COALITION FOR INNOVATION

CleanTech
Blueprint for the Future

Coalition for Innovation, supported by LG NOVA

Jami Diaz, Director Ecosystem Community & Startup Experience
William Barkis, Head of Grand Challenges & Ecosystem Development
Sokwoo Rhee, Ph.D., Executive Vice President, LG Electronics, Head, LG NOVA

Blueprint Chairs

Alex Fang, CleanTech Chair
Sarah Ennis, AI Chair
Alfred Poor, HealthTech Chair

Authors

Sayeed Ahmed, John Barton, Irene Chen, Darlene Damm, Alex Fang, Aman Johar, Ram Krishnan, Tin Hang Liu, Winston Morton, Jiri Skopek, Julia Yan

The views and opinions expressed in the chapters and case studies that follow are those of the authors and do not necessarily reflect the views or positions of any entities they represent.

Senior Editor, Alfred Poor

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Preamble

The Coalition for Innovation is an initiative hosted by LG NOVA that creates the opportunity for innovators, entrepreneurs, and business leaders across sectors to come together to collaborate on important topics in technology to drive impact. The end goal: together we can leverage our collective knowledge to advance important work that drives positive impact in our communities and the world. The simple vision is that we can be stronger together and increase our individual and collective impact on the world through collaboration.

This "Blueprint for the Future" document (henceforth: "Blueprint") defines a vision for the future through which technology innovation can improve the lives of people, their communities, and the planet. The goal is to lay out a vision and potentially provide the framework to start taking action in the areas of interest for the members of the Coalition. The chapters in this Blueprint are intended to be a "Big Tent" in which many diverse perspectives and interests and different approaches to impact can come together. Hence, the structure of the Blueprint is intended to be as inclusive as possible in which different chapters of the Blueprint focus on different topic areas, written by different authors with individual perspectives that may be less widely supported by the group.

Participation in the Coalition at large and authorship of the overall Blueprint document does not imply endorsement of the ideas of any specific chapter but rather acknowledges a contribution to the discussion and general engagement in the Coalition process that led to the publication of this Blueprint.

All contributors will be listed as "Authors" of the Blueprint in alphabetical order. The Co-Chairs for each Coalition will be listed as "Editors" also in alphabetical order. Authorship will include each individual author's name along with optional title and optional organization at the author's discretion. Each chapter will list only the subset of participants that meaningfully contributed to that chapter. Authorship for chapters will be in rank order based on contribution: the first author(s) will have contributed the most, second author(s) second most, and so on. Equal contributions at each level will be listed as "Co-Authors"; if two or more authors contributed the most and contributed equally, they will be noted with an asterisk as "Co-First Authors". If two authors contributed second-most and equally, they will be listed as "Co-Second Authors" and so on.

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The Coalition is intended to be a community-driven activity and where possible governance will be by majority vote of each domain group. Specifically, each Coalition will decide which topics are included as chapters by majority vote of the group. The approach is intended to be inclusive so we will ask that topics be included unless they are considered by the majority to be significantly out of scope.

We intend for the document to reach a broad, international audience, including:

- People involved in the three technology domains: CleanTech, AI, and HealthTech
- Researchers from academic and private institutions
- Investors
- Students
- Policy creators at the corporate level and all levels of government

Chapter 6:
EV Battery Swap Stations vs. Fast On-Demand Charging

Author: Tin Hang Liu

The transition to electric mobility is accelerating, driven by global fleet operators including Amazon and Uber who have committed to electrify their fleets. To support this shift, two prominent charging solutions –EV Battery Swap and Fast Charging – are often compared. Each has its strengths, but EV Battery Swap offers unique advantages in cost efficiency, battery longevity, safety, and environmental impact.

Total Cost of Ownership (TCO) for Fleet Operators

EV Battery Swap technology significantly reduces total cost of ownership (TCO) for fleet operators. By enabling quick, under-three-minute battery replacements, downtime is minimized, allowing fleets to operate continuously. For large-scale fleets such as Amazon and Uber, this translates to higher vehicle utilization and operational efficiency compared to the longer waiting times associated with Fast Charging.

Battery Swap technology also supports modular upgrades, delaying obsolescence and further reducing vehicle lifecycle costs. This aligns with the financial goals of fleet operators, offering a more cost-effective approach to electrification.

