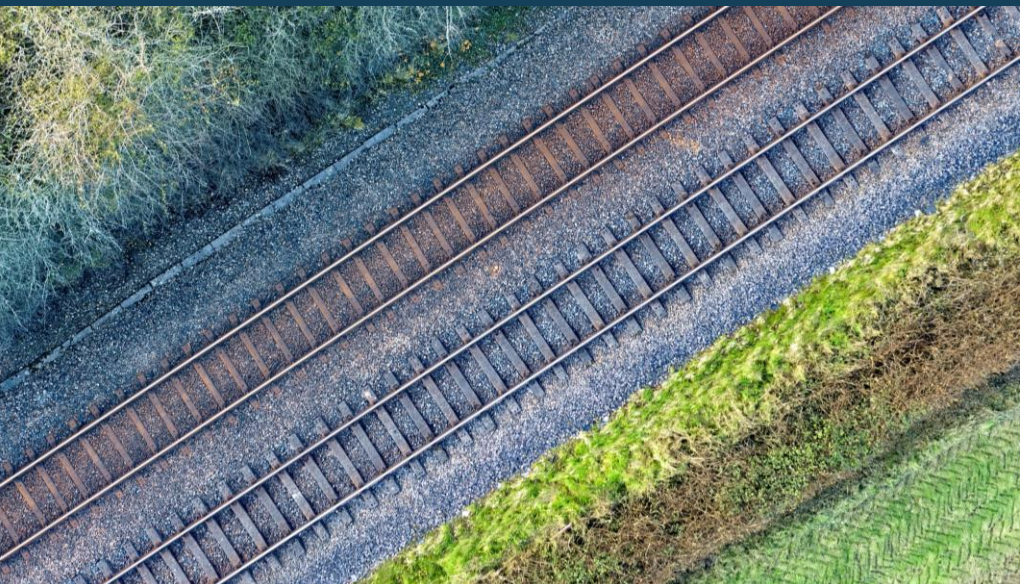




Study of Catenary Electrification of the North American Class I Railroad Network

February 2025



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Study of Catenary Electrification of the North American Class I Freight Rail Network

February 2025

I. Executive Summary

A. Introduction

The Association of American Railroads (AAR) commissioned this Study to provide a conceptual-level assessment for catenary electrification of the Class I freight railroad network across the U.S. and Canada as a strategy for reducing locomotive carbon emissions. This Study assesses infrastructure characteristics, capital costs, construction considerations, locomotive options, conceptual-level energy consumption, environmental considerations, and potential challenges of Class I freight railroad electrification.

B. Findings

This Study evaluated implementation of catenary electrification on up to 139,000 track miles of the Class I freight railroad network across the United States (U.S.) and Canada. The major findings are as follows:

Infrastructure

This Study evaluated two infrastructure scenarios. The first scenario assumed approximately 105,000 track miles of the Class I freight network would receive catenary electrification, but omitting light-density subdivisions. The second scenario assumed nearly the entire Class I freight network, approximately 139,000 track miles, would receive catenary electrification.

Catenary electrification of the Class I railroad network across the U.S. and Canada is estimated to cost between \$870 billion and \$1.1 trillion.

For comparison, the six Class I railroads generated approximately \$24 billion of combined net income in 2023.

Cost of Catenary System

The conceptual capital cost estimate for catenary electrification for the two scenarios ranges from \$870 billion to \$1.1 trillion U.S. dollars, including contingency.¹ For comparison, the six Class I railroads reported approximately \$24 billion of net income in 2023.² Thus, catenary electrification of all six Class I railroads would represent the equivalent of 36 to 47 years' worth of combined 2023 net income for all six Class I freight railroads.³

¹ All financial information is in United States dollars, unless otherwise noted.

² Financial information as reported in 2023 10-K of each Class I. Assumes \$1 Canadian dollar = \$0.72 U.S. dollars.

³ Does not account for inflation or discounting.

Infrastructure Construction Considerations

The U.S. National Blueprint for Transportation Decarbonization calls for elimination of “*nearly all greenhouse gas (GHG) emissions from the [transportation] sector by 2050...*”⁴ If Class I railroads in both the U.S. and Canada were to meet a 2050 timeline, and assuming field construction work would commence in 2030, installation would need to proceed at a pace of approximately 7,000 miles per year to complete the entire 139,000 mile Class I network.

Hundreds of crews would need to work simultaneously across the Class I network to meet a 2050 timeline. This level of construction activity would be disruptive to railroad operations, potentially resulting in service interruptions to customers and possibly impacting the North American supply chain network. Installation of the overhead catenary infrastructure could also create significant environmental impacts.

Locomotives

While there are currently no electric freight locomotives readily available in the North American market, established manufacturers likely have the capability to design and build such locomotives. This study assumes that electric freight locomotives would be equipped with small on-board batteries, allowing them to bridge short (five to ten mile) gaps in the catenary where existing, low-clearance overhead obstructions, such as tunnels or roadway overpasses, would otherwise prevent the installation of energized catenary wires.

Electrical Energy Demand

Catenary electrification would create significant new electrical demand, approximately 41.4 to 52.7 Terawatt-hours (TWh) each year and could require as much as 6 Gigawatts (GW) of power per day. The electrical demand would create large, intermittent loads on the electric power grid. The nature of these loads could be difficult for utilities to accommodate and could also necessitate significant investments in the electrical power grid.

Other Considerations

Catenary electrification would introduce the possibility of a single point of failure to rail operations. Trains would rely upon the catenary for power, but any damage to the catenary, such as from severe weather, could disrupt operations. Widespread utility power outages could also impact rail operations.

C. Summary

Catenary electrification of the North American Class I freight railroad network would be expensive to construct, with conceptual capital cost estimates ranging from approximately \$870 billion to \$1.1 trillion. The construction process, lasting decades, would also be disruptive to ongoing railroad operations. Catenary systems also introduce possible single points of failure into rail operations, which could reduce reliability of the rail network.

⁴ U.S. National Blueprint for Transportation Decarbonization, January 2023, <https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf>

II. Introduction and Background

A. Key Points and Overview

Key Points:

- Class I railroads are actively investing in research and development of low carbon and zero carbon locomotive technologies.
- The history of freight rail electrification in North America indicates that the viable use cases have been for short, isolated rail lines, requiring minimal electrification infrastructure, and without the need for interoperability with other parts of the larger freight rail network.
- The integrated nature of Class I freight railroad network would make catenary electrification of only short segments of the network operationally challenging.
- Recent North American electrification projects have been limited to passenger railroads.

Overview

The Association of American Railroads (AAR), an organization representing North American Class I railroads, has undertaken this Study to understand the likely implications of converting Class I freight railroad operations from the current diesel-electric energy source to an entirely electric system, with energy drawn from overhead catenary, as a potential approach to reducing greenhouse gas (GHG) emissions. The North American freight railroad industry is committed to reducing GHG emissions through science-based targets and is actively pursuing multiple paths to reduce GHG emissions. The freight rail industry currently has several projects underway, testing different technologies and approaches to reduce carbon emissions with the aim of identifying a technology, or technologies, which could cost-effectively reduce carbon emissions.

Freight railroads in the U.S. moved approximately 29% of ton-miles of freight but produced only 2% of transportation sector greenhouse gas emissions.

Examples of recent and ongoing projects include:

- Hydrogen Fuel Cell (HFC) locomotives – active development and tests on both Canadian Pacific Kansas City Railway (CPKC) and CSX Transportation (CSXT).
- Battery Electric Locomotives (BEL) – initial trials of a battery electric test bed locomotive designed to work in conjunction with other locomotives performed on BNSF Railway (BNSF) in 2021, with additional tests on Canadian National Railway (CN) scheduled for 2026.
- Battery Electric/Diesel-Electric Hybrid – active tests on Union Pacific Railroad (UP).
- Plug-in Hybrid – tests on CN scheduled for 2026.
- Low carbon fuels – all Class I railroads are actively testing low carbon fuels, such as renewable diesel or biodiesel, in their current locomotive fleets.

It is worth noting that railroads already move significant amounts of freight with relatively low carbon emissions. For example, based on U.S. government data, freight railroads in the U.S.

move approximately 29 percent of ton-miles of freight but produce only 2 percent of transportation sector greenhouse gas emissions.⁵

B. Background: Modern Main Line Diesel-Electric Locomotives

Modern diesel-electric locomotives employ a combination of a diesel engine coupled with an electric transmission and drive system. A diesel engine on each locomotive rotates a large alternator which produces electricity. In turn, this electricity is used to power smaller electric motors attached via gears to the axles of the locomotive.

The combination of diesel engine and electric transmission takes advantage of the best torque and power characteristics of both diesel engines and electric motors while avoiding a complex and costly mechanical transmission system. The diesel-electric system has been refined over decades with increasingly sophisticated diesel engines, electrical systems, electronic control components, and energy management systems to provide more traction (the force exerted at the wheels that moves a train) and continually increased efficiency, while also reducing fuel consumption, pollutants, and carbon emissions.

Modern main line diesel-electric locomotives are based on a handful of standardized designs, generally using a diesel engine rated at approximately 4,400 horsepower for line-haul locomotives. These standardized locomotive designs meet railroads' requirements for safety, reliability, flexibility, and interoperability, with over 25,000 diesel-electric locomotives in the Class I railroad fleet today.⁶

The North American freight railroad network relies on standardization and interoperability to facilitate commerce across the U.S. and Canada. The North American freight railroad network is an interconnected system of routes; every locomotive and every rail car must be able to – and often does – operate on any main line route. Locomotives and rail cars are often shared between railroads to promote speed and efficiency for the supply chain, and it is common that a train originating on one railroad moves, intact and with the same locomotives, along the route of other railroads to its destination. By sharing locomotives and operating them on through trains, railroads avoid operationally complex and inefficient stops to exchange engines each time a train changes from the tracks of one railroad to the tracks of the next railroad.

C. Approaches to Electrification Studied

1. Electrification of the Entire Main Line Railroad Network in the U.S. and Canada

The baseline scenario for this Study assumes that existing diesel-electric locomotives would be replaced with catenary-electric locomotives, i.e., locomotives that receive energy from a system of energized overhead wires, known as the overhead contact system (OCS), with

⁵ U.S. Bureau of Transportation Statistics “U.S. Ton-Miles of Freight”, <https://www.bts.gov/content/us-ton-miles-freight>, 2022 and U.S. Environmental Protection Agency, “Fast Facts on Transportation Greenhouse Gas Emissions, 2022 U.S. Transportation Sector GHG Emissions by Source”, <https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions>

⁶ Association of American Railroads, 2023 “Railroad Fact Book” and Railway Association of Canada, “Locomotive Emissions Monitoring Report”, 2022

power supplied by a traction power system (TPS). The OCS comprises overhead contact wires, wire tensioning systems, support poles, and other hardware. The TPS comprises substations, paralleling stations, switching stations, and associated utility connections. Note that this Study assumes that OCS would not be installed on yard tracks and industrial spurs across the network. Instead, this Study assumes locomotives would normally receive energy from the OCS but could operate for short distances (approximately five to ten miles) using energy stored in batteries small enough to fit on-board each catenary-electric locomotive.

