Electrification

U.S. Railroading: What Sector's Future Power Suppliers Will Need to Know

Among the elements of America's carbon-based industries and infrastructure being impacted by electrification, transportation exhibits, first, widespread economic and environmental impacts (private highway vehicles) driven by emerging technology, public policy, growing climate and health concerns, government stimuli and private collaboratives, and investment or management opportunities. Second it shows the more muted reassessments by freight and (to an extent) passenger railroads, both critical links in American supply chains.

Electrification has potentially major consequences for electric power companies and the grid as a whole, both of which are undergoing transformations as well. In this commentary on rail electrification, we examine whether railroads might or should electrify and how and when that may happen (or begin to happen). As owners that preside over a vast real estate network, railroads also have an opportunity to facilitate the expansion, reliability, and strength of the electric grid. As potential customers and even suppliers of power providers, railroads may in time opt for the greater energy productivity and efficiency that reliance on electricity can provide as a motive power, thereby entering a new and more dynamic relationship with electric generators, consumers, and delivery infrastructure.

COMMENTARY

The case for electricity as the primary fuel for railroads is not new. Its potential advantages for passenger and freight transportation, all things being equal, are widely acknowledged: better "grid-to-wheel" energy efficiency, perhaps as much as 20% savings on maintenance costs, lower direct and indirect carbon impacts, and regenerative braking capture in many cases. Many argue that electricity offers potential increases in flexibility and reliability, and reduced journey times.

Regardless of such contentions, most technologies that could electrify and propel locomotives today are proven and available, with the possible exception of hydrogen. Recent public policies affecting transportation tend to favor major climate-friendly improvements like electrification.

Yet, for several reasons, there are no discernible pathways to freight rail (or total passenger rail) electrification.

Although rail transport can lay claim to unique efficiencies and scale economies, the U.S. rail industry has been contracting, not growing. The 140,000-mile system is 60% smaller than it was in 1914. More recently, crews and routes have been cut to enhance operating ratios and, according to the Surface Transportation Board (DOT), rail has lost 2% market share to highway transport since 2006, a trend that could be further aggravated by a continued decline in coal shipments and expansion or electrification of rail's main competitor (i.e., trucking).

Railroads understand that imprudent investments can result in stranding costs at a time when recovery of long-lived capital equipment (namely, locomotives) costs may be buffeted by uncertainties about how to service the nation's critical value chains, in which railroads are the critical link. Most daunting for railroads is the sheer size of investment potentially required to electrify under any of the propulsion alternatives to diesel generation available to railroads. Most of the technology alternatives, including batteries and hydrogen fuel cells, entail costs of conversion (at the current stage of development) equivalent or greater than the initial cost savings of using grid power. So, while electrification may not be "patently infeasible," it will be absolutely necessary to pencil out the risks and rewards for electrification's economic opportunities and social benefits to be fully understood going forward. We think that process has begun, and we'll return to that at the end.

What Electric Companies Need to Know

Electrification Benefits Both Sectors—North America's two most critical infrastructure networks—the electric grid and freight railroads—have historically operated in relative isolation from one another, with some exceptions. More than a half century after railroad dieselization (1960) ended the reign of coal-fired steam generation, the U.S. finds itself with fewer miles of electrified rail than Uzbekistan. Its railroads have a declining share of the freight transport market (aside from declining coal shipments).

That is not to diminish the importance of railroads as a vital component of the U.S. and North American economies. It instead raises questions about the uneven state of infrastructure modernization across the transportation and other sectors of the American economy and the need to coordinate the evolution of these powerful network industries, their development, investment plans, and related public policies.

Nothing similar to the changes that swept the electric power business in the last half century—variously called restructuring, open access, or competition—are yet contemplated for railroads. Nor have electric utilities or the other components of the evolving power business contemplated the role that railroads (like electric vehicles) should play in their future operations and markets.

