THE NEW LOGISTICS:

ELECTRIFYING FREIGHT WITH MICROGRIDS

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Today, we present to you our newest industry report about the electrification of heavy transport. It is another step into the cleantech future.

Thank you for being with us, and enjoy the read!
The CleanTechnica Team

Foreword

by Reuben Sarkar, CEO of the American Center for Mobility (ACM)

Medium and heavy-duty freight trucks play a pivotal role in our economy, yet they contribute disproportionately to greenhouse gas emissions. The electrification of freight transportation will be a key enabler to achieving the imperative of zero-emission freight. As the transportation and energy sectors converge, the United States must develop integrated, scalable solutions that ensure charging infrastructure along freight corridors and hubs keeps pace with the market adoption.

This report lays out a pragmatic strategy for truck electrification and microgrid-enabled charging, recognizing the technological, economic, and policy challenges that must be overcome. It presents a roadmap that aligns industry stakeholders, fosters innovation, and accelerates deployment. By leveraging advanced charging networks, grid resilience strategies, and automation, we can create an ecosystem that makes electric freight trucking not only feasible but economically advantageous.

I commend the authors and strategists, Rish Ghatikar and Michael Barnard, for their deep expertise and forward-thinking approach to electrify the freight sector. Their combined experience in energy systems transportation electrification, and economic strategy lays a foundation for the actionable solutions outlined in this report. Their insights will help industry leaders, policymakers, and innovators drive meaningful progress toward a cleaner, more efficient freight network.

At the American Center for Mobility (ACM), we are committed to advancing safe, sustainable, and secure mobility solutions that drive American competitiveness. I applaud this effort and encourage stakeholders to embrace this vision for a resilient and electrified freight future.

Reuben Sarkar

CEO, American Center for Mobility (ACM)
Former Deputy Assistant Secretary for Sustainable Transportation, U.S. Department of Energy (DOE)

Executive Summary

For the big firms which operate hundreds or thousands of logistics depots or truck stops in the United States, electrification of road freight is a path to expanding market share and greater profits.

The United States faces a significant challenge in decarbonizing its transportation sector, which accounts for over a third of national greenhouse gas emissions and substantial air pollution. Among freight transportation options, road freight has the conditions for success to decarbonize using electric trucks.

That battery electric trucks will dominate over alternatives is a foregone conclusion. Big customers and affluent states are demanding green freight. Rail, which won't electrify for decades, is losing coal revenue and will be paying more for energy. Domestic ship freight is strangled by the Jones Act and the lack of domestic ship building. Trucks are already lower emissions than rail in eight states and counting.

Battery energy densities keep climbing and battery costs keep dropping, so weight and capital cost concerns are going away. Battery electric drive trains are more reliable and efficient, so operational costs for maintenance and energy are lower than for alternatives. The cost competition with rail and water is changing, and autonomous solutions are coming that will change it further. Freight transportation will increasingly move to highways in the next two decades.

The biggest challenge right now is reliably getting clean electricity into trucks, and the answer is grid-connected microgrids with solar and batteries that can be modularized and incrementally scaled for truck depots and stops.

The truck electrification strategy lays out the following seven self-reinforcing actions that collectively overcome challenges related to charging microgrids and enable firms building and adopting them to profit and expand.

1. Design charging microgrids incrementally for scalability
2. Take advantage of pricing flexibility to gain a market edge
3. Focus on charging, not hypothetical benefits
4. Lean Into modularity to get big things done
5. Focus on common solutions to enhance charging deployment
6. Target corridors with strong GDP and climate goals
7. Ensure charging success through stakeholder leadership

Big firms with hundreds or thousands of depots or truck stops and the turn-key vendors that build them that follow this strategy will win out over firms that don't or can't do this.

About the Authors

Rish Ghatikar has an extensive background in decarbonization, specializing in electric vehicles, grid integration, and demand response technologies. Currently, he's an Ambassador of the Open Charge Alliance and visiting Professor at the University of Southern Denmark supporting the Maersk Mc-Kinney Moller Institute to educate the future generation in energy informatics. At General Motors as Energy Fellow, he advanced transportation electrification energy services, as part of a broader climate strategy. At Electric Power Research Institute as Lead of the Information and Communication Technologies Program, he focused on digitalizing the electric sector. At Greenlots as Chief Research Officer he commercialized EV-grid and energy storage solutions. His work at the DOE's Lawrence Berkeley National Laboratory as Deputy Leader of the Grid Integration Group spearheaded demand response automation to support dynamic utility pricing policies. An active climate advocate, Ghatikar advises on policies and technologies that align the grid with transportation and energy use for sustainable growth.

Michael Barnard, a climate futurist, chief strategist at The Future Is Electric, advises executives, boards, and investors on long-term decarbonization strategies. He has published scenarios looking 40 to 80 years into the future for hydrogen, aviation, maritime shipping, grid storage, vehicle to grid technologies, steel and cement. His work spans industries from transportation and agriculture to heavy industry. Barnard is a co-founder of infrastructure digital twins firm Trace Intercept and an Advisory Board member for electric aviation startup FLIMAX. He contributes regularly to climate discourse as host of the Redefining Energy - Tech podcast, as an author in CleanTechnica, Forbes and forums such as the Journal for Sustainable Marketing. His work appears in books including Proven Climate Solutions, the De Gruyter textbook Green Chemistry: Advances in Alternative Energy and briefly in How Big Things Get Done, the best business book of 2023. He has researched and published reports on green hydrogen in northern Africa, purported air to fuel solution Carbon Engineering, machine learning cleantech ventures and wind energy and health court cases. He speaks regularly at conferences and business events globally. His perspectives emphasize practical solutions rooted in physics, economics, and human behavior, aiming to accelerate the transition to a sustainable future.

Table of contents

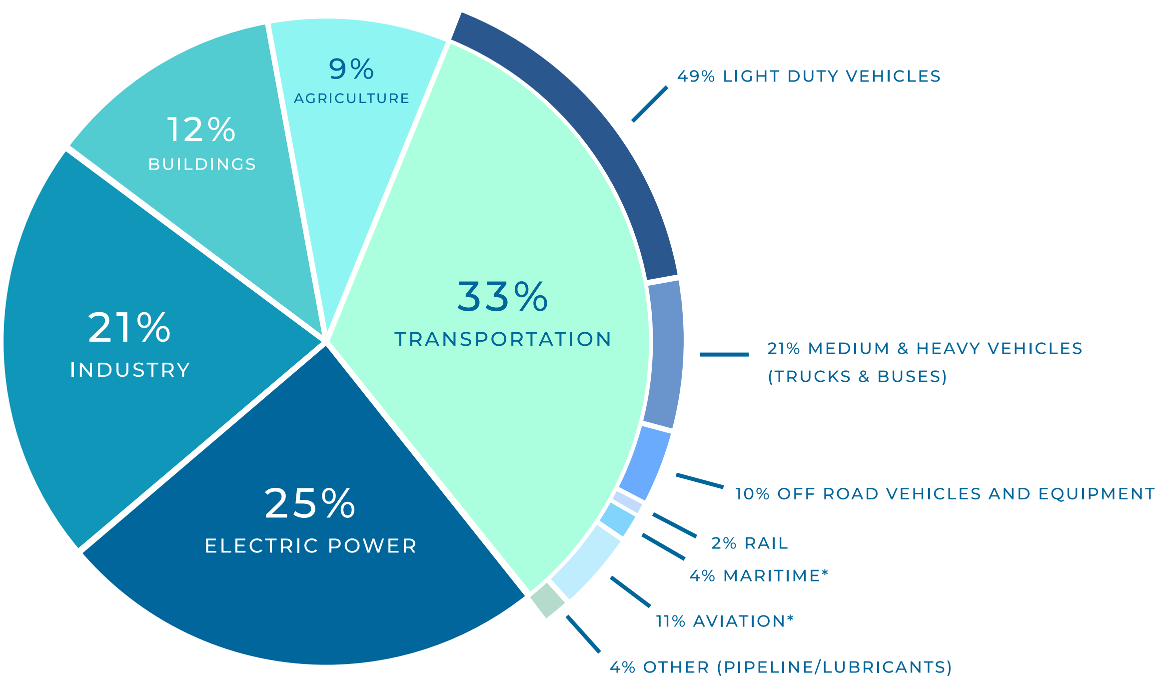
01

Why Trucking is Key to Reducing Freight Emissions

Key Takeaways

- Transportation is the highest emissions segment in United States
- Of rail, water and road, only freight trucking can readily decarbonize
- Electric trucks are cost-effective and rapidly advancing

The United States has unintentionally made itself into the country with the hardest to decarbonize transportation sector and it matters. Transportation produces a third of all greenhouse gas emissions for the country, more than electrical generation now, as well as contributing an outsized share of air pollution. The one segment of freight transportation with a potential for significant decarbonization in the near term, heavy-duty road trucking, faces headwinds despite contributing to 30% of total emissions of the transportation sector, and being only 5% of road vehicles. How can electrification of road trucking be accelerated so that this win can be realized quickly?



* AVIATION AND MARINE INCLUDE EMISSIONS FROM INTERNATIONAL AVIATION AND MARITIME TRANSPORT. MILITARY EXCLUDED EXCEPT FOR DOMESTIC AVIATION.

2022 GHG Emissions Sectors in the United States (Source: United States. DOT)

As the first section in this strategy lays out, the authors' intended audience is three-fold: 1) firms with major internal freight logistics and operations such as UPS, FedEx and Amazon which operate many depots; 2) large firms that own and operate many existing highway truck stops and depots; and 3) turn-key engineering, procurement and construction solution providers that can build all elements of charging at existing or new truck stops and depots. The reason is simple: these are the organizations with the ability to deliver repeatable, high-quality, low-cost truck charging solutions following the diagnosis and self-reinforcing actions contained in this series. Other stakeholders such as policy makers, truck makers, battery, solar, and charging equipment manufacturers, energy management companies and more should look at this material and determine how they can support the primary audiences.

The authors share the perspective that Richard Rumelt's Good Strategy Bad Strategy: The Difference and Why It Matters is the best book on strategic planning for businesses and policy makers available today, and will use Rumelt's framing to articulate their perspective.

At heart, Rumelt says a good strategy has a kernel with three things. First, a diagnosis of what is going on here, a clear-eyed look at all relevant aspects of the situation. Second, a policy which simplifies and focuses actions, designed to maximize benefits and minimize risks. Third, a set of self-reinforcing actions aligned with the policy. That's it: diagnosis, policy, actions. The book is a highly recommended read and provides example after example of bad strategies that don't have this.

Elements of a Good Strategy
(Source: Good Strategy Bad Strategy, Richard Rumelt)

And so, to the diagnosis of freight decarbonization. As noted in the introduction, the United States. has a challenge in decarbonizing the transportation sector. While this is true for the movement of people around the country in their daily rounds and trips, we'll set this aside and focus on freight road transport.

Per earlier assessments Barnard had done of global freight mode variances across major economic blocs, the United States has a breakdown of roughly 2 trillion ton miles (TTM) of road freight, 1.5 TTM of rail freight and 0.4 TTM of domestic water freight. Two of these modes face significant challenges in decarbonization in the coming two decades. Per the USA's transportation blueprint, which Barnard analyzed upon its release, the intent is mode shifting of freight from roads to rail and water.

However, the reality is that the inverse that will happen, for better or worse.

Water freight in the US is heavily constrained for growth. The Jones Act, the most restrictive cabotage act in the world, one which requires all domestic water freight vessels to be made in America, by American firms, owned by American firms, flagged in America and crewed by Americans, was intended to preserve the merchant marine in the aftermath of World War One, where it was a vital logistics arm of the US military. However, as Barnard pointed out in his assessment of US water freight challenges, in combination with the deindustrialization of the USA over the past four decades, American ship building has dwindled. Now the country isn't even in the top 15 of ship building countries, outstripped by much smaller European countries.

However, it isn't the European shipbuilders which are the challenge, although they will be running flat out to build the electrified ships of the future for that continent. It's that China is now by far the biggest shipbuilder in the world, with 59% of all new ship orders flowing to Chinese shipyards. That's followed by South Korea and Japan, both of which are also on the other side of the Pacific. While those two countries are US allies, having them build new, smaller domestic ships for the US market when they are building high-ticket large ships for global freight firms will be challenging. Of course, inland and short sea ships often can't cross oceans, so delivery of the vessels will be challenging as well.

Finally, inland and short sea shippings' largest lever in the coming years is battery electric, as that has the best economics and emissions savings. Per US Department of Energy Lawrence Berkeley National Laboratory studies in 2022 and 2024, 950 mile journeys break even economically with batteries that cost US$100 per kWh, and 1,900 mile journeys at $50 per kWh. The Chinese firm CATL, the market leader in electric vehicle batteries, delivers lithium iron phosphate (LFP) batteries at $56 per kWh today, however the United States. has put significant tariffs on Chinese batteries and has very limited battery manufacturing capacity.

Batteries built in the United States., with the possible exception of Tesla, will remain much more expensive, and cheaper batteries from China will be difficult to consider immediately. The authors recognize that the United States is pursuing domestic manufacturing policies and investments which have the potential to lower battery costs over the longer-term, but the recent failure of Northvolt, which Barnard analysed, means that those initiatives are high risk.

The small and aging fleet of merchant marine vessels operating domestically — only 93 vessels over 100 tons currently qualify — will be difficult to retrofit and new vessels will be difficult to build. That's true for dual fuel vessels for lower likelihood alternative fuels such as methanol and ammonia as well.

This leaves biodiesel repurposed from other parts of the United States economy as likely the only lever available for the small number of ships. Growing the water freight segment, as the blueprint suggests, is heavily constrained, and it's the smallest freight carrier today despite the excellent waterway and coastal resource the United States has.

Moving on to rail, the United States, uniquely among major economic blocs, has no heavy freight electrification. India is at 97% electrification this year after 15 years of their program and will hit 100% soon, and rail is the dominant mode of domestic freight shipping. China is well over 70% electrified. Europe, while moving little freight by rail as it prioritizes passengers there, has a high degree of electrification.

The lack of rail electrification in the United States is due to the corporate structure of heavy rail and bordering countries, Canada and Mexico. All of the tracks are owned by operators, unlike other countries where they are national infrastructure or public-sector assets. In the United States, investment in their maintenance, as well as strategic improvements are the responsibilities of the operators. The operators are constrained under United States fiduciary responsibility to only consider the requirements of their shareholders. Strategic investments that would impact quarterly profits, operations, dividends and earnings calls this year for benefit in five to ten years are close to impossible to get approved. United States rail operators are going to see seriously declining revenue in coming years as the full third of their tonnage which is coal and a bit of oil disappears as global demand diminishes. They will be operating under falling revenues and seeing an even lower ratio of freight tons per mile of track than they do today, when over the entire set of rails they are already at half of European levels and worse compared to India and China.

As a result of this situation, the American Association of Railroads official policy is that what every other major economy is just getting on with is impossible in the United States. They are formally and vocally opposed to rail electrification. Further, while they could operate their trains on biodiesel, it would increase their operating expenses and decrease their profits, so it isn't viable for them either.

The lack of a carbon price on fuels in the United States, with limited carbon pricing in only two states, means that rail operators have no economic incentive to purchase more expensive fuels. The Inflation Reduction Act, while it is subsidizing green hydrogen and synthetic fuels, still leaves resulting liquid fuels that are plug compatible with aging diesel electric locomotives far above the cost of diesel today.

The only lever is pressure from major logistics firms such as Amazon which are looking to decarbonize their supply chains, and while rail operators are listening, they aren't acting.

The situation brings us to freight road trucks where diesel-powered trucks still dominate. At the North American Council for Freight Efficiency (NACFE) Run on Less test month in September of 2023, two Tesla Semi's covered over 1,000 miles in a day of operation with two half-hour charging sessions. Other manufacturers had 500 mile days. The accomplishments show that the challenges of scaling electric technology in heavier and longer-distance trucks are addressable. However, the current share of electric trucks is statistically insignificant (<1%), relative to over 14 million freight trucks operating in the United States.

It is worth noting that the accomplishments are with today's battery technologies. This year CATL, the world's largest EV battery manufacturer, is delivering batteries with double the energy density, hence double the range when put into a Tesla Semi. The trends of batteries continue to be much cheaper in cost and higher in energy density. Truck manufacturers will have battery electric truck options with 1,000 mile ranges and lower prices in the coming years, making electric trucks a viable economic and environmental option.

Where weight is perceived as a concern, the allowances for heavier electric trucks carrying the same load will not harm roads. Michigan already allows trucks with double the weight of the Class 8 trucks that are the lowest commonly agreed on scale across North America, and hence the trucks used for most long-haul trucking.

Electric semi trucks and all lower scales are fit for purpose for the majority of trucking today and all of trucking tomorrow.

Per Barnard's earlier analysis, electric freight trucks are already lower carbon per ton mile in eight United States states, including California, as well as 70% of neighboring Canada. As grids continue to decarbonize, more and more states will cross over that threshold, and carbon emissions reductions for electrified trucking will continue to drop.

Trucks running on electricity have a significant economic advantage over diesel trucks. Fuel costs for diesel are 20% to 30% of costs, depending on fluctuation in diesel prices. This equates to an average of $0.46 per mile. Due to the economic sensitivity, many truck operators adopt fuel-saving measures such as optimized routing, AI-driven logistics, and increasingly electric trucks. The electric semis, with their very efficient drive trains, see in the range of $0.20 per mile or lower. Approximately 9% of truck expenses are for maintenance. Global data from electric fleets shows that the predicted savings of 30% to 40% on this expense are being realized.

