Forecasting a Realistic Electricity Infrastructure Buildout for Medium- & Heavy-Duty Battery Electric Vehicles

FINAL REPORT

March 18, 2024

Roland Berger

Contents

This document shall be treated as confidential. It has been compiled for the exclusive internal use by our client and is not complete without the underlying detailed analyses and the oral presentation.

A. Overview of methodology

Objective of this study is to estimate the investment need for the buildout of the infrastructure required to support full electrification of the U.S. MDHD fleet

Objectives of this study

I Determine the **total investment need** for the buildout of

- **electricity distribution** and **vehicle charging** infrastructure
- **electricity generation** and **transmission** infrastructure

to support **100% battery electric vehicle (BEV) penetration** in the **U.S. MD and HD CV fleet** and **compare to historic investment rates** (where available).

II Highlight **current challenges and constraints** in terms of **funding** of the infrastructure buildout, **permitting**, **charging service provider availability** as well as **practical challenges** of fleets.

We simulated charging networks for MDHD vehicles and analyzed implications for the electricity generation, transmission and distribution infrastructure

1 Charging network simulation

LOCAL CHARGING NETWORK

Geographic analysis

Analyze regional MDHD distribution (metro, sub-urban and rural areas)

Charging strategy

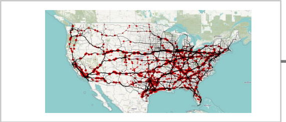
Allocate MDHD populations to on-site or on-route charging

Local charging network

Determine regional distribution of chargers and peak load

HIGHWAY CHARGING NETWORK

Charging location network



Map MDHD traffic flow and simulate highway charging network

Highway charger configuration

Determine number and power capacity of charge points for each location

Highway charging network

Determine regional distribution of highway chargers and peak load

2 Infrastructure needs assessment

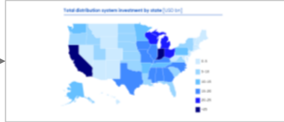
ELECTRIC LOAD IMPACT

Charging behavior and load impact analysis

Aggregate load profiles and overlay with available capacity by geography

DISTRIBUTION INFRA

Incremental distribution grid investment



Estimate local grid capacity upgrade needs and utility investment needs

INVESTMENT NEEDS

Investment analysis

Consolidate into total overall investment need

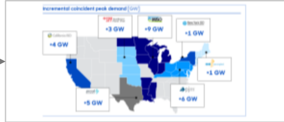
SITE INFRASTRUCTURE

Charging & "make ready" investments

Estimate on-site infra cost based on size and number of chargers

POWER SYSTEM INFRA

Incremental generation & transmission investment



Estimate investment in power system assets based on incr. capacity need

3 General challenges and constraints

Collect operational challenges for fleet operators

Identify other challenges and constraints to the infrastructure buildout

Note: MDHD includes Over-the -Road Bus (OTRB)

Two fundamental charging location types exist: on-site and on-route local charging and on-route highway charging for long-haul vehicles

Types of charging locations and strategies

Location	Local charging			Highway charging
Strategy	On-site charging		On-route charging	
Description	**Private chargers** installed at fleet's owned depot location	**Shared charging hubs** with dedicated availability for fleet customers	**Fully public-access** chargers for on-route or destination use	**Fully public-access** chargers along the highway network
Typical fleet characteristics	Large national fleets with **sufficient depot infrastructure**	Small to medium sized fleets with **insufficient depot characteristics**	Used by **various** fleet types (esp. for high-mileage use cases)	Used by **long-haul** vehicles (trucks and OTRBs)
Charger configurations[1)]	**Level 2** **Level 3** **DCFC** (limited cases)	**Level 2** **Level 3** **DCFC** (limited cases)	**DCFC**	**DCFC**

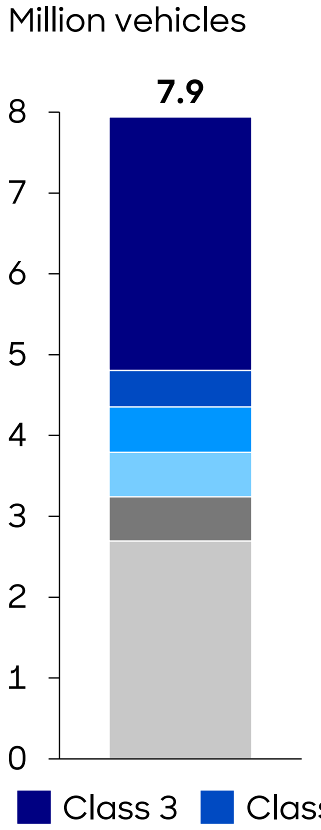
1) Level 2 charging refers to AC chargers less than 20 kW. Level 3 refers to DC chargers 50-150 kW. DCFC refers to DC fast chargers 350 kW and above.

Source: Interviews with market participants; Roland Berger Analysis

Within the MDHD population, we categorized four broader use case segments that can be mapped to the different charging location types

Use case segments

Vehicle count:



	Medium Duty (Class 3-6)		Heavy Duty (Class 7-8)	
Use case segment	1 **Local (low mileage)**	2 **Local (high mileage)**	3 **Local**	4 **Long-haul**
Description	MD vehicles (e.g., P&D, utility service, school buses, walk in vans) where daily driving distance **does not exceed usable range of BEV**	MD vehicles (e.g., P&D, utility service, school buses, walk in vans) where daily driving distance **exceeds usable range of BEV**	**All other Class 7-8** vehicles (e.g., drayage, distribution)	**Over-the-road** vehicles primarily running longer inter-regional routes, incl. trucks and OTRB
Charging locations	**On-site** at depot locations	**On-site** at depot locations, in addition to **on-route** charging at public locations	**On-site** at depot locations, in addition to **on-route** charging at public locations	Both top-up and overnight charging at **highway truck stop** locations

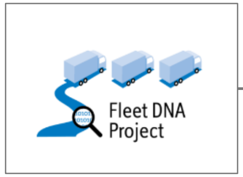
Note: Simulations are based on today's fleet size, except for long-haul trucks. The incremental weight of batteries results in a payload penalty. Trucks that weigh out today would exceed the maximum GVW limit and additional truck capacity is needed to carry the same amount of freight. For each diesel long-haul truck today, ~1.1 battery electric trucks will be needed.

Source: US Census Bureau; Roland Berger Analysis

For the local charging network, we analyzed where, when, and how much vehicles will charge, to determine the charging network and load profile

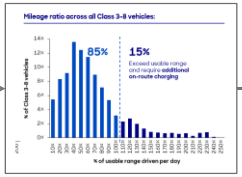
Methodology for local charging network and load profile analysis

Fleet telematics data[1)]



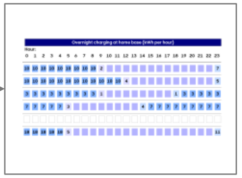
How are Class 3-8 vehicles (excl. long-haul) operated throughout the day?

Mileage distribution and duty cycle

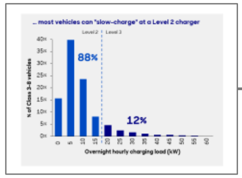


How much demand can be served by overnight vs on-route charging?

Overnight charging demand

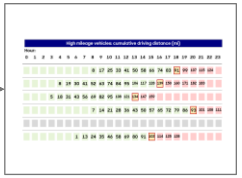


How much charging will occur at base?

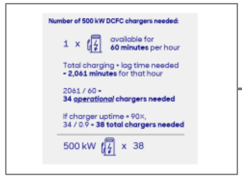


What charging infrastructure will fleets need to install?

On-route charging demand

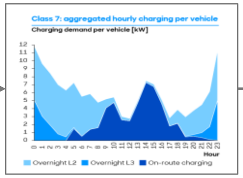


How much charging will occur on-route?



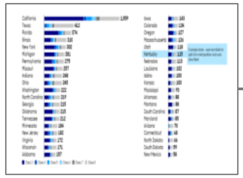
What charging infrastructure will public stations need to install?

Overall charging demand



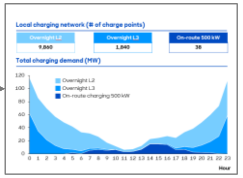
Aggregated average load curve per vehicle class

Vehicle populations



Regional vehicle distribution by weight class

Local network simulation



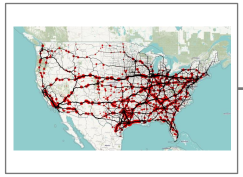
Charger installations and load curve **at the county level**

1) Data from NREL Fleet DNA Project

For long-haul vehicles we modeled a highway charging network that provides top-up charging capabilities and overnight charging

Methodology for highway charging network and load profile analysis

Highway truck stop locations



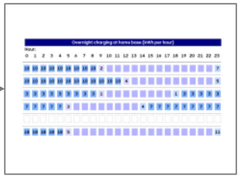
Where are long-haul vehicles refueling and parking today?

Long-haul truck traffic

How many long-haul vehicles are on the road at each location?

How many will recharge at each location?

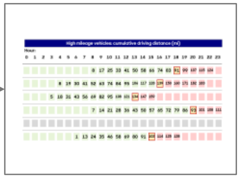
Top-up (MW) charging demand



How much top-up charging will occur on-route?

What charging infrastructure would need to be in place at each station?

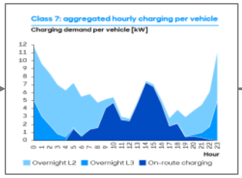
Overnight charging demand



How much overnight charging will occur on-route?

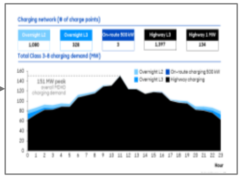
What charging infrastructure would need to be in place at each station?