2. Electrification of Only Certain Corridors

This Study considered a scenario where only certain corridors would be equipped with OCS. While there are high-volume corridors around North America, these individual corridors form only one portion of the longer routes over which trains operate. For example, trains frequently operate on one corridor for a relatively short distance before turning onto another corridor. The Class I network shown in **Figure 1** illustrates that all corridors are interconnected. Every train's path across the network is different, and individual trains can – and do – use combinations of different corridors during their journeys.

From an operational perspective, the integrated nature of the North American railroad network, including Class I railroads and smaller partner railroads, relies on operational flexibility and economies of scale. Today, most main line locomotives stay with their respective trains for an entire trip of hundreds or thousands of miles, with the flexibility of powering any train, over any main line territory.

By contrast, installing partial catenary electrification only on certain corridors or portions of the railroad network, thereby requiring one or more locomotive exchanges midway through a trip, would introduce operational complexities and inefficiencies, and could impact freight rail service. As a result, partial electrification was not studied further.

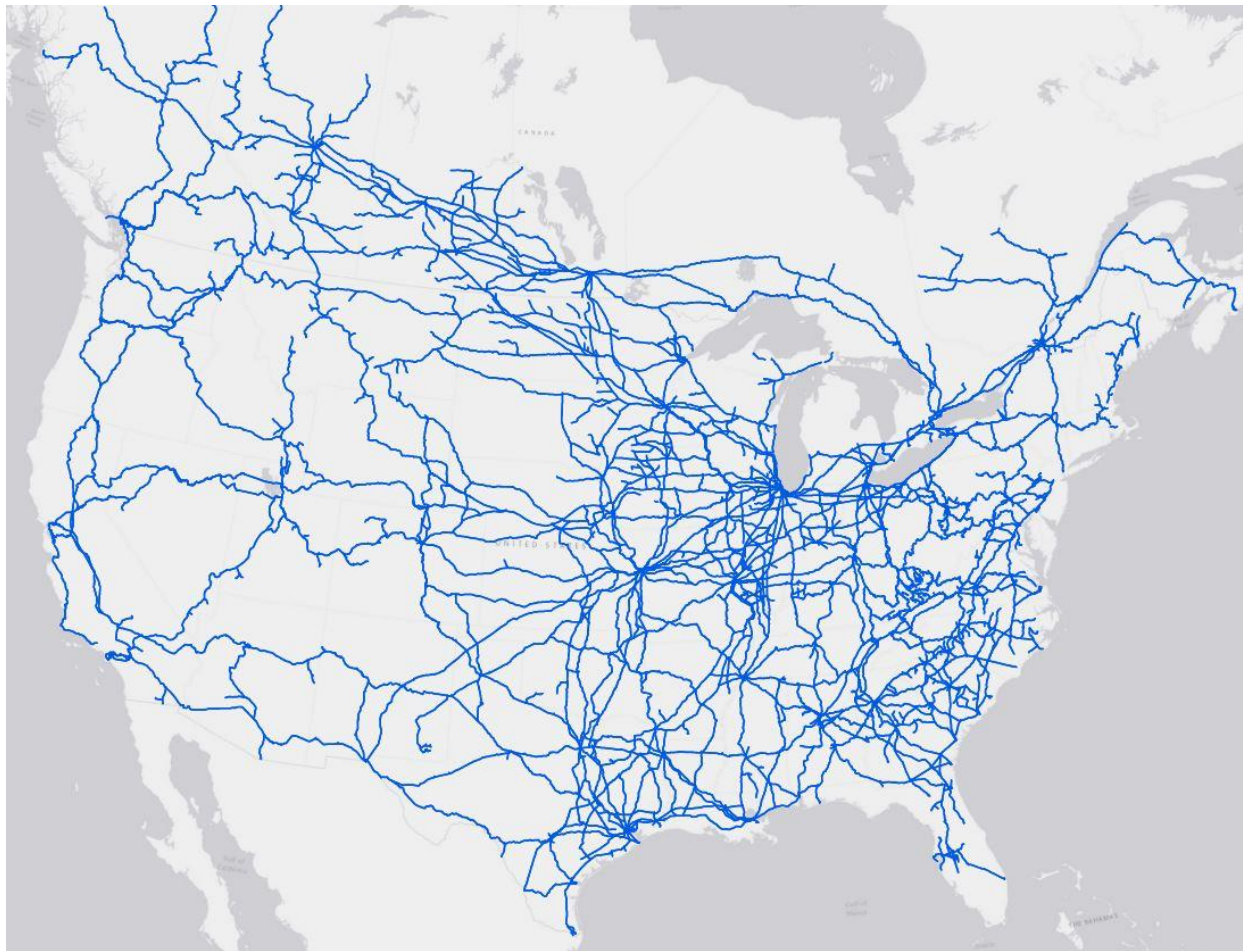


Figure 1: Map of North American Class I Rail Network (U.S. and Canada)

D. Overview of Previous Electrifications

To better understand the characteristics conducive to railroad electrification, it is helpful to look at analogs, other railroad electrifications, elsewhere in time and geography.

1. International Examples

There are examples of railroad electrification in other nations. However, in each case infrastructure was heavily, if not entirely, subsidized by the respective governments. The primary users in most cases have been passenger operators, who often need the acceleration and high-speed characteristics of electric trains to satisfy short-headway operations and additional train frequency in heavily trafficked passenger corridors.

It is important to note that the international railroad electrification projects have typically required substantial public subsidies for construction, and international experience on

privately financed freight routes has generally eschewed catenary electrification as financially infeasible.⁷

a. European Railroad Electrification

Several European railroads adopted electrification in the early 1900s, in part due to the prevalence of hydroelectric dams producing significant amounts of electricity. As of 1990, about 44 percent of the European railroad system was electrified. By 2022 – 32 years later – the proportion rose to 57 percent of the European network. In those 32 years, approximately 17,000 route miles were electrified, an average pace of approximately 530 miles per year.⁸ Expansions of European railroad electrification infrastructure was funded and subsidized by government sources.

Note that most Western European railroads are focused on passenger operations and electrification programs have offered improved acceleration characteristics and higher speeds, as well as environmental benefits, for passenger trains in high-density corridors. However, electrification of freight railroads in western Europe is largely a byproduct of projects designed for passenger operations. Most western European freight trains (approximately 2,500 feet) are shorter than North American freight trains (over 10,000 feet) despite European rail operators' knowledge that short train lengths limit productivity and appeal to shippers, meaning European electrified freight operations are not an analog to North American operations.⁹

b. Chinese Railroad Electrification

Most Chinese railroad electrification projects have been recent – occurring in the last 10 to 20 years. News reports indicate that construction, operations, and maintenance have been subsidized by the Chinese government.

2. Review of History of North American Railroad Electrification

The concept of large-scale railroad electrification in North America is not new. But, even in the early 1900s – when there were few freight transportation options – railroad electrification was rarely financially justified in North America. The only places where railroad electrification was viable were a select few corridors where both freight train and passenger train frequencies were very high, where tunnels were long, in very short, operationally isolated corridors catering to large mining operations, or where electrification represented an improvement over steam locomotives, a higher cost alternative.

Relatively recent studies, such as one performed by the California Air Resources Board (CARB) in 2016, determined that freight railroad electrification was not financially viable and due to increased costs for rail users, would result in mode-shift of freight to trucks. The

⁷ See, for example, the high-tonnage mining railroads constructed with private funds in Australia and Brazil. These high-tonnage lines would, in theory, have been the most favorable locations for catenary electrification, yet they selected conventional motive power.

⁸ European Union Eurostat; <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240313-1>. Note that at the pace of 524 route miles per year, it would require over 150 years to install catenary electrification on the Class I rail network in the U.S. and Canada.

⁹ Community of European Railway and Infrastructure Companies, "Longer Trains, Facts and Experiences in Europe, 4th Edition", 2018.

freight mode shift would, in turn, reduce the emissions benefits of catenary electrification since trucks produce more emissions than freight trains per ton-mile.¹⁰

a. North American Experience

i. Freight Electrification Projects

- **Short-Haul and Industrial Railroads**

In North America, there have been no new freight rail electrification projects since the 1980s. Electrified railroads that were constructed in the 1960 to 1980 era include the Muskingum Electric Railroad in Ohio (operational 1968 to 2004), Black Mesa and Lake Powell Railroad in Arizona (operational 1973 to 2019), Deseret Power Railway in Utah (operational 1983 to present), Navajo Mine Railroad in New Mexico (electrified 1984 to 2019, continues with diesel-electric operation), the Martin Lake Railway in Texas (operational approximately 1976 to 2011), and a six-mile long intraplant railroad of the Iron Ore Company of Canada in Labrador, Canada (operational 1963 to present).

Other, older short but high-density freight railroad electrifications (generally dating from the 1920s or earlier) were also discontinued in favor of diesel-electric locomotives throughout the 1970s and 1980s, including several mine railroad electrifications in, Montana, Utah, Nevada, and Arizona, with one in Ontario reportedly lasting until 2000.

The electrification projects identified above were generally less than 100 miles long, limiting the amount of electrification infrastructure. Each of those projects was specifically dedicated to moving high volumes of one commodity, such as coal, or to moving heavy mining traffic (i.e., copper, nickel, iron ore), from one point to another, with minimal operating variability. Each was an isolated operation, and each was owned by the company that produced or consumed the commodity (e.g., electric utilities or copper mining companies). Thus, the railroad was an adjunct to the electric power or mining company's business, meaning that the infrastructure investment was made with nearly perfect insight into the plans of the customer, with a guaranteed traffic level, and in the case of electric utilities, based on a long-term, guaranteed rate structure. Except for the six-mile-long iron ore railroad in Canada and the 35-mile-long Deseret Power Railway in Utah, all these electrifications have been discontinued and in some cases the railroads abandoned.

- **Main Line Electrifications**

Main line freight railroad electrifications, generally dating from the 1920s or earlier were also discontinued in favor of diesel-electric locomotives throughout the 1970s and 1980s, including the electrically-powered freight lines in Pennsylvania and also on the Northeast Corridor (the latter relying on infrastructure paid for by the U.S. government during the Great Depression for much of the distance) and significant segments of the Chicago, Milwaukee, St. Paul & Pacific Railroad electrified main line in the U.S. states of Washington, Idaho, and Montana. There were several even shorter projects – 150 miles or less – to avoid the challenges of steam locomotives in long tunnels, such as the Great Northern Cascade

¹⁰ California Air Resources Board, "Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations, Final Report," 2016. https://ww2.arb.ca.gov/sites/default/files/classic/railyard/docs/uoi_rpt_06222016.pdf

Tunnel Electrification. In the 1980s, the British Columbia Railway constructed an electrified line dedicated to assist hauling coal over steep terrain and through a long tunnel.

Each of these railroads electrified a relatively short route and each required a change of motive power for through freight trains. Each electrified freight operation was discontinued, though the railroads continued freight operations with diesel-electric locomotives, avoiding the locomotive change. The electrified Northeast Corridor continues to serve passengers.