Coming soon are autonomous trucking solutions, with major existing truck suppliers such as Volvo and Daimler, as well as new entrants like Tesla and Nikola, working on technologies which will enable convoying, where trucks can follow each other in a formation, reducing the need for driver input and enhancing fuel efficiency, with some drivers taking their legislated breaks while on the road. The labor cost advantage rail currently enjoys will be diminishing within the next decade as well. Labor is the biggest cost of trucking, approximately 43%, and could also see a cut of a third of that in coming years.

Electric trucking will immediately have operational margin increases sufficient to compete for more container traffic, and this margin will increase, even as rail costs stay the same or increase if they use biodiesel. This will shift container traffic from rail to roads, in addition to rail's loss of coal and oil, compounding that mode's challenges.

The massive logistical firms with strong decarbonization requirements such as Amazon and Walmart will move more containers to trucks and off rail in coming years due to this.

In the authors' analysis, road freight has significant opportunity for near term decarbonization, and further, a strong economic and equitable incentives to do so. This will result in a rebalancing of the United States domestic freight to road away from rail, and likely from water freight. This is far from ideal, but it's the reality of the United States.

The next section assesses the challenges facing electrification of road freight, once again diagnosing the situation and leveraging lessons from medium- and heavy-duty road electrification. This is the next step to creating a simple policy, or policies, to overcome those challenges and accelerate the electrification of road freight transportation.

02

Big Truck Stop and Depot Firms Will Dominate Electric Truck Charging

Key Takeaways

- Delivering inexpensive, reliable electric truck charging requires scale
- Major logistics, truck stop and turn-key services firms have the scale and will lead the way
- The big firms that embrace this will increase market share

Movement of freight in the United States (U.S) is going to shift more and more to roads on electric trucks, due to factors explained in coming sections. Utilities aren't able to address growing charging needs, and there are other concerns and blockers, but they are all addressable.

Major logistics players including big truck stop firms like Pilot, major depot owners like Walmart and Amazon and turn-key services, or engineering, construction and procurement firms like TLM have an opportunity to take market share and increase profits during and after this transition.

The nugget of the solution is incremental, modular charging microgrids, with lots of solar power and buffering batteries. What that all means and how it differs across the organizations which will be accelerating both market capture and decarbonization in the next couple of decades is explained over the series. The authors' focus is on creating a Google Maps level perspective, not a tightly granular perspective for a specific firm, and so there is latitude in the details that will have to be analysed and considered during strategy implementation.

Major freight logistics firms like Amazon, UPS, Fedex and Walmart with large numbers of depots are already considering electrification of freight trucking and have the volumes to accelerate the transition. Amazon has over 100 fulfillment centers, 50 sortation centers, 150 delivery stations, Prime Now hubs and Amazon Fresh distribution centers, at least 10 major air facilities supporting Prime Air and specialized centers for handling bulky items in the United States.

Walmart operates about 42 general merchandise distribution centers, numerous grocery distribution centers dedicated to perishable and non-perishable food items, several e-commerce fulfillment centers, specialty centers focused on specific product categories and Sam's Club distribution centers. There are 4,615 stores spread across 49 states and territories in the United States, many of which will be worth equipping with charging due to distance from the nearest distribution center, enabling two way trips without paying retail charging prices for electricity.

Major truck stop operator chains like Pilot Flying J, Love's Travel Stops & Country Stores and TravelCenters of America also have the scale to take advantage of the transition or lose during the process. Pilot has 750 locations, Love's has 600 and TravelCenters has 280 locations. That's a lot of charging microgrids. These chains have major capital behind them, with Berkshire Hathaway having a majority stake in Pilot and BP owning TA outright. While not as well known, the Love family fortune is around $10 billion, and they have access to capital that smaller players won't.

Major truck stop and depot construction turn-key services firms, especially the ones that offer close to turnkey solutions, are another group which has a significant opportunity.

TLM Development Company, Trinium Inc. and Snyder Construction Group are big in this group. These firms have all built many truck stops for clients across the United States. In the distribution center space, Gray Construction, Arco Design/Build and Ryan Companies are among the major players.

These vendors have the competitive opportunity to develop a short menu of charging microgrid increments as per the approach outlined in subsequent sections with tight control over what gets built. They can offer clients simplicity, and they can offer it to smaller operators who couldn't afford to develop the incremental and modular solutions themselves, and so would spend a lot more money for less reliable infrastructure. They could approach big organizations which own many sites and work to become their vendor of choice for this as well.

The thing these firms have in common is volume. Designing and engineering a single microgrid for megawatt scale truck charging is a significant overhead cost. Designing three to four microgrids for different capacities, ensuring modularity and commonality of components, and then building them potentially hundreds of times means that design and engineering cost is amortized over many sites, lowering the costs of all of them.

These are organizations which can negotiate for volume discounts which won't be available to smaller organizations. In the case of the Walmarts and Amazons of the world, they have access to global supply chains. That gives them the best ability to buy less expensive, high quality equipment globally and bring it to the USA. It also means that they could conceivably do much of the design, engineering and support work for depot charging in low cost geographies both inside and outside of the USA.

As the stakeholder matrix the authors sketch out in the series makes clear, every microgrid can require interaction with utilities, regulators, municipalities and — as the charging microgrid grows — up to federal stakeholders. Major organizations like Amazon and Pilot have significant economic and political clout that they can bring to bear to accelerate approvals and gain more attention to their files. When Walmart calls, phones get picked up. These organizations have centralized staff specialized in dealing with many of the organizations already, and strong relationships. This alone will reduce the time and cost to deliver charging microgrids for the major players.

For major depot operators, that means the operational cost advantages of electrified trucking can be achieved at a much lower price point with more reliable depot charging and less dependence on truck stop charging networks.

For major truck stop operators, they'll be able to have lower costs of charging for the same retail price of delivered electricity as the truck stop up the road, or charge less and get more traffic. They'll also be able to electrify faster than smaller competitors and so own the electrified road freight business of the future, likely putting smaller operators out of business and expanding.

For the turnkey services firms, this is an untapped market that's about to explode. The firm that does this well following the self-reinforcing actions the authors will outline could radically expand its customer base in the coming two decades. This is an opportunity at a strategic cusp moment that comes along once in a generation or less.

If you are a depot operator with a small number of depots or a truck stop operator with only a few or even one truck stop, don't try to do this alone. Go to the major turnkey operators, the strategic guidance from this report in hand, and find out which one is doing the hard work for you. Have them deliver the solutions so that you will still be in business in a decade.

Subsequent sections diagnose freight decarbonization in the United States, diagnose the challenges related to electric truck charging and lay out a simplifying policy and self-reinforcing actions that will enable the firms which take advantage of it to thrive. There's going to be a shakeout as this transformation sweeps through the USA. The biggest and fastest moving will survive and grow.

03

Microgrids Accelerate Transition to Electric Trucking

Key Takeaways

- Grid upgrades for high truck charging demands can take years
- Microgrids with buffering batteries and solar enable charging immediately
- Depots and truck stops require different charging technologies and have different energy profiles

One of the primary challenges of electrifying freight trucks in the United States comes down to adequate charging infrastructure without compromising freight operations. The economics of electric trucks, battery availability, scaling manufacturing, etc., could be another set of challenges. With focus on the intersection of freight truck electrification and electricity infrastructure, optimal siting of charging infrastructure, and availability and reliability of power for charging are real challenges that's stymying truck electrification.

The United States is advancing electric transportation with expanded charging networks, incentives, and investments in light- and medium-duty vehicle electrification to cut emissions and increase sustainability. Taking clues, one could conclude that electrified freight trucks may have fewer roadblocks to rapid decarbonization; however, it does not mean no challenges, or that there aren't multiple strategies that might achieve this end. Let's first diagnose the challenges, suggest some policies and focus on the policy we will elaborate on in this series – strategic grid-connected microgrids for truck stops and depots.

The authors' opinion is that scaling electric truck manufacturing is not a substantial barrier, and that as battery costs decrease and energy density increases, demand for electric trucks will drive multiple existing and new manufacturers to meet it rapidly. Only 203,000 semi trucks were sold in 2023, a volume which can easily pivot to battery electric and grow rapidly.

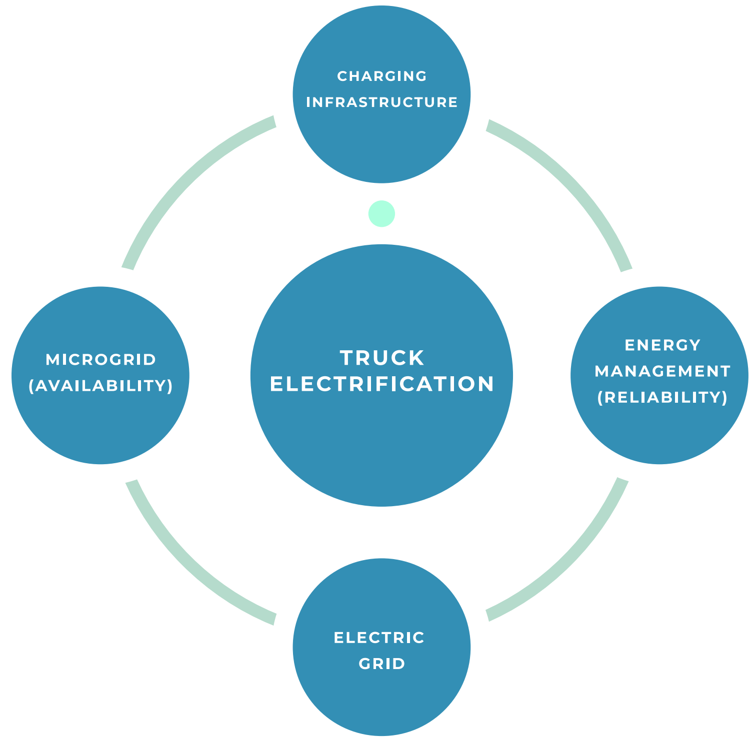
Charging at truck stops requires significantly higher power levels to accommodate the large battery capacities typical of freight and heavy-duty vehicles and lower dwell times, as longer charging times directly affect truck operator's productivity, and delay truck electrification plans. Fast charging of higher capacity batteries requires chargers with high power levels that are termed extreme fast chargers or megawatt charging systems.

Charging infrastructure at distribution centers and depots for trucks must be designed for first- and last-mile services. Trucks that operate over shorter distances can charge at truck depots where they are parked during non-operational hours. As highlighted by McKinsey and Company, addressing this need requires a design review and the need for significant investment in higher-capacity charging stations, tailored energy management systems, and smart scheduling to optimize charging during off-peak hours.

Understanding that the truck charging needs will drive the design of charging infrastructure, a distinction with the use of high-power charging infrastructure for truck stops and depots, is the standardization of charging used for electric flows to/from truck batteries. While light duty and medium duty electric vehicles use connectors like Society of Automotive Engineers' (SAE) J1772 for alternating current (AC), CCS for direct current (DC), and the recent standardization of the North American Charging Standard, SAE J3400 which handles both AC and DC, trucks currently require customized or emerging standards and connectors for megawatt charging.

Strategic microgrids across the freight corridors, truck stops, and depots paired with renewables, battery storage, and energy management features can be simplifying and coherent policies that can overcome these challenges across the transportation and electric grid industries.

Guide to Address Electricity Availability and Grid Reliability from Truck Electrification



The United States' grid had no need to expand or modernize for 30 to 40 years. Projected growth in electricity demand didn't materialize, even as total electrified services increased. The country uses far more lights far more of the time than it used to, but they are very efficient LEDs. The country has far more screens displaying static and moving graphics, but they are LED as well. Some efficiency measures have kept electrified buildings and heating or cooling technologies relatively reliable, although the end-uses have high use of gas and oil for heating.

Electrification of the United States economy has not significantly progressed as a ratio of total energy consumption for the past thirty-five years. Transportation and heating energy is still dominated by fossil fuels. This has meant that the grid hasn't changed much in that time. The wires carrying electricity to the end points of truck stops and warehouses have remained thin, with lower voltages and running overhead where they are more subject to impacts of extreme weather than in Europe, as an obvious benchmark. Upstream from the warehouses and truck stops, the distribution grid has not been proactively upgraded to handle greater loads and localized distributed generation that renewables, battery storage, and electric vehicles provide.

Meanwhile, substantial de-industrialization of United States electrical grid component manufacturing has occurred, with China building a greater and greater percentage of the market. China is now the largest manufacturer of transformers — which step voltages up or down — and converters

— which change between AC and DC. These are essential technologies for enhancing both the distribution grid and the end-points where trucks will charge.

There are two levels of charging that make sense for trucks. At depots where they overnight, Level 2 or low power levels of Level 3 charging are often sufficient. Level 2 charging for trucks refers to an AC charging that delivers a moderate amount of power—typically between 7 kW and 22 kW, depending on the specific setup. Level 3 charging refers to a DC charging that delivers high power levels for fast charging. These lower charging levels have the potential to minimally impact power availability and grid reliability, resulting from truck charging.

Where the depot can have more trucks that have heavier duty cycles, and so require more charging, Level 3 charging may be more prominent. Level 3 charging can be scaled up and is the fastest and most powerful type of charging currently available for electric vehicles, including trucks. Extreme fast chargers and megawatt charging systems — commonly used terms for higher levels of charging — use DC to charge a vehicle's battery directly, bypassing the onboard AC-to-DC converter used in Level 2 AC charging.

Where low charging power levels is all that is required and the fleet is small, no additional electrical supply may be required, whether from grid upgrades or alternatives. If minimal grid upgrades for this subset of depots are required, they are relatively less capital intensive and take less time. Where the fleet is large or higher power Level 3 charging is required, more power and energy are required and if nothing else is done, grid upgrades will be significant, capital intensive, and can take multiple years, depending on the site, region, and charging levels.

For truck stops, megawatt charging is designed to charge large truck batteries (often over 500 kWh in capacity and 250 to 350 miles of range per full charge) to 80% state of charge rapidly in the range of 15 to 30 minutes for extended-range travel with minimal charging downtime. For example, Nikola's battery truck has a range of 330 miles with a battery capacity of 733 kWh. Continued developments with electric truck manufacturers aim to improve range and operational efficiency.

Enabling even a single truck to charge with megawatt chargers at a truck stop, even with the present battery specifications, would require a significant grid upgrade if no other alternative existed. Enabling five or ten trucks to charge simultaneously gets into dicey grid infrastructure upgrade territory very rapidly. At present, this can mean years in waiting and millions of dollar costs to the truck stop, and if it were the only strategy available, would be prohibitive for business cases.

For depot charging, time of use billing, available from most utilities now, will enable energy management of charging truck fleets overnight with the lowest cost of electricity or when the grid power is not constrained, as long as the fleet size is not large. However, the larger the fleet size and heavier the duty cycles, the more it will be difficult to charge all vehicles in the time allocated, once again potentially driving up grid connection costs and justification for microgrids and energy management options.

Truck stops must charge trucks when the trucks arrive, not when it's convenient from time of use billing or grid conditions perspectives. In the United States, trucks tend to drive more during daylight hours, with truckers typically stopping in the late evening and sleeping for several hours. This is driven by driver regulations for total hours of driving in the day, as well as by diminished risks on better lit roads.

However, this pattern is at risk of being upended by autonomous trucking features, which multiple truck manufacturers including Daimler, Volvo, Tesla, and Nikola are working on. Early iterations of autonomous technologies will likely allow convoying, enabling trucks to roll through the night

with one or two drivers alert and overseeing the convoy while others sleep in their cabs. This will change the pattern of charging for depots and truck stops with the need for timely charging being prominent.

Electric trucks will change trucking patterns in urban areas too. At present, major urban areas frequently have night time noise limitations and concerns that limit last mile deliveries by larger diesel trucks. As electric trucks are much quieter, those concerns are eliminated and night time deliveries and hence higher speed depot top ups of batteries are likely to be required that are good use cases for microgrids and energy management features.

In the authors’ opinion, the simplifying policy — per Rumelt’s strategy kernel — which addresses all of these concerns is to deploy microgrids with buffering batteries and solar panels for larger depots and all truck stops..

As per the United States Department of Energy, a microgrid is “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island- mode.” A microgrid can be a small, localized network of electricity generation, storage, and energy resources that can operate independently or in conjunction with the main power grid. It typically can serve a specific area, such as a campus, industrial site, neighborhood, or even a single building or home. Microgrids are designed to assure power availability for reliable and resilient power, especially in areas prone to outages or where energy autonomy is desirable.

In the authors' model, the microgrids will be grid-connected and will be supported by local renewable generation such as solar and battery storage, to align with carbon mitigation objectives. These microgrids will leverage the flat roof tops of distribution centers, truck stops and parking area canopies with solar generation. They will have increasingly inexpensive and large buffering batteries to ensure availability of power when trucks need them and house energy management features to improve reliability and energy savings for the site.

The model of operation is straightforward. When grid electricity is cheap and abundant, the maximum amount of energy supported by the grid connection is stored in the buffering batteries. Note that this approach can also be leveraged for grid power with low prices or low carbon content. When the sun is shining, the maximum energy that can be stored in the batteries is stored and the rest is used to charge trucks. When the microgrid has a surplus, net metering is leveraged, providing electricity to the local distribution grid so that it does not have to be purchased by the utility from the third-party generator further away. This approach also improves grid reliability and resiliency by alleviating the grid congestion and supply-side constraints.