Overall charging demand



Aggregated average load curve

Local network simulation



Charger installations and load curve **at the county level**

Our analysis focuses on characterizing the investment needs and challenges across both charging infrastructure and energy infrastructure

Investment landscape analyzed in this study

	Not in scope	Charging infrastructure			Energy infrastructure	
			"Make ready" infrastructure			
	Vehicle	**Charger**	**Site**	**Electric service**	**Distribution grid**	**Generation/ transmission**
Investment need	BEV purchase	Charger cost & installation	Civil & electrical	Utility service upgrade	Increased grid capacity	New power system assets
Capital outlay	Fleets	Fleets Developers	Fleets Developers	Fleets Developers Utilities	Utilities	Utilities, IPP's and developers
Subsidies or public funding (including utility rate base)	• Federal EV tax credit • State incentives	• Federal EVSE tax credit • State rebate programs	• N/A	• Utility-side make ready support in some states	• Federal funding available in some cases	• Federal funding available in some cases

We looked at two alternative scenarios: Electrification based on currently available technology and electrification based on improved technology

Technology scenarios

	Current technology	Improved technology
BEV adoption	**Full electrification** of Class 3-8 vehicles	**Full electrification** of Class 3-8 vehicles
Scenario definition	Assuming performance characteristics of **today's commercially available** vehicles and charger products	Assuming improved capabilities based on **reasonably expected performance improvement** in the medium-term
BEV range	Based on **today's commercially available** Class 3-8 BEV models **Max. Class 8 range: 180 mi**[1)]	**Increased range for Class 6-8** vehicles due to improved battery density **Max. Class 8 range: 250 mi**
Maximum fast-charging capacity	**350 kW**	**500 kW** (local) **1 MW** (highway)

1) Currently no electric long-haul truck in series production. Range estimate is based on the Daimler eActros 600 (European model, also expected to become available in the US). Assumes 80%-20% SOC

Based on currently available Class 3-8 models, we derived assumptions for battery size, "spec" range, and "usable" range and projected future performance

Vehicle assumptions by class

	Example vehicles	Mileage efficiency [kWh/mi]	Current technology			Improved technology		
			Battery capacity [kWh]	OEM spec range [mi]	Usable range [mi][1]	Battery capacity [kWh]	OEM spec range [mi]	Usable range [mi][1]
Class 3	Rivian, Ford eTransit, MB eSprinter	0.7	100	150	**90**	100	150	**90**
Class 4	Workhorse W4CC	0.7	100	150	**90**	100	150	**90**
Class 5	Freightliner Mt50e, Workhorse W56	1.5	100	150	**90**	100	150	**90**
Class 6	Kenworth, Navistar eMV, Freightliner eM2	1.3	218	163	**98**	305[2]	228	**137**
Class 7	Kenworth, Navistar eMV, Freightliner eM2	1.3	218	163	**98**	305[2]	228	**137**
Class 8	Freightliner eCascadia, Volvo VNR	2.0	440	220	**132**	616[2]	308	**185**
Long-haul	No electric long-haul truck in series production today. Range estimate is based on the Daimler eActros 600[3]	2.0	600	300	**180**	850[2]	420	**250**

1) "Usable range" assumes the battery never falls below 20% SOC, and is never charged above 80% SOC
2) Assumed improvement in gravimetric density: 40%; OEMs use improvement to increase range while keeping battery weight constant
3) European model, also expected to become available in the US; specs for currently available OTRBs (e.g. Van Hool CX45E) comparable to RB assumptions

Source: OEM websites, Roland Berger analysis

B. Results and key takeaways

B.1 Current Technology

We analyzed the infrastructure needs and challenges to the electrification of medium- and heavy-duty CVs in the current technology scenario

Technology scenarios – Focus of this section

	Current technology	Improved technology
BEV adoption	**Full electrification** of Class 3-8 vehicles	**Full electrification** of Class 3-8 vehicles
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	Focus of this section	

1) Currently no electric long-haul truck in series production. Range estimate is based on the Daimler eActros 600 (European model, also expected to become available in the US). Assumes 80%-20% SOC

With the current technology landscape, only low mileage medium-duty vehicles are feasible to electrify; High mileage & heavy duty use cases face major hurdles

Charging infrastructure challenges – Current technology scenario

Vehicle cost/TCO not in scope of analysis

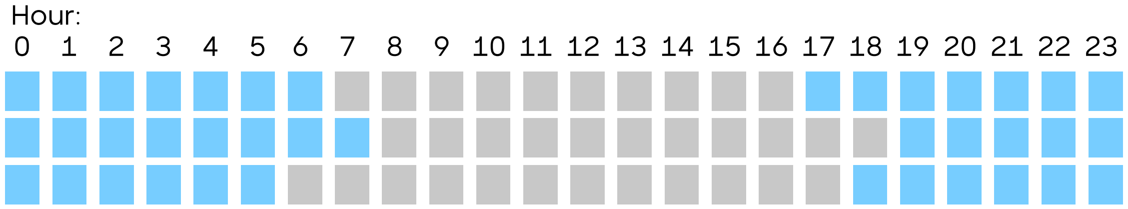
Use case segment	Vehicle	Charger (Charging infrastructure)	Site (Charging infrastructure)	Electric service (Charging infrastructure)	Key findings
1 **Medium duty - local (low mileage)**	Vehicle cost still high, but getting more cost competitive for some use cases	On-site Level 2 chargers sufficient and available at low cost	Upgrade cost is highly site-specific and can be substantial	Minor service upgrades for smaller fleets More extensive service upgrades for larger fleets	Smaller, low mileage fleets with least challenges, but still require significant upfront investment
2 **Medium duty - local (high mileage)**	Vehicle cost still high, but getting more cost competitive for some use cases	Only feasible with sufficiently dense on-route charging network	Upgrade cost is highly site-specific and can be substantial	Minor service upgrades for smaller fleets More extensive service upgrades for larger fleets	High mileage medium duty vehicles cannot electrify before a substantial buildout of on-route charging occurs
3 **Heavy duty - local**	Prohibitively high vehicle cost (>2X of diesel) negatively impact TCO (critical challenge)	High upfront cost for Level 3 and DCFC units	Highly site-specific costs	Expensive utility service upgrades	Heavy-duty local fleets face high upfront costs for chargers and utility service upgrades
4 **Heavy duty - long haul**	Prohibitively high vehicle cost (>2X of diesel) negatively impact TCO (critical challenge)	Time penalty from on-route charging negatively impact TCO (critical challenge)	Parking/space constraints at on-highway charging locations	Long lead time for inter-connection	Long-haul vehicles require increased range AND very high capacity chargers to reduce charging times

(critical challenge icon) xxx = Critical challenge / major adoption hurdle xxx = Major challenge xxx = Minor/no challenge

Low mileage medium-duty vehicles will not need on-route charging, and can use Level 2 chargers on-site, minimizing charger and make-ready investments

Illustrative charging and utility service need for MD local fleet (low mileage)

I Illustrative duty cycle for Class 6 delivery fleet



Available charging time at home base typically >12 hours

II Illustrative on-site charging need

x 30 fleet size	131 kWh effective full charge	13 avg. hours overnight	20 kW L2 x 30 on-site chargers needed	→ **600 kW** incremental service need

III Indicative cost of utility service upgrades

Minor utility service upgrades can cost in the range of

USD 7,500 per L2 charger

for typical fleet locations

Cost of utility service upgrade
(paid by fleet)

USD 225K total

USD ~7,500 per vehicle

However, for depot locations with a larger number of vehicles, a more extensive service upgrade may be needed …

- This same example fleet, if it consisted of 150 vehicles instead of 30, would require a **3 MW service level**
- For individual sites requiring significant power capacity (~ 1 MW and above), **utilities may need to upgrade more upstream infrastructure** (e.g. feeder segments, larger transformers), which can translate into much larger investment need on a per vehicle basis
- These costs are highly variable, depending on existing infrastructure

at home base | on-duty

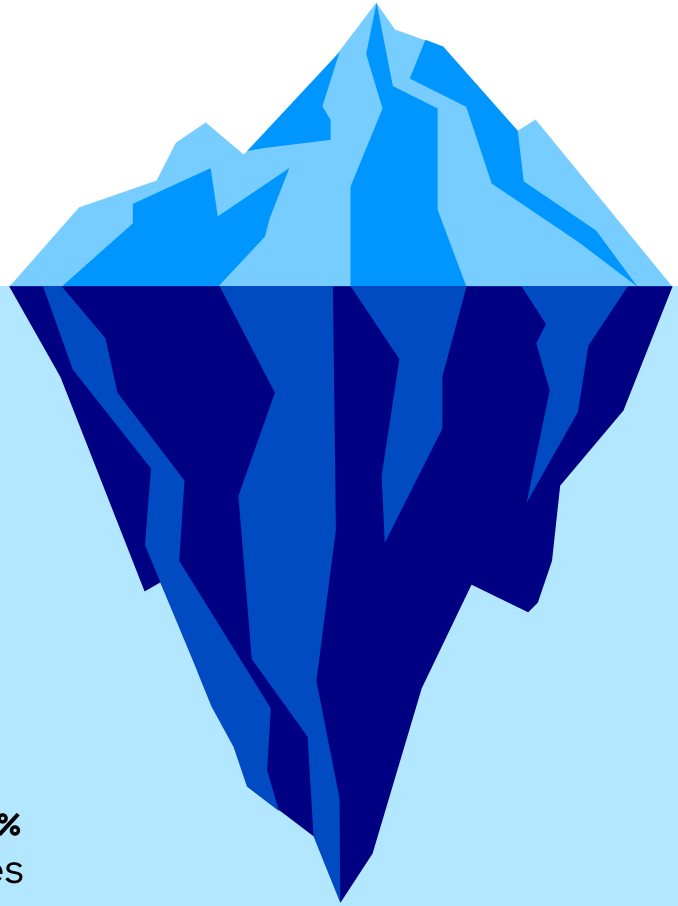
Source: NREL; Roland Berger analysis

However, regardless of charger capacity, there are several sources of hidden or unforeseen costs that can greatly increase upfront investment for fleets

Hidden cost of depot electrification

Vehicle
Relatively transparent, and not site-specific

Charger
Relatively transparent, and not site-specific



Site
The specific nature of **civil engineering / construction work needed** is highly site-specific (e.g., need for conduits, clearances, etc.)

Electrical
The scale and cost of **wiring** and other electrical components **can vary by +50%** even across comparable sites

Utility
The cost of a **service upgrade** can vary greatly based on state policy, existing grid infrastructure, and scale of load increase required

Operational
Need for **backup solutions** in case vehicles cannot be (sufficiently) charged before they need to be redeployed

Source: Interviews with market participants

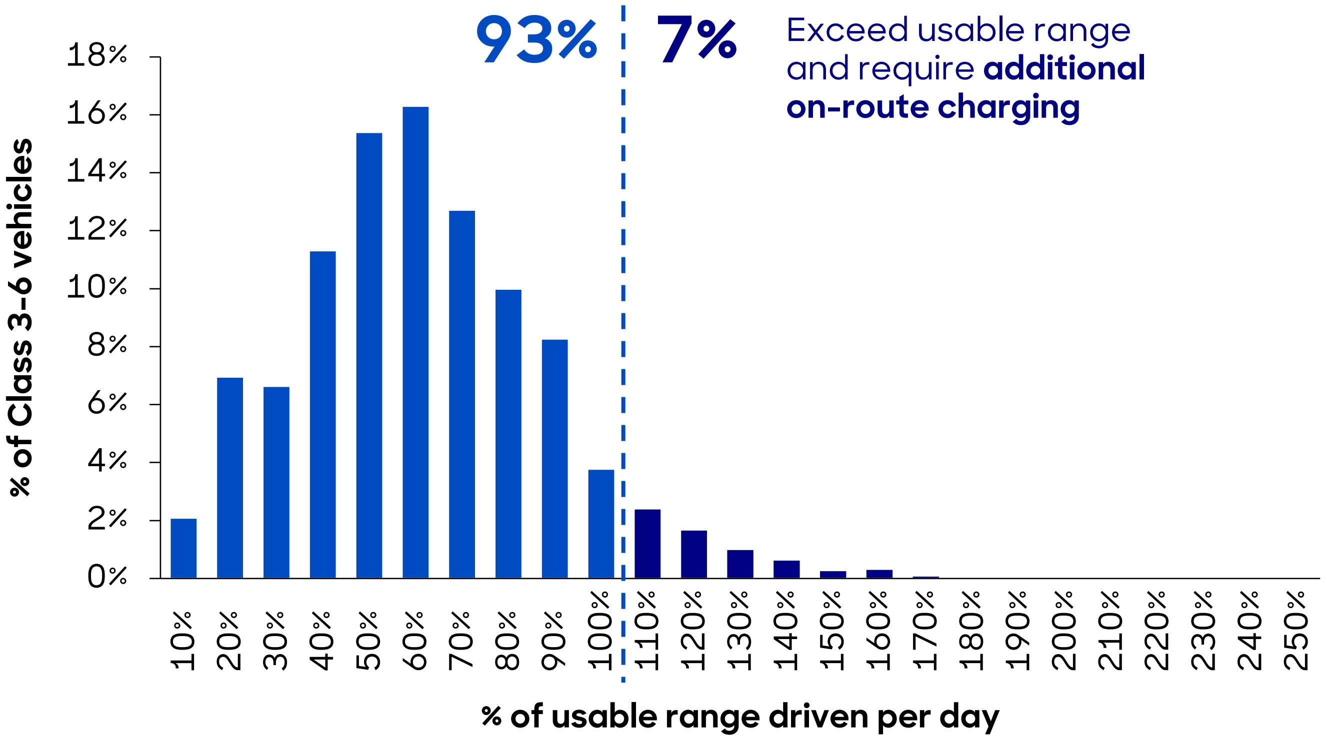
For local medium-duty fleets, a small share of vehicles are "high mileage" use cases – these vehicles cannot electrify without an on-route charging network