The history of these main line electrification projects is relatively consistent: they were only financially viable for short-distance, high-tonnage railroads, most were built in the steam era when motive power and train crew changes already occurred frequently, and where steam locomotive maintenance and operation was extremely expensive. All were discontinued as diesel-electric locomotives, which could remain with their trains for long distances, eliminated the inefficiencies of changing motive power and the higher cost of steam locomotive maintenance.

ii. Recent North American Passenger Experience

The most recent experience with new railroad high-voltage electrification in North America is the Caltrain passenger corridor, linking San Jose with San Francisco, California. Caltrain upgraded an existing, diesel-electric powered commuter railroad to a 25 kilovolt (kV) system, including OCS, traction power equipment, new vehicles, as well as necessary railroad signal infrastructure upgrades to accommodate the electrification.

iii. Recent Electrification Studies by the California Air Resources Board

CARB commissioned a study that identified the complexities, infrastructure required, and approximate cost to exchange locomotives in the 2016 study “Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations”¹¹. This study evaluated the feasibility of installing catenary electrification on rail lines in California and exchanging diesel-electric locomotives for catenary-electric locomotives as each train entered the electrified territory, or vice versa. CARB issued a subsequent report, “Technology Assessment: Freight Locomotives.”¹²

A study commission by CARB found that full-scale catenary electrification in Southern California was not economically viable, and would result in mode shift away from rail, a transportation mode with relatively low carbon intensity, to trucks, a more carbon-intensive mode.

CARB’s studies found that exchanging locomotives on every freight train entering or leaving California would require a large expansion of track infrastructure to accomplish the locomotive exchanges and would delay each train by one to four hours in the process.¹³ CARB identified that the fixed infrastructure required for railroad electrification plus the cost of acquiring new locomotives exceeded potential benefits. CARB also found that the

¹¹ California Air Resources Board [Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations -FINAL-2016-Spring-R2](#), 2016

¹² California Air Resources Board [Technology Assessment: Freight Locomotives \(ca.gov\)](#), 2016

¹³ California Air Resources Board, “Transitioning to a Zero or Near-Zero Emission Line-Haul Freight Rail System in California: Operational and Economic Considerations, Final Report,” 2016, Section 7.1.3

additional delays and costs to railroads would ultimately impact shippers and encourage modal shift away from rail (one of the lowest carbon-intensive land transportation modes), to trucks, (a more carbon intensive land transportation mode).

Based on the operational complexities and costs identified in the CARB studies and the integrated nature of Class I rail operations, this Study does not consider options that would involve locomotive changes enroute.

III. General Approach to the Study

The Study approach was to describe and define conceptual parameters and considerations for a Class I catenary electrification system and to evaluate three main cost components:

1. Energy used for electrified train operations,
2. Capital costs for infrastructure and equipment, and
3. Operation and maintenance costs.

Most rail projects have a relatively well-defined scope and each of the three cost components can be defined with specificity. However, the footprint for this Study is effectively the entire Class I network. A geographic information system (GIS) was used to compile information across the U.S. and Canada.

An energy model was developed to represent electrified operations on several territories typical of freight railroad main lines. Using the GIS system, the results of the energy model were assigned to segments of the Class I freight network across the U.S. and Canada to evaluate the amount of electricity that would be required for operations.

To assess conceptual infrastructure costs, the characteristics of the catenary electrification system (i.e., the catenary, substations, utility connections, etc.) were defined at a conceptual level (as described in this report), total quantities of various infrastructure elements were determined with the help of the GIS system, unit costs assessed based on the nature of the respective elements, and the unit costs applied to those quantities. Motive power costs were assessed based on publicly available data.

To evaluate maintenance costs, a conceptual staffing plan was developed based on existing electrification systems and reliability needs, and costs assigned to that staffing plan.

The following sections discuss the technical considerations within each of these cost components. They also describe, at a high-level, the considerations and complexities of constructing, operating, and maintaining a catenary electrification system.

IV. Train Energy Usage

A. Key Points and Overview

Key Points

- Catenary electrification of the Class I railroads would create new demand for large amounts of electricity.

- The capacity of the electrical infrastructure that delivers electricity to trains is fixed, based on the initial estimated energy requirements. The resulting infrastructure is not easily adaptable to changes in transportation patterns. Due to fixed capacity of electrification infrastructure:
 - Railroads would need to “overbuild” the electrical infrastructure to accommodate the maximum theoretical amount of demand.
 - Conversely, if newly built infrastructure serves corridors where demand later decreases, the relatively high catenary infrastructure costs are sunk and cannot be recovered.
- Supply chains that rely on railroads could be affected in the event catenary infrastructure was unable to deliver sufficient energy to trains, which could result from short-term operational disruptions, power outages, or emergencies.

Overview

A major consideration of railroad electrification is the demand for electrical energy and the infrastructure required to deliver that energy to trains. This Study developed a conceptual model to estimate energy demand for the Class I network using publicly available sources.

A train's resistance to motion is the major factor in energy consumption. Key inputs to calculate train resistance include the number, type, and total weight of vehicles (locomotives and cars) in a train, the characteristics of the track (i.e., curves and grades), and train speed.

A GIS database, using data sets from the Federal Railroad Administration (FRA) and Transport Canada (TC), was used to develop a route map of the Class I freight railroad network. Elevation data was imported into GIS and combined with the track locations to approximate track grades around the entire North American Class I network. Train frequency data, gathered primarily from FRA and Transport Canada (TC) GIS sources, was also superimposed onto that map. The AAR provided characteristics for a typical train operating on the North American Class I network. Thus, the average number of trains, average weight of trains on each route, and the grades along each route, were defined. Approximate train speeds were developed using software designed to analyze railroad electrification; the same software calculated the energy usage for a typical train on each type of territory. These calculations were made for Class I routes across the U.S. and Canada. Additional information about the methodology is included in **Appendix A – Train Energy Usage**.

1. Results of Train Energy Usage Analysis

Energy usage estimates are presented as a range based on two scenarios.

The low end of the range represents a scenario including only those corridors with an average of six or more trains per day would be operated with catenary electrification. The low end of the range also represents an idealized condition where regenerative braking (sometimes described simply as “regeneration”), a process whereby energy is captured during braking and returned to the OCS to power other nearby trains, would be used to the maximum extent possible.

The high end of the range represents a scenario where all Class I railroad routes, approximately 139,000 track miles (except auxiliary tracks, such as yard tracks, spur tracks, and minor industrial leads) would be operated with catenary electrification, but with no

allowance for regenerative braking, simulations showed that regenerative braking would not be feasible in many circumstances (because there would be no nearby train to absorb the regenerated energy).

a. Average Energy Usage

The results of the train energy usage simulations are summarized in **Table 1**, which illustrates the approximate amount of electrical energy that would be used to operate trains in the two scenarios described above. Note that the energy usage shown below is based on estimated traffic levels developed from the FRA and TC data sets.

Table 1: Estimated Class I Average Energy and Power Usage in Gigawatt Hours (GWh) and Terawatt Hours (TWh), Based on 2024 Data.

Average Daily Energy Usage	Average Annual Energy Usage
114 GWh – 145 GWh	41.4 TWh – 52.7 TWh
Average Daily Power	
4.7 GW – 6.0 GW	

Note: (1 TWh = 1000 GWh)

Spread evenly over 24 hours, 145 GWh of energy (the high end of the range) translates to 6.0 GW of constant power.¹⁴ For comparison, a typical nuclear reactor produces about 1 GW of power.¹⁵ That means, if railroads implemented electrification for their main lines, power generators around North America would need to provide the power equivalent of approximately 6 new nuclear reactors. Alternately, assuming renewable generation, the annual energy required by Class I freight railroads would be the equivalent of approximately 11 million solar panels, or 1,800 utility-scale wind turbines.¹⁶

As a point of comparison, the energy used by catenary electrification, up to 52.7 TWh, could power approximately 5 million average U.S. homes for an entire year.¹⁷

b. Peak Energy Usage

Railroad volumes are seasonal and geographically dispersed, with peak volumes typically occurring in the late summer and fall. Based on the average of the last six years of data provided by the AAR, the peak number of rail carloads per month averages 5.6 percent above the annual average number of monthly carloads. This implies energy requirements to move the additional carloads would also be approximately 5.6 percent higher than the

¹⁴ Energy is the ability to do work, while power is the amount of energy over a given period of time.

¹⁵ See U.S. Department of Energy (DOE), accessed on October 15, 2024 at <https://www.energy.gov/ne/articles/nuclear-power-most-reliable-energy-source-and-its-not-even-close#:~:text=A%20typical%20nuclear%20reactor%20produces,gigawatt%20coal%20or%20renewable%20plant> for additional information on nuclear power. Note that many nuclear power plants have more than one reactor.

¹⁶ See U.S. Department of Energy (DOE), accessed on October 15, 2024 at <https://www.energy.gov/eere/articles/how-much-power-1-gigawatt> for information on solar panels and wind turbines.

¹⁷ U.S. Energy Information Administration, "Use of Energy Explained", average annual U.S. household energy consumption of approximately 10,500 kWh per year, <https://www.eia.gov/energyexplained/use-of-energy/electricity-use-in-homes.php>

average energy requirement. **Table 2** reflects estimates of peak daily energy and power usage, assuming a 5.6 percent increase above the average daily energy usage.

Table 2: Estimated Peak Energy and Power Usage (Based on 2024 Data)

Peak Daily Energy Usage	Peak Daily Power
120 GWh – 153 GWh	5.0 GW – 6.4 GW

Compared to the estimated average daily power usage, the estimated additional daily power usage during a peak time would be up to 0.4 GW.

c. Future Energy Usage: 2050

The U.S. Department of Transportation (USDOT) developed the Freight Analysis Framework (FAF) model to analyze and predict future freight traffic trends. FAF indicates a 0.8 percent compound annual growth rate in rail ton-miles between 2025 and 2050. In absolute terms, this represents approximately 22.5 percent growth in ton-miles over the 25-year period. Assuming that energy demands grow proportionately to ton-miles, **Table 3** illustrates the estimated energy demand of a catenary electrification system in 2050 based on application of this growth rate to both U.S. and Canadian Class I railroads.

Table 3: Estimated Future Year (2050) Energy and Power Usage Based on USDOT FAF Growth Rate

Average Daily Energy Usage	Average Annual Energy Usage	Average Daily Power
139 GWh – 177 GWh	50.8 TWh – 64.6 TWh	5.8 GW – 7.4 GW
Peak Daily Energy Usage		Peak Daily Power
147 GWh – 187 GWh		6.1 GW – 7.8 GW

It can be seen from the table above that the high end of the range of the estimated peak daily power usage in the year 2050 is 7.8 GW. Compared to the base year (2024) estimated peak daily power usage (6.4 GW), there would be approximately 1.4 GW of additional power demand in 2050.

d. Avoided CO₂

Existing diesel-electric locomotives emit carbon dioxide (CO₂) through the combustion of diesel fuel. The U.S. Environmental Protection Agency (EPA) has determined that combustion of one gallon of diesel fuel in a line-haul locomotive releases 10.15 kg of CO₂.¹⁸ Line-haul fuel consumption (i.e., excluding switching fuel consumption) for the six Class I railroads in the U.S. in 2023 was a total of 2.89 billion gallons. This equates to 32.3 million U.S. tons (29.3 million metric tonnes) of CO₂ released by line-haul locomotives.