The plummeting costs of batteries has made the return on investments from large batteries in truck stops and other locations quite short in duration. Barnard explored this when the news of CATL's $56 per kWh LFP batteries was announced early in 2024, finding that up to 22 trucks a day could be charged with megawatt charging with no grid upgrades with a reasonable sized and priced battery in 2025, and have a return of investment under three years just on time of use billing arbitrage. That was without solar power on the site or the other revenue increasing and cost avoidance potential.

Grid upgrades would eventually be required in truck stops and depots with heavy duty cycles as electric fleets increased, but batteries in microgrids could defer those costs for years, enable immediate megawatt charging deployment, reduce the total size of the grid upgrade and have strong operational revenue and cost advantages even with a more robust grid connection.

What was even three years ago unlikely — large scale battery buffering of electricity for megawatt charging of heavy trucks — is economically advantageous today. Similarly, the plummeting of solar panel costs, despite the 50% tariff on Chinese panels, means that commercial solar installations at depots and truck stops are less expensive and with a faster return on investment than ever.

The simplifying policy that the authors propose is that the vast majority of freight truck charging will be done on depots and truck stops with grid connections, solar panels and large battery storage systems, deferring grid upgrade costs and allowing immediate start of deployment of trucking. The collective strategy has the potential to accelerate electrification of truck charging.

04

Overcoming Barriers to Charging Microgrid Implementation

Key Takeaways

- Microgrids speed power availability and deployment of freight truck charging
- Specific challenges face charging microgrid deployment that must be overcome
- There are federal, state, and non-profit organizations that can assist and have different energy profiles

As previous sections have made clear, microgrids, strategically designed for truck stops and depots, are a path forward for electric truck charging in the United States. Customer-sited storage and solar with a grid connection enables two flows of energy into the battery depending on time of day and cost of electricity, and high-power charging of trucks as needed. This can get significant electric freight truck charging operational long before major grid connection upgrades can be established. Microgrids face hurdles to their deployment in the country, but the strategy addresses them with a set of self-reinforcing actions in subsequent sections.

This section explores the challenges of deploying microgrids in the USA, enabling future sections to explore action plans that mitigate each challenge.

High initial costs of microgrid deployment continue to pose a significant barrier to widespread adoption, as highlighted by recent studies from the National Renewable Energy Laboratory (NREL). Microgrid projects often require large upfront investments in infrastructure, including power generation sources, energy storage, and sophisticated control systems to manage both local and grid-connected power. According to NREL, these initial costs can deter smaller communities and private entities from pursuing microgrid solutions, despite potential long-term benefits in resilience and energy savings. In a 2023 report, NREL stressed that although technological advancements have gradually lowered some component costs, financing remains a major hurdle, especially for rural areas and low-income communities.

Complex regulatory and policy barriers remain a substantial roadblock for microgrid deployment in the United States, according to recent insights from the National Association of Regulatory Utility Commissioners (NARUC). As many regulations governing energy distribution and grid operations were crafted with traditional centralized grids in mind, they often do not account for the decentralized, resilient structure that microgrids offer. NARUC's latest policy recommendations underscore that without clear standards on ownership rights, operational responsibilities, and compensation for microgrid services, projects can face lengthy approval processes and inconsistent rules across jurisdictions. In a recent report, NARUC calls for state-level regulatory reform, suggesting standardized frameworks and incentivized policies to help microgrids become a reliable and scalable solution for energy resilience. These updates, NARUC argues, would allow microgrid operators to participate fully in energy markets and contribute to grid stability, helping close the regulatory gaps that currently hinder deployment.

Interconnection and utility coordination present ongoing challenges for microgrid deployment, as detailed in recent findings by the Electric Power Research Institute (EPRI). The institute's studies show that while microgrids can enhance energy reliability and resilience, integrating them smoothly with the existing power grid requires careful coordination with utility providers. Many utilities view microgrids as potential competition, adding complexity to interconnection processes and often creating friction in project approval. EPRI's report recommends collaborative frameworks that encourage utilities and microgrid developers to work together, ensuring that both parties can leverage the benefits of microgrids while maintaining grid stability. This approach, EPRI argues, could streamline interconnection processes and foster more supportive relationships between utilities and microgrid operators.

A lack of standardization across microgrid technologies continues to slow adoption, according to a 2021 report from the Department of Energy's National Renewable Energy Laboratory (NREL). Microgrids often rely on a mix of components from various vendors—ranging from power generation and storage to advanced control systems—which frequently lack interoperability due to differing technical specifications. NREL's findings highlight that without a unified set of standards, developers face increased costs and complexities, as systems often need costly custom integration to function cohesively. The report advocates for industry-wide standards to simplify integration, reduce costs, and accelerate deployment, enabling microgrids to fulfill their potential in supporting a more resilient energy future.

Uncertain revenue streams are a major hurdle for microgrid operators, as highlighted in a recent analysis by Microgrid Knowledge, a key industry platform supporting microgrid advancement. Although microgrids offer valuable services such as demand response, peak shaving, and grid stability, the financial returns from these services remain unpredictable. Microgrid Knowledge points out that revenue models are highly dependent on local energy markets and policies, which vary significantly and can change unexpectedly. In its latest industry report, the organization underscores the need for more consistent policies and market structures that fairly compensate microgrid operators, ensuring these resilient energy systems can achieve financial viability and attract broader investment.

Cybersecurity concerns pose a significant risk to the expansion of microgrids, as detailed in research by the Electric Power Research Institute (EPRI), which specializes in energy grid technology and resilience. With microgrids often operating through interconnected digital control systems, they are vulnerable to cyber attacks that could disrupt power supplies or compromise system operations. EPRI's findings warn that as microgrids are integrated more widely into the energy grid, they could become prime targets for cyber threats. The institute advocates for rigorous security protocols and investment in advanced cybersecurity measures to protect these systems, calling on stakeholders to prioritize resilience as they deploy microgrid infrastructure. EPRI suggests that adopting secure communication standards and real-time monitoring could help safeguard against cyber attacks, ensuring the reliability of microgrid operations.

Measuring resilience and reliability benefits remains a complex challenge for microgrids, according to a report from the National Renewable Energy Laboratory (NREL), a leader in microgrid research. While microgrids are widely valued for their ability to enhance energy resilience, especially during power outages, quantifying this resilience in a way that supports financial and regulatory decisions has proven difficult. NREL's findings reveal that without standardized metrics for resilience, it is challenging to assess a microgrid's full value, creating barriers to securing investment and regulatory support.

Limited awareness and expertise around microgrids continue to slow their adoption, as highlighted in a report by the Clean Energy States Alliance (CESA). CESA, an advocate for clean and resilient energy solutions, emphasizes that many local governments and smaller organizations lack the technical knowledge needed to implement and manage microgrid systems. This knowledge gap can deter decision-makers from pursuing microgrid projects, even when these systems could provide critical energy security and sustainability benefits.

Capital expenses will precede revenue for the organizations which build the infrastructure necessary for increased road freight electrification. Specific to truck stop charging, a barrier is the need for a network of charging stations to be built along key routes prior to significant truck volumes. As an indicator of potential approaches to overcoming this, the Environmental Protection Agency has awarded nearly $250 million to a coalition of four states—New Jersey, Connecticut, Delaware, and Maryland—to establish 24 electric truck charging sites along the Interstate 95 freight corridor. This project aims to reduce greenhouse gas emissions and support the adoption of electric trucks in the region.

Potentially large and complex stakeholder groups to manage are a concern with microgrids. Existing literature and efforts frequently attempt to add value propositions like local grid resiliency, utility demand management, national grid cybersecurity and the like to microgrid efforts. This can bring a significant number of often slow-moving stakeholders to the table attempting to maximize the benefit for their purposes. The authors address an approach to dealing with these varied value propositions and stakeholders that enables accelerated delivery of truck charging in a pair of related sections later in the report.

These challenges all apply to greater or lesser extents to specific microgrids for trucking. However, the story is not all about the challenges that must be overcome, but also the support available to organizations building microgrids.

Several federal programs are now accelerating microgrid deployment with targeted funding, technical assistance, and policy support. The Department of Energy (DOE) leads many of these efforts through its Microgrid Program, which supports research, development, and demonstration projects to advance microgrid technology and its integration into the larger grid.

Further support for microgrid deployment comes from the DOE's Grid Resilience and Innovation Partnerships (GRIP) program, which, under the Infrastructure Investment and Jobs Act, recently awarded $3.46 billion in grants to enhance grid resilience and develop innovative grid solutions, including microgrids. Meanwhile, the Microgrid State Working Group, co-led by the National Association of Regulatory Utility Commissioners (NARUC) and the National Association of State Energy Officials (NASEO), collaborates with the DOE to improve state-level policies and regulatory frameworks for microgrid expansion. Together, the initiatives aim to reduce deployment barriers, strengthen the grid, and enable clean energy access through microgrids.

Subsequent sections articulate a set of self-reinforcing actions and approaches to depot and truck stop charging microgrids to avoid and overcome the challenges while taking advantage of the existing programs and support structures. The intent is to create a framework for a forward thinking organization to build the road freight charging network of the future and expand its market share.

05

Design Charging Microgrids Incrementally for Scalability

Key Takeaways

- Trucks won't all be electric immediately, so don't build charging for 100% electric
- Design charging microgrids for standardized increments of capacity
- Analyze all sites and design increments that are good enough

Gaining the benefits of electric trucks, including significantly reduced maintenance and operations costs and increasing market share, doesn't have to start big. In fact, the best way to start is small, within the constraints of the grid, leveraging buffering batteries and onsite solar to enable a portion of the fleet at the depot or visiting truck stops to be electric immediately. Adding capacity to the microgrid, often aligned with the ability of utilities to add grid connections and approval for larger solar arrays, can be integrated with increases in electric fleet sizes.

The target audiences for this material — major logistics firms like Walmart which own and operate many depots, owners of significant numbers of truck stops and likely turn-key vendors of microgrids for truck charging — must consider not only the solution of a microgrid, but an approach to charging-based microgrids that is optimal given the challenges and constraints to charge electric trucks.

A key challenge of installing charging systems with an optimal mix of power levels is that a grid connection capable of delivering a megawatt or more of power to each of several charge points for heavy trucks simultaneously can take years to be approved and delivered. It requires the utility to restructure the grid from the truck stop to the secondary distribution substation and likely to the primary distribution substation. It can require new wires capable of delivering the higher power required. It will require a very significant scale of transformer at the truck stop.

A second key challenge is that there won't be that many trucks to charge initially, so high capital costs would need to be serviced until truck and charging throughput volumes increase.

The authors propose a design principle, which is to plan for optimal capacity, start with small build-outs, and incrementally add charging, generation, and storage capacity to the microgrid as more demand is anticipated, likely in two to three subsequent increments. The corollary to this is that the components chosen for the microgrid must be amenable to this, something explored more fully in the next section on microgrid component modularity for truck charging.

A small starting point can be achieved with a suitable grid connection in months, not years. One of the authors, Barnard, explored this with a hypothetical truck stop in the article *Dirt Cheap Batteries Enable Megawatt-Scale Charging Without Big Grid Upgrades Right Away*, inspired by the announcement by EV battery giant CATL of $56 per kWh LFP batteries deliverable in the fourth quarter of 2024. Such microgrids ensure power is available to trucks when needed.

Truck stops already consume a good deal of electricity for the pumps, air pressure hoses, repair services, restaurant facilities, climate control, etc. They have much more grid connected load than the average residence, typically capable of delivering 360 kW or more of power. That's used well under maximum potential power and energy demand levels, as they are overbuilt to avoid challenges and enable later growth. Further, there are peaks and lulls over the day, with typical rush points when many trucks arrive simultaneously, along with other truck stop customers.

The figure below is a simplified example of what battery buffering at a truck stop can achieve. The flat line near the bottom is a constant draw of about 80% of maximum power from the grid over 24 hours. The bright colored, tall and peaky line is the charge of a 1.5 MWh capacity battery pack. The dashed lines are trucks charging.

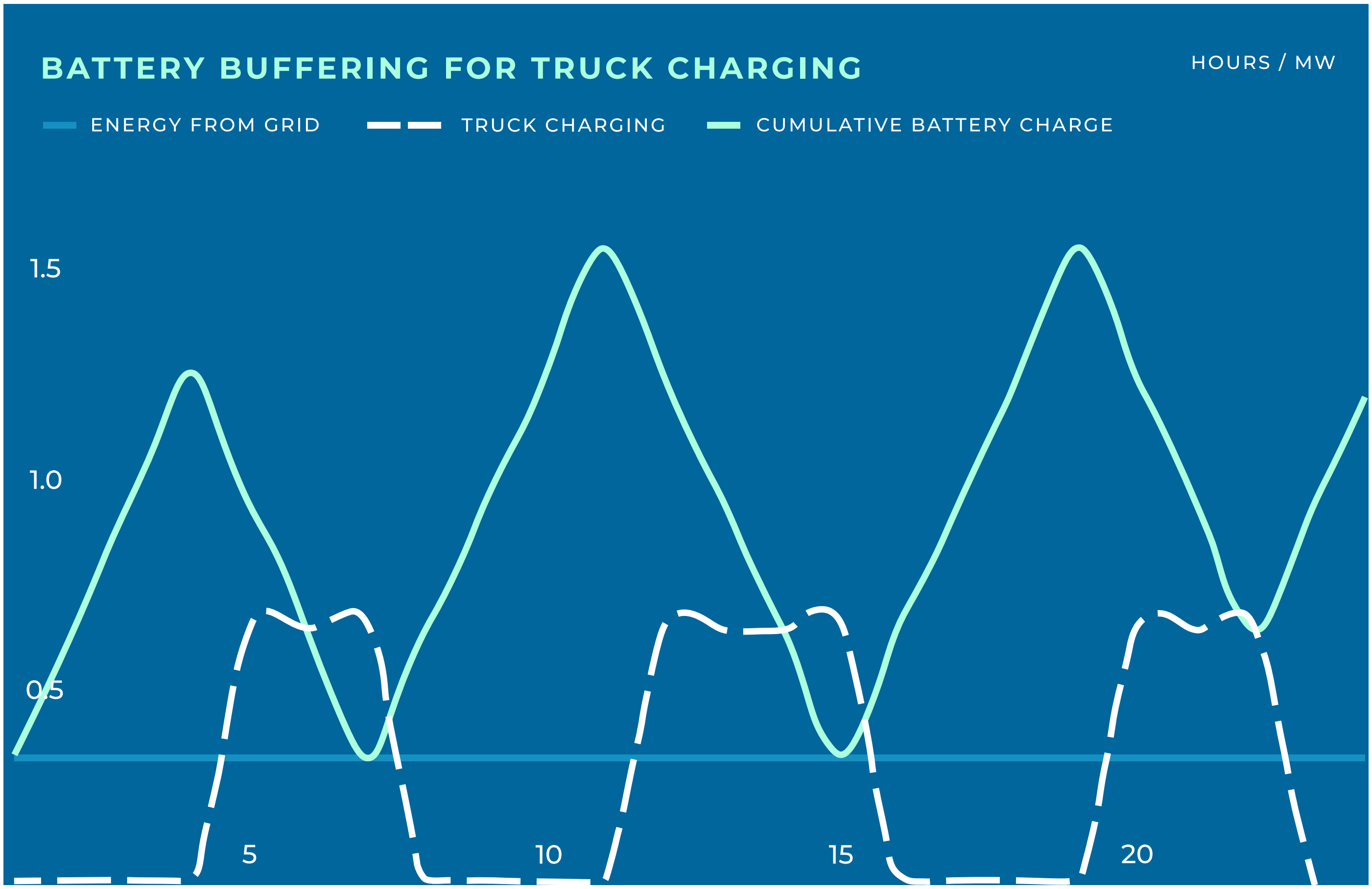


Figure 1: simple battery buffering pattern for low levels of trucks

Over the 24 hours, the battery's charge goes up and down, but demands from the grid remain constant. When a truck rolls in needing its one MWh battery charged, it will likely be at 20% charge and wish to get to 80%, the normal procedure for the fastest charge for the highest range with the lowest battery degradation. Batteries charge more slowly from 80% to 100%, so recharging from 20% to 80% is optimal for normal use and increases battery lifespan.

600 kWh is sufficient for a Tesla Semi to drive 300 miles before recharging is again

required, and for other current models of trucks like the Nikola, about 270 miles. That's five to six hours of driving time, half of the permitted driving time for a driver in the U.S per day.

This simple model with a relatively inexpensive buffer battery at the rapidly lowering battery costs we're seeing serves 10 semi trucks a day from one or two megawatt-scale chargers, sufficient for initial truck volumes in most cases for most truck stop locations in the first year of electrification of trucking.

Obviously this simplified model doesn't account for other electricity demands in the truck stop, including the increasing numbers of electric cars that will undoubtedly want to quickly charge and move on as well. However, this scale of power demand, 360 kW, typically takes 1-3 months to install, so adding it to the existing solution isn't significantly expensive or time consuming.

Typically it takes less than a year to put in a power connection sufficient for double that power draw, 720 kW. A slightly bigger battery would enable over 20 trucks to be charged in rush periods.

Of course, it also makes sense to add solar panels on all rooftops, and canopies including parking lot shading canopies constructed to maximize local generation, as well as nearby fields, when available, that can be leased for the purpose. This too can be done in stages as the microgrid expands. This can eliminate day-time power demands from the grid entirely, and over time provide local grid stabilization, demand management and net metering returns of energy to avoid utilities from having to purchase more capacity.