Daily mileage requirement vs. range for MD local fleet (high mileage)

Results across Class 3-6
[% requiring on-route charging]

Class 3	100 kWh battery	90 mi usable range	4% need on-route charging
Class 4	100 kWh battery	90 mi usable range	9% need on-route charging
Class 5	218 kWh battery	90 mi usable range	3% need on-route charging
Class 6	218 kWh battery	98 mi usable range	8% need on-route charging

Mileage ratio distribution for local Class 3-6 vehicles:

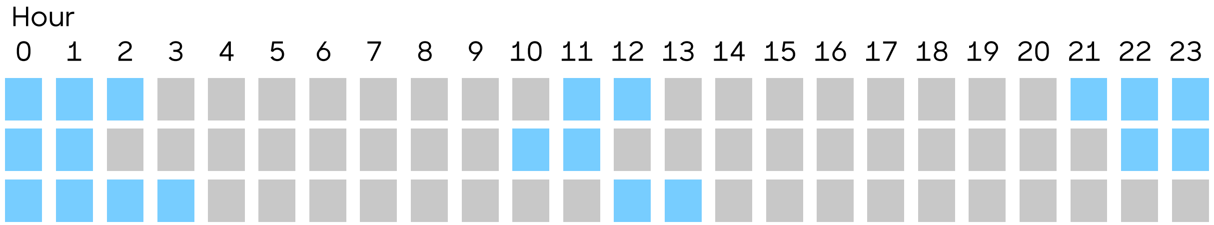


Source: NREL; Roland Berger analysis

For many local HD use cases, fleets would need high capacity L3 or DCFC chargers on-site, but just the cost of utility service upgrades can be prohibitive

Illustrative charging and utility service need for HD local fleet

I Illustrative duty cycle for Class 8 high-mileage local fleet



Available charging time at home base 2-6 hours

II Illustrative on-site charging need

x 30 fleet size	264 kWh effective full charge	1.5 max vehicles per charger	350 kW x 20 on-site chargers needed	→ **7 MW** incremental service need

III Indicative cost of utility service upgrades

Large utility service upgrades can cost anywhere from

USD 500K – 2.5M per MW

of additional electric load

Cost of utility service upgrade (paid by fleet)

USD 4-18M total

USD ~150-600 K per vehicle

For HD local fleets, the potential paths to electrification all involve significant cost and risk:

- If high-capacity charging is prohibitive because of utility cost, there are no good alternatives for fleets:
  - Charging vehicles at lower rates will require additional vehicles to ensure continued operation
  - Rely heavily on public charging (at higher electricity rates and additional operational risk)
- In all cases, the incremental cost needs to get passed down to customers, or negatively hits the profitability of fleets

To remove this roadblock, regulators would need to approve use of ratepayer funding for service upgrades and other "make ready" investments, removing the burden from individual fleets

at home base | on-duty

Source: NREL; fleet interviews, Roland Berger analysis

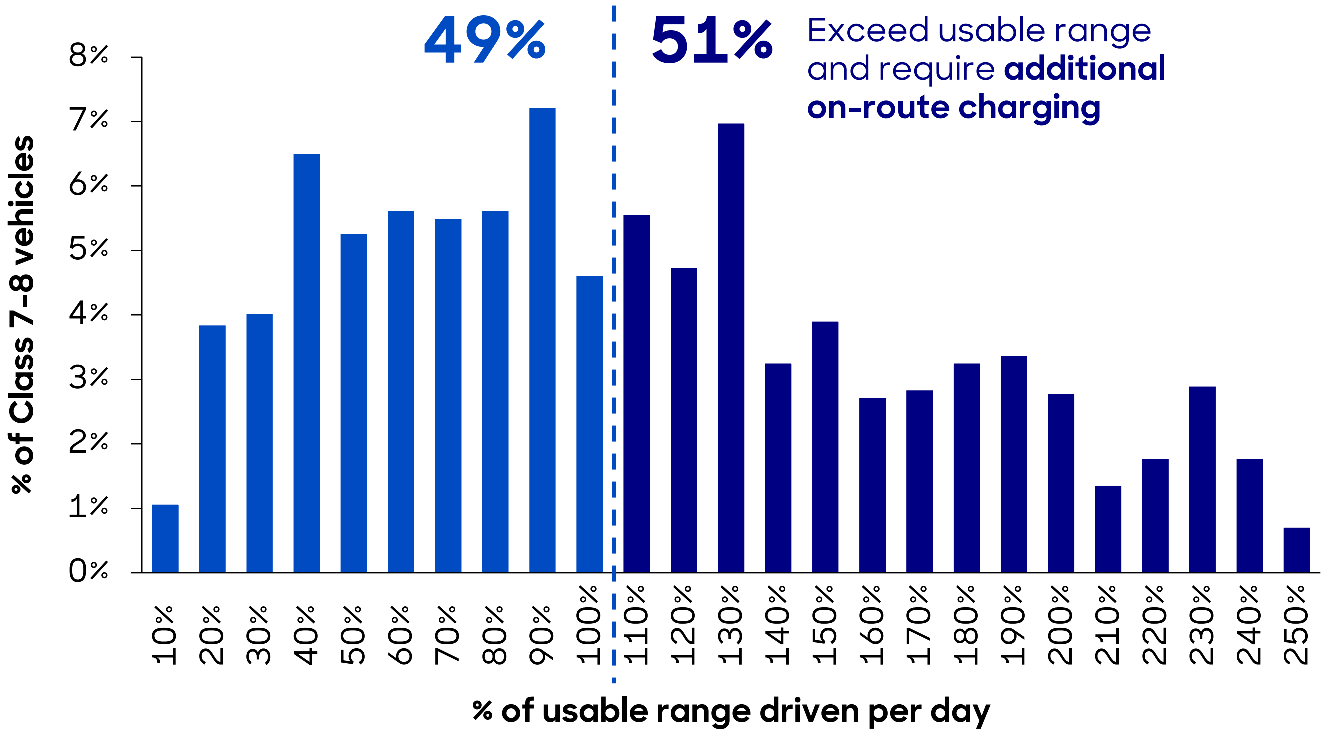
At today's vehicle range, half of the heavy-duty local fleet would exceed the usable range of BEVs, and require access to on-route fast-charging

Daily mileage requirement vs. range for HD local fleet

Results across Class 7-8
[% requiring on-route charging]

Class	Battery	Usable range	Need on-route charging
Class 7	218 kWh battery	98 mi usable range	48% need on-route charging
Class 8	440 kWh battery	132 mi usable range	59% need on-route charging

Mileage ratio distribution for local Class 7-8 vehicles:

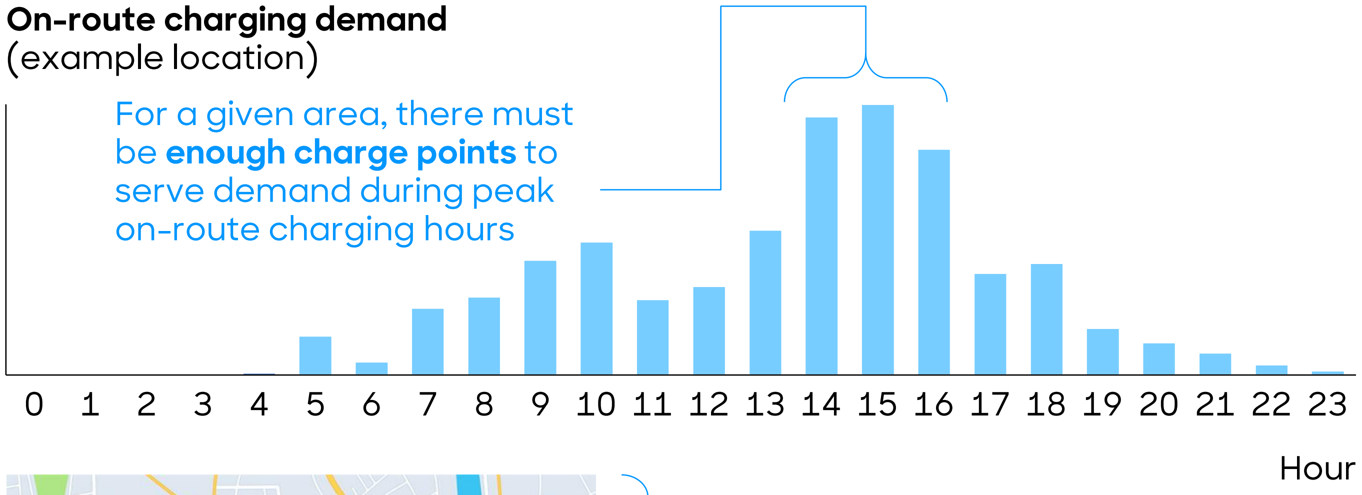


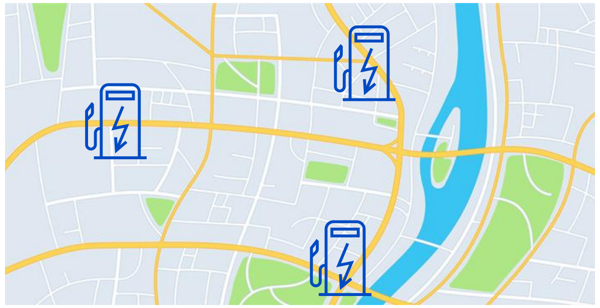
A reliable local on-route charging network must exist before high mileage vehicles can electrify, but utilization risk poses a major challenge to investment

Challenges and investment hurdles for on-route charging

A sufficiently dense network needs to exist to avoid queueing …

On-route charging demand
(example location)





Further, those charge points must be geographically dispersed such that they **align with fleet traffic volumes and existing routes**