¹⁸ U.S. Environmental Protection Agency, "2020 National Emissions Inventory Locomotive Methodology", 2022. https://www.epa.gov/system/files/documents/2023-01/2020_NEI_Rail_062722.pdf

The USDOT issues guidance for the value of each avoided metric tonne of CO₂ for the purposes of assessing the ratio of benefits to costs for public investment projects. For 2023, USDOT valued one metric tonne of CO₂ at \$228.¹⁹

Thus, based on USDOT estimates, the cost of all CO₂ emitted from the US line-haul locomotive fleet in 2023 was approximately \$6.68 billion. If the entire Class I line-haul fleet were converted to electric operation, and the electricity were from entirely CO₂-free sources, that would represent the estimated value USDOT places on the avoided CO₂ emissions.

Compared to the value USDOT assigns to avoided CO₂ emissions, existing U.S. commercial carbon markets place a lower value on CO₂. For example, California's carbon market priced a metric tonne of CO₂ at a high of \$43 in first quarter of 2024 (the California secondary market price has since declined to approximately \$35 per metric tonne in third quarter 2024).^{20,21} Applying the higher, \$43 per tonne California price to CO₂ emissions for all locomotives around the U.S., the cost of the 29.3 million metric tonnes of CO₂ emitted from the Class I line-haul locomotive fleet would be \$1.26 billion, significantly lower than the price based on the USDOT methodology.

However, the current portfolio of electrical generating capacity is not carbon-free. The U.S. Energy Information Administration (EIA) determined that, in 2022, the combined U.S. electrical generating capacity, including both renewable and conventional generating capacity, emitted, on average, 0.39 kg of CO₂ per kilowatt-hour of energy produced.

EIA's estimate can be used to project the CO₂ emissions from train operations via catenary electrification assuming that, in the near-term, emissions from U.S. generating capacity (which would supply the energy to power a catenary electrification system) remain relatively constant.

When considering only U.S. Class I railroads (i.e., omitting Canadian railroads, since U.S. DOT CO₂ values are being used for this example), the current energy consumption from catenary electrification would be approximately 37.5 TWh per year. Assuming that all such energy is provided by generating capacity at the 2022 CO₂ emissions rate of 0.39 kg/kWh, the resulting power plant CO₂ emissions would be approximately 14.6 million metric tonnes. This would be a net reduction of 14.7 million metric tonnes of CO₂, compared to the CO₂ produced by the current line-haul diesel-electric locomotive fleet.

The value of the 14.7 million metric tonne reduction in CO₂, using the US DOT price of \$228 per metric tonne, would be \$3.4 billion, while using the California carbon market price of \$43

¹⁹ U.S. Department of Transportation, "Benefit Cost Analysis Guidance for Discretionary Grant Programs (December 2023)", www.transportation.gov/sites/dot.gov/files/2023-12/Benefit%20Cost%20Analysis%20Guidance%202024%20Update.pdf

²⁰ Bloomberg New Energy Finance, "Global Carbon Market Outlook 2024", February 21, 2024.

²¹ California Air Resources Board, Cap-and-Trade Program Dashboard, accessed on November 2, 2024 at: <https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/program-data/cap-and-trade-program-data-dashboard>

per metric tonne, would be \$0.63 billion.²² The value of the annual reduction in CO₂ can be compared to the estimated capital cost of electrification of the railroad network, which ranges from \$870 billion to over \$1.1 trillion.

Note that this analysis of avoided CO₂ emissions represents figures only for the U.S. and it includes only the avoided CO₂ emissions through operation. It does not capture the hidden costs of carbon and other emissions that would be produced to construct the enabling works (i.e., OCS infrastructure, power transmission and distribution, railroad infrastructure upgrades, locomotive and facility investment, and so on).

2. Infrastructure Constraints on Energy Delivery

The information discussed so far, including the survey of other North American electrifications and North American freight railroad operating patterns, reveals a key challenge of catenary electrification: the dependence upon energy from the national electric grid and potential lack of adaptability to changing conditions.

The OCS, substations, utility feeds, and other equipment must be sized for a specific level of power consumption, based on an assumed or projected power demand at the time the system is designed and constructed. Once the fixed electrification infrastructure is installed, changes to increase the system's electrical capacity (such as installing more or larger substations, heavier-gauge contact wire, or securing additional utility power) would take months or years to implement. As will be seen later in this Study, changes in demand that affect the national electric grid, such as a sudden or sustained increase in power demand by an electric railroad, can be difficult to predict.

For example, in a catenary electrification scenario, the ability to operate more frequent or substantially heavier trains over a given territory could be limited by the electrical infrastructure (e.g., substation capacity) and utility generating and transmission capacity in that region. To provide the resiliency necessary to accommodate such shifts in traffic, the electrical capacity of the catenary system, including OCS and feeds from the national electric grid, would need to be designed for worst-case scenarios. This would mean the electrical system, including utility power feeds, would need to be designed and constructed to match the theoretical maximum track capacity and heaviest trains, which is often substantially higher than the capacity used during normal operations. This would increase the upfront costs for catenary electrification.

Conversely, the current railroad locomotive fleet, consisting of individual diesel-electric locomotives, each operating independently with its own energy supply stored on-board (i.e., in the fuel tank), allows the number of locomotives (and the power produced and consumed by locomotives) to be easily scaled for any operating condition. There is also operational flexibility in terms of the many established refueling locations and ease of fuel delivery for diesel-electric locomotives.

²² It is acknowledged that inputs from several different years are being used based on available data, such as U.S. generating fleet emissions per kWh in 2022, fuel consumption by the line-haul locomotive fleet in 2023, and the price of CO₂ in 2024. However, for the purpose of this high-level discussion, the effects of year-to-year changes are expected to be relatively minor.

Changes in railroad traffic patterns should not be considered a remote eventuality, or a shift that occurs only gradually. Changes in railroad traffic patterns are a certainty. For example, the decline of coal traffic resulted in significant declines in traffic on certain corridors and has occurred over a relatively short period of time. While some changes in traffic patterns do happen over long periods of time, it is less well-known that on a daily basis, there are significant, if short duration, shifts in traffic.²³

a. Re-Routing Trains

For example, when there is a weather emergency or other disruption on a given railroad corridor, the affected railroad may be able to reroute many of its trains onto a parallel route in order to keep the railroad network (and thus national supply chains) fluid. In some cases, railroads also have mutual aid agreements wherein one railroad can accommodate another railroad's trains in an emergency. Such rerouting of rail traffic substantially increases the number of trains – and, in a catenary electrification scenario, would substantially increase the amount of electrical energy needed – on the alternate route for several days or, in some cases, weeks.

Moreover, in a scenario where trains relied on catenary for energy, the recovery time from an emergency could be increased, since both the catenary infrastructure and the electric grid would need to be restored before train operations could resume.

Today, in situations where trains are rerouted, there are no operational limitations based on availability of energy. If catenary electrification was adopted across the U.S. and Canada, unless the electrical infrastructure everywhere were sized for these worst-case scenarios, it might be difficult (or impossible) to re-route trains to avoid disruptions.

b. Changing Traffic Patterns

In addition to occasionally re-routing trains, railroad traffic patterns respond to changing customer demands. For example, there are annual peaks in intermodal traffic and grain traffic. Although there is typically a late summer and early fall peak for intermodal traffic in

In 2024, Hurricane Helene caused significant damage across the Southeastern U.S. Had railroads in the path of the hurricane installed a hypothetical catenary electrification system, the damage to OCS from falling trees and flooding of substations would have taken weeks if not months to restore. In the intervening time, train operations, reliant on the OCS, would be stopped at a time when supply chains would need rail service the most.

Even weeks after Helene, continuing power outages were an indication that large portions of a hypothetical catenary electrification could also be without utility grid power for an extended period, leaving trains stranded. It is also possible that power outages could be so widespread that even rail "detour" routes would also have been without power.

²³ As an example of the difficulties increasing electrical capacity, Europe has contemplated increasing the length of freight trains to increase "the effectiveness and efficiency of the freight rail system." However, the fixed electrical capacity of previously constructed railroad substations and OCS has been identified as a constraint (Community of European Railway and Infrastructure Companies, "Longer Trains, Facts and Experiences in Europe," 4th Edition, 2018).

advance of the winter holiday consumer buying season, both the intermodal and grain peaks can be unpredictable since these traffic segments respond quickly to changes in international trade patterns and commodity markets.

Supply shocks can also trigger changes to traffic patterns. For example, high yields for agricultural crops may lead to higher-than-expected international exports, or significant construction material demand may lead to higher-than-expected shipments of raw materials and manufactured goods to and from production centers.

Port congestion, resulting from an excess of shipments or reduced port productivity from labor actions or other causes, can also play a role in short-term, yet significant, shifts in traffic patterns and supply chains. Port congestion in one location can result in diversion of ocean shipping to other ports, with peaks in rail traffic following the international ocean shipping patterns. Thus, not only is the magnitude of the peak variable, but the location of the rail corridors experiencing the peak are also variable since rail traffic will adapt in response to customer needs.

Changes in railroad traffic patterns reflect changes in the commerce of the U.S. and Canada. To provide supply-chain resiliency, a catenary electrification system would need to be overbuilt to accommodate both worst-case operational demands and future growth.

Fundamentally, changes in railroad traffic patterns reflect changes in the commerce of the U.S. and Canada. Today, railroads accommodate these changes by assigning the appropriate number of diesel-electric locomotives, each with its own on-board energy supply. In a catenary electrification scenario, locomotives would be dependent upon overhead catenary for energy. If the catenary, traction power systems, or utilities were unable to meet the energy demand

resulting from shifts in rail traffic patterns, supply chains could be affected. Unless the electrification system were overbuilt to accommodate worst-case scenarios, the ability to adapt to changes in commercial trends or structural shifts in the economy would be jeopardized.²⁴

V. Railroad Infrastructure for Catenary Electrification

A. Key Points and Overview

Key Points

- Catenary-electric locomotives receive energy from the OCS, comprising foundations, poles, and overhead wires. The OCS is the most significant and most expensive component of electrification infrastructure.

²⁴ Note that this Study has not evaluated the cost of over-building that might be required to address short-term changes in traffic patterns or long-term structural shifts in the economy that might result in changing traffic patterns. The cost effects of this could be significant since the electrical system would need to be built to accommodate the both the current traffic patterns and the predicted future traffic patterns.

- Traction Power Systems (TPS) receive energy from the national electrical grid, transform that electricity to a lower voltage, and supply it to the OCS. The TPS also provide electrical balancing and isolation functions.
- Additional infrastructure, such as power dispatching centers, access roads along the right-of-way (ROW) for construction and maintenance of the OCS, and modifications to maintenance facilities would be required.
- Major modifications would be required to existing railroad signal systems.
 - Most wayside signal systems would require significant modifications.
 - Due to electrical interference, the existing, proven, constant warning time equipment at highway-rail grade crossings equipped with active warning devices would need to be replaced with equipment that would result in more variability in warning time to motorists.
- The process of constructing OCS is complex and lengthy, requiring years to plan and construct even short segments of OCS. Construction activities would disrupt existing railroad operations and the customers that depend upon them.