Conceptually for a truck stop, as shown in the illustration below, a first increment would put solar panels on the drive through truck fueling canopy and the truck stop building. A pair of megawatt scale chargers would replace two fuel pumps or be added to the end of the fueling canopy. A battery electric storage system sized for the required capacity would be built in an appropriate place on the lot. The second increment would add solar panels on canopies over the car park, adding shade amenity and some car charging, more megawatt scale chargers and more battery capacity. The third increment would include a solar farm in a nearby field, when available, and more megawatt scale chargers, more battery capacity and finally an upgraded grid connection. Collectively, solar generation and battery energy storage with microgrid energy management collectively function as a distributed energy resource. Note that in the diagram, BESS is an abbreviation for battery energy storage system, a commonly used acronym in the space.

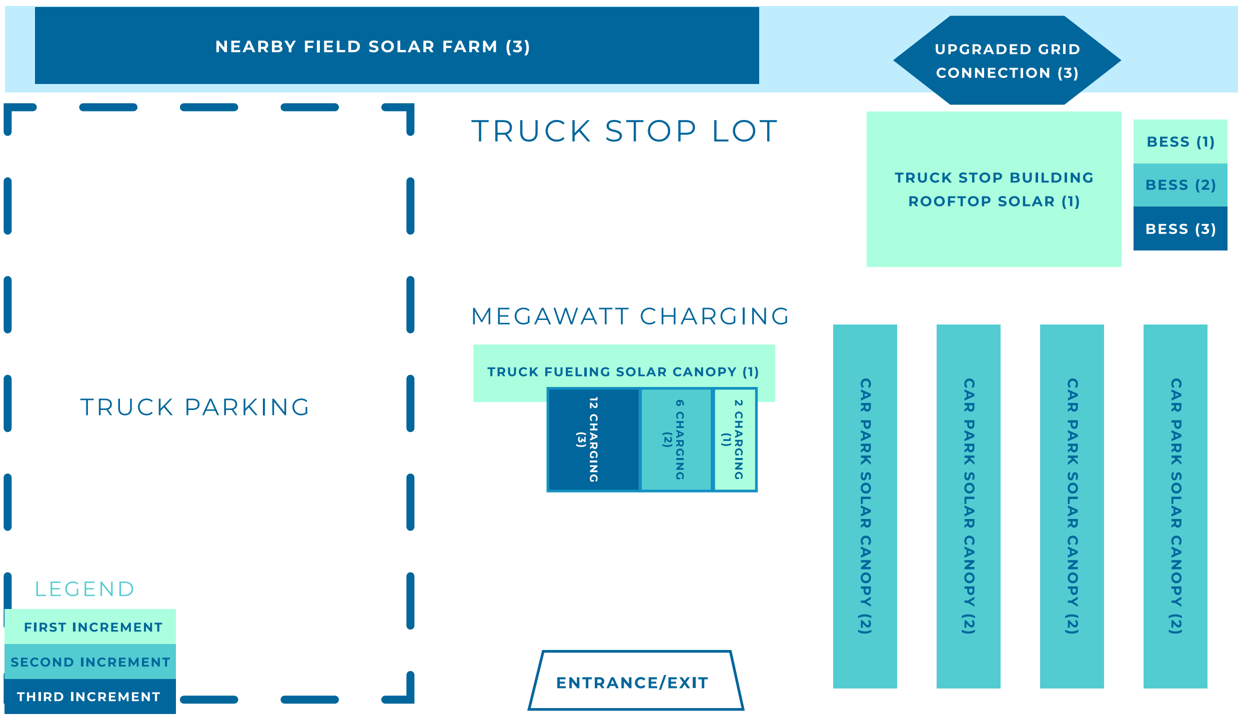


Figure 2: Simplified layout of increments of additional capacity

The pattern for depot charging will be different of course, shown conceptually in the illustration below. A typical depot pattern of night-time parked fleets and day time deliveries can minimize the need for megawatt scale charging. Depot vehicles usually have shorter service day mileage than long haul trucks and so will require fewer kWh of charging each day. Also these vehicles have longer dwell times, and slower charging levels can meet the charging needs. A buffer battery may need to have a higher capacity to shift more electricity from solar generation into the night time, as an obvious example of distributed energy resource sizing optimization.

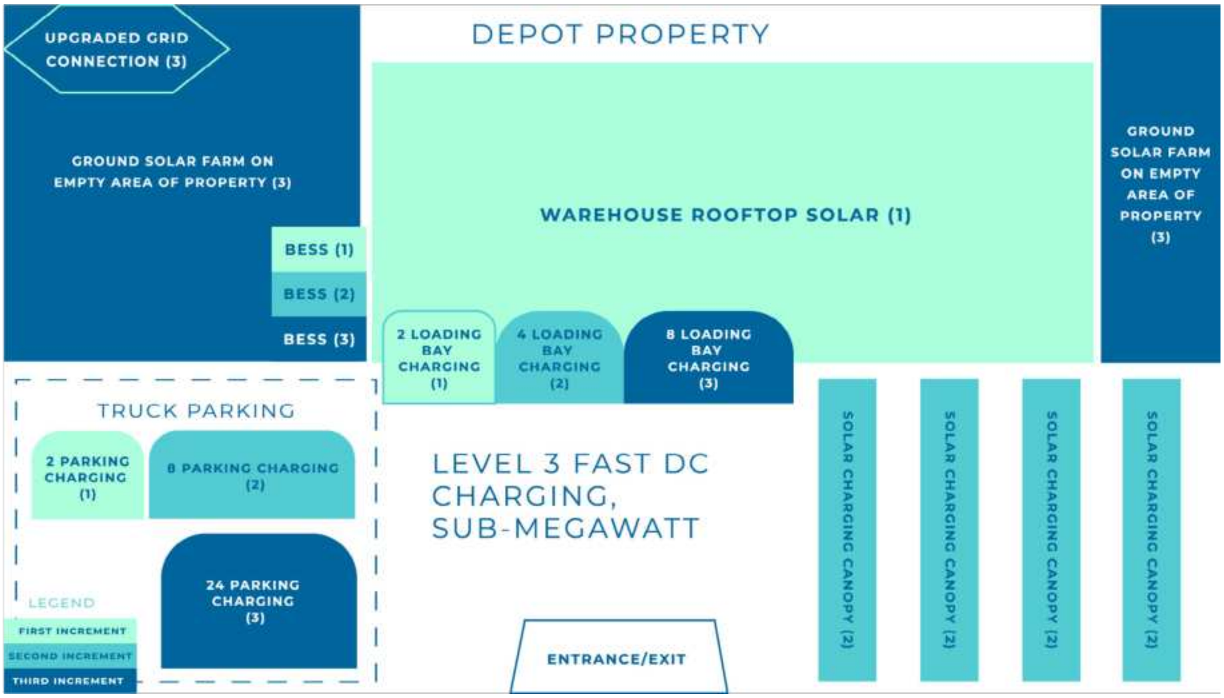


Figure 2: Simplified layout of increments of additional capacity

Conceptually, the first increment of depot charging would have warehouse rooftop solar, an appropriately sized battery, some parking Level 3 or even Level 2 charging and some loading bay Level 3 charging for top ups. The second increment would add more parking and loading bay charging and solar canopies with Level 2 charging for light vehicles including delivery vans and employee vehicles, as well as additional battery capacity. The third increment would complete loading bay charging potential, include all truck stalls with chargers, put additional solar on empty fields on the property and finally upgrade the grid connection.

When land and electric expansion is possible, megawatt charging stations for microgrids must be designed to incrementally scale with power systems capable of high power loads, which may involve reinforced grid interconnections or integration with on-site energy generation and storage solutions. To support high power demands and reduce grid dependency, such microgrid truck charging must use sustainable distributed energy sources such as solar panels and energy storage. Use of solar panels and energy storage systems aligns with sustainability targets for fleet operators looking to lower carbon footprints and meet their environmental, social, and governance plans. Such solutions not only offer microgrid resiliency (to operate in an islanded mode), it can also reduce long-term operational costs by using lower-cost renewable energy and energy management services. The costs of microgrids for trucks at both depots and stops depends on the number and types of chargers installed and magnitude of distributed energy sources, site size, and electrical interconnection, to name a few.

Any sizing and electrical connection needs must be optimally designed to ensure adequate sizing based on local freight operational needs. Any lower sizing of charging strains freight logistics' confidence in electric truck charging to meet their operational needs. Conversely, higher sizing of charging strains grid power procurement from utilities or grid operators and increases operational costs for microgrids.

What's been observed in electrifying fleets that follow this pattern is that total productive hours for drivers can actually increase. In many cases, a depot truck's first stop in the morning is a gas station nearby, and lineups for gas pumps are a fact of life. Driving to the gas station, fueling and then driving to the first delivery point is replaced with driving straight to the first delivery point. Fleets are finding up to an hour of additional delivery time in a day with battery electric vehicles that are charged when drivers show up to work.

For a major organization considering a series of microgrids, standardization of the components, sizes and vendors is key. There will be a pareto optimum size for likely three or four increments over time, and the authors' recommendation is that each is a standardized size, power, capacity and components mix that is repeated multiple times. No site is unique. Creating a simple menu of three to four sizes of charging microgrid to pick from and a simple sizing algorithm avoids what Flyvbjerg terms the uniqueness bias and will accelerate deployment, reduce risks and reduce costs. More details on differences in sites and the key requirement for standardized modularity are in a subsequent section.

Obviously, a small initial increment will mean faster planning and construction time, and lower capital costs, matching expenditures more closely to increased revenue.

The next action for the target audiences is to consider the locations that they have under their control, and rank them by volume. Either develop the expertise in house or hire an external consulting firm to develop an initial microgrid capacity increments set that make sense for your business and volumes. This will inform later actions and may be adjusted.

06

Take Advantage of Pricing Flexibility to Gain a Market Edge

Key Takeaways

- Early adopters of charging microgrids can gain a competitive edge with flexible pricing
- Solar-powered microgrids cut costs with zero marginal cost energy
- Collaboration on green corridors boosts savings and revenues

First movers with electric truck charging microgrids have a superpower, much more flexible energy pricing options to maximize profit. The big truck logistics firms that operate numerous depots, truck stop chains, and turn-key services vendors need to put on this cape.

Truck logistics firms and truck stop and depot operators have few levers to deal with the margin that they can make on the energy services that they rely on today. Wholesalers of diesel are trucking a fully commoditized product.

Upstream cost and price fluctuations can be exploited for short term increases in margin by truck stops, but just represent additional expenses for logistic firms. Every truck stop is price aligned in local markets because competition is fierce. Margins on fuel sales today are in the 1% to 5% range, hence the captive market goods and services sales that have exploded at truck stops.

Locations with on-site refueling facilities typically meet specific operational and logistical criteria. These facilities are most common in depots supporting large fleets with high fuel consumption, where centralized refueling reduces costs and improves efficiency. Remote locations or urban areas with heavy traffic often necessitate on-site options to save time and ensure fuel availability. Additionally, bulk fuel purchasing and centralized monitoring of usage make on-site refueling appealing for cost control and operational oversight.

Truck depots with tight schedules or integrated maintenance services often benefit from this setup, enabling seamless truck turnaround and compliance with regulatory safety standards.

The United States has over 577,000 registered motor carriers with the majority of them operating a form of depot or facility for freight operations. Of the roughly estimated 15,000 major logistics depots with larger terminals in the country, perhaps a quarter have onsite refueling facilities today, per a rough estimate of the likelihood of factors converging to make it worthwhile by the authors. This comes with downsides, as onsite refueling typically creates the same environmental remediation challenge for the real estate as is found with public refueling stations, something that can prevent later resale and some rental use case for the property in the future.

For both truck stops and depots, the cost-benefit balance changes substantially when electrified trucking and charging infrastructure is considered.

Consider a hypothetical scenario for a large heavy-duty truck stop that can also charge light-duty vehicles (see figure 1 below). It has battery storage beside a restaurant, repair, and rest facilities providing 8 MWh of buffering storage energy. It has a refueling/charging canopy, rooftop and parking lot canopy solar charging covering eight acres in total, capable of generating 5.2 MW of electricity when the sun is shining, and will still generate some on cloudy days. It has six megawatt scale truck chargers and perhaps 20 Level-3 light vehicle chargers under the solar canopies. It has a grid connection capable of providing 2 MW of power to the battery 24/7/365. (The state of charge of the battery in MWh isn't shown as the chart is already somewhat busy.)

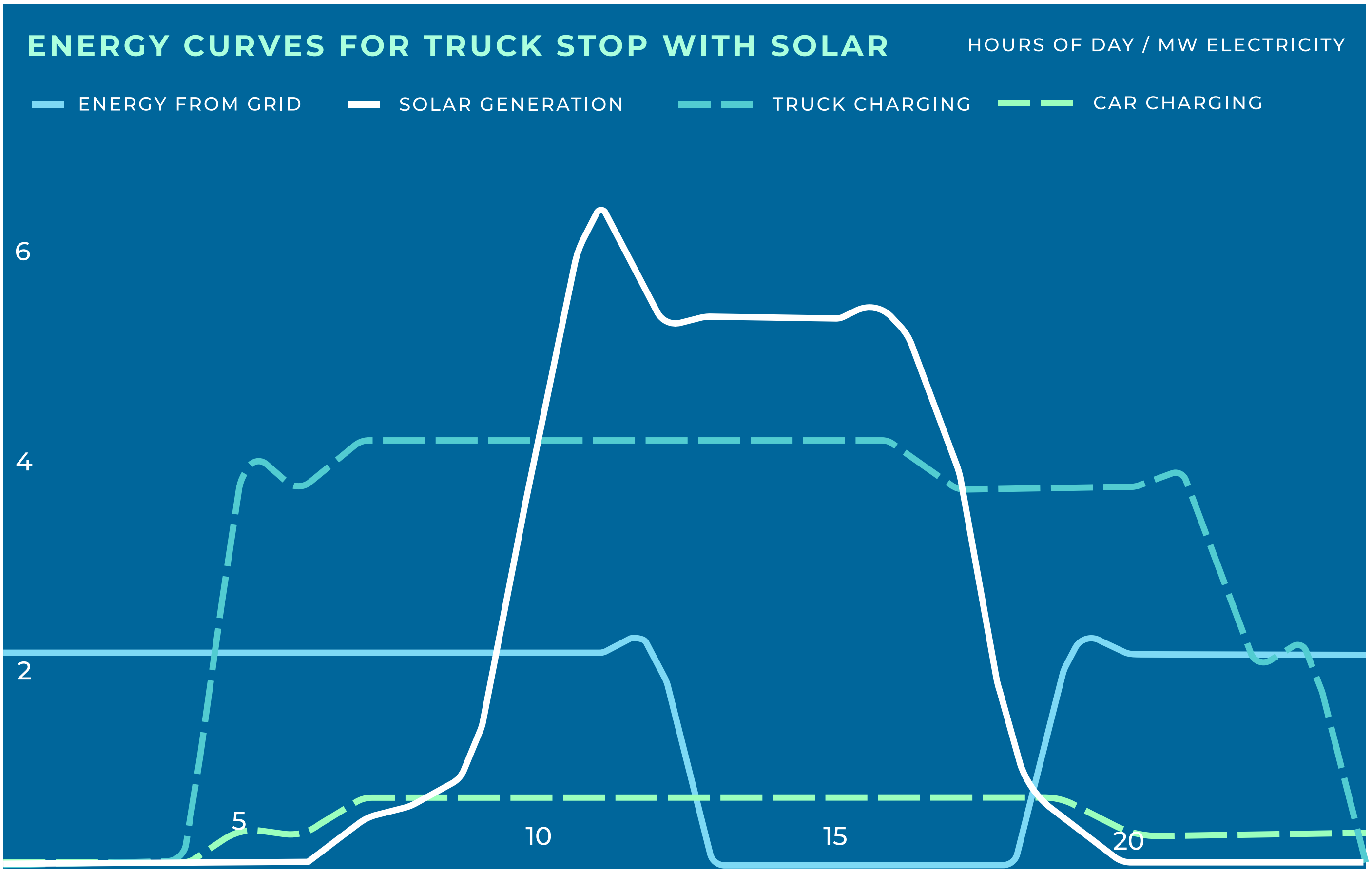


Figure 1: Electricity supply and demand curves for solar and battery microgrid truck stop

This configuration can charge around two hundred light duty vehicles and heavy duty trucks each per day, about 80 MWh of electricity. The solar panels — which have zero marginal cost of electricity and are inexpensive, commoditized 30 year assets with virtually no maintenance requirements — would provide a greater percentage of the charging electricity than would be drawn from the grid, roughly 60%. The grid connection would be much smaller and faster to deliver — while still a year or more — than attempting to charge this volume of vehicles from the grid alone. This increases the argument of availability and resiliency of electricity for heavy duty and medium duty vehicles.

The battery can be charged from the grid more in the lowest electricity rate hours or when the grid demand is low during the day. At present, this simplified energy scenario shows no grid draw when solar generation is at its peak, but it could equally be optimized for higher draw at low electricity costs during solar peaks, something that modeling will refine. At night it can charge up to optimum levels for expected day time demand and supply. During the mid-day solar depressed electricity pricing regime which is already being experienced in multiple jurisdictions, the batteries can be filled for the evening charging period when grid electricity rates and/or the axiomatic grid peak demands are high.

Computerized electricity management systems can juggle the equation of grid electricity price, projected charging demand, projected solar supply and battery performance to get the lowest possible cost of electricity provided to trucks every day. It will still service approximately 200 heavy and light vehicles each daily. This is another operational revenue that the truck stop operators and heavy and light duty vehicle owners can uniquely benefit from.

Because the solar electricity supply has zero marginal cost to the truck stop, with only the capital costs to service, the truck stop operator has significant flexibility in retail pricing of electricity and its operational use.