A New Business Model for Battery Manufacturers

Battery manufacturers including LG Energy Solution can adopt a Battery-as-a-Service (BaaS) model. This model allows them to retain ownership of batteries, offering them as a subscription service. Chinese competitor CATL has already demonstrated the viability of this approach through its partnership with NIO, forming a joint venture called NIO Power. By embracing BaaS, manufacturers can diversify revenue streams while ensuring a steady supply of up-to-date batteries for EV users.

Mitigating Battery Degradation

Fast Charging stresses batteries by charging at high temperatures and speeds, especially when the battery is nearly depleted. This accelerates degradation, reducing the battery's lifespan. In contrast, EV Battery Swap eliminates the need for immediate charging. Swapped batteries can be charged under controlled conditions, optimizing temperature, and charging rates to extend battery life.

Research from Battery University demonstrates the significant impact of charging voltage on battery longevity: standard charging at 4.20V delivers 300-500 cycles, while reduced voltage charging at 4.00V can achieve 850-1,500 cycles, and conservative charging at 3.92V can reach 1,200-2,000+ cycles. This represents a conservative 3x improvement (from 300 to 850+ cycles) and potentially up to 6x improvement (from 300 to 2,000+ cycles) depending on the charging protocol employed.

Battery swap systems can implement these optimized charging strategies in controlled depot environments, where temperature management and reduced charging stress are feasible without impacting vehicle availability. This approach can significantly extend battery lifespan compared to frequent high-voltage fast charging, substantially reducing costs and resource consumption while supporting the circular-economy principles of longer first-life battery utilization.

Source: Battery University BU-808:
https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries

Emerging battery technologies such as sodium-ion, magnesium-ion, and solid-state batteries offer promising improvements for electric vehicles (EVs).

- Sodium-ion batteries use plentiful sodium resources, which can reduce the need for scarce materials such as lithium and cobalt. They also provide better thermal stability, enhancing safety in EVs.
- Magnesium-ion batteries are being studied for their potential to deliver higher energy densities and safer chemistries compared to current lithium-ion batteries. Research into quasi-solid-state magnesium-ion batteries has shown promise in achieving these goals.
- Solid-state batteries replace flammable liquid electrolytes with solid materials, aiming to improve safety and energy density. Recent advancements include the development of anode-free, sodium-based solid-state batteries, which can charge quickly and last for several hundred cycles.

EV battery swap systems are designed to work with various battery types. This design allows for the easy integration of new battery technologies into existing vehicles without major redesigns. This flexibility is crucial because new battery types often take many years to become affordable and widely available. For example, lithium-ion batteries took decades to become cost-effective for mass EV adoption. EV Battery swap stations can speed up the adoption of new technologies by allowing manufacturers to introduce improved or experimental batteries gradually.

For instance, more expensive but compact solid-state batteries could first be used in specific fleet applications through swap systems, avoiding the need for immediate consumer affordability while reducing the overall weight of the EV. On the other hand, less expensive sodium-ion batteries could quickly expand through the same infrastructure once they are ready. This approach ensures that fleets are not stuck with outdated technologies, allowing operators to adopt sustainable innovations as they develop, while reducing risks related to material shortages or changing regulations.

This flexibility allows for the easy integration of upgraded or experimental batteries into current EV models. It's similar to how London's iconic black cabs or Hong Kong's taxis keep the same vehicle design over several decades while replacing or updating components as needed. Drivers can continue using their familiar vehicles while benefiting from advances in battery technology.

Enhanced Safety

Safety concerns around EV batteries have grown following incidents like the August 2024 explosion of a Mercedes-Benz EQE in an Incheon parking lot, that damaged over 140 vehicles. EV Battery Swap stations mitigate such risks by performing real-time health checks on batteries during every swap. These checks detect early signs of wear or defects, ensuring only safe batteries are deployed. Swapped batteries are also stored and cooled appropriately, reducing the likelihood of thermal runaway. This proactive safety measure can reassure consumers and enhance public confidence in EV technology.