Overview

A significant amount of specialized infrastructure would be required to implement catenary electrification on any railroad. While the overhead wire is the most visible infrastructure element, the new infrastructure extends far beyond the overhead wire. This Study groups the infrastructure into four main categories:

- OCS, including contact, messenger, static, and feeder wires, an automatic tensioning system (“auto-tensioning”) for the wires, poles, and foundations.
- TPS, including traction power substations (TPSS), autotransformers, and switching stations.
- Other supporting infrastructure (e.g., access roads, power dispatching systems).
- Modifications to existing infrastructure (i.e., signals, bridges, tunnels, third party utilities).

Each will be discussed in turn, including descriptions of the various components and construction considerations, as well as the assumptions for each infrastructure category that was incorporated into this Study and the accompanying conceptual infrastructure cost estimate.

Because the OCS, and particularly the OCS pole foundations, are major cost drivers, they are discussed in detail. Installation of OCS pole foundations would be on the critical path for construction and could be the activity most disruptive to ongoing railroad operations.

B. Overhead Contact System

The OCS delivers electricity to trains via a conductive wire (the contact wire), which is suspended over the track by cantilever assemblies or from beams spanning the track. Catenary-electric locomotives receive electrical energy from the contact wire via a sliding shoe and movable supporting frame (pantograph) mounted on the roof of each locomotive (see **Figure 2**). The pantograph slides along the underside of the contact wire and is equipped with an electrically conductive carbon strip that collects electricity from the contact wire.

In total, the OCS is a complex system of supporting structural elements, tensioned wires, and insulators that keep the contact wire in proper geometric relationship to the track and trains while simultaneously transmitting electricity and insulating the energized components from the ground. This Study assumes the OCS would be energized at 25,000 volts alternating current (25 kV AC), which is the standard voltage for most modern main line electrification systems, discussed further in **Section V.C - Traction Power System**. The OCS is the most visible element of a railroad electrification system and represents one of the major capital cost drivers for any electrification project.

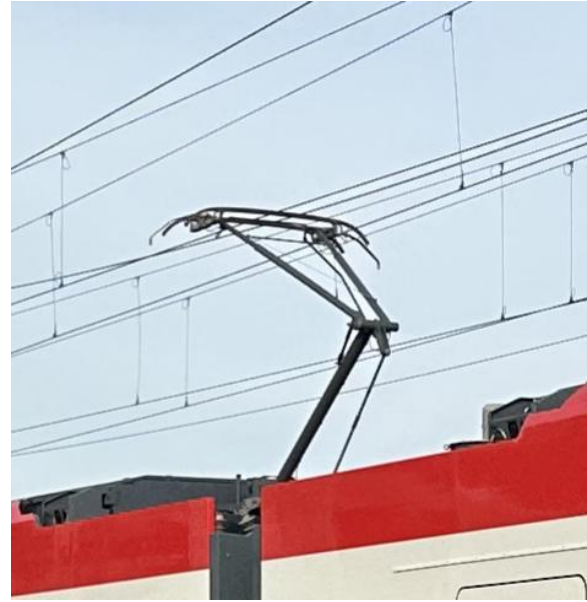


Figure 2: Photograph of Pantograph on Roof of Rail Equipment

This Study assumes that the OCS would consist of an independent support pole adjacent to each track. This configuration is consistent with the type of construction employed on recent passenger railroad electrification projects within the U.S., Canada, and Europe. Where there is a single main track, there would be a single pole installed on one side of the track supporting the contact wire system. Where there are two tracks, there would be one pole installed on the outside of each track because, in general, where there are two existing tracks, the tracks are too closely spaced to place a single pole between the tracks. This Study assumes that poles would be spaced an average of 175 feet apart as a representative spacing over the entire network. While it would be possible to increase pole spacing on tangent track, pole spacing on curved track would be closer, as little as 100 feet apart, and additional poles would also be needed for special trackwork and tensioning systems.

The following sections include a simplified description of the OCS and associated constructability issues. **Figure 3** identifies the key components of the OCS. **Figure 4** illustrates a typical section for double-track catenary and the photo in **Figure 5** shows a portion of completed OCS on a double-track railroad (approximately corresponding to the configuration shown in the typical section).

Overhead Contact System (OCS)

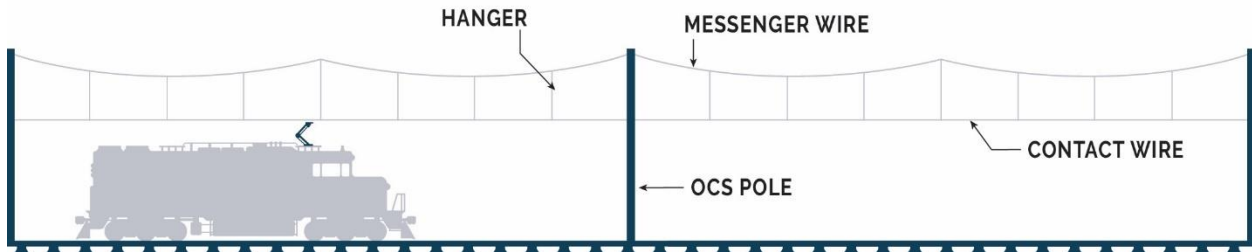


Figure 3: Key Components of OCS

TYPICAL OCS SUPPORT STRUCTURE: TANGENT TRACKS IN OPEN ROUTE

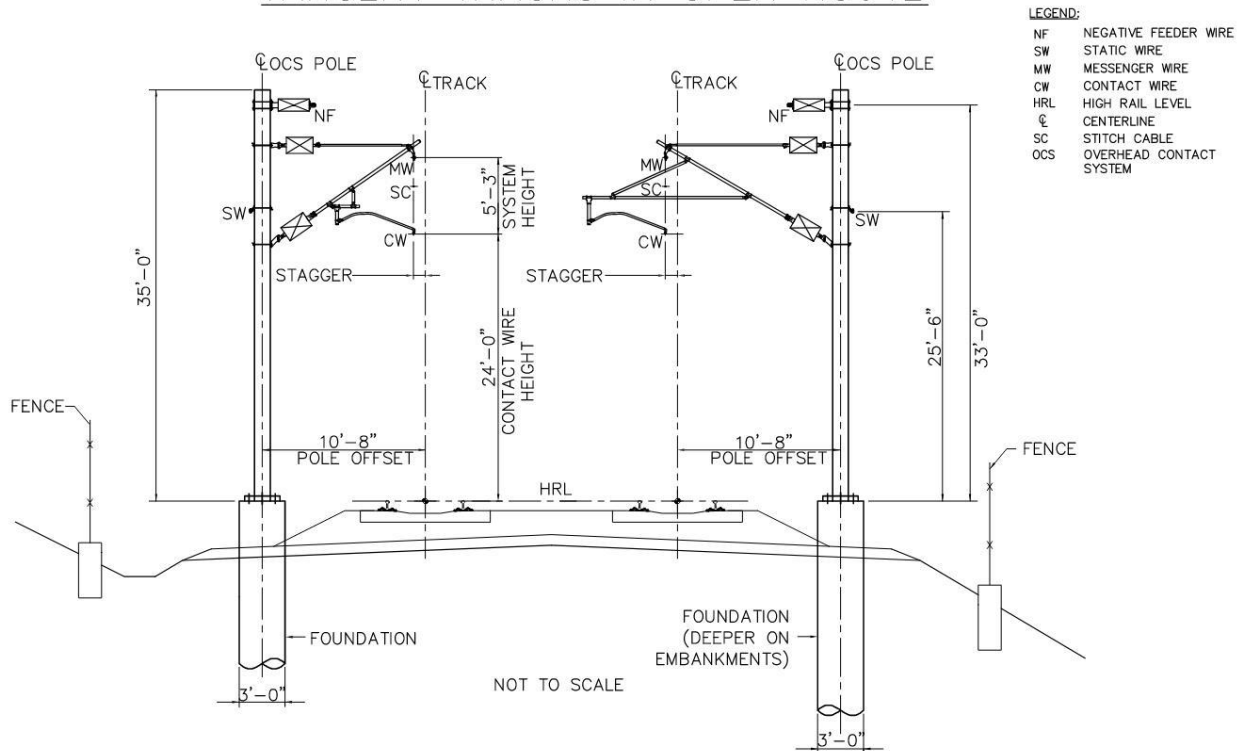


Figure 4: Typical Section for Double Track OCS



Figure 5: Photograph of Typical Double Track OCS Showing Support Poles

Note: Cantilever Assemblies Hanging Over the Track, and Messenger, Contact, Feeder, and Static Wires

For simplicity, this Study has not considered “portal construction”, which involves a crossbeam spanning several tracks to support the cantilever arms, messenger wires, and contact wires for each of the tracks underneath (see **Figure 6** for an example of portal construction). Portal construction is often necessary where there are three or more tracks, and sometimes even necessary in areas with only two tracks. Portal construction is generally more expensive than independent support poles and is also significantly more visually intrusive than construction employing independent support poles for each track. Recent electrification projects in North America have favored an independent support pole for each track. A detailed analysis would be needed to determine where portal construction would be necessary.



Figure 6: Example of Portal Construction.

Note: Steel crossbeam over tracks.

1. Foundations

a. Foundation Description

Foundations are the below-grade components that support the poles and aerial catenary components. This Study assumes a uniform foundation type consisting of a 36-inch diameter steel-reinforced concrete foundation cast in a drilled hole approximately 15 feet deep (known as “cast-in drilled hole”, “drilled pier”, or simply “concrete” foundations). Where railroad tracks are located on embankments, the adjacent foundations would need to be even deeper to provide sufficient support to the poles and aerial components. The foundation would have anchor bolts embedded at the top surface to which the steel poles would be fastened.

This Study evaluated steel pipe pile foundations, consisting of large diameter, thick-wall steel pipe driven into the ground with impact or vibratory hammers. These steel foundations were determined to be more expensive than concrete foundations and potentially unsuitable for locations with rocky ground conditions, corrosive soils, or adjacent to

buildings, where soil movement or vibration from pile driving may damage building foundations. Note that recent electrification projects have selected concrete foundations over other foundation types both for OCS installations along existing operating rail lines (such as Caltrain and Amtrak), and for new-build systems (such as Denver's electrified commuter rail line), even where soil conditions could permit driven steel piles.

While there may be some areas where foundations could be smaller than 36-inch diameter or shallower than 15 feet deep, there would be other areas where the foundations would need to be of larger diameter or greater depth. For example, where foundations would be installed in weak soils, the foundation size would be increased in order to distribute loads over a larger area of soil. Conversely, in locations where bedrock is close to the ground surface, such as the Appalachian, Rocky, Sierra Nevada, or Cascade Mountain ranges, or the Canadian Shield, the foundations might be smaller, but it could be necessary to use rock hammers to install foundations, increasing costs.