One key factor in pricing consideration models for electrification is still the average cost of diesel. All potential price points should be below the energy cost per mile of diesel truck to strategically create more value to electrified customers. The margin on sales of electricity will still be high, but price gouging is not a strategically wise move, as pushing other competitive truck stops that don't electrify as quickly out of business is a design point of the strategy.

In the scenario the authors envisage, the truck stop chain would centralize this power management and provide it as a service to local truck stop managers. Shrewd turnkey services contractors building truck stops would provide the same service.

When 60% of the fuel a truck stop provides every day is essentially free, the flexibility for profit maximization is high, especially in early days when they are the only game in town. Over time as more electrified truck stops emerge, the competitive landscape will change, but in the initial rush, early movers that can build incrementally scaled microgrids will be able to expand their market share.

The scenario is different for major logistics depots (illustrated below in figure 2). The same grid connection and the same solar generation again will service roughly 200 heavy duty and light duty vehicles each day. In this model, due to lower travel distances per vehicle due to a more local and regional duty cycle, two-thirds of all electricity in this scenario has zero marginal cost to the logistics firm. (Similar to figure 1, battery state of charge is excluded to reduce the busy-ness of the visualization.)

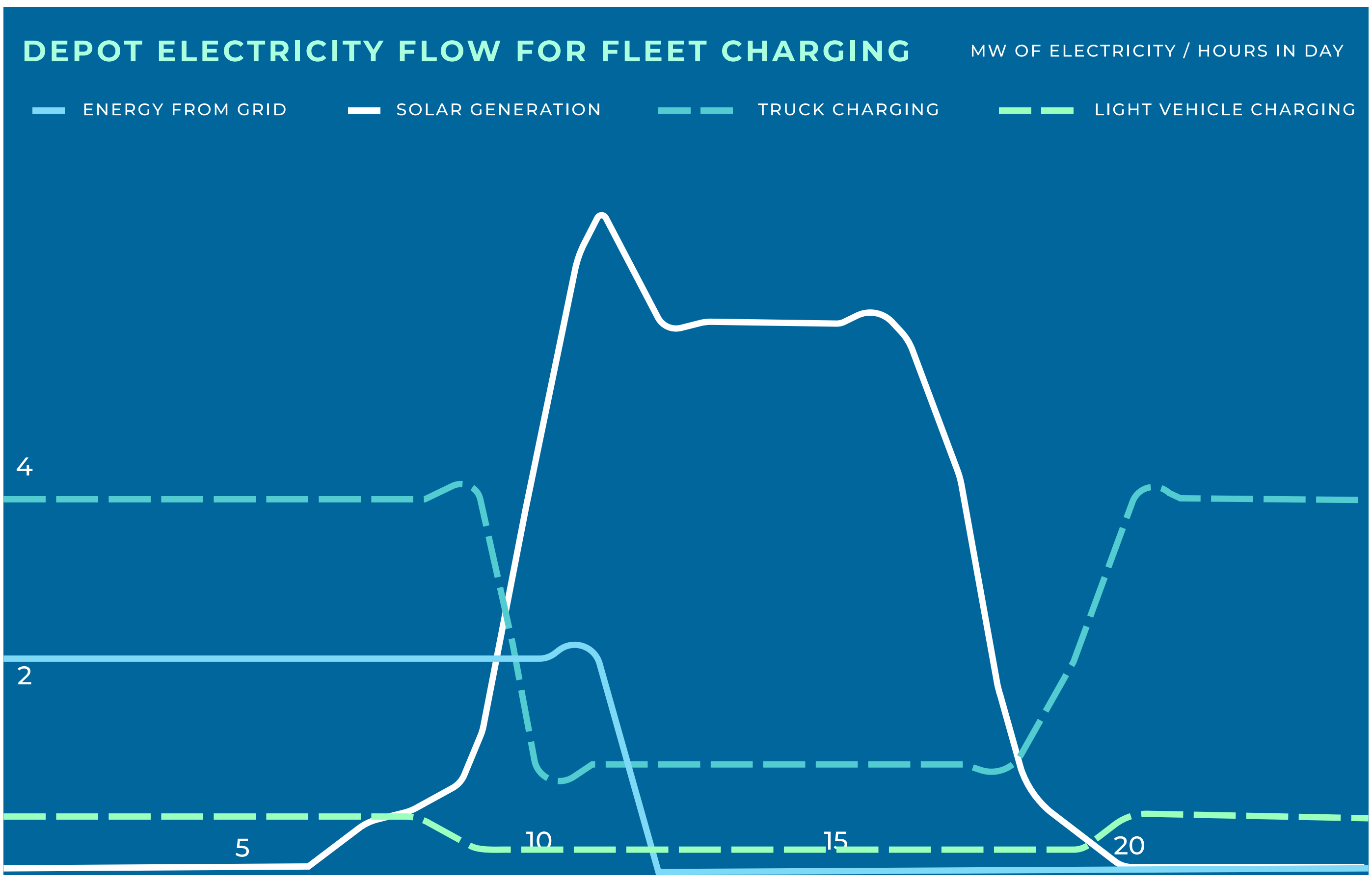


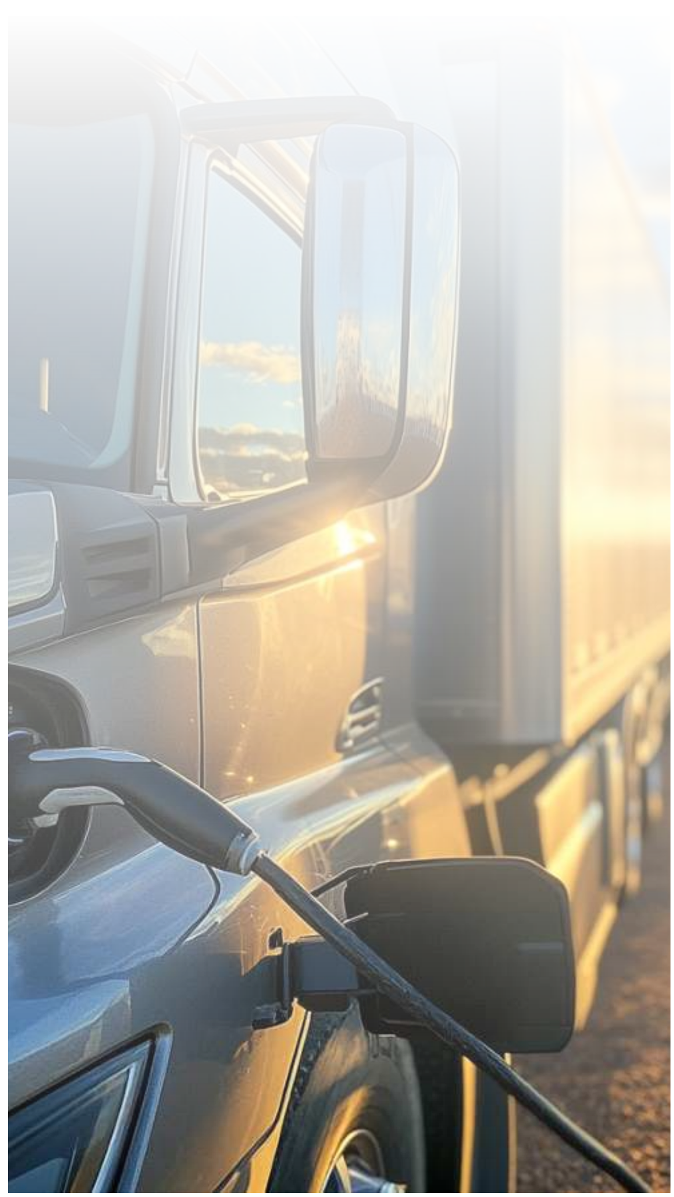
Figure 2: Electricity flows for charging trucks and light vehicles at depot

However, the requirement for megawatt scale chargers and power equipment is optimally sized and replaced with many more Level 3 and Level 2 chargers. Each vehicle's dominant pattern is overnight charging in this scenario, with much lower levels of electricity flowing into each one at any given time over a longer duration. Further, depot fleet vehicles, on average, travel fewer kilometers per day and can increasingly depend on en route megawatt scale charging for longer journeys. The buffering battery must be scaled up for this and the megawatt scale chargers on site are replaced with many more Level 3 and Level 2 chargers.

One key challenge that has to be designed into the truck fleets and charging solution is that standardized megawatt scale charging adaptors are different from present Level 2 and 3 charging adaptors, so fleet charging and flexibility may be inhibited, depending on the vehicle manufacturer if they don't support both. This challenge will not be relevant when projects deploy the North American Charging Standard chargers and trucks support them.

At this point, the profit maximization model looks at each vehicle's expected route for the following day with contingency, and optimizes the amount of electricity it receives for that journey. It's unlikely that it will ever be more profitable to charge at retail locations barring exceptionally long routes. Over the night hours, a pareto optimum can be identified for the size of the grid connection vs the size of the buffering battery for the use cases for the depot. More optimization can occur with operational data analyses between depot and logistics operators.

Once again, building to this point is an incremental process with this degree of electrification being the third or fourth



increment. Early increments will optimize lower revenue against lower capital costs and be constrained by grid connection time frames.

Organizations considering this will quickly realize that the solar generation curves in the examples above are for a notional average day in spring or fall. On longer summer days, more solar power will be generated, more than the buffering batteries and vehicles can absorb. Almost every utility in the U.S. has net metering in place, where local power generators can put electricity they don't require into the grid and receive compensation for it. The scenarios above have electricity from the grid going to zero for much of the day, allowing for zero marginal cost fuel. However, electricity flowing back into the grid provides another revenue lever.

But the larger concern with this average is not long, sunny days in July, but short, dark days in December. The solar curves will be much lower, but trucks will still have to roll. Thankfully, there are three easy answers. Upscaling the battery capacity and solar by 10% each covers 40% more of the declining curve of days outside of the sweet spot. During the microgrid increments design process, modeling a dozen sites around the U.S. against historical weather data per day — available on an hourly basis from the National Oceanic and Atmospheric Administration with historical records stretching back years — will enable optimization of each increment for scale and charging cost and benefits.

After those two levers are pulled, however, there will still be days without sufficient electricity for the needs of trucks. What's the answer there mission-critical sites beyond a bigger grid connection that delays all charging? Diesel, in two ways. For such selective depots and truck stops, diesel will remain a part of the truck energy equation for a couple of decades. Depots and truck stops already have backup generators intended for emergency use. During the modeling exercise, the days with insufficient solar generation and grid supply for the expected charging demand and what the electricity shortfall is will be clear. Running the backup generator to charge the buffering batteries on those days can be modeled. In many cases, the existing backup generator will be completely adequate. In others, part of microgrid deployment will be increasing the size of the generator at some sites.

Doesn't this defeat the purpose, many will ask. No. First, if trucks are running on solar generated electricity and increasingly low carbon grid electricity 95% of the year, running them on diesel generated electricity for 5% of the year is still a major reduction in emissions, which is a significant part of the point. Second, an electric truck running on diesel generated electricity is actually lower emissions than a diesel truck due to both the generator and the truck operating at optimal efficiency. Depot operators also have the opportunity to keep a few of their diesel trucks around on much lower duty cycles, using them on those dark December days, if that's the optimal solution.

Depots that electrify charging with solar and battery buffering isolate themselves from fluctuations in both diesel prices and grid electricity prices, and have 66% zero marginal cost energy for moving goods. This gives them a strategic pricing advantage over legacy depots that don't have the ability to invest, enabling early movers to take business away. One of the authors, Barnard, was discussing this strategic disruption coming to the road freight industry with a freight forwarder in Brussels recently, who projects 10% to 20% expense reductions for battery electric trucking operators, and hence a very different competitive landscape.

The major logistics firms that take advantage of this integrated microgrid charging strategy early will be about to outcompete the ones that don't, taking market share during the transformation.

Vehicle grid integration services facilitate interaction between electric trucks, microgrid infrastructure, and the electric grid to enhance grid reliability and integrate renewable energy. These services include managing charging based on grid prices or demand, using parked trucks (e.g., depots) to power local infrastructure, and powering the grid, when the freight operations allow it. Ghatikar has focused on improving vehicle grid integration operational economics and enabling interoperability of transportation systems across the grid stakeholders from standards. The standards cover data and communications, charging controls, and bidirectional energy flow, enabling trucks to be ready to offer vehicle grid integration services. Key standards include those developed by organizations such as SAE International, Open Charge Alliance, OpenADR Alliance, IEC, IEEE, etc., which addresses the technical specifications for power systems' connectivity. Standards for these services help cost-effective management of peak loads, grid reliability, and smart charging that aligns with integrating renewable energy sources into microgrids and managing grid reliability – and thus increasing the certainty of revenue streams, while providing environmental and social values.

For both logistics firms and truck stop or depot operators, solar and battery enabled microgrids with dynamic energy management open up new pricing and competitive levers – to provide high-grounds. This gives them the opportunity to overcome part of the challenges of capital expenses preceding revenue and uncertain revenue streams identified in the diagnosis section of this self-reinforcing strategy.

For green corridors, the differences in charging vs sunshine suggest that it would be in the best interests of both truck stop operators and logistics firms to compare notes to optimize costs vs revenue. There's the possibility to reduce the battery and solar arrays at depots, increasing dependence on en route charging at microgrid-enabled truck stops, at a lower total cost of ownership for the logistics firm and greater revenue for the trucking firms.

For all three audiences, as initiators, starting to explore their strategies around microgrid truck charging and developing revenue models that accommodate the changes becomes important.

07

Focus on Charging, Not Hypothetical Benefits

Key Takeaways

- Charging trucks is the first, second and third priority
- Side benefits to the site are welcomed, but can't be allowed to drive design decisions
- Don't let potential local or hypothetical value propositions distract from charging delivery

As the people who will be building electric truck charging microgrids engage in their design and implementation, they are going to hear a lot of things about how amazing microgrids are. To paraphrase the late comedian Gallagher, *microgrids slice, they dice, they even make julian fries, but you have to hit that sucker just right.*

The people charged with designing and deploying the incremental, modular charging microgrids at logistics truck depots and stops, whether they work for major logistics firms like Amazon or UPS, major truck stop firms like Pilot J or the engineering, procurement and construction firms that they engage, will be tempted to add value propositions from the laundry list of additional benefits they can bring. This has to be avoided for as long as possible, and definitely in the first round. Adding value propositions adds complexity and trade offs, and the focus needs to be on providing adequate charging infrastructure to trucks.

This doesn't mean that some of the benefits of microgrids won't accrue somewhat automatically, but they must remain secondary to the primary use case, getting energy into trucks as efficiently as possible.

Some of this is related to Parkinson's Law of Triviality, also known as bikeshedding, which states that "the amount of time spent discussing an issue in an organization is inversely proportional to its actual importance." The example Parkinson used in his 1957 book was of an organization building a nuclear reactor which spent vast amounts of time on the location, size and amenities of the shed for workers' bicycles.

This isn't to say that many of the value propositions of microgrids aren't useful and important, but many of them aren't useful and important to the organizations that need electric trucks fully charged and ready to roll. It's worth going through a list of them to explore which ones will be of merit, but which can't be permitted to override the primary concern.

Microgrids can cut costs by reducing reliance on expensive peak-hour electricity and optimizing energy use. With local power generation and storage, they can enable organizations to avoid high utility charges while potentially earning income by selling surplus power back to the grid and improving its resiliency. Smart energy management can save reasonable amounts of money. Prioritizing this above truck charging needs, however, could lead to poor optimization of charging trucks.

Modeling this out to optimize the cost case will be useful, and while each charging microgrid will be highly self-similar following the guidance in this strategic guidance report, local pricing on net metering and utility programs will have an impact. In general, however, the focus needs to be on maximizing the delivery of energy to trucks from the smallest grid connection that's feasible to avoid the long delays in large scale grid connections that could support large two-way flows of electricity.

Where grids are unstable and services are mission critical, then microgrids can offer organizations resiliency services, keeping the organization running even if the grid connection goes down. Given the scale of the buffering batteries required, potentially tens of MWh, running most facilities' other draws off of them in the event of a grid disruption is certainly going to be possible, but to be clear, the facilities that require charging — logistics depots and truck stops — already have diesel generators for that purpose. In the U.S., the average disruption per customer is about two hours per year, well above the European average and far above best of breed grids like Germany's and Denmark's, where the average is under 15 minutes per customer.

Initial increments for truck stops are going to charge relatively few trucks per day and week as the electric fleets build. Similarly, the initial increments of charging at logistics centers will have smaller buffering batteries as only a portion of the fleet will be electric in initial years. The first increment should be focused on rapidly getting charging enabled, not making the facility more resilient in the event of lower likelihood outages where a generator already exists. There will be time for site resiliency to be optimized in later increments. And to be clear, the diesel generator is a source of energy for electric truck charging that will likely be exploited part of the time.

Most of the other purported value propositions of microgrids are for other stakeholders who aren't particularly interested in ensuring that trucks can deliver loads and should be avoided as much as possible.

Putting storage and solar at the end of the distribution grid helps utilities to avoid buying more electricity wholesale in a couple of ways. The first is simply that if organizations are generating their own electricity with solar and using the environment to provide heating and cooling solutions through heat pumps, then there will be less demand on the grid to supply the electricity. This is a win for the utility that comes for free by building a charging microgrid, and should be leveraged as such in discussions, but isn't the point. The point is that the local grids can't supply truck charging fast enough or inexpensively enough, and microgrids with local generation are required to accelerate the transformation.