The catalysts for change—good and bad—are nevertheless hiding in plain sight. The government funding for research into electric vehicles and support for electric trucks have been historic despite the added weight such vehicles entail, reducing payload capacity, and greater wear and tear on bridges and roads. The American Society of Civil Engineers grades U.S. domestic railroad infrastructure as "B" (or B-minus if passenger rolling stock is excluded), in comparison to the "D" it assigns to the highway system. While Class I and Class II railroads want to stem the tide of continued decline of coal traffic and relative stagnation of other commodity shipments due to relative absence of manufacturing growth, they are strategically committed to a return to growth. Because of the limited opportunities for modal shift of freight business from road to rail, the result has been increased emissions and highway congestion. Additionally, diesel-electric rail is between two and four times more fuel-efficient and therefore more environmentally friendly than trucking, although federal "SuperTruck" programs are spurring highway transport to improve quickly.

Electrification, especially using renewable energy, would arguably reduce or eliminate the adverse health and environmental impacts of the fossil fuel supply chains for both rail and highway transport. But rail transport of heavy freight already has advantages. A loaded railcar carries the equivalent load of some 3½ trucks on the road with considerably greater safety. Both the rail and power industries, not to mention consumers, could potentially be healthier and even safer if they were to join in support of a real shift of freight and passenger traffic from roads to rails and a shift from high- to low-emission fuels. This would potentially open opportunities to deliver new economic and environmental benefits to the nation. The potential for this kind of "modal shift" deserves further study. That said, rail electrification is a choice yet to be made.

What might the scope and technological drivers of this electrifying transition look like? A critical if secondary question is whether, in the event that railroads do move away from onboard diesel generation, the electric power industry is prepared to meet the probable demands on it that rail electrification will entail when (or as) it occurs. In the face of limited communication between these critical infrastructure behemoths in recent decades, there are no pat answers. So, just as railroads will need to come to terms with the current evolution of the power business previously described, electric power companies of all stripes—generators, transmitters, distributors, and technologists, public and investor-owned, competitive and franchised, state-based or multi-regional—need to gauge where on the learning curve they need to be with respect to modernization of the railroad system.

B**oth Sectors Face Transformational Winds—**Like electric companies, railroads provide public services that are "affected by" the public interest, principally at the federal level given their historically multi-state operations. They too are capital-intensive, privately-held companies, and pay taxes on their assets and operations. But although railroads own and maintain their operating facilities, they differ from other modes of transportation that operate on taxpayerfunded infrastructures (e.g., airports and highways). In fact, between 1980 and 2022, freight railroads invested $780 billion on capital improvements and maintaining infrastructure. Load-serving utilities spend $20 billion year-in and year-out on just their distribution-level infrastructure alone, which is generally recoverable in rates.

The challenges confronting railroad operations resemble those of modern utilities but are also different in nature. Although the freight rail industry appears remarkably diverse—620 freight railroads operate across the 140,000-mile freight rail network—the industry is actually quite concentrated. Six Class 1 freight railroads account for 94% of freight revenues, including intermodal services with trucking. Hundreds of regional and short lines play an important but more limited role in transporting freight to state, local, and specialty (e.g., mining) markets. Government's principal direct involvement in railroads nationally relates to safety regulation, the efficiencies of shared use of trackage, and regional passenger rail services such as Amtrak's electrified Northeast Corridor operations. Although the ownership and use of existing rights-of-way and the impacts of operations on surrounding communities can also be subject to state law, states dedicate more resources to promoting railroads' role in economic development, such as in periodic rail plans, than to issues like how their assets are managed.

The likelihood and scale of any future electrification of freight and passenger rail will be a function of the ways in which Americans choose to attack and solve multiple economic and environmental challenges such as climate change. Rail electrification could have profound implications for all forms of emissions, transportation services or operations, the security of energy and other commodity supply chains, and decarbonization generally. That said, the economy succeeds only if rail's core business also succeeds.

Although not strictly a rail electrification issue, the advantages of commercial engagement with the power industry on such matters as co-location of facilities within or alongside trackage, as a means of minimizing or circumventing the regulatory complications of siting and permitting generation or transmission facilities on private or "greenfield" properties, are demonstrable. The strategic location of railroad rights-of-way or rail yards may make them natural hosts for battery charging facilities, energy storage, and other distributed energy assets and facilities that can contribute to the stock of renewable resources or serve as responders to extreme weather and other threats to reliability or dramatic load growth.