As the above-ground equipment (i.e., cantilever assemblies, messenger and contact wire, etc.) gets heavier or higher above the rails, where long-reach cantilever assemblies might be needed to suit local conditions, or where foundations are installed below track level on embankments, the forces on the poles and foundations increase, requiring that all components be more robust. These locations would need to be determined on a case-by-case basis. As noted above, however, this Study assumes a consistent foundation size.

Foundations would be on the critical path for any construction effort, meaning that the foundations, if delayed, would delay subsequent activities and completion of a segment of electrification. Additionally, constructing foundations would be extremely disruptive to ongoing railroad operations (as described below), and significant impacts to rail capacity would occur wherever foundations (or other OCS components) were under construction. The magnitude of the foundation construction effort would be massive: over four million foundations would be required for electrification of the entire Class I network. Note that there would be costs associated with the operational disruptions caused by construction activities, though such costs would be specific to each corridor and have not been included in this Study.

b. Foundation Constructability

The proximity of the foundation holes to the centerline of the track is the chief constructability consideration. The centerline of the foundations would generally be located 10 to 12 feet from the centerline of the track. Thus, the edge of the 36-inch diameter foundation holes nearest to the track would typically be located 8.5 feet to 10.5 feet from the centerline of the railroad track. These holes would be drilled with large auger equipment operating from access roads adjacent to the track. Between the time the foundation hole is drilled and the time the rebar cage is placed and the hole filled with concrete, the hole would be open and the walls unsupported.

Unsupported excavations adjacent to the track can be problematic for rail operations because passing trains impose significant forces on the track structure (i.e., rails, ties, and ballast). These forces are, in turn, transmitted downward and outward from the track, through the soil that supports the track, with the forces dissipating as they are transmitted further from the track. However, the foundations for the OCS system, and more specifically,

the holes needed for the foundations, would be in an area close to the track, where the high forces from passing trains are distributed through the soil mass. This area is known as the “zone of influence.”

When a deep excavation is made close to the track, within the zone of influence, the soil may have insufficient strength to support the trains above. As a result, foundation holes excavated next to the track must be continuously supported, either requiring a steel casing to support the sides of the hole, prior to placing rebar and concrete, or placement of concrete to fill and stabilize the hole prior to passage of trains.²⁵ Special drilling rigs capable of drilling cased holes in close proximity to the tracks would be required to provide this continuous support. The drilling operation would need to be closely followed by placement of the rebar cage and backfill with concrete, requiring coordination of all these operations prior to returning the adjacent track to service. Alternately, train operations on the adjacent track could be stopped during the time between excavation of the foundation hole and placement of the concrete, thereby allowing use of more common drilling equipment.²⁶

The need to protect foundation excavations is not unique to a railroad electrification project. The railroad industry has established similar procedures for all excavations within the zone of influence in order to protect the integrity of the track, train operations, and workers themselves.

2. Catenary Poles and Cantilever Assemblies

Catenary poles (mounted on the foundations) and cantilever assemblies (mounted on the catenary poles) are the most visible elements of the OCS system. Please refer to **Figure 4** for the individual components.

Catenary poles are generally simple steel structural sections mounted to the foundations with anchor bolts. The size and thickness of steel is dependent upon the structural demands placed upon each pole. At an average of 30 poles per mile, approximately 4.2 million poles would be required to electrify the approximately 139,000 track miles across North America.

Constructing catenary over the entire North American railroad network would require large amounts of steel. The steel in the OCS poles and foundations alone would require nearly 5 million tons of steel – over 5% of one year's worth of U.S. domestic steel production.

Constructing catenary over the entire North American railroad network would require a large amount of steel. The steel in the OCS poles (about 1,700 pounds each) and reinforcing steel in the concrete foundations (about 600 pounds of steel for each foundation) alone would require nearly five million tons of steel – over five percent of one year's worth of U.S. domestic steel production.²⁷

²⁵ The AREMA Manual for Railway Engineering describes the requirements and process.

²⁶ Driven steel pipe pile foundations would present different challenges. For example, pile-driving operations close to the track can cause “down-drag” of the adjacent ground and destabilization of the track as the piles are being hammered or vibrated into place.

²⁷ Steel production based on American Iron and Steel Institute press release on 2023 Annual Statistical Report, issued June 5, 2024.

The cantilever assemblies support the messenger wire (which in turn supports the contact wire) and also steady the contact wire. The cantilever assemblies hold both wires in proper alignment over the track. Because the wires would be energized at 25 kV, the cantilever assemblies include insulators to insulate the energized components from the steel support poles which are electrically grounded.

Like the excavations necessary for the foundations, due to their proximity to the track, the cantilever assemblies could only be installed or adjusted while a track is out of service.

The catenary poles are also the mounting point for the auto-tensioning equipment, a system of weights or springs connected to the contact wire and messenger wire that maintain a constant tension on these wires throughout the ambient temperature range. The constant tension helps maintain the wire in correct horizontal alignment, maintains the correct wire elevation and catenary curve (as established by the messenger wire and hanger system), and reduces the amount and effects of sag in the wire.²⁸

3. Contact Wire, Messenger Wire, Feeder Wire, and Static Wire

The overhead contact wire is the copper wire centered above the track upon which the pantographs slide. The contact wire is both a conductor of electricity and a wear surface for the pantographs and is positioned within a controlled height range above the rails. The contact wire is typically elevated as high as practical over highway-rail grade crossings and yard and maintenance tracks but may need to be at a reduced elevation to pass under overhead bridges, through tunnels, or other areas with low vertical clearance. The gradient of the wire relative to the rails is controlled to avoid having the pantographs “bounce” or lose contact with the wire. Poor pantograph to contact wire pressure can cause electrical arcing, which damages both the wire and current collector on the pantograph. To maintain the proper height and prevent sagging, the contact wire is suspended at approximately 30-foot intervals from the steel messenger wire by hanger assemblies of specific lengths.

The messenger wire itself is allowed to sag in a controlled manner, following a geometric shape known as a catenary curve, much in the same way the deck of a suspension bridge is kept level while the main suspension cables sag. This entire system, including the cantilever assemblies and pipes, insulators, and brackets, is held together by multiple pins and fasteners at every pole location and at each hanger assembly. The proper alignment and elevation of both the contact wire and the messenger wire are critical and rely on the constant tension provided by the auto-tensioning system.

²⁸ Maintaining correct wire tension is critical. Without an auto-tensioning system, the contact wire would, by definition, be fixed at each end and the tension in the wire would change as the wire stretches, expands, and contracts in different temperature conditions and is heated by high electrical currents. Without constant maintenance, the resulting sag and wire alignment changes could produce dangerous conditions.

The contact wire and messenger wire both conduct energy supplied to trains. In the 2x25 kV system, a negative feeder wire carries a 25 kV current 180 degrees out of phase from the contact wire. An additional wire, the static wire, is a ground wire linking all the poles together. The conductor sizes for each wire must be coordinated with each other, and even with the size of the running rail (which is part of the electrical return circuit), and affect the electrical properties of the system.

The quantity of copper wire needed alone would be significant. The copper contact wire, sized at 300 MCM (a measure of wire area) for this Study, would require approximately 2.4 tons of copper per mile. Assuming

approximately 114,000 miles of OCS across

the U.S. (only) Class I railroad network, the contact wire alone would require approximately 271,000 tons of copper, representing approximately 22 percent of the annual U.S. domestic copper production. This amount does not account for the additional copper that would be needed for substations and other electrical infrastructure.

To add OCS to the just the U.S. Class I network, the contact wire alone would require 271,000 tons of copper. This amount of copper represents nearly 22% of an entire year of U.S. domestic mined production of copper. Even if spread-out over a 25-year implementation period, it would still represent nearly 1 percent of U.S. domestic production every year for the entire 25 years. This does not account for the additional copper needed for substations, transmission and generation improvements, and other electrical equipment

4. Other Considerations for OCS

OCS is both an electrical system and a structural system and, while the overall design would be standardized to the extent possible, each segment of railroad would likely include specific areas that required a bespoke design and construction approach to address local conditions. Examples of these local conditions that would require specific design attention include closely spaced curves, turnouts where tracks converge, overhead obstructions, and buried obstructions that would force foundations to be located farther from the track.

In constrained corridors, such as corridors with many tracks and turnouts, corridors where the track is close to the edge of the ROW, or corridors where the area between the track and the edge of the ROW are encumbered with third-party utilities, design of the OCS system becomes particularly complex because there may be insufficient space for foundations. In these situations, additional ROW may be required to accommodate either OCS foundations or relocated utilities. This Study has not considered these specific situations and, while unusual compared to the thousands of miles of "standard" construction, the unusual situations would be especially complex, require a disproportionate amount of effort, and contribute disproportionately to the cost of the overall system.

C. Traction Power System

The overall traction power system (TPS) consists of traction power substations (TPSS), paralleling stations, and switching stations, all located at regular intervals along the railroad corridor. The TPS receives electrical energy at high voltage from the national electrical grid and converts it to 25 kV for use in the overhead contact system to power trains. The electrical energy from the national grid would come from transmission lines, generally those

exceeding 115 kV with sufficient capacity to accommodate the railroad electrical loads (explained in more detail in **Section V.C.4 - Utility Power Availability and Analysis**).

The system selected for this Study is known as the 2x25 kV alternating current system, which has been the standard for recent electrification projects in North America. For example, the 2x25 kV system was adopted for Amtrak's electrification between New Haven, Connecticut, and Boston, Massachusetts, for Caltrain's project between San Francisco and San Jose, California, and is proposed for the California High Speed Rail system for the route between Los Angeles and San Francisco.²⁹ The 2x25 kV system energizes the contact wire at 25 kV and also energizes a negative feeder wire at 25 kV, but 180 degrees out of phase from the contact wire. Thus, this system achieves the efficiency benefits of transmitting electricity through the OCS at 50 kV between phases, even though voltage supplied to trains is 25 kV.

The 2x25 kV system has the benefit of using off-the-shelf electrical components with less potential difference across insulating materials (compared to a 50 kV system), an important consideration since insulating materials degrade over time. Another benefit of the 2x25 kV system is that it reduces induced currents by use of the negative feeder mounted on the support poles. The negative feeder minimizes the combined electromagnetic field around the relatively closely spaced negative feeder and contact wires such that the respective fields more nearly cancel each other. Autotransformers included in the system tend to balance current between their windings and thus between the two legs of the 2x25 kV system.

The arrangement of traction power substations, autotransformers, and switching stations adds reliability and allows any one TPSS to be disconnected from the OCS, with its segment being fed from the two adjoining substations (assuming the adjoining substations remain in operation). This level of redundancy is important in the event of power failure from the commercial utility feed, or during inspection or maintenance of the TPSS equipment.

This representative electrification model has been used to size the respective elements of the TPS for the capital cost estimate. A schematic arrangement of the 2x25 kV system used for this Study is illustrated in **Figure 7**.