… but the investment case to develop such a network is very challenging …

- **Timing & adoption:** given that significant adoption of high-mileage vehicles will not occur before a sufficient network exists, there is a **"first mover disadvantage"**
- **Utilization & economics:** at full density, individual locations may see **low utilization rates**, which would require **large price premiums** at the plug (which fleets would have to absorb)

- **Planning and coordination needed to ensure efficient sizing and placement of chargers**
- **Economic support may be required to overcome utilization risk**
- **Concern over utility ownership of public charging infrastructure remains a key regulatory uncertainty**

Source: Expert interviews, Roland Berger analysis

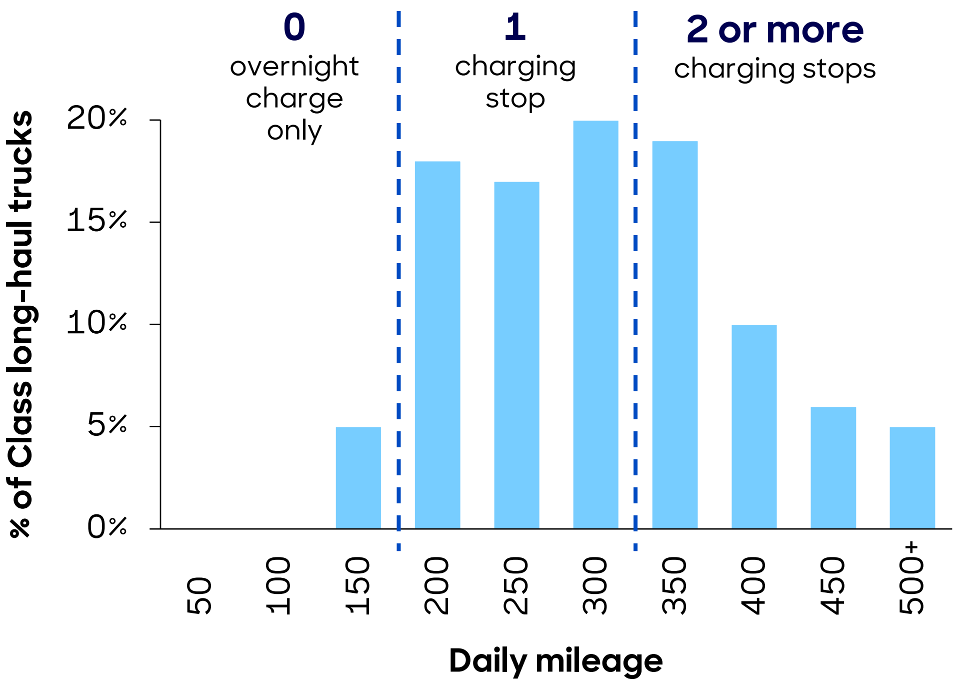
Long-haul vehicles, at current range and charging levels would incur a downtime penalty of 1-2 hours per day from top-up charging, negatively impacting TCO

Suitability of current technology[1] electric trucks for long-haul

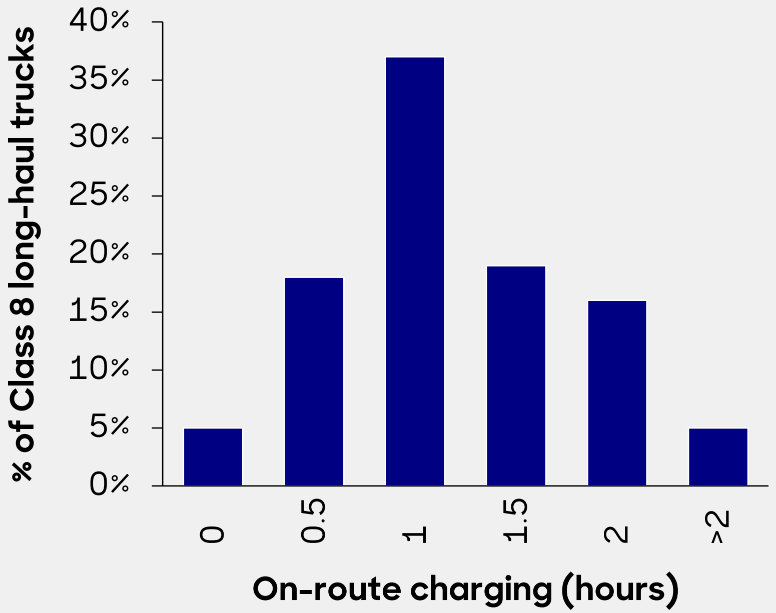
Range of long-haul electric vehicles in the near-term is still insufficient compared to typical daily mileage requirements…

180 mi

usable range[1] of Class 8 long haul BEV



…and with 350 kW chargers, drivers would need to spend long periods of time charging on-route:



Electrification of long-haul use case not feasible with current technology due to high uptime penalty from charging

1) Currently no electric long-haul truck in series production. Range estimate is based on the Daimler eActros 600 (European model, also expected to become available in the US). Assumes 80%-20% SOC

Source: 2021 VIUS (Vehicle In-Use Survey) - US Census; Roland Berger analysis

B.2 Improved technology

In the advanced technology scenario, vehicle range is expected to increase, esp. for long-haul vehicles and higher-capacity chargers are expected to be available

Technology scenarios – Focus of this section

	Current technology	Improved technology
BEV adoption	**Full electrification** of Class 3-8 vehicles	**Full electrification** of Class 3-8 vehicles
Scenario definition	Assuming performance characteristics of **today's commercially available** vehicles and charger products	Assuming improved capabilities based on **reasonably expected performance improvement** in the medium-term
BEV range	Based on **today's commercially available** Class 3-8 BEV models **Max. Class 8 range: 180 mi[1)]**	**Increased range for Class 6-8** vehicles due to improved battery density **Max. Class 8 range: 250 mi**
Maximum fast-charging capacity	**350 kW**	**500 kW** (local) **1 MW** (highway)
		Focus of this section

1) Currently no electric long-haul truck in series production. Range estimate is based on the Daimler eActros 600 (European model, also expected to become available in the US). Assumes 80%-20% SOC

Even with improved vehicle and charger technology, fleets and charging location developers face many challenges related to charging infrastructure

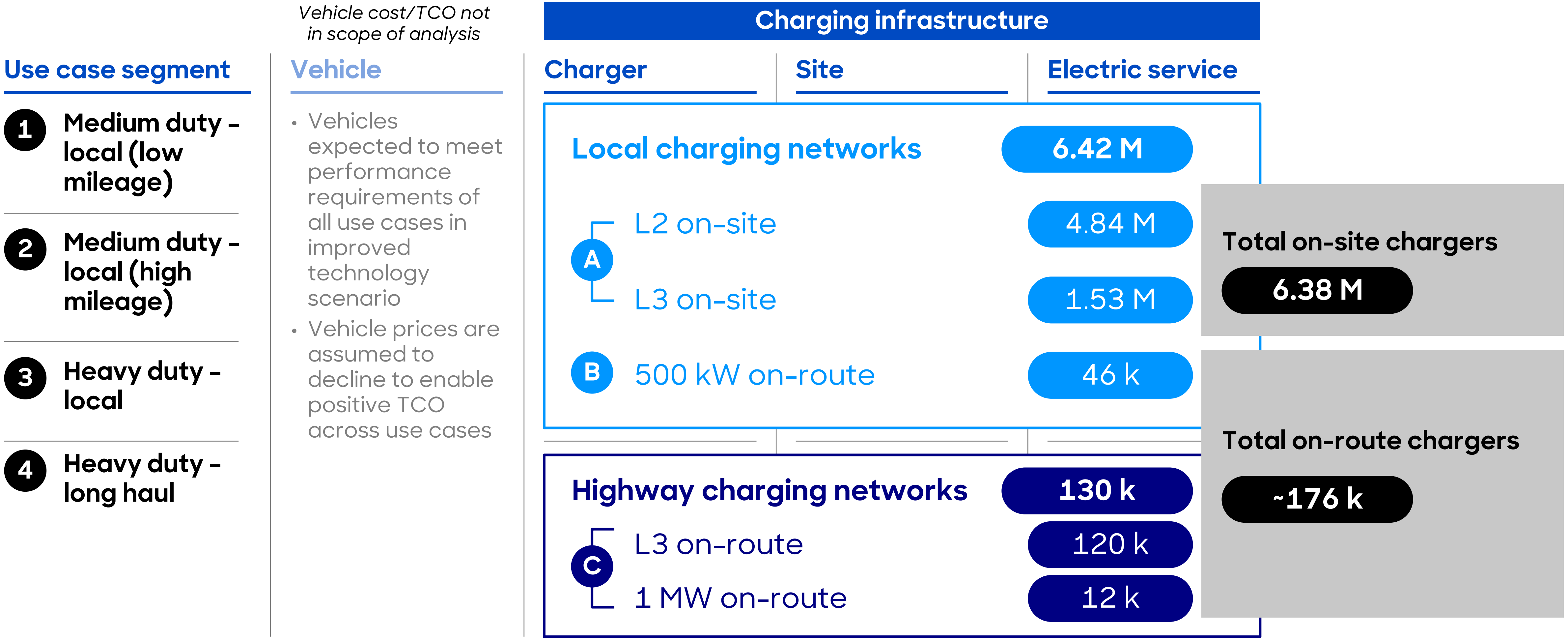
Charging infrastructure challenges – Improved technology scenario

Use case segment	Vehicle (*Vehicle cost/TCO not in scope of analysis*)	Charger (Charging infrastructure)	Site (Charging infrastructure)	Electric service (Charging infrastructure)	Key findings
1 Medium duty – local (low mileage)	• Vehicles expected to meet performance requirements of all use cases in improved technology scenario • Vehicle prices are assumed to decline to enable positive TCO across use cases	On-site Level 2 chargers sufficient and available at low cost	Upgrade cost is highly site-specific and can be substantial	Minor service upgrades for smaller fleets More extensive service upgrades for larger fleets	Smaller, low mileage fleets with least challenges, but still require significant upfront investment
2 Medium duty – local (high mileage)		Only feasible with sufficiently dense on-route charging network	Upgrade cost is highly site-specific and can be substantial	Minor service upgrades for smaller fleets More extensive service upgrades for larger fleets	High mileage medium duty vehicles cannot electrify before a substantial buildout of on-route charging occurs
3 Heavy duty – local		High upfront cost for Level 3 and DCFC units	Highly site-specific costs	Expensive utility service upgrades	Heavy-duty local fleets face high upfront costs for chargers and utility service upgrades
4 Heavy duty – long haul		Only feasible with sufficiently dense highway charging network	Parking/space constraints at on-highway charging locations	Long lead time for transmission interconnection	Long-haul vehicles require increased range AND very high capacity chargers to reduce charging times

xxx = Major challenge (blue text) xxx = Minor/no challenge (grey text)

About 6 m on-site charges and ~176 k on-route chargers will be needed to support full electrification of the US medium and heavy-duty vehicle fleet

Charging infrastructure needs [charger counts]



To deploy all of this infrastructure, fleets and charge point operators will need to invest USD 620 billion into chargers, site infrastructure, and utility service costs

Charging infrastructure investment needs

Use case segment

1. **Medium duty – local (low mileage)**
2. **Medium duty – local (high mileage)**
3. **Heavy duty – local**
4. **Heavy duty – long haul**