Energy Management and Sustainability

Fast Charging requires synchronous energy consumption, which often coincides with peak grid demand. This urgency leads to higher costs and reliance on coal-based energy in many countries, increasing the carbon footprint. In contrast, EV Battery Swap enables asynchronous energy management. Batteries can be charged during off-peak hours when renewable energy sources including wind or solar are more available. This reduces strain on the grid, lowers charging costs (e.g., as low as $0.10/kWh in Italy compared to $0.90/kWh during peak hours) and maximizes the use of green energy.

EV battery swap stations can engage in energy arbitrage, charging batteries when energy prices are low and potentially selling energy back to the grid during peak demand. This not only supports grid stability but also creates an additional revenue stream.

Environmental Impact

Extending the lifespan of batteries aligns with the principles of the circular economy. EV Battery Swap promotes longer first-life use of batteries and facilitates their transition to second-life applications, such as energy storage systems (ESS). By contrast, Fast Charging often leads to uneven cell degradation, making retired batteries less suitable for second-life use. The extended lifespan of batteries in swapping systems can reduce the frequency of recycling and disposal, contributing to substantial CO2 reductions.

For example, a battery lasting three times longer with swap technology equates to approximately 67% fewer emissions over its lifecycle. EV Battery Swap also supports Sustainable Development Goals (SDGs) #7 - Affordable and Clean Energy and #9 Industry, Innovation, and Infrastructure, with KPIs tied to CO2 reduction and maximized battery utilization.

Coexistence of Technologies

While both EV Battery Swap and Fast Charging have their roles, they serve different user needs. Battery Swap is ideal for fleet operators who require 24/7 uptime and rapid turnaround. Fast Charging, used sparingly, remains suitable for private EV owners who do not rely on their vehicles for continuous operation. As swap networks expand, Battery-as-a-Service could also extend to private EV owners, offering them the same convenience, lower upfront costs, and improved battery health currently enjoyed by fleets. Together, these technologies ensure a more robust and flexible EV charging infrastructure.

Conclusion

EV Battery Swap offers a compelling alternative to Fast Charging, particularly for fleet operators, battery manufacturers, and sustainability advocates. Its ability to lower TCO, extend battery life, improve safety, and optimize energy use addresses critical pain points in the electrification journey. By integrating this technology, stakeholders can contribute to a more sustainable and efficient electric mobility ecosystem.

Case Study: Electrifying India's Prime Freight Route - The Role of Battery Swap Along the Mumbai-Delhi Corridor

Overview

The Mumbai–Delhi corridor spans approximately 1,400 kilometers and serves as India's most vital logistics artery. Over 50% of the nation's freight travels this route. Electrifying this corridor is central to decarbonizing India's road transport sector. However, the operational realities of current charging methods for electric trucks (e-trucks) present serious limitations, especially for time-sensitive, long-haul freight.

Charging infrastructure, battery longevity, and uptime efficiency are critical. Today's fast- and slow-charging methods create trade-offs between speed and battery health. EV battery swapping emerges as a structured, fleet-optimized alternative, engineered to overcome these systemic constraints.

The Charging Challenge on a 1,400 km Route

Electric trucks available today typically offer **a range of 180–220 km per full charge**. To complete the Mumbai–Delhi journey, this means a minimum of **6 to 8 charging stops**.

Let's compare three operational charging approaches over the 1,400 km corridor:

Charging Mode	Avg. Time per Stop	Total Stops	Total Downtime	Trip Duration	Battery Impact
Slow Charging	8–10 hours	6	48–60 hours	~3 days (72+ hours)	🟠 Normal degradation
Fast Charging	~1 hour	6	6 hrs	~30 hours	🔴 Degrades 2–3x faster[1]
Battery Swap	~3 min	6	~18 min	~24 hours (driving only)	🟢 Controlled, no rapid degradation

As detailed in **Mitigating Battery Degradation** above, aggressive fast charging protocols can reduce battery cycle life to the lower range of 300 to 500 cycles, while controlled charging environments achievable through battery swapping can deliver 850 to 2,000+ cycles depending on voltage optimization strategies.