²⁹ Higher contact wire voltages, such as 50 kV, were considered for this study, but they require larger air gaps between conductive elements and additional insulation in all equipment (for example, not only in the OCS, but also in transformers and switchgear in wayside equipment and in locomotives), which increases costs and is susceptible to degradation. Higher voltages could also exacerbate electromagnetic interference issues. As noted, when presented with options, other North American electrified passenger rail systems that have recently been constructed or are advancing to final design have selected the 25 kV system, such as Caltrain's recent electrification, Amtrak's Northeast Corridor between Boston, MA and New Haven, CT, and the California High Speed Rail project, which is currently designing a system over 500 miles long.

TRANSFORMER FEEDER SYSTEM CONFIGURATION
FOR FREIGHT RAILWAYS ELECTRIFICATION –
2X25 KV AC SYSTEM

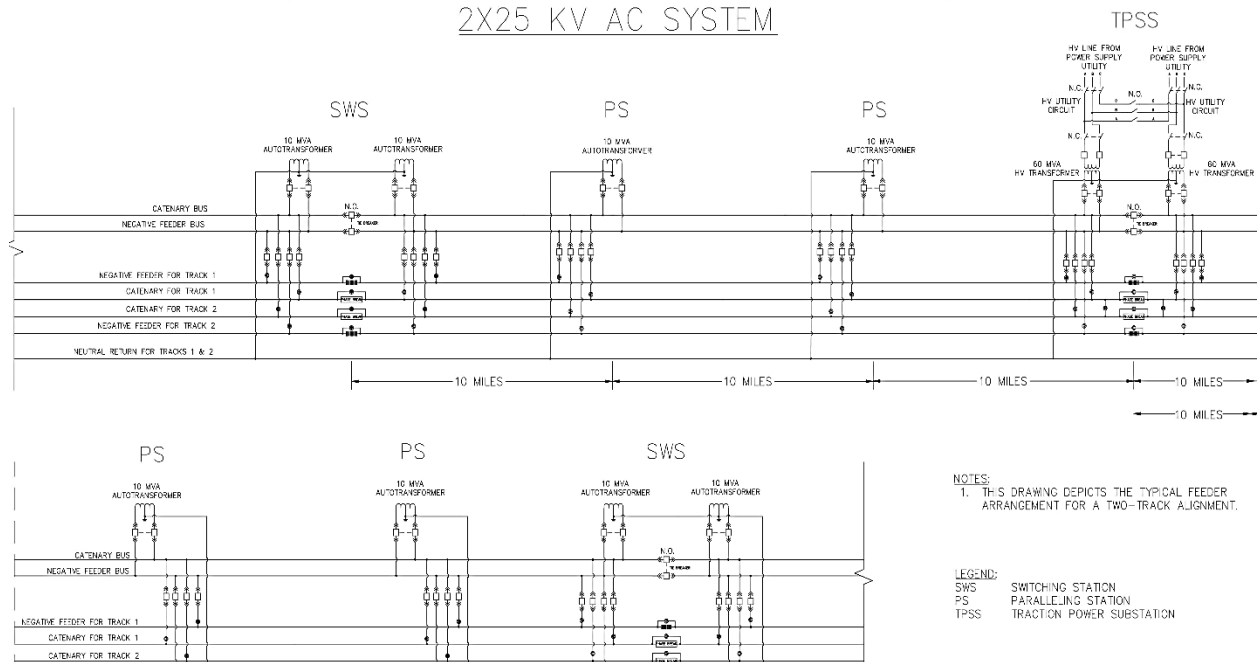


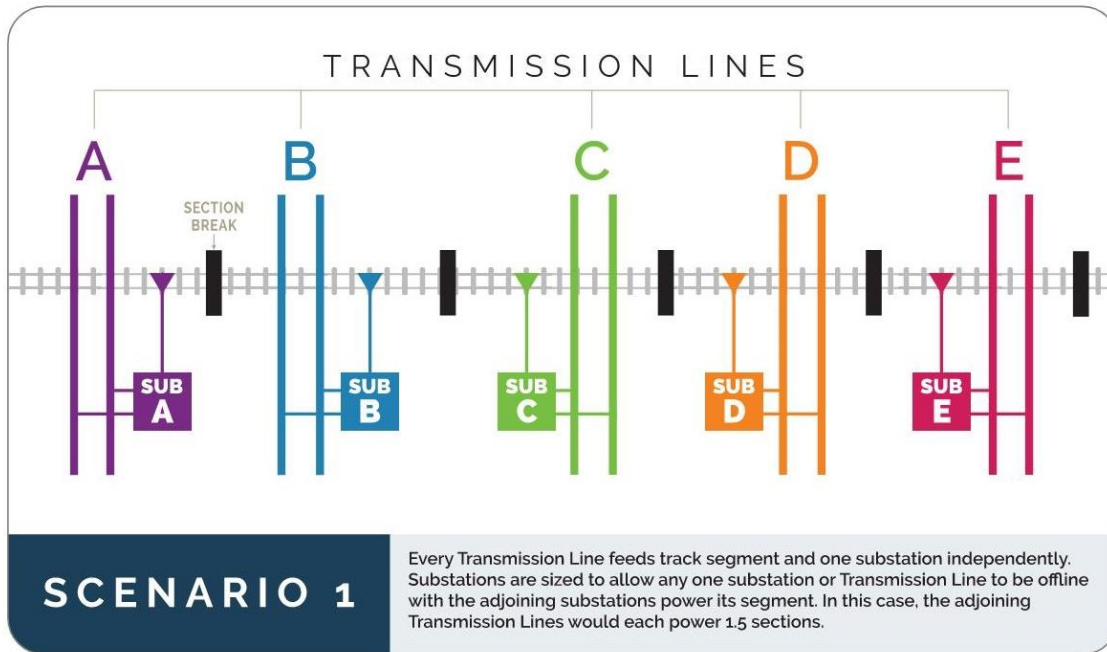
Figure 7: Representative Schematic Arrangement of 60-Mile Segment of the 2x25 kV Traction Power System

It is important to note that individual states and other government jurisdictions have safety regulations related to high-voltage power systems, including regulations on minimum clearances for different voltages. There are also regulations governing the utility power system that feeds the traction power system. These regulations could introduce inconsistencies in the OCS and TPS designs in different states and provinces.

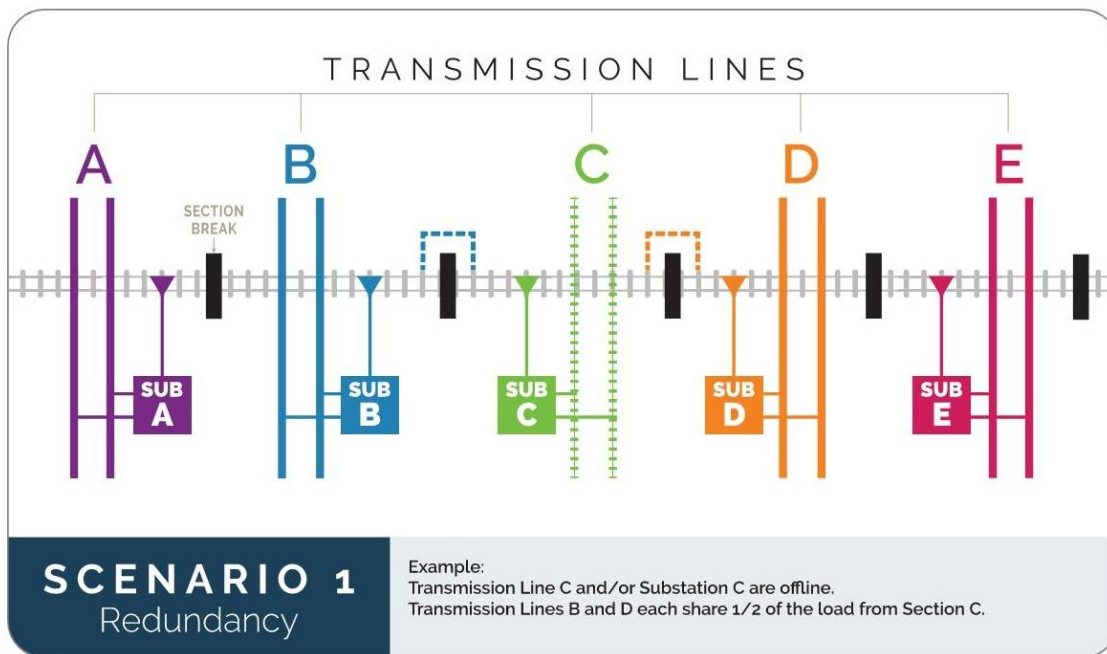
Since the TPS could be a single point of failure in the system and the consequences of a failure are quite high (i.e., interruptions to train operations), the TPS includes redundancies for key components. These redundancies allow portions of the TPS to be de-energized for necessary maintenance and inspection while allowing train operations to continue, provide back-up in case of failed components, and reduce the likelihood of trains and crews being stranded due to lack of electrical power. Absent redundant components, all trains within a specific power feed section would stop each time maintenance or inspection was required, or in the event of power failure or detection of an equipment fault. As noted, a benefit of such redundancy would be the ability of any one TPSS to be removed from service, with its territory powered by the adjoining TPSS.

Utility power failures are another consideration. Since only one TPSS could be offline at a time (with power to its section provided by adjoining TPSS), each TPSS would need to be fed from a unique utility power circuit. Thus, a single utility power line circuit paralleling a railroad should not power multiple TPSS. If a single power line circuit feeding multiple TPSS were deenergized (for maintenance, emergency, etc.), each connected TPSS would also be deenergized, with no way to power the OCS and trains. Instead, to achieve redundancy of utility power supply, each TPSS should be connected to a unique power line circuit. This significantly complicates the development of utility power feeds and may increase the distance of “build-ins” from power lines to any one TPSS.

Figure 8 shows a scenario that highlights the approach to providing redundancy in a TPS and the associated TPSS sizing considerations



NOTE: Concept only. Not all electrification infrastructure shown.



NOTE: Concept only. Not all electrification infrastructure shown.

Figure 8: TPSS Scenarios Highlighting Redundancy

The elements of the Traction Power System are described below.

1. Traction Power Substations

The TPSS receive high voltage electrical energy from the national grid and convert this to the 2x25 kV system for use by the trains. Incoming utility voltage would likely be in the range of 115 kV to 230 kV. The TPSS would operate automatically with no staff required onsite. Because of the high voltages, exposed conductors, and critical nature of the infrastructure, TPSS are secure areas, intended to exclude the public and all but the relatively small group of employees who have the special training necessary to work around high voltage conductors. The physical footprint of a TPSS is relatively large, about 0.75 acres (ac), to provide the necessary spacing between components operating at different voltages, between energized components and ground, and to provide working space around the various components.

The TPSS include the gantry structures to terminate the incoming high voltage conductors from the utility grid, high voltage switchgear to provide electrical switching and isolation, redundant transformers to step-down the incoming utility voltage to the 2x25 kV used in the OCS, switchgear on the 25 kV side to connect the correct phases to the OCS and to provide isolation, and supervisory control and data acquisition (SCADA) equipment to monitor and control all of the above equipment and provide security surveillance.