Vehicle

Vehicle cost/TCO not in scope of analysis

- Vehicles expected to meet performance requirements of all use cases in improved technology scenario
- Vehicle prices are assumed to decline to enable positive TCO across use cases

Charging infrastructure

Charger | Site | Electric service

Local charging networks	**565 B**
A – L2 on-site	163 B
A – L3 on-site	333 B
B – 500 kW on-route	69 B
Highway charging networks	**57 B**
C – L3 on-route	30 B
C – 1 MW on-route	27 B

Total on-site charging investment needed: 496 B

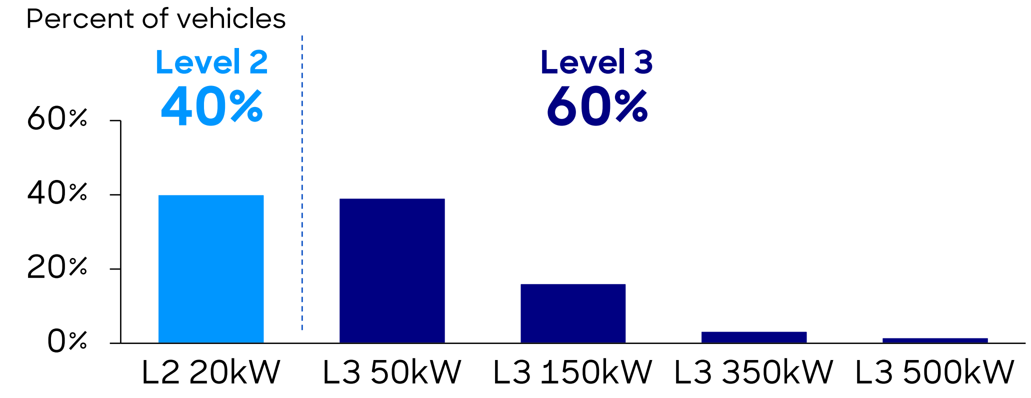
Total on-route charging investment needed: 126 B

The total investment need for local on-site charging of USD 496 B is driven primarily by the heavy-duty segment requiring Level 3 charging

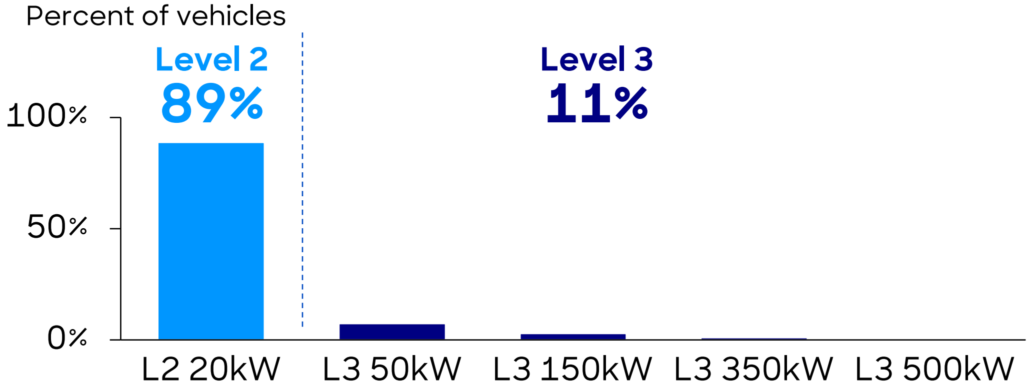
Investment need for local on-site charging network

Segment | **Required on-site charger technology**

Heavy duty – local



Medium duty – local



Total investment need local on-site charging network [USD]

	L2 on-site		L3 on-site
Total	163 B		333 B
	22 B	HD	220 B
	141 B	MD	113 B

Charging infrastructure investment per vehicle [USD]

Heavy duty – local: **145 K**

Medium duty – local: **54 K**

Heavy duty vehicles have more intensive charging requirements, and will require ~3X the infrastructure investment per vehicle compared to medium duty

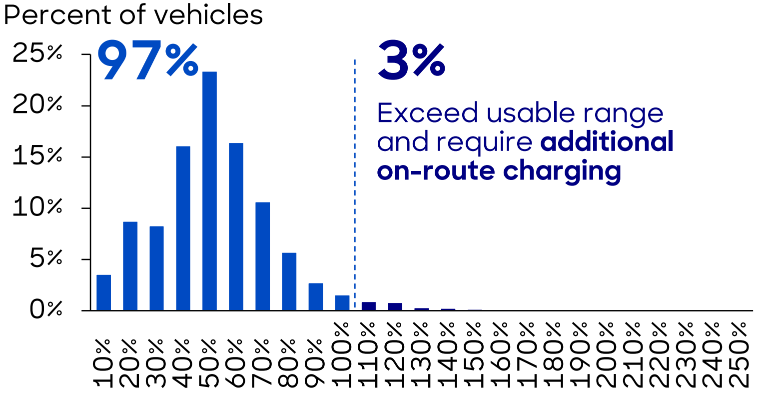
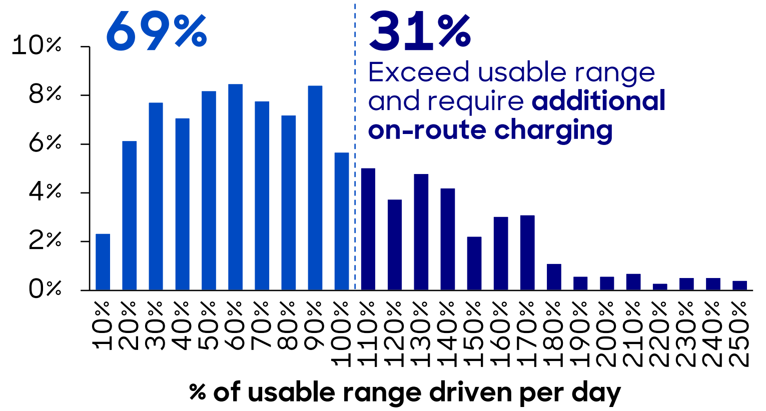
Source: NREL; US Census Bureau, Roland Berger analysis

Even with improved technology, a significant share of the HD local fleet requires access to on-route fast-charging locations, driving investment need of USD 69 B

Investment need for local on-route charging network

Results across Class 3-8 [% requiring on-route charging]

Class	Battery	Usable range	% need on-route charging
Class 3	100 kWh battery	90 mi usable range	4% need on-route charging
Class 4	100 kWh battery	90 mi usable range	9% need on-route charging
Class 5	305 kWh battery	90 mi usable range	3% need on-route charging
Class 6	305 kWh battery	137 mi usable range	1% need on-route charging
Class 7	305 kWh battery	137 mi usable range	28% need on-route charging
Class 8	616 kWh battery	185 mi usable range	38% need on-route charging

Segment	Mileage ratio distribution
Medium duty – local	
Heavy duty – local	

Total investment need local on-route charging network [USD]

On-route 500 kW

69 B

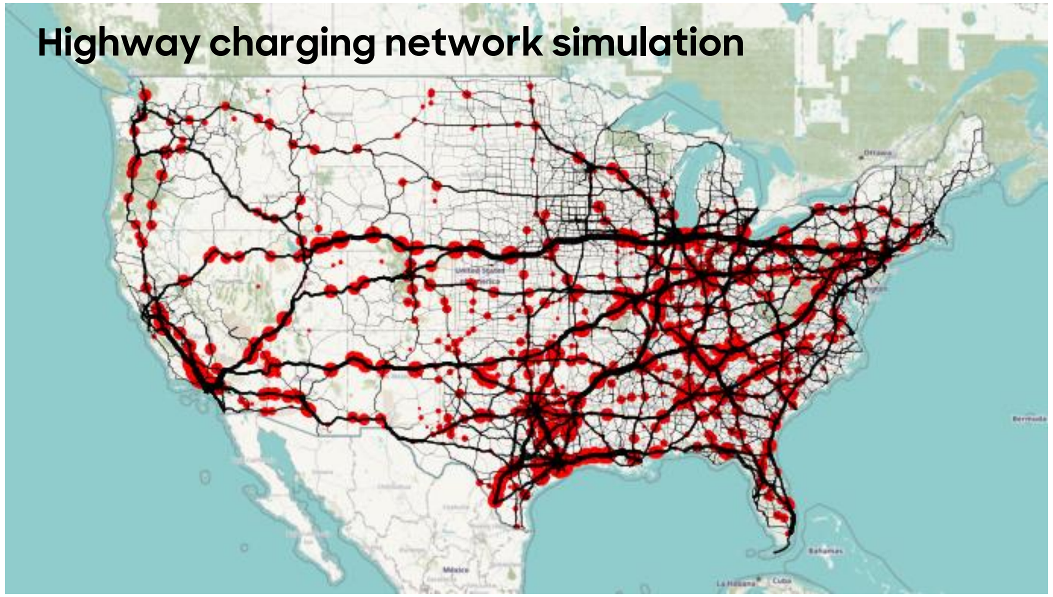
Heavy duty vehicles need larger physical footprint at the charging station – likely requiring dedicated charging locations

Source: NREL; US Census Bureau, Roland Berger analysis

To support full electrification of long-haul vehicles, USD 57 bn need to be invested in converting truck stops into a sufficiently dense charging network

Investment need for highway charging network

Highway charging locations have been simulated across rural and metro areas …



Land cost and space constraints may challenge development, esp. in metro areas

… and each one will need to deploy significant fast charging and overnight charging infrastructure in order to electrify:

Average number of charge points per location:

Rural	Fast chargers	20-25
	Overnight chargers	150-200
Metro	Fast chargers	30-45
	Overnight chargers	200-300

Total investment need highway charging network [USD]

L3 Overnight	On-route 1 MW
30 B	27 B

Total highway charging investment

57 B

Traffic volume of long-haul combination trucks at simulated charging locations (charging stations will also be utilized by OTRBs)

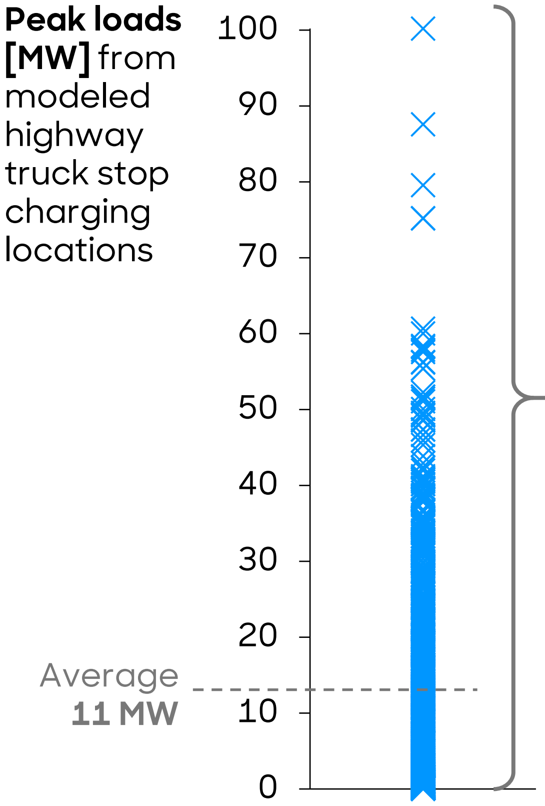
Source: NATSO; DOT Freight Analysis Framework; Roland Berger Analysis