Source: Battery University BU-808: https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries

EV Battery Swap: Logistics Efficiency Without Compromise

Battery swapping replaces the need for on-road recharging with **standardized, pre-charged battery exchanges**. For long-haul fleet operators, this enables:

- **Continuous driving** with <30 minutes of total idle time over 1,400 km
- **Optimal battery charging conditions** (temperature-controlled, slower charge speeds)
- **Predictable operational windows** with minimized variability
- **Smart energy billing** through automated BMS integration that detects incoming battery charge levels

Energy Credit System

EV Battery Swap stations utilize automated systems with integrated Battery Management Systems (BMS) to detect the exact energy remaining in each incoming battery. Service providers can implement flexible commercial models: for example, if a swapped battery contains 30% remaining charge, the customer pays only for the 70% energy differential from the freshly charged replacement battery, plus a standardized swap service fee. This pay-per-swap model with energy crediting ensures fair billing regardless of remaining charge levels.

Current Indian Regulatory Framework

India has established comprehensive driving hour limits for commercial truck drivers under two primary regulations: Motor Transport Workers Act (MTWA), 1961 mandates:

- Maximum continuous driving: 5 hours without a break
- Mandatory rest interval: "at least half-an-hour" after every 5 hours of work
- Daily hours: "No adult motor transport worker shall be required or allowed to work for more than eight hours in any day"
- Weekly limits: "forty-eight hours in any week"
- Daily spread-over: "shall not spread-over more than twelve hours in any day"
- Weekly rest: "at least one day off in a week"

Source: Motor Transport Workers Act, 1961 - Ministry of Labour and Employment: https://labour.gov.in/sites/default/files/the_motor_transport_workers_act_1961.pdf

These regulations are reinforced by Central Motor Vehicles Rules (CMVR) Rule 132, which establishes similar driver duty and rest requirements.

Operational Reality for Long-Haul Routes

For interstate operations like the Mumbai-Delhi corridor (≈1,400 km), transport operators commonly use two-driver crews to maintain vehicle movement while respecting individual driver hour limits. Each driver alternates duty periods, allowing continuous vehicle operation while both drivers stay within their personal 8-hour daily and 48-hour weekly limits.

Energy Replenishment Time Comparison:

Method	Time Required	Battery Impact	Operational Feasibility
Diesel Refueling	5-7 minutes	N/A	✅ Compatible with 30-min rest breaks
DC Fast Charging (50-150kW)	45-90 minutes*	🔴 Reduces battery life to 300-500 cycles*	❌ Exceeds mandatory rest periods
Battery Swap	2.5-3 minutes	🟢 Enables 1,200-2,000+ cycles	✅ Well within 30-min rest breaks

**For typical commercial truck batteries (300-400 kWh), charging from 20% to 80% capacity*

Current DC Fast Charging Reality in India

Most commercial DC fast charging stations in India operate between 50kW to 150kW, with newer installations reaching 240kW. For a commercial truck with a 350kWh battery pack:

- 50kW charger: ~4.2 hours for 20-80% charge (210kWh)
- 150kW charger: ~1.4 hours (84 minutes) for 20-80% charge
- 240kW charger: ~53 minutes for 20-80% charge (optimal conditions)

Critical Charging Limitations

- Charging speed reduces significantly above 80% state of charge
- High-power fast charging requires specialized infrastructure often unavailable on highway corridors
- Battery degradation penalty: As detailed in Section 3 (Mitigating Battery Degradation), frequent fast charging can reduce battery cycle life to 300-500 cycles compared to 1,200-2,000+ cycles achievable through controlled charging in battery swap depot environments

Current Operational Benefits of Battery Swap

- Regulatory compliance: 2.5-minute battery swaps occur within legally required 30-minute driver breaks without extending trip time
- Fastest energy replenishment: Battery swapping is 2x faster than diesel refueling and 17-34x faster than fast charging for equivalent energy delivery
- No infrastructure dependency: Eliminates reliance on high-power charging infrastructure availability along highway corridors
- Battery longevity: Preserves battery investment through controlled depot charging, potentially extending battery life by 3-6x compared to frequent fast charging scenarios

Future autonomous advantages:

EV Battery Swap is the ideal energy solution for autonomous driving, delivering autonomous energy powered by AI. Designed for complete automation, these systems operate without any human intervention. In contrast to plug-in charging, which requires human oversight to ensure safety and secure connections, AI-driven autonomous battery swapping enables:

- Continuous operation around the clock without driver rest constraints once autonomous vehicles are deployed
- Fully unmanned energy replenishment engineered to integrate with autonomous vehicle systems
- Seamless compatibility with autonomous fleet management platforms for operational optimization
- Removal of charging infrastructure bottlenecks that could limit the scaling of autonomous fleets

This level of technological readiness ensures that current investments in battery swap infrastructure will directly support the future of autonomous commercial vehicle operations. Energy replenishment becomes a purely algorithmic process, independent of human schedules, regulatory rest requirements, or charging infrastructure availability.