Railroad C-suites and denizens of Wall Street may be skeptical when it comes to blazing a path forward to the clean energy future, helping the troubled electric grid, or joining the stampede to electrify basic industry. While electrification proponents do well to resist "magical thinking" about the "inevitability" or universality of rail electrification, any argument that rail electrification is "impossible" or lacks both merit and potential benefit is unrealistic. In short, the proverbial path forward needs to be illuminated by a growing understanding of where each of these industries are in their respective progress toward improved efficiency and performance.

Electrification of railroad operations may impact any nearby load-servers' obligations, just like the burgeoning data centers have exploded power demand in certain (often rural) locations to the detriment of existing load and existing transmission capacity. Such new load may be deeply concerning for utilities and grid managers that are already trying to integrate new generating technologies and resources, often widely distributed, into their planning and operations. Interconnecting renewable energy facilities into the grid already lags behind demand and social benefit goals, and questions surrounding the viability of the system's major generation resource—natural gas—could jeopardize system reliability and resilience to extreme weather. Domestic energy and climate policy, arguably supported by the best science, anticipates that greenhouse gas emissions must be reduced to net-zero by mid-century but, as the Electric Power Research Institute forecast dramatizes, the size of the net-zero challenge—achieving net-zero carbon emissions in the U.S.—would require almost a 500% increase in electric generating capacity by 2050. Getting to net-zero in that timeframe would entail integrating hundreds of gigawatts of renewables to the grid, in part by building miles of new electric transmission or otherwise improving regional transfer capability by other means.

So, in a nutshell, the challenges facing the electric power industry may give railroads second thoughts about how and when to approach electrification, given a choice. The current stresses on electric reliability could render reliance on the grid a significant risk to regular operations. Serving mobile customers like trains that might use possibly different propulsion technologies as they move across multiple service territories and markets, would be problematic. No doubt, wind, solar, geothermal, biodiesel, fuel cells, or other renewable energy can fit the needs of mobile transportation, but industry will need to develop relatively settled answers to such questions. To date, the two industries have no mutually understood roadmap to a broader system of electrified transportation.

Railroads will first have to sort out motive power alternatives or combinations like overhead catenary and batteries deployed in "discontinuous" fashion to meet topographical and engineering challenges. Because diesel-electric locomotives have long useful lives and are often rebuilt multiple times, retiring 25,000 diesel-powered units will take many years. The potential benefits of electrification to railroad and to society—generally in terms of cost savings in maintenance, lower fuel costs, operational flexibility, speed, or other potential advancements—surely must be complementary (if not equivalent) to the reciprocal benefits of a train's potential interactions (e.g., peak shaving, line conditioning, backup power) with the grid. We are a long way from having penciled out these relationships. Even if the business solutions become clear, these industries need Congress and regulators to find ways to facilitate siting and permitting essential transmission facilities, because our complex commercial and regulatory systems have generally failed to respond to the need for collaboration, swift decision-making, and effective long-term planning.

What Rail Electrification Looks Like: Motive Power Options

There are several promising technologies with which freight or passenger railroads could be electrified, such as battery-diesel, battery-electric, and overhead catenary. Many of these can be operated alone or in combination with other electric or non-electric options. None are universally acknowledged as the best bet or most applicable motive power solution, although access to the grid (e.g., through a combination of overhead wires and battery systems) has proven operational and economic worth in delivering electric power directly from grid resources for transit passenger and light-rail systems. Nevertheless, due in part to this lack of consensus, electrification of domestic heavy freight rail and inter-city passenger rail has not spread more widely in recent years. Because it is the most proven and understood motive power technology, overhead catenary systems (OCS) may be the most feasible electrification option long-term due to its superior "tractive effort per unit" and the advantages to freight trains of not carrying the weight and extra machinery of on-board fuel storage and generation in addition to heavy loads.

Analysts argue that the economic benefit of OCS would be very consequential even if it is deployed on only the 10% of the rail network that handles 30% of the gross ton-miles, and consumes at least 35% of railroad system energy. In other words, a profitable technological option for replacing diesel-electric on an important segment of the network may not be an immediate or complete solution. That said, the appetite for conversion to electric motive power in the next decade will depend on making individual business cases based on estimates of "fuel" efficiency, the attractiveness of high grid reliability, the cost and impacts of power versus the cost and impacts of fossil fuels, the potential maturation of technologies like energy storage, the entrepreneurial bent of railroad management, and the drive, guidance, and possible funding coming from government.