Investment in highway charging will be challenged by very long lead times for transmission infrastructure development and regulatory/planning processes

Highway charging network deployment hurdles

Highway charging depends on transmission infrastructure:

Peak loads [MW] from modeled highway truck stop charging locations



To support full electrification of long-haul vehicles, **many truck stops** would each need as much **power supply** as a **large industrial plant**

Transmission development is a prolonged, multi-stakeholder process:

1. Local permitting & approval processes
2. System planning studies, cost allocation, and portfolio prioritization
3. Competitive solicitation and long construction lead times

While charger installation can be completed in a matter of months, **larger transmission interconnections and upgrades** can take anywhere from **3-8 years to approve and construct**

Additional challenges:

- **Land and parking space constraints:** Overall space requirements for tractor-trailers and OTRBs significantly higher compared to conventional fueling stations, given 2-3x number of ports
- **Technology obsolescence**: Earlier generation chargers (less than 1 MW) will eventually become obsolete once MW charging network is in place

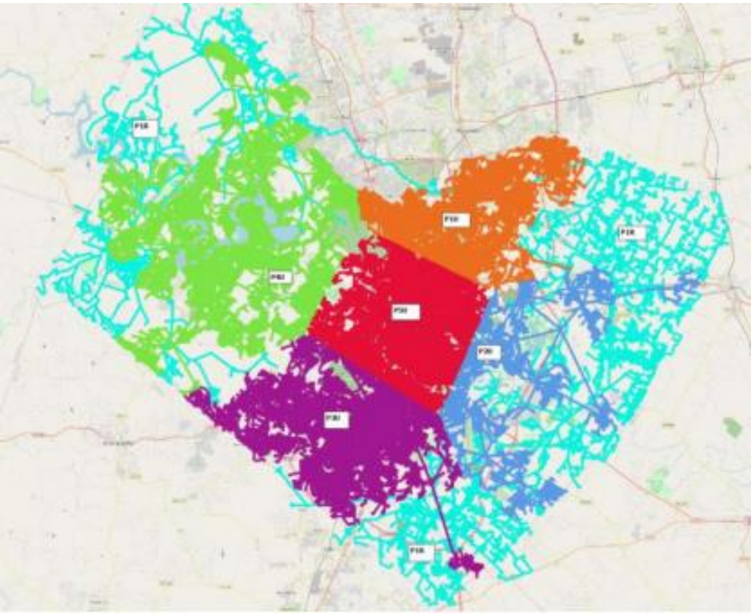
Source: NATSO; DOT Freight Analysis Framework; Roland Berger Analysis

We ran a detailed analysis of distribution grid impact and investment need for select geographies across CA, TX, and NC – covering rural and urban areas

Methodology for distribution grid impact analysis (1/2)

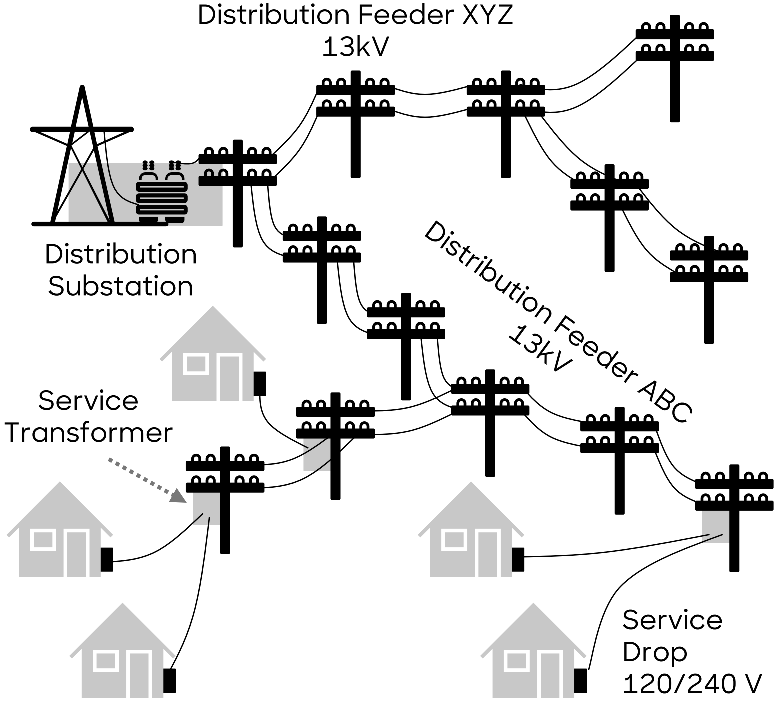
Selected geographies

Example: Austin, TX



Grid infrastructure models are available for selected geographies from NREL Smart DS[1)]

Distribution system components



We analyzed the impact of MDHD's on every feeder and substation within each geography

Customer, load, and infrastructure data

Region: Austin, TX

- **Substation 1**
  - **Feeder 1**
    - **Customers**
      - # of residential, commercial, industrial
    - **Load profile**
      - One year of hourly load
    - **Capacity**
      - Aggregate transformer capacity
    - **Grid assets**
      - line voltage
      - # miles of low voltage conductor
      - # miles of medium voltage conductor
      - # 1-phase and 3-phase transformers
      - # breakers, reclosers, switchgear, etc
  - **Feeder …**
  - **Feeder 12**
- **Substation …**
- **Substation 74**

Smart DS dataset includes customer counts, load profiles, and detailed infrastructure data

1) Analysis was run on NREL Smart DS simulated distribution grid architecture and customer load datasets for Austin TX, Greensboro NC, and Northern California regions

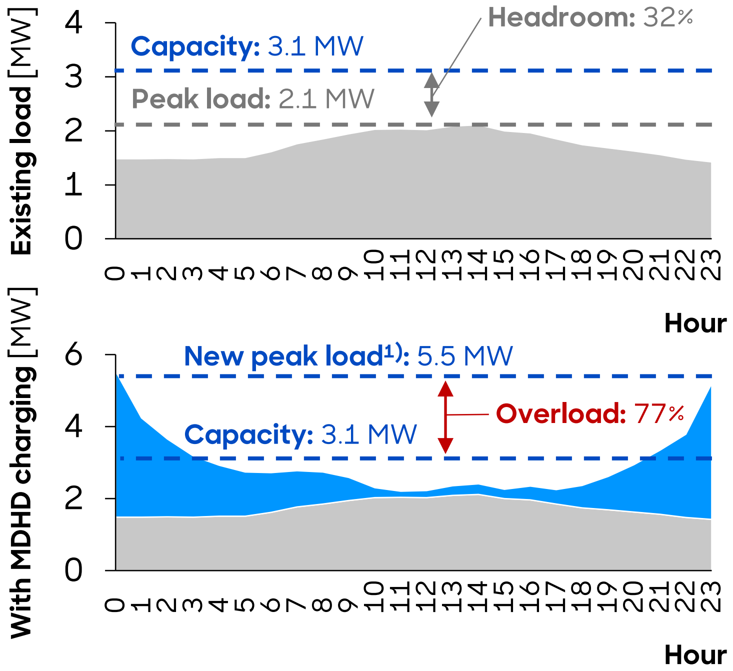
Source: NREL, Roland Berger analysis

We simulated the impact of MDHD charging on existing grid infrastructure, and estimated the "overnight cost" of increasing capacity of impacted grid assets

Methodology for distribution grid impact analysis (2/2)

Feeder-level load impact

Example of an impacted feeder:



We layered MDHD charging onto existing load for each feeder to determine impacted assets

Capacity expansion options

Feeder level:

1. **Reconductoring**
   Replace overloaded lines and equipment with higher voltage rating

If reconductoring is insufficient:

2. **New build**
   Add new circuits to distribute load

Substation level:

If reconductoring any downstream feeders:

3. **Transformer upgrade**
   Add/replace to manage increased voltage

If total downstream feeder load exceeds substation capacity:

4. **Substation rebuild**

There is a limited solution set for utilities to expand capacity of impacted grid assets

Cost of upgrade or new build

Feeder architecture (non-exhaustive):

Low voltage conductor	Medium voltage conductor	3-phase trans-formers	Reclosers	...
24.4 miles	**14.1** miles	**48** units	**2** units	**...** ...

Equipment + installation costs:

Low voltage conductor	Medium voltage conductor	3-phase trans-formers	Reclosers	...
0.6 M USD/mi	**1.3 M** USD/mi	**81 K** USD/unit	**126 K** USD/unit	**...** ...

Cost of reconductoring (non-exhaustive):

0 USD	**18 M** USD	**4 M** USD	**250 K** USD	**...** ...

Based on the architecture of each feeder, we determined the cost of each upgrade

■ Local MDHD charging ■ Existing load

1) County level results for MDHD charging load profile were distributed across each underlying feeder by analyzing the distribution of commercial and industrial customers

Source: NREL Smart DS, NREL Distribution Unit Cost Database, Roland Berger analysis

We analyzed the grid impacts and investment need for each of the counties within our grid dataset, to determine investment needed on a "per vehicle" basis

Distribution grid investment per vehicle

Example: distribution investment analysis [Lake County, CA]

For each region, we analyzed the impacts of MDHD charging on all of the grid assets located within each individual county…

	Loading[1)] [%]	Recond-uctoring [USD]	Feeder new build [USD]	Transformer upgrade [USD]	Substation rebuild [USD]
Substation 1	78%			4 M	
Feeder 1	169%	11 M	0		
Feeder 2	426%	25 M	42 M		
Feeder 3	66%	0	0		
…	---	---	---	---	---
Substation 2	165%				13 M
…	---	---	---	---	---

…to determine the county-level distribution investment need:

Lake County, CA	**16.5 M** Feeder investment [USD]	**98 M** Substation investment [USD]	**115 M** Total distribution investment [USD]

1) A grid asset is considered "overloaded" and in need of intervention if peak loading is at or above 95%

For each county analyzed, we determined the total distribution investment need on a "per vehicle" basis:

	Total distribution investment [USD M]	Class 3-8 vehicles [count]	Distribution investment per vehicle [USD K]
Guilford County, NC	204	16,703	12
Travis County, TX	486	19,256	25
Solano County, CA	859	11,752	73
Lake County, CA	115	1,020	113
…	---	---	---