The second is that big batteries are a catnip for utilities in two ways. The first is demand management, paying organizations to lower demand from the grid at times of high demand, late afternoons and early evenings typically. This has been done traditionally with major industrial demand segments like pulp and paper mill drying ovens and aluminum smelters. However, the point of the charging microgrid is to minimize the grid connection and provide as much energy behind the meter as possible.

Similarly, utilities often look at big microgrids as backup storage that they would like to draw on to provide energy to more households and businesses in the local grid area. Avoid being drawn into discussions with utilities on these last two points. They are distractions from getting electricity into trucks. If utilities try to gain access, lean into the advantages the microgrid is providing by just existing and draw the line there.

Microgrids are often claimed to increase grid security from risks of foreign or domestic terrorism. A decentralized grid, the thinking goes, is much harder to disrupt. That's not the concern of the people who just need to put electricity in trucks. Once again, avoid opening that door, as time wasting cybersecurity and physical security types will flood through it, wasting time and money.

This doesn't mean that ensuring that the basics of physical and cybersecurity for the charging microgrid, the centralized management site and the communications links put in place, as well as any mandated utility and Federal Energy Regulatory Commission (FERC), and state's cybersecurity compliance requirements aren't important, but they are like the energy management system and the battery management system, just services in aid of keeping things running and grid secure. Get accurate and useful threat assessments, and don't let the budget for cybersecurity grow like kudzu.

Something that's both true and irrelevant to the needs of logistics and truck stop organizations is the value of microgrids in tackling energy poverty and enabling economic development in marginalized regions. Truck stops and logistic depots will often be in low income rural counties, and in many cases will be the biggest energy consumers for miles around with electricity, theoretically, to spare. In the event of a major power outage due to severe weather or other concern, by all means open the doors of the facilities if they are the only ones with electricity and people would be freezing in the dark.

But in general, the benefit of the charging microgrid to the region is future-proofing local employment at the truck stop or logistics center, not trying to ensure that impoverished people in the area have access to reliable electricity. There are other organizations working on that. If local municipal organizations try to engage in discussions about sharing the microgrid electricity abundance more broadly, point to the employment and local tax revenues from the facility's continued existence and focus on getting charging working.

The last one is a pitfall disguised as a shiny bauble, technological innovation. Microgrids are seeing a lot of efforts around cutting edge AI optimization of power, best-of-breed batteries, and brand new power management solutions. Avoid everything cutting edge. Get what works and is proven to work reliably. Charging grids aren't sandboxes for innovators, they are the equivalent of diesel tanks and gas pumps. The sandbox is the central staging site and the pilot or three that destruction-test the design before field deployments.

To these points, in most cases major logistics and truck stop operator organizations will be engaging contractors to design, build and operate the charging grids, not having the expertise in house (at least not immediately). When working with them, these guidelines for what to focus on and what to avoid have to be discussed early and regularly. It's easy for these extraneous value propositions to be injected by microgrid enthusiasts as it's relatively early days for this form of technology, and many people working in the space have the air of evangelists more than pragmatic deployers.

The key challenges related to charging microgrids identified in introductory sections for this strategy that this approach will address include risks related to interconnection and utility coordination, uncertainty related to revenue streams, badly or over-optimizing cybersecurity and avoiding the challenges in resiliency and reliability measurement. A strong focus on getting trucks charged will simplify the program significantly.

When engaging an engineering, procurement and construction firm to design and build incremental, modular microgrids, make it clear that the most reliable, least expensive charging of trucks is the first, second and third point, that secondary benefits outside of that to the site are just that, secondary and must not drive design decisions, and that larger local value propositions are restricted solely to what is automatically delivered by having a microgrid at all.

08

Lean Into Modularity To Get Big Things Done

Key Takeaways

- Tailor charging solutions for heavy-duty trucks at stops and depots
- Modular and standard component choices are key to scalability
- Optimize charging for local and grid resiliency, and utility engagement

The principles of cause and effect have deep roots in scientific exploration, ancient philosophy, religious teachings, and later, reflecting humanity's attempts to understand and explain the world's workings throughout history. Modular microgrids with optimal charging infrastructure is one such effect that can accelerate economic and environmental benefits from truck electrification. In support of truck electrification, this section focuses on modular deployment of charging infrastructure for trucks and related microgrids.

In Bent Flyvbjerg's book *How Big Things Get Done*, the book that topped business book charts in 2023, he and co-author Dan Gardner chapter nine asks *What's Your Lego?* The concept for success encapsulated in this is modularity, repeatability and manufacturability. It's a core design concept for the electric truck charging transformation over the coming decades.

To effectively support microgrid-centric charging infrastructure for HD trucks, infrastructure must be modularized and designed to incrementally meet low or high charging requirements and align with freight operations. Trucks need megawatt charging to minimize downtime, particularly at truck stops.

As noted in the earlier section related to the diagnosis of truck charging realities in the United States, depot charging and truck stop charging have different charging levels and hence energy usage patterns and technologies.

For truck stops, megawatt charging is required. An initial microgrid with two megawatt chargers, battery buffering and some rooftop and canopy solar would suffice for initial volumes of truck, and as per the design point for incrementalism, more capacity can be added in carefully designed increments. For depots which house fleets of trucks, lower levels of charging for longer periods overnight typically suffice, but for all but small fleets will still require microgrids with buffering batteries and rooftop solar.

The first sections on actions recommended starting with small-size microgrids with lower investment and electrical supply needs and then incrementing them as the full fleet electrification requires procuring larger grid connection permits and time frames, more chargers, increased local generation capacities, demand flexibility, etc.

One key point regarding this is that several of the technologies are inherently Lego. Batteries and solar panels are among the most modular, manufacturable items we use in our economy today. Megawatt scale chargers are modular as well and can be added incrementally as charging demands increase, something explored more fully in the first section on incrementally adding charging capacity to microgrids. However, megawatt charging isn't standardized yet, so expect some change management to occur with related costs in the first few years.

A challenge that the target audiences for this material must also consider is that at present transformers and converters aren't as modular and are constrained in supply.

Transformers, which step the power from the grid up or down to the required levels, and converters, which shift the power between alternating and direct currents, currently face three challenges in the U.S. The first is that legacy manufacturers such Hitachi and Virginia Transformer build them to specifications for the site. This slows the process as each unit is generally subject to a complete engineering, design and quality assurance process instead of being manufactured on an assembly line.

The second problem is that as with many other industrial products, factories for them have mostly left the U.S and China dominates the market. Hitachi, to deal with this, has a strategy of having smaller factories in many countries, not just China, so it can provide the technologies to the U.S without concern of tariffs or the — frequently expressed and unwarranted — fears of cybersecurity risks.

The third problem is that everyone in the world is buying transformers and converters as the world electrifies transportation, heating and industry, and builds vast quantities of wind and solar energy. There's a shortage, and in some cases where big grid connections are required, sometimes getting the power management components can take almost as long as getting the grid connection itself.

Firms like Florida-based AmePower, which currently services and maintains transformers and converters from multiple vendors in the United States, are attempting to resolve this with modular, manufacturable units which are software configurable to perform both transformer and converter duties, and can be combined in serial or parallel depending on the power and energy requirements.

They intend to build them in the United States for the US market. Finding a partner like AmePower and enabling them with the capital they require is a logical step for a major organization like Amazon.

The modularity of battery systems leads to easy incremental additions to capacity without having to replace the first deployed batteries. Similarly, intelligent choices about where to put solar in the first, second, third and any other increments will mean that initial deployments can simply continue to operate as new capacity is installed. Careful attention is required to the converters and transformers to avoid having to rip and replace them when upgrading. This is possible, but isn't common today, and moving smaller transformers and converters between sites at different levels of capacity might end up being required.

This action helps address the challenges of high initial costs, lack of standardization, cybersecurity concerns and limited awareness and technical expertise that were identified in the diagnosis of charging microgrids early in the series.

Incremental capacity approaches differ for major depots and truck stops, but modularity is key to both. Find your lego and stick with it.

09

Focus on Common Solutions to Enhance Charging Deployment

Key Takeaways

- No truck stop or distribution center is unique
- Establish corporate control and management of the program
- Optimize the mix of vendors and staff for different phases of the program

The uniqueness bias is a finding of Professor Bent Flyvbjerg, global megaprojects expert and author of the 2023 business book of the year, *How Big Things Get Done*. It is the tendency of decision-makers, especially in large-scale projects, to overestimate the novelty or distinctiveness of their project, leading them to believe that standard benchmarks, historical data, or lessons from other projects do not apply.

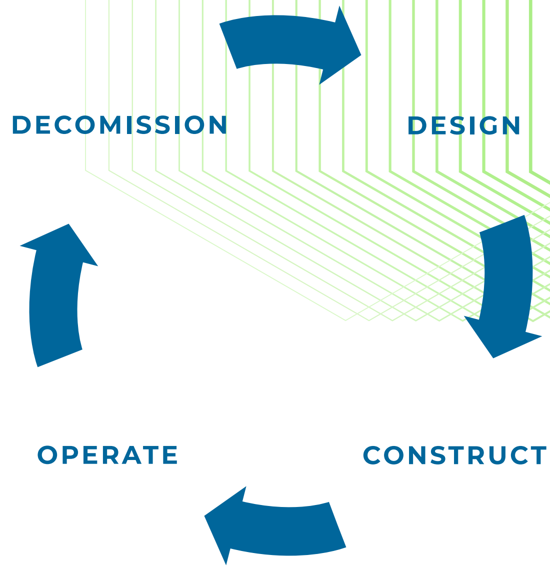
And it's the enemy of incremental charging microgrids.

Every site will claim it has unique attributes that require a custom solution. Every engineering, procurement and construction firm will attempt to get you to engineer a solution for every site's purportedly unique characteristics. Every microgrid component vendor will attempt to upsell you on their product. Every local politician and business development agency will try to get you to use local — or at least well connected — vendors for the microgrid in their county or municipality. They'll all be touting the unique challenges or benefits faced.

It's all nonsense. A big truck stop is a big truck stop and a big distribution center is a big distribution center, regardless of whether it's in Minnesota or Louisiana. It may get a little less sunshine and more snow, but it's the amount of space that determines how much solar can be put on the site, not the weather. It may be hot or it may be cold, but the batteries still need thermal management. It may have a more robust local utility or one that can't keep the lights on, but trucks still need charging. It still needs battery management systems. The utilities providing power connection may be different, yet they all need the same electrical connections.

The target stakeholders for this strategy for microgrid charging operate hundreds or even low thousands of sites, or build those sites for their customers. The cookie cutter strategy outlined in other chapters in this set of internally reinforcing actions call for incremental additions of highly standardized and modularized components over time, but the increments and components have to stay the same, or the benefits start to erode.

Target stakeholders must consider the replicability during the design, construction, operation, and decommissioning processes that we refer to, as microgrid charging lifecycle. The microgrid charging lifecycle is a set of interconnected processes where the lessons from one process must be incorporated into new microgrid processes for improved efficiency and economics (e.g., issues identified during construction and operation can lead to better design process).



CHANGING MICROGRID LIFECYCLE

As we consider the challenges, an initially small microgrid that grows in increments with standards-based modular components addresses many of them. It avoids significant capital costs early in the lifecycle of the microgrid charging and improves operational efficiencies during construction and operational phases. It is much easier to shepherd through often complex regulatory and policy barriers, typically avoiding them entirely. It makes interconnection and utility coordination much simpler, potentially reducing it to simple municipal electrical inspections and approvals. It specifically leans into components and communications standardization.

For optimal operations and procurement of microgrid systems and grid integration, consider standardized control strategies and communications for energy services that generate revenue – particularly for depots with more charging flexibility. Summary actions to standardize components and software at all stages of microgrid charging lifecycle are listed here.

DESIGN (ENGINEER, PROCURE)	**CONSTRUCT** (INSTALL, TEST, COMMISSION)	**OPERATE & DECOMISSION** (SYSTEM, SOFTWARE, SERVICE)
• Standardize infrastructure & procurement plans. • Modularize megawatt charging & distributed energy resources for infrastructure. • Engineer & procure standardized hardware, software & components. • Ensure compliance to regional utility needs. • Pre-test full system for procurement compliance.	• Install & test megawatt charging & distributed energy resources for grid-connected and islanded modes. • Ensure full-system is compliant to engineering & procurement terms. • Test software & service compliance. • Obtain commissioning & operational certificates.	• Conduct annual safety tests for all system software and & services. • Use monitoring systems for day-to-day operation. • Add energy services to stack on revenues and increase grid resiliency. • Develop maintenance and training procedures for efficient operations and decommissioning.

The lifecycle approach ensures capabilities exist and avoids concerns about balancing local grids and providing resiliency and reliability services when not needed. Those capabilities can be added later as the microgrid grows, but trying to build them in initially as a good neighbor will simply bog the entire process down, defer revenue and add complexity.

Standardization enables an installation team and local contractors to deploy the same thing over and over with no local flavors. Microgrid components can be assembled and tested in regional staging sites and shipped virtually intact for deployment. Tesla does this today with its Superchargers, assembling several of them on a poured concrete slab at the factory with all of the power connections and power management technology, and then delivering the slab by flatbed to the site for lowering onto the parking lot and connecting to the grid. That's the model to work toward emulating.

A strategic and competitive vendor management approach with the providers

of transformers, converters, battery systems, solar panels, charging systems and the software systems which manage them will enable the best prices, the highest reliability and the best service levels. A patchwork quilt of different vendors around the United States (U.S.) would lead to higher overall costs and lower service levels.

Over the course of the fifteen to twenty years of transformation of all sites, millions will be spent on each site, with the total program being over a billion dollars. This is a megaproject of many individual projects and needs to be treated as such.

The authors of this strategy series between them have extensive experience with major programs. Ghatikar ran decarbonization programs with the US Department of Energy, including a focus on microgrids, and worked for GM in their energy division as they considered how that firm could accelerate delivery. Barnard's work experience includes running projects delivering new computer and telecommunication upgrades to 1,400 physical locations, including five on permafrost in the far north, authoring incremental major program management methodologies and solutioning and kicking off billion dollar technology projects on four continents.

Beyond the advice to buy How Big Things Get Done and read it, they have some key recommendations for ensuring that the uniqueness bias doesn't dissolve the benefit case over the time scale in question.

First, establish a corporate team devoted to this. It's not something that is going to be done off the side of anyone's desk, it's not something that local teams will figure out, it's not something the corporation can put in the normal project hopper for the operations team to figure out. This is a major, potentially billion dollar plus program that is going to last a couple of decades. It needs executive leadership, visibility and budget

.

Second, centralize design authority in the corporate team. Regardless of what regional managers or technically talented site operations teams think, this is a corporate function. If there are talented site operations teams that have been experimenting with this, bring them into the fold and ensure that they are working according to the major program, incremental and modular play book. Hire talent into the corporation if it isn't present.

Third, do serious modeling and simulation of sites and projected growth to establish the increments that make sense. Test those increments virtually with simulations. As Flyvbjerg says, this is a place to think slow and act fast. The time spent up front will speed deployment later and reduce overall program cost.

Fourth, seriously consider bringing engineering, procurement and construction in house. Establish a strategy around those functions. Having a third party firm running a two decade program for you starts to look a bit odd after a while, and when it's up and running, most of the design decisions will have been made, with only local approvals and inspections requiring variance. Firms will need the talent for oversight, control and deployment, and whether it is inside or outside the firm is a choice.

Fifth, lock down the design of the increments. Establish clear change order policies for what can be approved and what can't be approved by the people running the day to day deployments. Deployment will require local contractors who will be looking to maximize their revenue with change orders, and that can lead to both inflated costs but also lack of the standardization the solution requires.

As the program continues, there will be clear reasons to adjust the design of the increments, whether due to plummeting battery costs or soaring battery energy density changing the optimal mix, significant strategic changes in site scale or other reasons. Make changes to the design of the increments a significant governance decision. There is strong value in standardization, and changing is a serious choice that requires consideration and care. Sixth, feet on the ground site surveys by the microgrid function are critical. Corporate data on sites is only so good, and corporate data systems weren't created and filled with the needs of a charging microgrid in mind. The site surveys are about fitting the increments into the site and confirming which increment is appropriate, not changing the design of the increments. Seventh, data is key to this. Establish a database of sites with the specifics of what the surveys find, the contractors that will be engaged, the status of submissions and approvals, the specific components to be deployed and the schedule. This isn't a Microsoft Project GANTT chart, it's a centralized, managed and maintained database. At any given moment, it should be possible for the executives and staff in the corporate function to know exactly what microgrid components are at the site, and what is happening next.

Eighth, an executive dashboard of objectives and key results (OKRs) for the program is going to be required. The program needs to establish the OKRs, track them and report on them regularly, quite possibly at the Board level given the expenditures involved and the level of transformation of the business being undertaken.

Ninth, weed out innovators when their useful time is over. The first phases of the program will require people who delight in building something new, figuring out the different optimal solutions and deciding between them. But when the program shifts into deployment of the same incremental charging microgrids time after time after time, innovators will be unhappy. Find something else for them to do and bring in operational efficiency experts and people who love knowing exactly what to do. Both types of people are valuable, but the mix of them will change over the project, and if it's not carefully attended to, something like the Tesla Supercharger mass firing can result, a disaster Barnard wrote about when it occurred. That was a failure of management, and it's an obvious risk to avoid.

The key challenges related to charging microgrids identified in introductory sections for this strategy that this approach will address include the risk of lack of standardization, cybersecurity concerns and the lack of site awareness and expertise.

Delivering high quality and reliable charging microgrids isn't rocket science. Solar panels and batteries are inexpensive, commoditized and reliable components. Charging is well understood and there are reliable, scalable solutions there. But not treating the program seriously and as a megaproject will result in a variety of predictable and expensive failures. Think slow and act fast.

