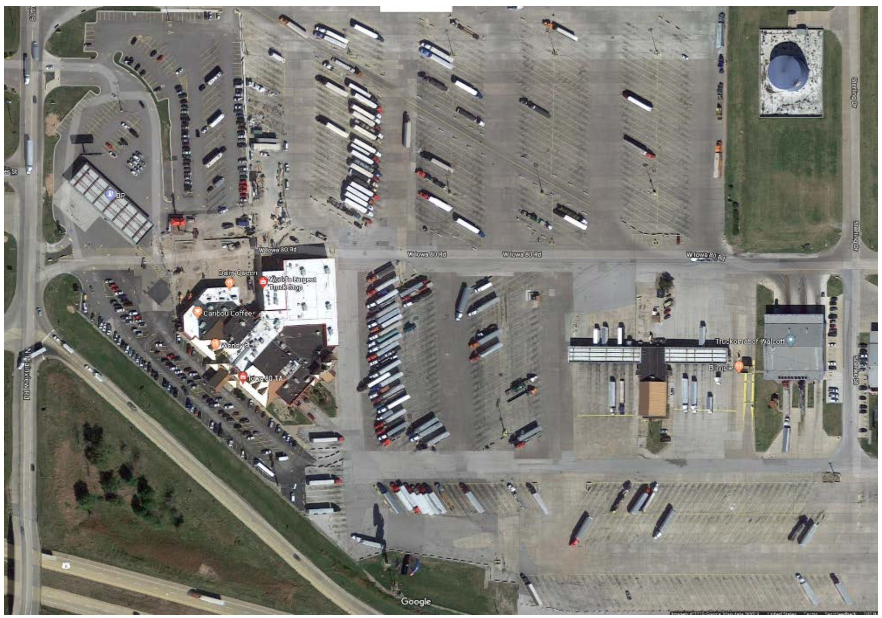


http://www.paytongroup.com/webfiles/files/5000.pdf

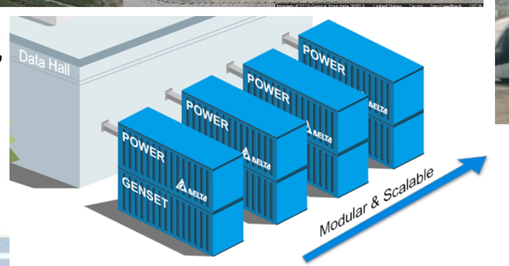
https://www.deere.com/assets/pdfs/common/industries/electronic-solutions/macneil-pd400-product-sheet.pdf

Use Cases; Facility Space Requirements for Peak Shaving Storage, Switch Gear, Power Electronics

Trenched vs overhead connections, impact in installation costs/permits
Others promote stacking it up like data center UPS/storage systems (Delta Electronics)
Heliox promotes pad mounted fueling islands between vehicle charging lanes



I-80 TA Travel Plaza, Iowa



Charging Equipment Installation Footprint Examples; Central Feed

Present Case: Heavy power electronics with larger footprint requires substantial structure above vehicles, or long cables from chargers to truck location (Daimler/Heliox example; CCS, J3105)
At 20,000 lbs per 450kW station, that is 80,000lb plus structure (capital equipment cost, installation/foundation costs)

Charging Equipment Installation Footprint Examples; Central Feed

Future Case: Prefabricated power conversion and battery storage in shipping container footprint (3MWhr Tesla Megapack); AC-to-DC (DCaaS) located at edge of charging plaza; overhead box truss structure distributed DC power/cooling and DC/DC output regulator at each vehicle (1000lb each?), robotic coupler, cord handing units