Electric rail is highly energy-efficient: overhead catenary achieves more than 70% overall "grid-to-wheel" efficiency, with battery-catenary hybrid at 77% and battery-only at 71%, based on today's technology. Several other factors may hasten electrification. Of course, the need for system interoperability means that the rail network requires a standardized, interoperable set of equipment, both moving (locomotives) and stationary (e.g., charging facilities, cables, substations, etc.), which limits the ability to pick and choose from among the available propulsion technologies.

For example, rail yard electrification and replacement of aging switch engines may be initiated in isolation from the rest of the system, driven initially by immediate economic necessity and then by policy or environmental considerations. Moreover, short lines and feeder lines may represent limited opportunities for electrifying freight transport, in the absence of high-density or line haul locomotive traffic. Overhead AC electrification (at 25kV or 50 kV) of a more extensive network would involve a progressive major construction program, which would necessitate changes in either power source or locomotive unit (probably with delays and crew changes) or dead haul of locomotives, which would require extra power and use of already long trains. Finally, overhead electrification requires additional space above the tracks for catenary, provided attention is paid to double-stacked container trains, overbridges, and tunnels along the line.

When diesel locomotives replaced coal-fired steam (before 1960), railroad efficiency vastly improved. The U.S., Canadian, and Mexican Class I railroads operated 28,000 locomotives in 2022, all of them diesel-electric (using diesel to generate electricity to drive traction motors and power the wheels). Additionally, there are about 9,000 locomotives operating at regional railroads, short lines and private owners; they are often cascaded from Class Is from freight systems. In 2022, the Class I railroads spent $11.37 billion on diesel fuel.

New line haul locomotives cost between $3.5 million (freight) and $12 million (passenger). Freight railroad locomotive frames are theoretically capable of up to 50 years' useful life with equipment rebuilds (generators, etc.) at 25-year intervals. The cost of new locomotives (about $3 million for Tier 4 freight units or $2.7 million for switcher units, and ranging up to $12 million for passenger-commuter units) make rebuilds an attractive alternative. In recent years, very few newly-built locomotive designs were adapted to meet some of today's more stringent emission standards. Short lines, which typically have smaller scale and l significantly lower traffic revenues, seldom buy new units and often seek biodiesel and renewable diesel options instead of electrification.

"Classification" rail yards often create concentrated emissions from multiple diesel locomotive operations. Rail yard locations and routine idling in them can be detrimental to disadvantaged populations. Potentially, these emissions sources can be addressed during shorter line haul duty cycles through adoption of battery locomotives accompanied by installation of charging stations and associated electricity supply infrastructure.

Finally, different modes of propulsion can be used in innovative combination to ease the switch to electricity. For example, passenger trains are often operated by dual- or treble-power trains. Amtrak has ordered a fleet of "Airo" trains for the NE Corridor services, with the trains powered by overhead electricity. They can switch to diesel generators to serve non-electrified destinations that extend the NE Corridor routes (such as Richmond, Virginia, and possibly Charlotte, North Carolina). In addition, freight hybrids currently fall into two distinct duty-cycle-based solutions. One is a battery locomotive as part of a "consist" with diesel locomotives. Because current battery locomotive technology doesn't provide the power and tractive effort to move a long, heavy train, especially uphill, diesel-powered units "help" as part of the consist. On the downhill stretches, the batteries can be recharged in part through regenerative braking, where excess heat is converted to electricity and fed back to the batteries.

There are several promising alternative motive power configurations. Combining a hybrid hydrogen fuel-cell and battery is worth consideration. Currently, Class I freight railroads are exploring the viability of this option which will become more practical if there is a nationwide hydrogen supply network, although converting Class 1s to hydrogen will require a massive investment in hydrogen production. Currently, using green hydrogen produced from fueling-site electrolysis using renewable electricity is only about 25% efficient. In addition, the Class 1s will test utilization of a "battery tender" behind the locomotive(s). This solution has appeal due to its relative simplicity and proven technologies, yet it involves towing what amounts to dead-weight (non-revenue-earning mass) and swapping such vehicles from the train when the batteries need to be recharged. Recharging batteries on the move through induction or electro-magnetic resonance is another potential long-term solution, provided it can be made to work in the somewhat harsh railroad environment. Finally, there are currently other, perhaps more unusual, options such as "hoovering-up" excess CO_2 emanating from diesel locomotives for sequestration. So far, recent innovations not tied to the grid must be considered speculative.