10

Target Corridors with Strong GDP and Climate Goals

Key Takeaways

- Focus on high-potential corridors with strong GDP, climate action, and low-carbon electricity
- Drill down to county-level data to align charging infrastructure with local needs
- Start with collaborative pilots and scalable microgrids to drive adoption

When rolling out electric truck charging microgrids for depots and truck stops, a key question to ask is: Where first? The audiences for this strategic perspective — major logistics firms like UPS and Amazon, major truck stop chains like Pilot and major turn-key truck stop and depot contractors like TLM and Gray — may agree with designing a menu of incrementally bigger capacity microgrids for truck charging, but which of the hundreds of depots or truck stops they own and operate, or the thousands of depots and truck stops across the USA should they start with?

The authors have identified a key set of filters to assist with this strategic choice, and roughly tiered US states into these categories. Our starting filters were gross domestic product (GDP) per capita, climate action orientation and carbon dioxide or equivalent per kilowatt hour (CO_2e/kWh) of electricity.

GDP per capita was chosen as a proxy for three things. The first was purchasing power per person, the likelihood that a lot of freight would be flowing on roads within the state. The second was the ability of consumers to pay a green premium, if any, for early additional costs for shipping. The third is the ability of the state to fiscally support incentive programs for decarbonized trucking and charging microgrids.

Climate action orientation was chosen not for ability but for willingness to pay. It's a proxy for consumer willingness to pay a bit extra or to feel positive about lower carbon deliveries. It's a proxy for a state being willing to allocate budget dollars to decarbonized trucking and charging microgrids.

The carbon intensity of electricity, CO2e/kWh, was chosen because it has a direct correlation to the carbon intensity of freight trucking. As one of the authors, Barnard, published in mid-2024, road freight trucking with electric semi tractors is already lower carbon than rail in eight US states. This means that in these states, where there is any impetus for lower carbon shipping, trucking will empirically be lower carbon and hence more preferred by organizations measuring that and delivering to their customers' and stakeholders' preferences.

CO2e/kWh was averaged from the different grid subregion data produced by the US Environmental Protection Agency in their eGrid dataset, most recently published in early 2024 for the year of 2022. While state-level aggregation is appropriate for this detailed analysis, logistics and truck stop firms will want to do the modeling at a county-by-county level to ensure that locations' electricity carbon intensities are accurate, as side-by-side grid sub-regions can have substantially different intensities, and some states are a patchwork of sub-region grids. Both Alaska and Hawaii, for example, have two grid sub-regions with quite different carbon intensities.

As a reminder, the trajectory of carbon intensity in all grid subregions in the

United States is downward, but some grids are greening faster than others. Texas continues to surprise observers as the dominant jurisdiction for wind and solar generation deployment, rhetoric from the state not matching investment on the ground. Renewable generation is just cheaper, so it's outcompeting even natural gas generation in purchasing decisions across the country. Every MWh of renewably generated electricity displaces a MWh of electricity generated with natural gas or coal, so the effect is lower carbon emissions from electricity everywhere.

However, the authors have carefully chosen carbon dioxide or equivalents as the measure, provided by the eGrid material. This measures not on carbon dioxide, but also methane and nitrous oxides. Methane, the dominant component of natural gas, has a very high global warming potential, 30 to 80 times that of carbon dioxide depending on the timeframe considered. Nitrous oxides are in the range of 270 times more heating than carbon dioxide. Natural gas generators and the extraction, transmission and distribution systems that lead to them leak methane. When natural gas is burned in generators, nitrous oxides are a result. This is gaining much more focus, and measurement is finding higher leakage at every step of the value chain than previously assumed. Natural gas heavy grids are likely to see adjustments upward of CO2e/kWh as a result.

This matters for both accurate assessment of carbon intensity of electric trucking, but also for supply chains that lead to exports to Europe and need to be accurately reported on. Europe's carbon border adjustment mechanism will include methane and nitrous oxides in 2026, the same year that imports to the economic bloc will start incurring the carbon price. Ignoring these two potent greenhouse gasses isn't advised.

As noted in the diagnosis of all freight modes in the United States' ability to decarbonize, while freight rail is under pressure by major logistics firms such as Amazon, rail organizations' likelihood to actually decarbonize given the major headwinds in the country is low. This puts the country at odds with every other major economy in the world, and the technical reasons given are specious, but effectively the federal government would have to pay for the electrification of roughly 50% of all tracks in the USA and for conversion of the majority of locomotives in order for it to occur.

For each of these we gathered state level data, and then extrapolated to a score of one, two or three for each state, with three being highest. California, for example, scores a three in each category, while Missouri scores a one in each. These were summed to create a state score out of nine, and then the states sorted and grouped by scores.

As a note on the methodology, both authors have created multiple scoring methodologies for various strategic ranked choice initiatives over the couple of decades of their global careers. However, in recent years Daniel Kahneman's book Noise: A Flaw in Human Judgment with Olivier Sibony and Cass Sunstein has persuaded us to change our approach. The authors of the book make the clear statistical case that in scoring matrices, fewer criteria with no weighting give more reliable results.

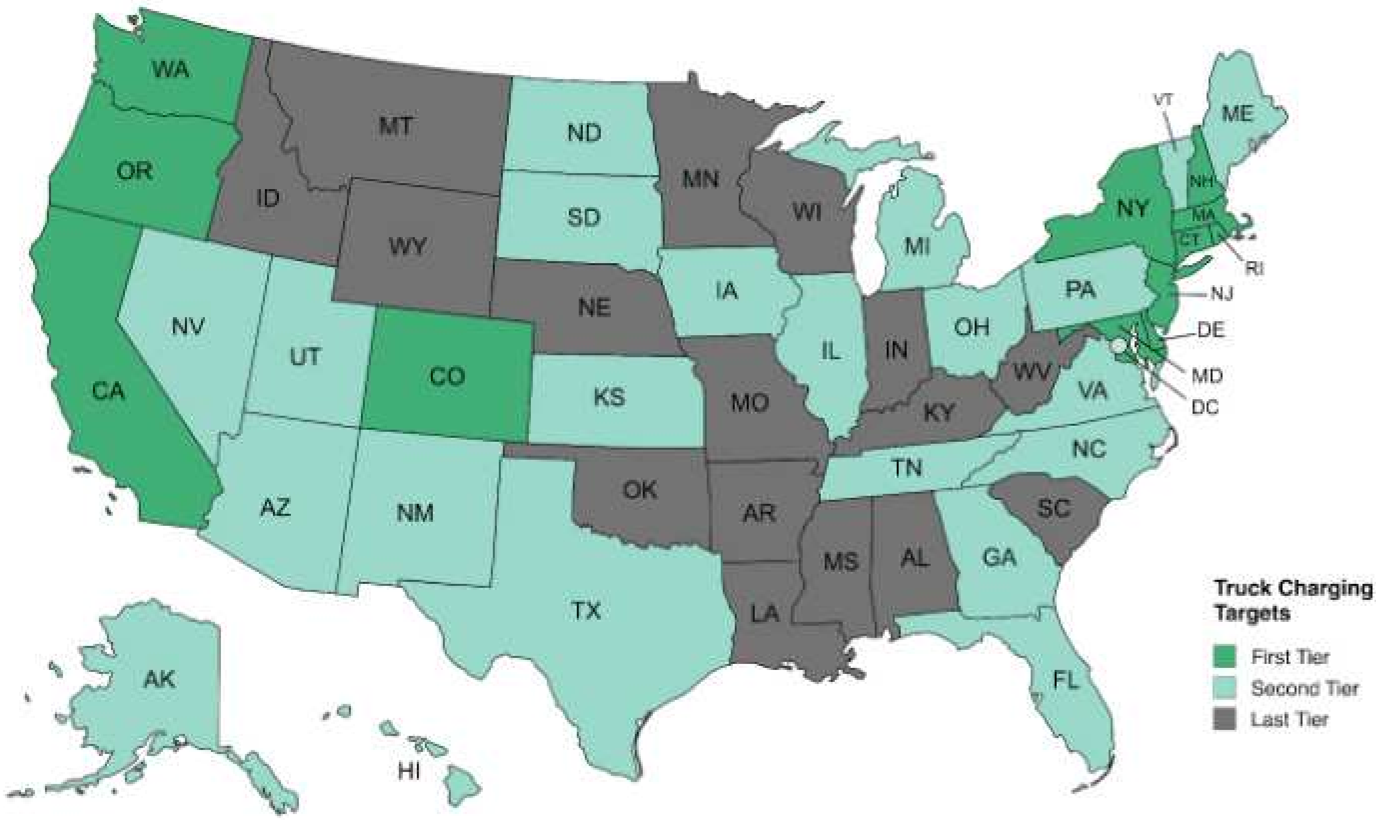


Figure 1: Map of Prioritized States For Microgrid Truck Charging

At first blush, the map of states coded with tiers is an unsurprising result. If the analysis had shown anything other than that the western and northeastern coastal states were highly ranked based on the criteria, the analysis would clearly have had an error. Obvious green truck charging corridors for the first waves are up and down the west coast and into affluent, climate-focused British Columbia, and likely from New York state to Virginia.

Second wave green truck charging corridors are likely from Virginia to Florida and from Texas to California.

Third wave green truck charging corridors would include two cross-country routes from Florida to California and from New York to Indiana, then possibly down to Kansas and straight across to California, taking advantage of Colorado's strong showing.

For the target audiences for this microgrid strategy, there are three actions to take. The first is to do a more comprehensive analysis of this type, but include the factor of existing facilities for logistics firms and truck stop chains, and for market connections and strength for turn key firms that build depots and truck stops. This will firm up the strategic order of events.

The second is to subdivide the analysis down to the granularity that makes sense for your business, the county level for physical locations to get the accurate carbon intensity of electricity, high-volume routes for logistics firms and other factors.

The third is to assess the major routes that emerge to look at specific locations, traffic volumes today, likely traffic volumes in the future given a shift of additional container volume from rail, and compare to the initial microgrid incremental sizings to see if there's any requirement for adjustment.

At this point, there is sufficient information to identify a pilot route or two. They must be high enough profile that there's skin in the game, and have willing participants in the local management and workers. Picking from the highest tier of routes with the most favorable local governments will assist with success.

For truck stop firms, an analysis of distances traveled for electric trucks between truck stops will be necessary, as current trucks vary considerably in terms of usable range. An analysis of current and near future ranges will assist in sub-selecting the truck stops out of the route to target first. Picking locations in low carbon intensity grid subregions and enabling driving across high carbon intensity grid subregions is a good refinement to make.

The challenges that this approach takes reduces the complex regulatory and stakeholder barriers that building microgrids face in many jurisdictions. The affluence of customers and potential for increased market share by taking volume from rail reduces somewhat the challenge of capital expenditures preceding revenues. The combination of actions the authors are suggesting address all of the challenges, without eliminating them.

11

Ensure Charging Success through Stakeholder Leadership

Key Takeaways

- Those benefiting from charging microgrids must spearhead their build
- Stakeholders must collaborate to share growth and revenues
- Use federal and state-level incentives to enhance bankability

R. Edward Freeman, an American philosopher and scholar, is best known for his work in the field of business ethics and strategic management. In 1984, he published a book, "*Strategic Management: A Stakeholder Approach*," and its foundational *Stakeholder Theory*. The theory emphasizes that businesses should create value for all stakeholders, and has significantly influenced how companies approach corporate social responsibility and ethical decision-making – all while focusing on the profits.

In the United States (U.S), electrification of freight transportation is an opportunity that creates economic, environmental, and equitable value across stakeholders and communities. While the freight transportation sector is responsible for about 10% of the total greenhouse gas (GHG) emissions in the U.S. the medium- and heavy-duty (MD, HD) trucks are the largest contributors. This underscores the importance of stakeholder efforts to deploy microgrid-centric charging to foster electric truck adoption. To simplify the requisite processes, this section focuses on action for a core set of initiators who, as a team, create value across all the other stakeholders.

Focusing on the three major audiences or initiators – freight operators; owners and operators of truck stops or depots; and turn-key engineering procurement, and construction (EPC) firms – this section highlights how the initiators can create value across the stakeholders, coordinate charging and microgrid build outs at truck stops and depots, and navigate state and federal policies for incentives. The suggested actions originate from one of the challenges identified in the diagnosis of microgrid charging, the high potential number and complexity of stakeholders for microgrids extant in the literature and due the many purported value propositions.

As shown in the illustration below, an owner and operator of the truck stop or depots such as Pilot Flying J, TravelCenters of America, etc., should engage with the freight operators such as FedEx, UPS, etc., to identify truck charging requirements and partner with a turnkey EPC firmfocused on depots or truck stops such as TLM Development Company, Trinium Inc., Snyder Construction Group, etc. to develop charging infrastructure. An EPC firm designs and builds modular and standardized microgrids and scales it across truck stops or depots. The firm further coordinates with all the necessary stakeholders (e.g,. utility, microgrid operator) to build a microgrid and its increments.

In this teamwork, each of the initiators mutually benefit from the partnerships. The truck or depot operator meets the charging needs of the freight operator, who in return creates new revenue to the operator. Similarly, the operator of truck or depot stops bring new business to the EPC firm. The coordination is simplified and the benefit is enhanced when a freight operator is also the owner and operator of a truck stop or depot. The ownership of truck depots is closely tied to the largest truck operators, as they operate extensive networks of distribution and service hubs for efficient freight operations, critical to their transportation services.

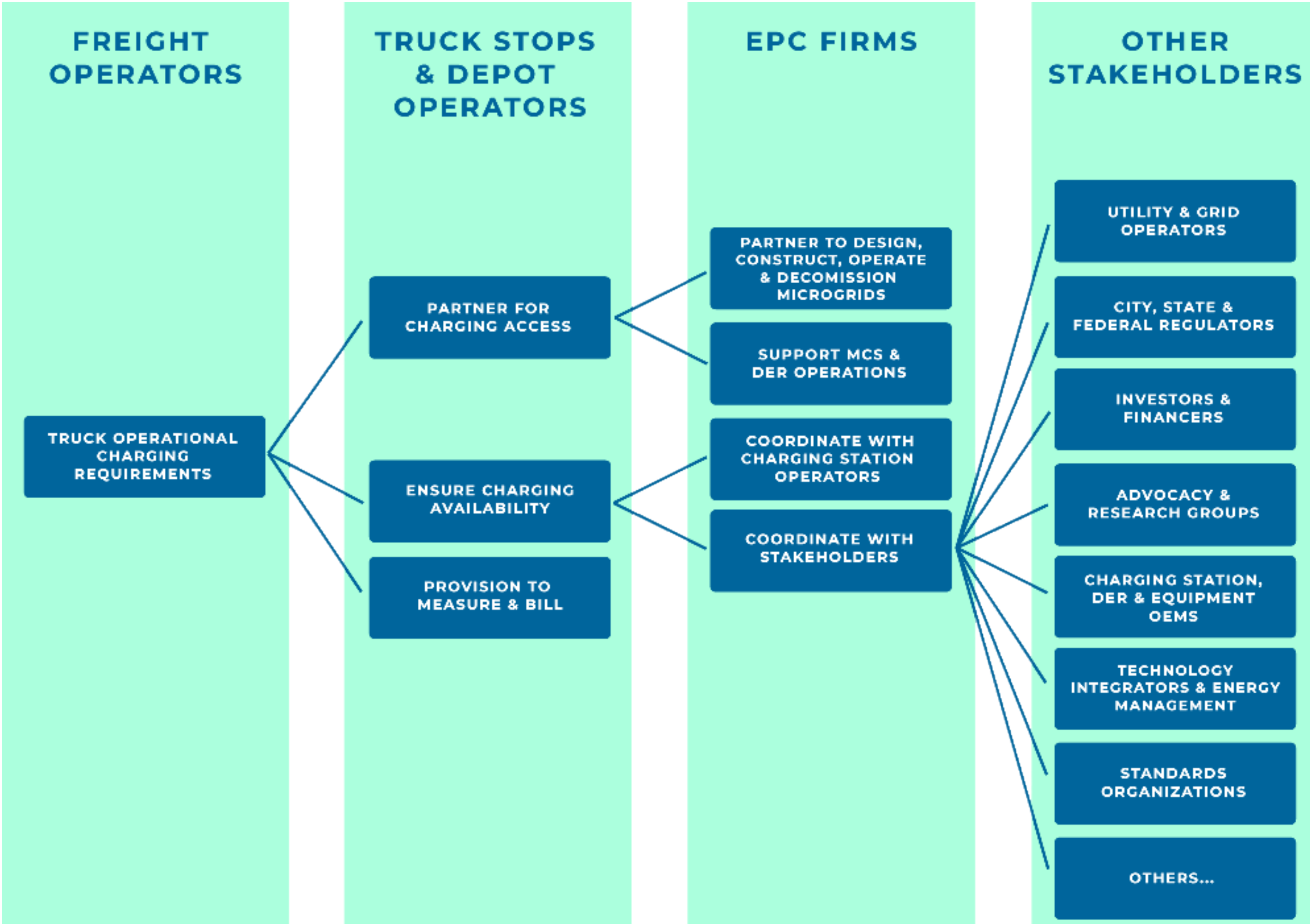


Figure 1: Simplified Stakeholder Coordination Action for Freight Truck Electrification

Actions such as standardizing microgrid components, software and processes must be targeted to modularize and scale microgrids, which reduces cost. Incremental expansion of charging and distributed energy resources must be iteratively planned and modeled to assess economic and environmental benefits from buildouts. Even with the EPC firms' turn-key solutions, and modularized and standardized equipment, any microgrid expansion must conduct a review for any further coordination with other stakeholders. Examples include land expansion needs with other land owners, and review of energy service revenue options with utilities. Planning for truck charging and supporting distributed energy resources and power systems equipment require coordination with stakeholders that the EPC firms can address with the knowledge of the location of truck stop owner and operator. For location-specific regulations, the EPC firms should proactively plan and coordinate with all regulatory agencies, utilities and grid operators, research and advocacy groups, and standards organizations to ensure that all requirements are identified and can be complied with.