Strategic station placement every 200–250 km ensures full corridor coverage with 5–6 swap points, matching existing logistics rest schedules.

Performance, Uptime, and Battery Health

Battery longevity is a critical factor in overall fleet economics. As demonstrated in Section 3 (Mitigating Battery Degradation), charging protocols significantly impact battery cycle life and operational costs through voltage optimization and thermal management.

Commercial Impact Analysis

For commercial truck operations, premature battery replacement represents substantial costs. The difference between high-stress and controlled charging protocols creates a 4-6x variation in cost per cycle, dramatically affecting total fleet economics.

Battery Swapping's Operational Advantage

Battery swapping mitigates degradation risks by enabling controlled charging environments with optimized temperature management, reduced charging stress through lower C-rates in depot facilities, and voltage optimization strategies not feasible during on-vehicle fast charging. Based on the research detailed in Section 3, this controlled approach can **conservatively extend battery lifespan by 3 times** compared to frequent fast charging scenarios. In optimized depot charging conditions, battery life improvements of **up to 6 times longer** are achievable, creating what can only be described as an **unfair advantage** for fleet operators adopting battery swap technology.

Economic Benefit:

This dramatic lifespan extension translates to proportional reductions in lifecycle battery replacement costs, significantly lowering cost per kilometer and supporting longer fleet asset utilization periods. For commercial operators, this advantage transforms battery costs from a major operational expense into a manageable, predictable component of fleet economics.

Unlocking the Corridor's Strategic Potential

By implementing battery swap stations along the Mumbai-Delhi route, stakeholders can unlock tangible system-level benefits:

- **Trip Duration Reduction**: From 72+ hours (slow charge) or ~30 hours (fast charge) to **~24 hours total** including swaps, matching diesel trip benchmarks.
- **Zero Battery Ownership Burden**: Fleets can adopt a **Battery-as-a-Service (BaaS)** model, paying per km/kWh and/or per swap, avoiding upfront battery CAPEX.
- **Fleet Electrification at Scale**: Higher vehicle utilization and asset turnover, with reduced strain on the national grid via asynchronous charging

Recommendations for Implementation

To fully realize the benefits of battery swapping across the corridor, we recommend:

1. **Station Network Development**: Build swap stations at 200–250 km intervals, co-located with logistics hubs, rest stops, and warehousing clusters.
2. **Battery Lifecycle Hubs**: Use centralized facilities for controlled charging and predictive maintenance to maximize pack longevity.
3. **Regulatory Alignment**: Work with policymakers to streamline approvals, land access, and incentivize fleet-level electrification through swap-friendly EV designs.
4. **Integration with Smart Logistics Platforms**: Optimize scheduling, route planning, and fleet tracking with real-time swap station data.

Conclusion

The electrification of the Mumbai-Delhi corridor is not a question of "if," but "how." While traditional charging methods introduce operational compromises, battery swapping allows logistics fleets to scale electrification **without sacrificing efficiency, uptime, or battery health**.

By addressing core friction points in long-haul EV logistics, battery swap technology provides a mature, scalable, and economically viable pathway toward India's sustainable transport ambitions.

Author (In order of contribution)

Tin Hang Liu, Y Combinator alumnus, co-founder & CEO of Open Energy, keynote speaker
Tin Hang Liu is the co-founder and CEO of Open Energy, and a Y Combinator alumnus developing AI-powered EV battery swap systems for sustainable transportation and logistics. His award-winning technology, recognized across Europe and Asia and hailed as the “DeepSeek moment” for EV infrastructure, is redefining how vehicles are powered. A recognized expert in New Mobility & Energy, Tin has shared insights at global forums including the Seoul Mobility Show 2025, IndiaEV by Entrepreneur Magazine, and CNBC Converge Live.

For more information about the Coalition for Innovation,
including how you can get involved, please visit coalitionforinnovation.com.

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