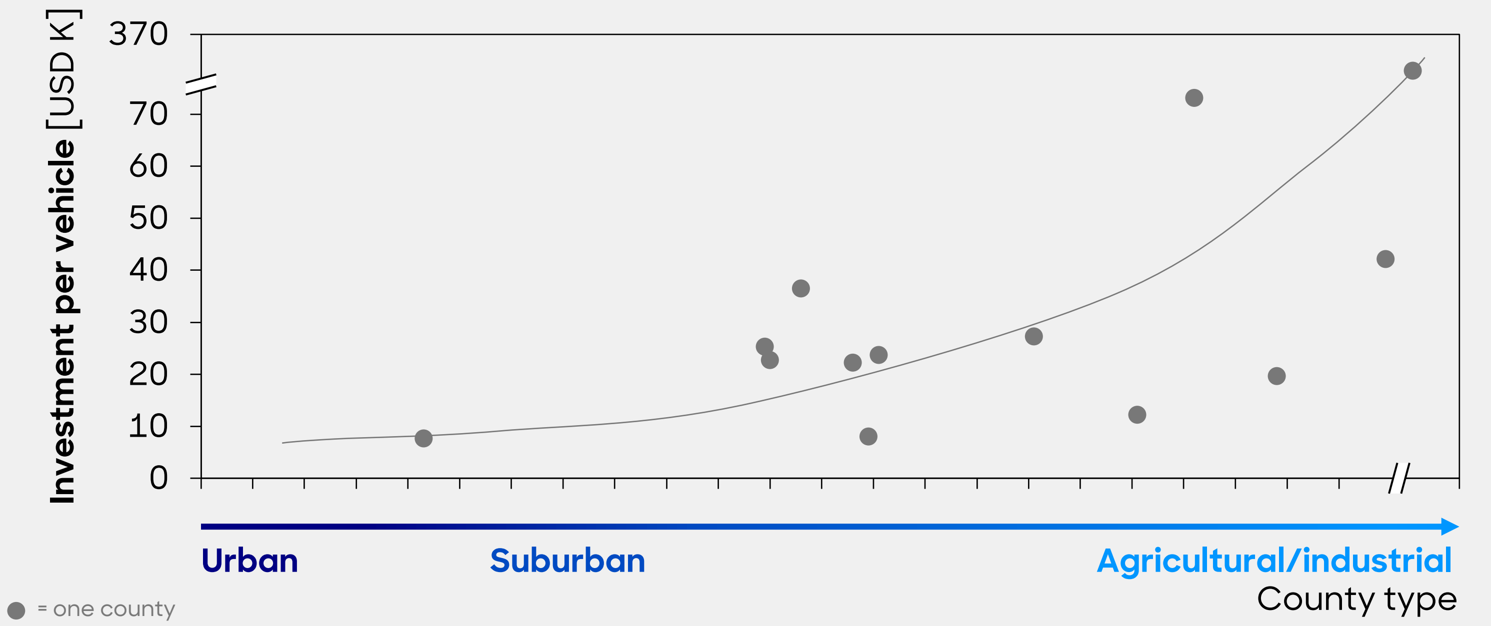
Investment need per vehicle varies significantly across geographies, but this variation is predictable by specific factors (see next page)

Source: NREL, US Census, Roland Berger analysis

In more rural and industrial areas, utilities will need to spend more per vehicle – we quantified this relationship to extrapolate these results to other geographies

Key drivers of variation in distribution investment – rural vs urban

Distribution grid investment needs (per vehicle) increase farther away from denser urban areas:



Key drivers of variation:

- In more rural geographies, the average distance between customers is much greater than in dense urban areas, **requiring more miles of conductor when replacing or upgrading grid capacity** in these regions

We applied this correlation[1] to determine the "per vehicle" investment need for all other US counties

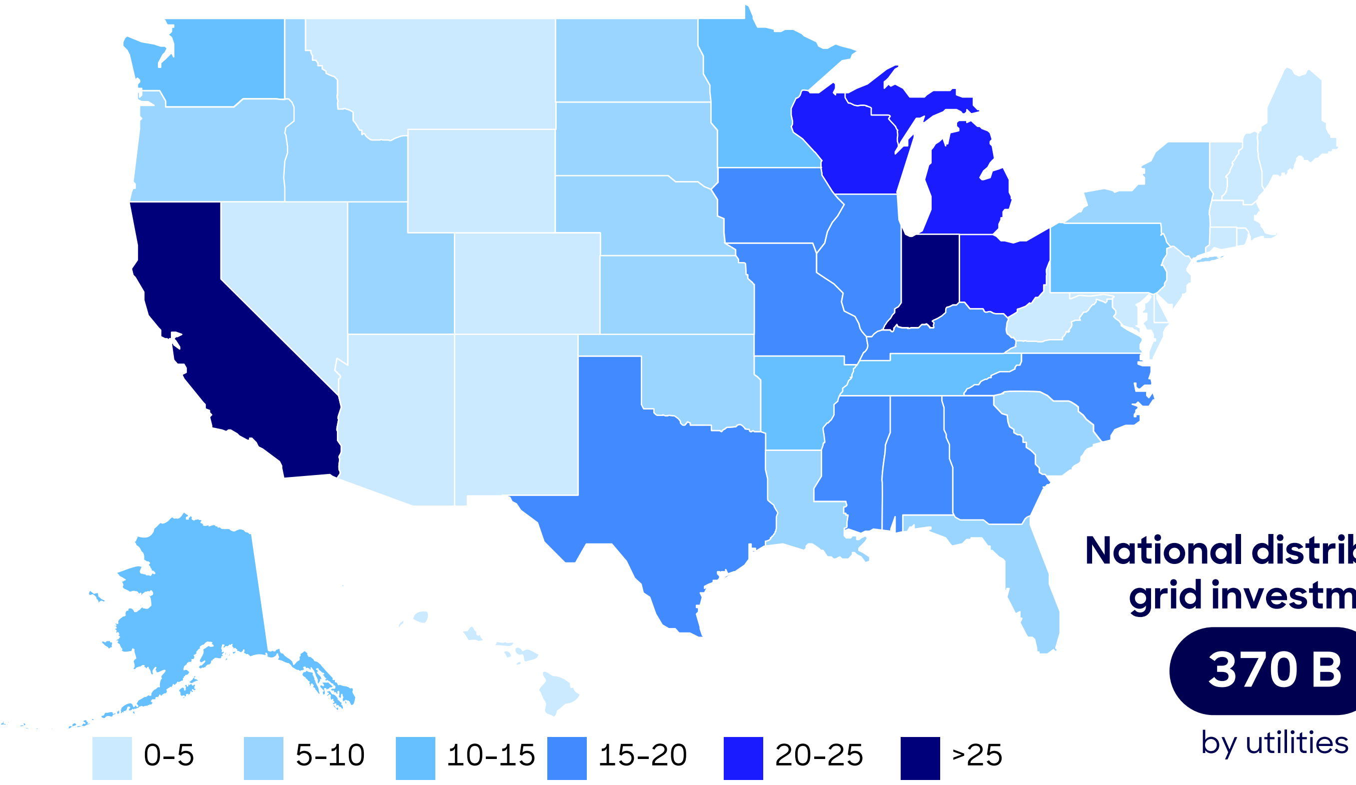
1) Predictor variable used for correlation is the % share of total county-level employment in agriculture, construction, and manufacturing sectors

Source: NREL Smart DS, US Census CBP, Roland Berger analysis

Nationally, utilities will need to invest around USD 370 billion[1)] on distribution grid upgrades and new builds to serve local charging demand[2)] from MDHD vehicles

Distribution system investment need - nationwide

Total distribution system investment by state [USD bn]



National distribution grid investment

370 B

by utilities

Challenges and constraints:

- **Utilities will need to build** infrastructure ahead of demand **ahead of MDHD adoption** to avoid bottlenecks and delays
- However, these investments require more **sophisticated grid planning** as well as **regulatory support** – both limited to date
- The overall **pace of utility investment** will still be **constrained** by the need to control rate increases and **maintain affordability**

Potential mitigating factors:

- **This analysis shows** the grid impacts and investment need given **"unmanaged" charging**
- If fleets were able to **shift or manage peak charging** load (e.g. with battery-integrated chargers), **utility investment could be significantly reduced**
- However, **appropriate incentives** and/or price signals would need to exist **to support fleet economics**

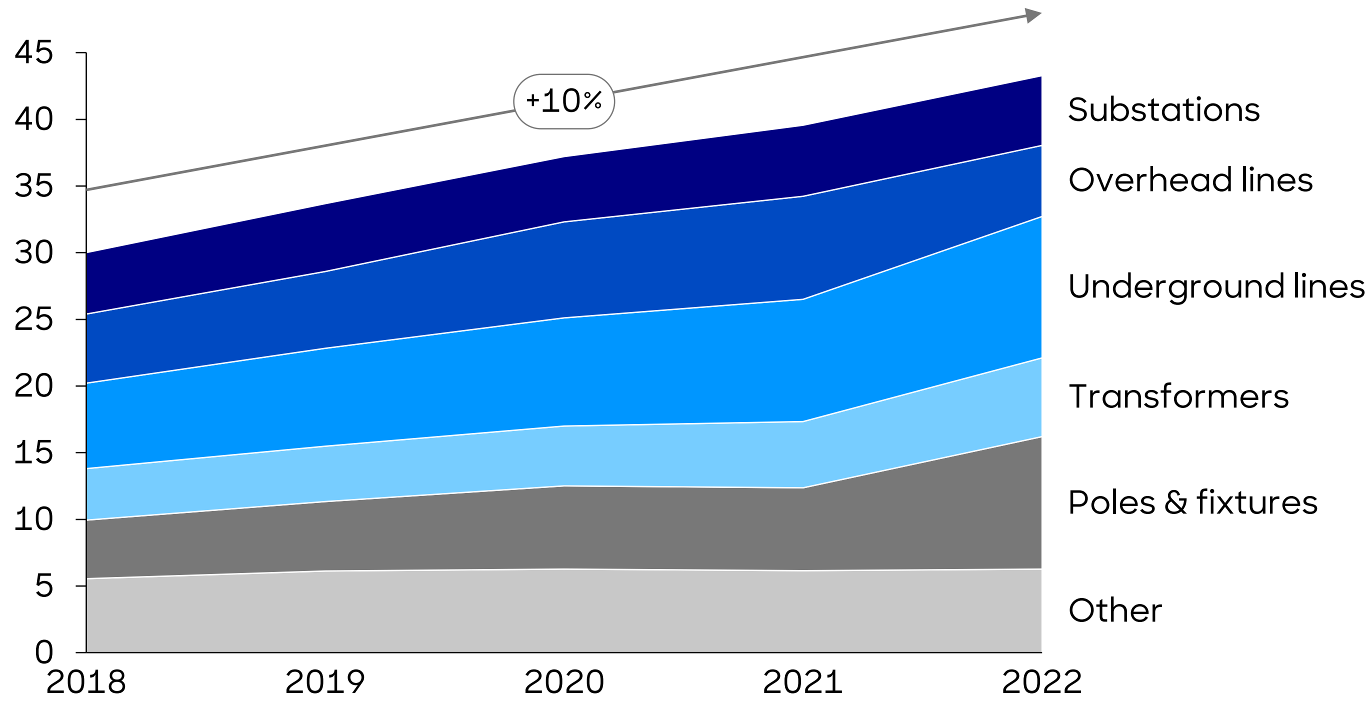
1) Based on "overnight" capital cost of grid infrastructure at current price levels – actual utility investment will be higher due to 1) price inflation of labor and equipment, and 2) Utility guaranteed rate of return
2) Distribution grids will serve on-site and on-route charging demand from local fleets – long-haul vehicles/ highway charging stations will be served by the transmission grid and bulk power system

Source: NREL, US Census, Roland Berger analysis

Just to support MDHD charging, utilities would need to spend nearly the equivalent of what was spent on the entire system during the past 15 years