Key stakeholders worth highlighting are electric utility or grid operators, and microgrid operators. The utilities or grid operators play a crucial role to facilitate a successful deployment, integration, and operation of microgrids with electric supply and energy services that can also benefit the overall energy system and community resilience. The energy service offerings from the utilities or grid operators creates new revenue opportunities that are shared between the truck stop or depot operator, and freight operator. In coordination with utilities and grid operators, a turn-key service EPC firm can further engage with advocacy and research groups and standards organizations to better understand regulatory requirements and leverage tools and expertise available for their compliance at all the stages of microgrid charging lifecycle, as highlighted in earlier actions.

Another stakeholder, specifically when the operator of the truck stops or depots cannot engage in the day-to-day microgrid operations, is an operator and maintainer of microgrid and charging infrastructure. Truck stop and depot operators should monitor basic microgrid operations with software tools (e.g., dashboards with key metrics and basic controls). Complex monitoring and maintenance (e.g. power quality, battery safety) require subject-matter expertise. One can anticipate that over time, the owner and operator of truck stops and depots, depending on the value, also operates and maintains a microgrid. In the interim, a microgrid operator must ensure safe and reliable operations of microgrids and charging infrastructure. In such instances, the truck stop and depot operators must coordinate with EPC firms to identify the stakeholder and include the procurement terms in the EPC service contract.

When considering a new microgrid buildout or an expansion, the owners and operators of truck stops and depots face a key challenge, i.e. lack of awareness of economic and environmental value a microgrid-centric charging provides. The operator of truck stops and depots and EPC firm must conduct techno-economic and benefit-cost evaluations to identify value streams, and also the terms for microgrid charging lifecycle, as highlighted in earlier actions.

Additionally, the EPC firms should identify all state and federal government incentives that reduce the overall costs for the owner. In 2024, U.S. federal and state agencies provide incentives for truck charging owners, aiming to foster the adoption of charging infrastructure for MD and HD freight vehicles. These incentives include grants, tax credits, and programs focused on infrastructure development. Examples of federal incentives include the National Electric Vehicle Infrastructure (NEVI) Program that provides $5 billion over five years to states for the development of a high-speed charging network along designated alternative fuel or electric truck freight corridors. The Investment Tax Credit (ITC) from the Inflation Reduction Act (IRA) allows certain charging station owners for tax credits up to 30% of installation costs, with higher credits for projects located in disadvantaged communities. States such as California, Texas, New York, etc., offer grants, fundings, and rebates to reduce costs for charging station owners and expand the infrastructure needed to support truck electrification. California has awarded $100 million in funding so far to truck and bus charging. The U.S. Department of Energy's Alternative Fuels Data Center is a helpful resource and hosts up-to-date information that the EPC firms review.

Even when an EPC firm manages complex coordination, the complexities that arise from engagement beyond the core group must be incrementally staged. Prepare for 3 or 4 incremental sizings of microgrids and resulting stakeholder coordination complexity. Similar to system increments approach for a medium- and large-size microgrid charging from earlier action, closer stakeholder coordination with logistics firms, charging and distributed energy resources

OEMs, grid interconnections, regulators, standards and research organizations, etc., must also be coordinated in increments, as shown in the illustration below.

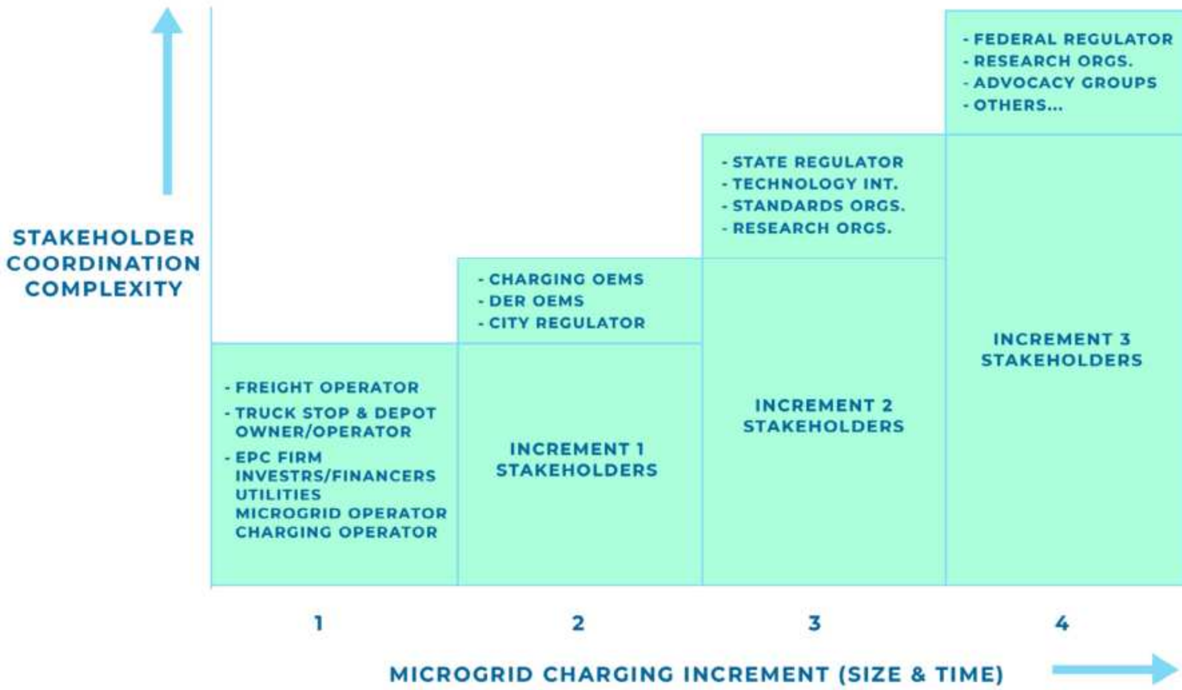


Figure 2: Notional increase in complexity and number of stakeholders with increments

Microgrid charging must be well-coordinated, modularized and standardized to lower capital and operational costs, increase speed, charging availability and reliability, and create new revenue opportunities. Environmentally, such microgrids reduce GHG emissions by trucks, support sustainability by integrating renewable energy sources, and equity with improved air quality and local job opportunities. Make microgrid-centric charging a compelling choice for locations like truck stops, depots, and community charging hubs, contributing to the broader goals of sustainable economic development and clean energy transition. Addressing limited expertise in charging and microgrid construction requires a multi-faceted approach to determine capacity, share knowledge, and foster skilled professionals. By addressing the awareness and expertise gaps, build the knowledge and skills necessary to support the widespread adoption and successful construction of microgrid-centric charging and its increments.

The incremental coordination action helps address the challenges of complex regulatory and policy barriers, delays in interconnection and utility coordination and limited awareness and technical expertise, identified in the diagnosis of charging microgrids early in the series.

Collectively, this section highlights the action for stakeholder coordination with focus on the initiators, and the value they collectively bring for and gain from microgrid-centric charging. The coordination yields dual value propositions – economic and environmental. Economically, it lowers costs, increases charging availability and reliability, and creates new revenue streams or business opportunities to all the stakeholders. Environmentally, it reduces GHG emissions and supports sustainable renewable sources. Microgrid-centric charging is a compelling choice for locations like truck stops and depots, contributing to the broader goals of businesses with new revenues that create value for all stakeholders, aligning with the Stakeholder Theory.

Appendix:
Distractions to Ignore and Deflect

This strategy doesn't bother to talk about a lot of different things, sticking to what will actually work instead of things that don't have the conditions for success in the United States.
In order to stave off questions, here's a set of alternatives that the authors discussed and discarded, having between them analysed each of them and published extensively in the space.

Our recommendations to organizations which lean into this strategic approach is to shut down conversations about these subjects as quickly and cheaply as possible. Spending time on them isn't profitable.

Hydrogen and Fuel Cell Trucks

Techno-economic assessments over the past 25 years by credible analysts including Dr. Joe Romm in his 2004 book The Hype About Hydrogen have made it clear that green hydrogen would always remain expensive to make and expensive to get to trucks and other vehicles. That's been proven true on multiple continents now.

Light hydrogen vehicles have failed because even the cheapest, high emissions hydrogen is very expensive at refueling stations due to distribution and technical costs. Hydrogen refueling has been consistently failure prone, with seals giving out regularly due to pressures equivalent to being 4.3 miles under the surface of the ocean and the world's tiniest molecule.

High-duty hydrogen vehicles such as buses have proven to be much less reliable than diesel ones and also less reliable than battery electric vehicles. Maintenance costs and vehicle downtime have not improved despite billions of investment and trials over 25 years.

Hydrogen isn't actually a climate solution. The realization was made 25 years ago that it interfered with methane breaking down in the atmosphere and so was an indirect greenhouse gas. That's been quantified now in major, peer-reviewed studies and hydrogen is 13 to 37 times more potent as a greenhouse gas than carbon dioxide. Because it's the smallest molecule and very high pressures or liquification are required, it leaks at most handling points. The combination means that hydrogen vehicles are dozens of times higher in emissions than battery electric vehicles and often around the same as or even worse than diesel vehicles.

Hydrogen vehicles will always be more expensive to buy, more expensive to operate and much higher emitting than battery electric vehicles. The market is speaking already, but in both North America and Europe, sluggish bureaucratic processes and cognitive inertia mean that big subsidies are still available for them, and vendors get more money per truck for hydrogen vehicles, so are caught in a strategic trap.

The hydrogen house of cards is already falling down. Hydrogen trucks will be a rounding error for road freight and within a few years won't exist.

Liquid & Compressed Natural Gas (LNG & CNG)

LNG and CNG are widely claimed to be lower carbon than diesel. That's true up to a point. When burned, less carbon dioxide is emitted, about 30% less. But LNG & CNG are mostly methane, a very potent greenhouse gas with 29 to 86 times the potency of carbon dioxide.

They are easier to keep inside containment than hydrogen, the Houdini of molecules, but unfortunately the natural gas supply chain leaks and natural gas burning engines have much higher rates of methane slippage than was assumed.

Studies of methane burning engines in oil and gas facilities, ships and trucks have consistently found much higher rates of slippage than the averages indicated. Shell is replacing natural gas engines that provide power at its Canadian oil and gas process and distribution facilities with electric motors because it found they were the biggest source of leakages from their operations. The International Council on Clean Transportation reported on slippage from marine engines in January of 2024 with the results from the Fugitive and Unburnt Methane Emissions Study (FUMES) and found almost double the slippage, making marine engines burning LNG actually higher emissions than those burning bunker fuel.

Meanwhile, battery electric trucks keep adding range, getting cheaper, and becoming more technologically advanced every year.

Wind, Small Hydro, Biomass & Geothermal Generation

The strategy excludes multiple forms of low-carbon electrical generation often proposed for microgrid and behind-the-meter solutions. These are all viable technologies in different ways, but the simplified strategy only includes grid-tied electricity, solar generation on site or on nearby fields and diesel generators.

The reason is that solar is cheap, modular and highly commoditized and can be put at every depot and truck stop on roof tops, solar canopies and nearby fields. Wind is site specific and requires a year of local measurement of wind to see if it’s viable, and that’s a complication not worth considering. A strong part of the strategy is focusing on repeatability of a standardized set of increments of microgrids enabling more and more trucks to charge, and anything that can’t be done at every site becomes a source of complication, additional costs and decreased effectiveness.

Small hydro, typically run-of-the-river, has the same challenge. It requires a river running through the facility with a sufficient slope to enable generation. Once again, site specific and adds complexity and cost.

Biomass generation is frequently used for combined heat and power situations. Charging doesn't require heat and these are depots and truck stops on roads, not farms or lumber mills.

Geothermal generation, especially advanced geothermal, is getting a lot of press these days. However, it's still in its infancy as a technology, although having received a large boost from fracking and shale oil technologies. It has multiple failure conditions that might require multiple holes to be drilled, and has no guarantees of being economic on any given site.

Inductive and Pantograph Charging

It's technically possible to have trucks with pantographs on top of them getting electricity from overhead wires, just as trains outside of the United States do the majority of the time. Similarly, there are embedded road systems that use magnetic induction just like putting a smart phone on a flat charging plate instead of plugging it in.

However, those solutions require significant governmental top down deployment, standardization, and cost reductions to deliver it at scale with multi-truck vendor and operator agreements to use it. The conditions for success for either system, despite decades of demonstrations and studies in Europe and North America, have not been realized. While it would solve the problem, it's not going to be built in any way that's of use to trucking for decades, if ever.

Battery Swapping

Here's a list of conditions of success for battery swapping to scale that Barnard identified while assessing global battery swapping implementations.

- Fleet Characteristics: The fleet should be homogeneous, comprising similar vehicles from the same manufacturer, operating intensively within a confined geographical area or on well-defined routes.

- Operational Scale: High operational volumes are essential to justify the substantial investment in automated swapping facilities and additional batteries, enabling cost amortization over numerous swaps annually.

- Standardization and Market Presence: A large market dominated by a few major vehicle manufacturers is necessary to facilitate the engineering of swappable batteries and automated swapping systems.

- Governmental Involvement: Active support through policy frameworks, subsidies, and investments can help overcome initial barriers, incentivize adoption, and standardize infrastructure across the industry. This includes aligning stakeholders on interoperability standards and providing financial incentives for swapping stations.

These factors are particularly relevant in contexts like urban cement truck operations or other high-utilization, predictable-route vehicles.

These conditions of success don't exist for road freight in the United States.

Engagement From Smaller Players

This strategy is for big corporations with hundreds or thousands of depots or truck stops and for the turn-key vendors that build them. Smaller players are excluded because they can't follow this strategy and it may not be economical to scale. Having a centralized design standard for three to four incremental sizes of charging microgrid based on a deep analysis of hundreds or thousands of sites, running a corporate charging deployment program for potentially 20 years, having a centralized staging, assembly and maintenance site for microgrids and their components that can be deployed rapidly to sites and other things are beyond the capabilities of small firms. They don't have the access to the funds required to implement the strategy.

Small truck stop chains or owners of a small number of depots will likely be forced out of the market with bigger players outcompeting them and acquiring their properties as they fail. At the same time, small players can work with big corporations that may not have technologies for full project success. Partnerships or acquisitions could be possible, unless smaller players are able to secure large-scale financing to complete projects of this scale.

Utility and Grid Operator Engagement

The grid-connected microgrid strategy requires close coordination with electric utilities and grid operators to build the necessary electric infrastructure and reliable grid operation resulting from increased truck charging demand. To limit the complexity of coordination across many stakeholders, the strategy focuses on minimal utility and grid operator interventions in the beginning and recommends proactive engagement in increments, as the power demand for truck stops or depots increase and inverter-based distributed energy resources are added. This approach also avoids potential interconnection permit delays and allows the microgrid design and construction to be expedited for truck electrification.

One such approach piloted by the utilities is the flexible interconnections with dynamic control approaches that allow microgrids with large distributed energy resources connections to be approved faster. Collectively, electric utilities and grid operators plan and manage grid impacts, develop rate structures, and develop programs that can allow renewable energy sources to support electric truck charging. Microgrid developers and operators can also work with utilities to develop or engage with energy management companies to integrate technologies for better grid management, renewable integration, regulatory compliance, and energy service offerings to ensure availability and reliability of electric supply, and avail recurring revenue opportunities.

Uniqueness of Proposed Charging Microgrid Solution

While microgrids are not unique and have been deployed in the United States over the years, primarily for critical infrastructure, there are some unique solutions here that are worth noting. Much of the charging infrastructure does not guarantee clean power availability due to the high costs and time of adding back-up power. Any large-scale microgrid operator that builds microgrid-centric and megawatt-scale truck charging will need to own or acquire land. Even when both these challenges are addressed the costs to build and operate hundreds and thousands of microgrids can be insurmountable to many. To address these issues, our strategy uniquely focuses on: 1) have renewable based local generation and battery storage buffering that not only reduces the interconnection delays, it also ensures power availability to trucks when they need it; 2) focuses on existing truck stop and depot owners and operators, including those owned by freight logistics companies, to leverage the land and utility connections to readily deploy microgrid charging at scale; and 3) leverage standardized components and modular design to incrementally scale within and across many microgrids.

Uniqueness Relative to Non-United States Deployments

The strategy focuses on electrification of freight logistics in the United States. While some recommendations should also apply to other parts of the world, diagnosing the realities in the deployments elsewhere is key to ensuring success. Success in electric truck freight electrification requires a nuanced approach. For example, key differences for a European perspective relative to the United States include denser road networks, shorter travel distances, a more developed intermodal system, freight driver regulations, and a more fragmented logistics market. Electric utility- and grid operator-specific regulations must be reviewed for smooth build and operation of microgrids and energy service offerings.

Understanding these unique factors, such as infrastructure, regulations, utility industries, and market dynamics, is crucial to optimize microgrid-centric charging infrastructure deployment and to ensure successful adoption. This nuanced approach is essential for any country seeking to develop a strategy that effectively electrifies its road freight sector.

The New Logistics:
Electrifying Freight with Microgrids

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