Grid Deployment and Railroad Rights-of-Way

Besides the impacts that rail electrification could have on a region's and perhaps the nation's electric system, another interaction with the electric transmission grid has potential for significant mutual benefits. We don't need to restate here the seemingly tractable difficulties that federal and state infrastructure siting and permitting requirements, the prospect of eminent domain litigation, or foot-thick multi-volume NEPA documents present for the development of an expanded and integrated grid. The time and expense consumed in those processes vastly exceeds the time and cost for gaining approval of other terrestrial energy facilities like pipelines.

Hence, virtually no major interregional transmission was built in the U.S. for the first two decades of this century despite the burgeoning need to move remote renewable resources to distant loads, ensure grid resilience in an era of extreme weather events, and meet the rising demand from the electrification of loads such as EVs. Existing rights-of-way offer a pathway for resolution in many cases.

A railroad's rights-of-way are perhaps its biggest asset, yet they earn no direct revenues. Instead, rights-of-way regularly incur capital and maintenance costs and represent an ongoing tax liability. So, it's not surprising that some rail companies, once asked by electric power developers to consider leasing rights-of-way for transmission and other development, responded positively. Transportation rights-of-way can provide ideal pathways for the continuous, linear, and interregional electric transmission that connect resources and loads across state, regional, and market boundaries. The geography of the U.S. rail system, stretching 140,000 miles (not including unused or abandoned lines and many trackside facilities) is ideally suited to accommodate long-distance high-voltage lines that transfer large amounts of power efficiently and, if direct current, with minimal impact on train operations or communications post-construction. In many circumstances, such co-location will be increasingly attractive as a way to minimize the costs and delays associated with the interminable permitting and siting of projects across “greenfield” properties.

The utilization of existing transportation rights-of-way such as those alongside railroads and highways, as well as the reconductoring of existing lines, have only recently become popular ways to reduce costs and delays, accelerate transmission planning, and deploy new competitive, technologies. The SOO Green HVDC Link (Iowa and Illinois), the New England Clean Power Link (Vermont), and the Champlain Hudson Power Express (New York) are three examples of transmission projects that are co-located partly or entirely on railroad property, consistent with railroad operations.

Overhead lines, either towers for transmission or catenary for train operations, necessitate new levels of coordination with utilities to mitigate any potential technical problems. It’s important to note that there is no necessary relationship between the placement of high-voltage transmission in a linear rail right-of-way and the potential electrification of the locomotives themselves on that route; HVDC must be converted to AC and stepped down to provide power directly to the rail system. That said, the proximity of power to rail operations may generate both new revenues and opportunities to switch fuels in the future, or produce valuable relationships with utility suppliers and other entities. Until we learn more about the new private commercial transactions that lead to co-location, including their terms, how rights-of-way are conveyed, and the relevant consideration, these arrangements will resist standardization. These land transactions would likely afford railroads a long-term stream of revenue with minimal risk of loss, operational impact, or undue encumbrances on affected property. More immediate concerns will probably relate to whether construction of an underground transmission line or overhead catenary could interfere with operations, allocation of cost responsibility for any toxic waste clean-up, potential communications problems, or episodic maintenance issues.

The Road Not Yet Taken

At the time of the financial and regulatory crises addressed by Staggers Act (1980) and the Four R Act (1976), American freight railroads had had a half-century of experience with electrified mainline railroads. Its feasibility was unquestioned but, for several reasons, electrification initiatives topped out at 6,300 track-miles during World War II, a mere 2% of total U.S. trackage confined largely to the Northeast, with the notable exception of the Milwaukee Road across the difficult terrain of the northern tier.