Distribution investment – comparison to historical investment rates

Historical distribution system investment by US investor-owned utilities [USD bn]



Key takeaways:

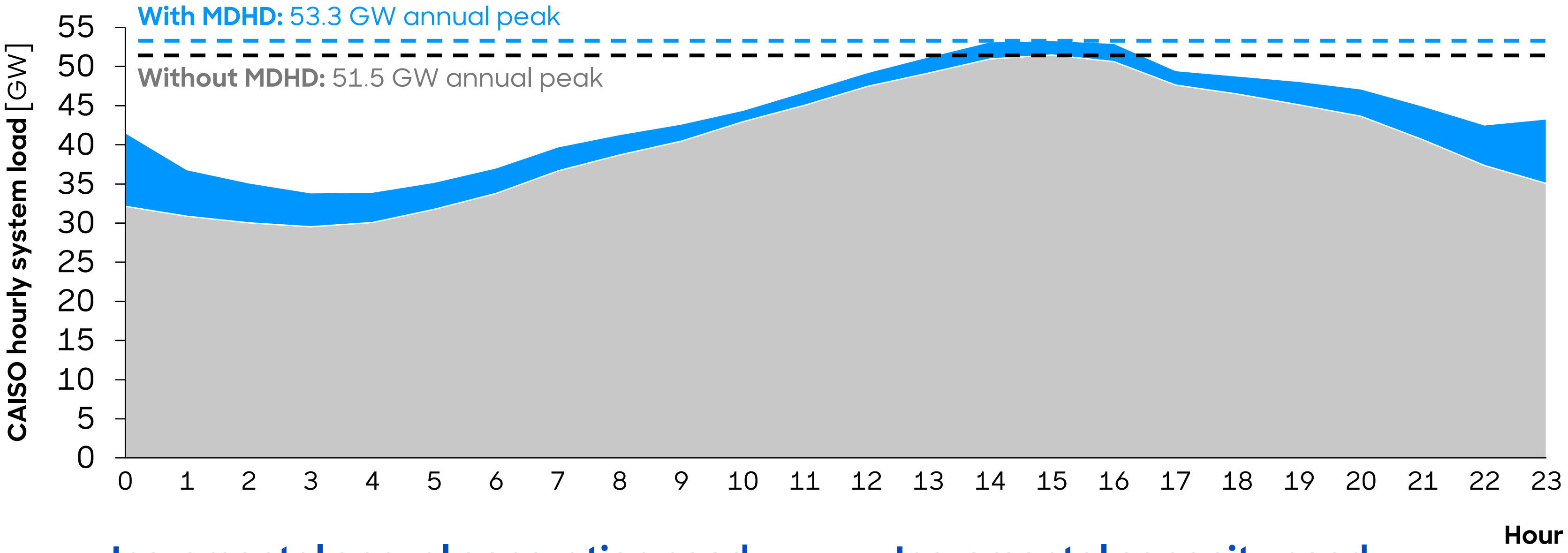
- Cumulatively over the last 15 years, utilities invested roughly USD 450 B across the US **for all distribution investment needs**
- In comparison, the **estimated 370 B** just for upgrades and new construction **related to MDHD** charging represents **82% of what was spent** on all distribution grid investments **over the past 15 years**
- Moreover, distribution **spending is expected to continue increasing** across multiple priorities (e.g. DER integration, resiliency), of which **MDHD electrification is just one competing priority**
- **Proactive investments will likely be constrained by limits on rate increases**, potentially delaying charging infrastructure buildout

Source: FERC, S&P Capital IQ

At the power system level, the impact of MDHD charging on peak energy demand is diminished, as most charging occurs overnight – avoiding the system peak

Impact of MDHD charging on bulk power system (CAISO example)

California ISO: impact of MDHD charging on annual peak load
[hourly load during annual system peak day, GW]



Incremental annual generation need

31,000 GWh
(+14%)

Incremental capacity need

2 GW
(+4%)

Generation vs capacity needs:

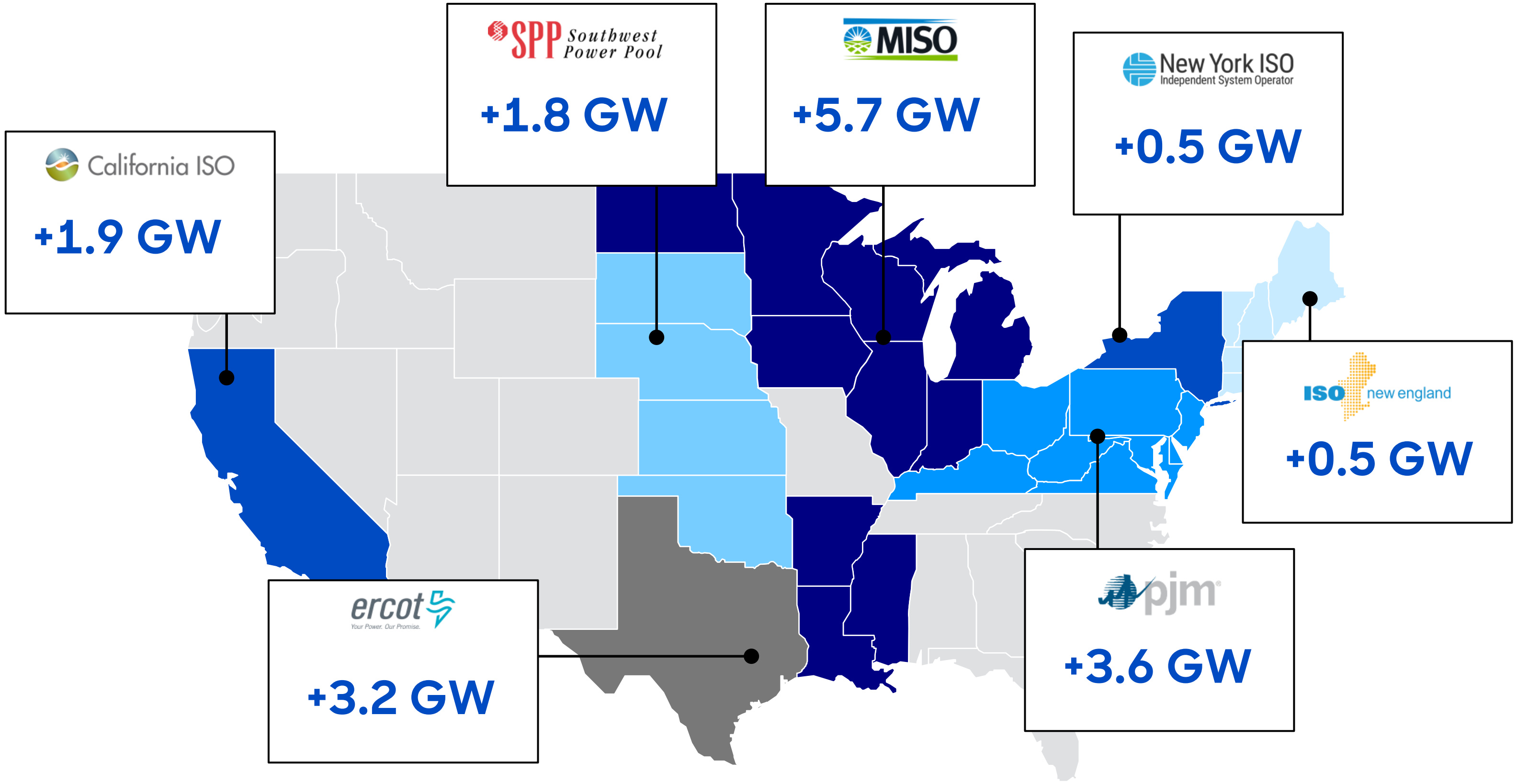
- MDHD charging will require a meaningful increase in energy generation
- However, charging will have a less significant impact on **system capacity requirements**, which are primarily **a function of peak energy demand** across a region
- The level of **investment in generation and transmission** resources for a given region is **driven by system capacity requirements**
- Whereas increased **energy generation need** typically translates into **increased utilization of existing resources**

Source: S&P Capital IQ, Roland Berger analysis

While there will be some incremental capacity need (and investment need) created by MDHD charging…

MDHD charging – impact to annual system peak load by ISO

Incremental coincident peak demand [GW]



Incremental investment in generation and transmission capacity:

Generation

22 B

Transmission

12 B

Based on EIA forecasted mix of resource additions and forecasted capital costs (by year of addition) through 2040

Source: EIA AEO 2023, S&P Capital IQ, ISONE 2050 Transmission Study, Roland Berger analysis

…power system operators are already planning for significant generation and capacity growth from transportation electrification, as well as from other trends

MDHD load impact vs ISO forecasts of overall load growth

ISO region	Generation: 2022 annual generation [GWh]	Generation: MDHD charging [GWh]	Generation: Increase from MDHD [incremental % of 2022]	Generation: 2040 ISO load forecast [incremental % of 2022]	Capacity: 2022 peak load [GW]	Capacity: MDHD peak impact [GW]	Capacity: Increase from MDHD [incremental % of 2022]	Capacity: 2040 ISO load forecast [incremental % of 2022]
SPP Southwest Power Pool	283,187	19,932	**7%**	**48%**	53	1.8	**3%**	**26%**
MISO	665,254	64,493	**10%**	**17%**	120	5.7	**5%**	**18%**
pjm	795,214	45,998	**6%**	**39%**	148	3.6	**2%**	**20%**
California ISO	223,677	30,980	**14%**	**68%**	52	1.9	**4%**	**42%**
ISO new england	118,887	8,180	**7%**	**46%**	25	0.5	**2%**	**72%**
ercot	429,895	31,556	**7%**	**58%**	80	3.2	**4%**	**29%**
New York ISO Independent System Operator	152,681	8,284	**5%**	**34%**	31	0.5	**2%**	**44%**
	Historical	**RB estimate**	**RB estimate**	**ISO forecast**	**Historical**	**RB estimate**	**RB estimate**	**ISO forecast**

Source: ISO long-term load forecasts, Roland Berger analysis

C. Other operational challenges

In addition to the economic hurdles, regulatory constraints, and operational challenges already discussed, further challenges still need to be addressed

Additional operational challenges raised by fleet operators

1. **Prohibitively high purchase prices**
   While electric LCVs are more affordable, electric vehicles in Class 6-8 segment are still prohibitively expensive today due to limited scale

2. **No TCO benefit today in Class 6-8**
   In combination with increasing electricity prices, there is currently no TCO benefit versus Diesel trucks in the Class 6-8 segment

3. **Tank truck segment especially hit by incremental battery weight**
   Certain use cases, esp. in the tank truck industry weigh out before they cube out and incremental battery weight leads to a payload penalty. Without the ability to increase current thresholds (bridge formula), fleets will be forced to absorb the cost

4. **Vehicle portfolio still immature**
   Limited choice of vehicles with many coming from startups without sufficient track record and unclear service support offering

5. **Drivers need to get compensated during charging times**
   Drivers will need to get compensated if they have to wait for vehicles being charged during their hours-of-service window. Lower driver utilization negatively impact fleet profitability or drives up freight rates

Roland
Berger