

Modular Power: Evaluating Scalable Alternatives for Low-Emission Locomotives

A Technical White Paper Prepared for Rail Operators and Influencers Globally

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Executive Summary

This paper explores practical strategies for implementing low-emission locomotive technologies, focusing on modular, portable, and energy-agnostic power systems. As the rail industry transitions toward decarbonization, a wide range of solutions have emerged, each with distinct benefits and constraints. Rather than advocating a specific product, this paper considers broader implementation approaches such as battery-electric, hydrogen fuel cell, and hybrid configurations with particular attention to systems that prioritize operational flexibility, serviceability, and infrastructure adaptability. Modular power systems that allow for portable, swappable energy units may offer a scalable, lower-risk pathway to modernization without requiring wholesale infrastructure overhauls.

1. Introduction: Navigating the Rail Decarbonization Landscape

Railroads are under increasing pressure to reduce emissions, optimize fuel use, and adopt cleaner technologies. While the ultimate goals are often clear, i.e. reduced carbon footprint, regulatory compliance, and improved operational efficiency, the pathways are more complex. Rail operators and locomotive operations face diverse infrastructure constraints, geographic challenges, and fleet management demands, all of which shape the feasibility of decarbonization strategies.

This paper aims to assess alternative propulsion architectures and technologies with a focus on flexibility and practicality. By examining how each solution aligns with real-world rail operations, it offers a foundation for decision-making and future exploration.

2. Overview of Propulsion Alternatives

2.1 Traditional Battery-Electric Locomotives

Battery-electric systems store energy onboard and eliminate direct emissions during operation. While they offer strong environmental benefits, key limitations include charging infrastructure needs, long dwell times, and constrained range. Fixed battery banks can limit

flexibility and may require major yard upgrades. Additionally, the electrical grid in many areas is already operating near capacity, making the introduction of high-demand fast charging potentially damaging to delicate or underserved grid segments. This creates both a logistical and financial hurdle for railroads considering rapid deployment of traditional charging-based battery systems.

2.2 Hydrogen Fuel Cell Locomotives

Hydrogen fuel systems convert hydrogen into electricity via fuel cells, producing only water vapor as a byproduct. Their appeal lies in high energy density, but challenges include limited hydrogen supply chains, safety regulations, and infrastructure investment costs. Refueling times, while faster than full battery charging in some cases, are still longer than conventional diesel fueling, and the safe transport of hydrogen remains logistically difficult due to its low volumetric energy density and flammability concerns. Additionally, not all hydrogen is produced equally — green hydrogen is generated from renewable energy sources and offers significant environmental benefits, whereas blue hydrogen, derived from natural gas with carbon capture, still relies on fossil fuel extraction and raises concerns about lifecycle emissions.

2.3 Hybrid Locomotives

Hybrid locomotives combine diesel engines with energy storage systems, often batteries or ultracapacitors, allowing for regenerative braking and reduced fuel consumption. These systems extend range and reduce peak fuel usage but maintain some reliance on combustion engines.

3. The Case for Modular, Portable Energy Systems

While each propulsion method has technical merit, many fail to address a key barrier to adoption: infrastructure readiness. In today's era of precision railroading, where locomotives are tightly scheduled and used leanly across optimized networks, any operational disruption can ripple quickly across the system. Modular, portable energy systems, particularly those that are swappable and fuel-chemistry-agnostic, offer a new path forward. These systems decouple the power source from the locomotive chassis, enabling:

- Rapid energy module exchange with minimal downtime
- Scalable deployments across fleets of different sizes
- Compatibility with future chemistries or energy sources (e.g., next-gen batteries or hydrogen cartridges)

- Reduced investment in fixed infrastructure

By shifting energy storage offboard and embracing interoperability, railroads can modernize incrementally, without being locked into one fuel type or technology.

4. Implementation Considerations

For modular systems to succeed, they must meet rigorous technical and operational requirements:

- **Serviceability:** Units must be easy to access, inspect, and maintain without disrupting operations.
- **Durability:** Modules must be rugged enough for harsh rail environments.
- **Safety:** Battery and alternative fuel systems must pass thermal, vibration, and crashworthiness standards.
- **System Integration:** Control systems must recognize and interface with different module chemistries seamlessly.
- **Standardization:** Future adoption depends on developing industry-wide connectors, enclosures, and protocols.

5. Looking Ahead: Pathways to Commercial Success

The modular, portable approach is still in its early stages, with limited commercial deployment to date. However, the growing interest across the industry suggests that foundational work is underway. Progress depends not only on technological readiness but also on how these systems align with the operational and economic realities of railroads.

Success will likely be defined by several key factors:

- **Proven Reliability:** Demonstrating long-term performance in real-world operations.
- **Total Cost of Ownership (TCO):** Competitive life-cycle economics compared to conventional systems.
- **Ease of Integration:** Compatibility with existing fleets, training procedures, and maintenance workflows.
- **Infrastructure Neutrality:** Avoiding costly upgrades and leveraging existing facilities.

- **Regulatory and Safety Compliance:** Meeting evolving standards without compromising service.

As the industry continues evaluating cleaner locomotive options, modular systems may emerge as a practical bridge offering meaningful emission reductions and fuel savings while maintaining operational flexibility.

6. Conclusion

The path to low-emission rail transport is not a single track. Success will come from flexible, scalable strategies that align with each railroad's operational and infrastructure realities. Modular, portable energy systems represent a practical, infrastructure-light option that deserves industry-wide attention and investment.

As the industry continues to evolve, embracing adaptable solutions will ensure railroads can meet sustainability targets without sacrificing reliability, uptime, or financial prudence.