It’s unclear whether modern technology or today’s public policies provide a better answer about when or the extent to which rail electrification may once again be feasible, critically important, or inevitable. When the benefits shown are high enough and risks and costs low enough, we may get the answer. The modern drivers of electrification in other industries such as climate change mitigation, deployment of clean energy resources, and the need for system resilience may affect railroads differently. Freight rail managers are not persuaded that electrification is the answer to the system's underperformance in terms of the decline in market share and carloads delivered. By one account, their CEOs are also "tired of being micromanaged on pesky things like climate change by minority shareholders." No doubt, railroad shareholders will demand reassurance that electrification will not sacrifice the system's current measures of economic efficiency, productivity, or stable returns. So far, the potential benefits of rail electrification have flown under the radar of public policy makers, including energy regulators. Consequently, the pathway to electrification of U.S. freight rail is not entirely discernible, but lines with the heaviest traffic density appear to constitute the ripest opportunity.

The prospect of liberating all transportation from their fossil fuel supply chains and related costs and liabilities may lose its political luster in Washington in the near term, However, despite a sea of unknowns, a 2024 study funded by the Federal Railroad Administration and conducted out of the University of Texas at Austin (note that we advised its authors) shows that electrifying a heavy-density line can yield competitive returns from operations, as well as other revenues such as leasing rights-of-way. Entitled "Cost and Benefit Risk Framework for Modern Railway Electrification Options," the study surveys today's most practical electric propulsion alternatives, proposes a risk-based benefit-cost framework for understanding electrification (including social as well as economic benefits), analyzes ways to value and negotiate rights-of-way sharing (with transmission lines), and contains case studies of electrification along two representative rail corridors, with surprisingly positive results regarding affordability. It is a constructive platform for continued examination of the means and strategies for electrifying trains.

What can the electricity business take away from all this? For an industry as strategic and so in need of investment as rail, adapting to new competitive realities is a necessity. Freight rail starts with distinct, historical advantages with respect to the of its track infrastructure base, even compared to the D-rated (publicly funded) highway system. Diesel-electric railroads are between two and four times more environmentally friendly than trucking, not counting the fuel supply chain it supports. After treading water for several years, Class I and Class II railroads are frank about their new "pivot to growth." Since the economic benefits of the Staggers Act and other regulatory reforms of the 1980s have arguably been exhausted, that growth may well require basic technological and operational improvements. Perhaps electrification and the operational advantages that come with it will be part of the mix. But, in the final analysis, affordability—not policy—will determine when, where, and how railroad motive power and rail operations overall can be converted to electric power, even partly. The choice that rail investors will face, initially and for some time to come, is how to select from among the available fuels and assortment of established and evolving electrical technologies. That choice is fraught.

Moreover, without a public commitment, whether in policy, financial support, public-private partnerships, or the kind of inducements Congress laid out in the Inflation Reduction Act or the Infrastructure Investment and Jobs Act, rail electrification will be an unacceptably spotty, slow, and burdensome process. It will render talk about net-zero carbon deadlines virtually meaningless. That said, one cannot underestimate the transformational power of drivers such as emerging technologies, new studies and collaborative initiatives, growing climate and health concerns, the goals of better electric grid planning and transmission deployment, or the need for continued infrastructure investment.

Whatever form rail electrification takes, the power business will find it no more difficult or less beneficial than the advent of large electrical loads such as AI and data centers, hydrogen production facilities, and EV charging centers. It may complicate demand forecasts, transmission planning, maintenance of grid stability, and interconnection and reliability risks. In other words, at the center of a modern, more or less decarbonized rail system will be a genuine partnership with the grid advocates and operators in the power industry. The bottom line is this: electrification is not just one thing, one technology, or one process. There are good motive power options and bad, proven technologies and those mainly speculative or obscenely expensive. No industrial policy is dictating the pace of electrification, at least not yet. Railroad rights-of-way represent a prime revenue-generating opportunity but not all rights-of-way are usable, safe, or in the right place relative to energy resources or load. The upfront costs of electrification may be high and immediate benefits low; perhaps only the stout-of-heart need apply. The rewards may nevertheless be substantial, as the Texas study demonstrates. Rail electrification may be a true test of America's creativity and the benefits of modernization.

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