The train energy model provided the inputs needed for an analysis of voltage and current profiles in representative segments of catenary electrification to determine the spacing and capacity of the TPSS. Based on this analysis, substations of 60 megavolt-ampere (MVA) capacity were assumed to be spaced at approximately 60-mile intervals along electrified corridors.

2. Paralleling Stations

Based on the representative electrification model, paralleling stations would be spaced evenly between the TPSS and switching stations, with a total of four paralleling stations between each substation. The paralleling stations are the locations for the autotransformers, which help balance voltage and current between the contact wire and negative feeder wire and provide the ability to use opposing phases of the 2x25 kV system. The intermediate paralleling stations and autotransformers allow the distance between substations to be increased (with the concomitant benefit that the number of high voltage utility connections is decreased). The combination of the autotransformers and negative feeder (the negative feeder being 180 degrees out of phase from the contact wire) mounted on the OCS poles also reduces voltage and current induced in nearby conductors.

The typical footprint for the paralleling stations is assumed to be about 0.25 ac each.

3. Switching Stations

Switching stations allow power to be isolated midway between TPSS sites. The arrangement of electrical switchgear at both switching stations and substations allows power in the OCS to bypass a given TPSS, thus allowing the segment of catenary normally fed by a given TPSS to be fed from the adjacent TPSS. This allows for any one TPSS to be removed from service for maintenance, inspection, or unexpected reasons (such as utility power outages).

4. Utility Power Availability and Analysis

A detailed analysis of the electric grid would be required at every connection point. Traction power loads are unusual, since they have the potential for sudden, high, and unbalanced loads on individual legs of the three-phase utility transmission line circuits. This situation can affect the commercial utility lines supplying the power and each utility would need to analyze its network for capacity and compatibility with the railroad electrification. Examples of the necessary types of analysis include harmonic, phase unbalance, electromagnetic interference, flicker, and power factor. Each of these would be a location-specific study to address the railroad operating conditions and load flow characteristics at a specific substation, as well as the effects of that electrical load on the specific utility transmission line to which it would be connected. Given that railroad substations would be located approximately every 60 miles, large parts of the utility network across both the U.S. and Canada would need to be analyzed in order to implement full electrification.

An interconnection analysis of this size alone would be a major undertaking for the utility companies. The interconnection analysis would be lengthier and more complex than typical customer connection studies that utilities commonly perform due to the unique nature of the railroads' electrical needs. The process would commence with the railroads developing a load flow model of their networks. They would send those predicted loads to the utility companies for analysis of the utility networks. This could be an iterative and lengthy process.

Note that, unlike a typical industrial facility, railroad electrical loads are not consistent and stationary; they fluctuate and vary with the movement of the trains across both the railroad network and across different parts of a utility's network. The utilities would need to understand the peak demands on the network and have available a high short circuit capacity (electrical stability) at the supply points. The interconnection to the utility for a 2x25 kV traction power system also introduces a two phase (rather than three phase) connection to the transmission lines or substation busses. This configuration can result in voltage and current unbalance conditions on the utility supplying electricity. Utilities limit the amount of unbalance they can accept, and such unbalanced power can only be drawn from utility lines having relatively high system inertia, which are generally only available at transmission line voltages of 115 kV or higher (as opposed to lower-voltage distribution lines), limiting the number of utility lines that could feed a railroad electrification.

For these reasons, a railroad substation cannot always be connected to the nearest utility power line. Candidate power lines must be within the correct voltage range and be able to accommodate the electrical load from the railroad. Other, recent passenger rail electrification projects have encountered this issue, resulting in the need to either upgrade utility infrastructure or to extend connecting power lines (feeder lines) from the proposed railroad substations to distant utility transmission lines that have sufficient capacity. These feeder line extensions would be a major cost driver of an overall electrification program. Moreover, in regions without sufficient generating or transmission capacity, it is possible that nearby railroads would compete for existing electrical capacity. There would need to be a system for allocating that capacity and apportioning costs for necessary utility grid upgrades amongst railroads and other customers.

D. Other Supporting Infrastructure

The OCS system requires other infrastructure improvements for both construction and maintenance:

1. Access Roads

Access roads allow for construction and maintenance equipment to access the OCS without occupying the track (known as “off-track” access). While this may seem like a small matter, on a main line railroad the time available to occupy the track with construction equipment is extremely limited and would compete with train operations for track capacity. Because of the wide range of heavy equipment necessary for construction of the OCS poles and foundations (i.e., drill rigs, concrete trucks, cranes, crew trucks, material delivery trucks, etc.), the ability to access the construction sites without occupying the track would be critical.

Material delivery and staging is another activity that would require access from the side of the track. Access roads would allow these materials to be delivered and staged adjacent to the worksites in advance of the actual work, keeping material logistics off the critical path.

In areas where access road construction would be infeasible, some construction activities could be performed from the track using specialized “on-track” equipment (i.e., construction equipment mounted on rail wheels). However, in addition to productive work time, such equipment also needs substantial amounts of the track to travel to and from work sites, and to set-up and take-down the equipment. During all this time, no trains would be able to use the track.

Even if only a few construction locations per corridor required access from the track, added-up over thousands of work locations, this would result in both reduced productivity for the construction operations and significant train delays. Because of these disruptions, the total length of the segments accessed from the track would need to be significantly restricted, underscoring the need for construction to proceed using off-track equipment.

Access roads would need to be usable year-round, which implies some grading and drainage improvements, which in turn creates the potential for environmental impacts where railroads traverse sensitive areas. Based on industry experience in the power transmission sector, resolving these issues could create significant delays due to environmental clearance and permitting processes.

Upon completion of construction, these access roads would also be necessary to support maintenance activities.

2. Power Dispatching Center

Each Class I railroad has one or more centralized dispatching centers housing the train dispatchers who remotely direct the movement of trains and equipment over the railroad. For an electrified rail network, the supply of traction power would also need to be controlled by power directors who would monitor and control the flow of electrical energy throughout the railroads’ OCS and TPS systems, coordinate with the outside utilities that furnish electricity to the railroads, and also authorize sections of OCS and TPS to be de-energized for maintenance activities, or re-energized when those activities are complete.

Class I railroads would need to expand and modify their existing centralized dispatching centers to accommodate power directors, who are typically co-located in the same center as the train dispatchers with whom they work. If existing facilities could not accommodate the additional staff, new facilities would need to be developed to house the power directors.

In addition, significant new technology systems would need to be installed to send data to and receive data from the SCADA systems at the remote OCS and TPS sites. Space would be needed for this back-office technology infrastructure.

E. Modifications to Existing Facilities

There are several types of facilities that would need to be modified to accommodate catenary electrification. For example, existing overhead facilities may not provide sufficient clearance for energized OCS, and railroad signal systems, originally designed without any allowance for traction power current in the rails, are generally incompatible with 25 kV electrification and would require modification. Similarly, existing locomotive maintenance facilities are not configured for electric locomotives. The degree to which modification would be required is site-specific, based on the nature of the infrastructure.

1. Overhead Obstructions to OCS

The assumed standard height of the OCS contact wire (energized at 25 kV) over a freight railroad would be approximately 24 feet above top-of-rail. This allows electrical clearance for the energized conductors as well as clearance for proper operation of the pantographs, the vehicle dynamic envelope, construction tolerance, uplift of the catenary, shifted loads, loose, or shifted load tie-down systems or coverings, and maintenance activities which could raise the track elevation. The assumed minimum height above top-of-rail would be approximately 23 feet. Any existing facilities offering less clearance would need to be modified or reconstructed to accommodate energized OCS.³⁰

Catenary-battery hybrid locomotives offer the possibility to avoid modifying such structures; catenary-battery locomotives are discussed in more detail in **Section VII.C - Catenary-Battery Hybrid Locomotives**. This Study assumes that most line-haul locomotives would have a limited amount of on-board battery capacity, sufficient to move an average train a few miles without OCS, past most overhead obstructions, such as roadway overpasses or tunnels. The OCS above the track could be omitted at these specific, isolated locations, and the existing overhead infrastructure could remain, largely unmodified. However, the energized conductors would need to be routed past these restrictions in order to maintain electrical continuity on both sides of the obstruction.

Even overhead structures with sufficient existing clearance would still require modifications. Along the bottom of each structure, above the OCS, arc flash plates would need to be installed to protect the structures. Fencing would need to be installed where roadways pass over the track to prevent pedestrians from accessing the energized conductors below them. All these elements would need to be linked to an extensive grounding system, since conductive elements in close proximity to the OCS can pick-up induced currents which can cause electric shocks to people or potentially corrode steel structural members. In addition,

³⁰ AREMA Manual of Railway Engineering (MRE), 2024 Ed., Chapter 33 Electrical Energy Utilization, Part 2 Clearances; Tables 33-2-2 and 33-2-5 and Figure 33-2-3.

where insulators are affixed to these structures (such as tunnel roofs), the insulators would need regular inspection and cleaning to prevent current leakage into the structure.

2. Switches and Track Appliances

Under unusual circumstances, such as the failure of an electrical return path, stray traction power currents can energize normally grounded components. For example, equipment in contact with the rail, such as the operating rod for a switch stand or switch machine, could, in very unusual circumstances, also become energized, presenting a possible safety hazard for employees. Such equipment would need new operating rods with electrical insulation.

3. Parallel and Perpendicular Facilities

Parallel facilities that are conductive, such as fences, buried pipelines, and power lines, would also require protection or modification. Many of these facilities are owned by third parties. In the case of underground or overhead utilities, responsibility for modifications to these facilities, including the costs of those modifications, may be the responsibility of the facility owner.

An electromagnetic field study would need to be performed to determine the field strength at varying distances from the OCS and determine which parallel installations would need to be grounded or otherwise protected.

a. Fences

There is extensive existing fencing along railroad rights-of-way (ROW) in rural areas; much of it is metallic barbed wire or wire mesh fence. The fencing systems, including gates, would need to be grounded at regular intervals to protect them from accumulating induced currents and to avoid presenting a safety hazard to railroad workers, the public, livestock, or wildlife. Since many of these fences have been patched or repaired over time, the resulting short sections of wire are not reliably connected to each other. To ensure effective grounding, much of the fence wire would need to be replaced with continuous sections and grounded.

Railroads would need to decide whether to install additional fencing to discourage the public from approaching the OCS system.

b. Utilities – Parallel and Perpendicular

Parallel utilities, such as buried pipelines, fiber optic communication lines, and overhead power lines also present challenges. In some areas, railroads have permitted utilities to construct facilities parallel to the railroad track (in some cases for long distances) or perpendicular to the track (crossing from one side of the ROW to the other). Installation of OCS over the Class I network could require relocation of thousands of miles of utilities within the railroad ROW as a result of physical conflicts between the location of OCS foundations and existing buried utilities close to the track, or vertical conflicts with existing overhead wires that cross the track.

For example, many fiber optic cables were installed only a few feet away from the ends of the railroad ties. These buried fiber optic lines would be in direct conflict with the foundations for the OCS. There are literally thousands of miles of such fiber optic lines along railroad corridors. Along single-track corridors, it might be possible to install the catenary

poles on the opposite side of the track from the buried fiber optic lines (barring other obstructions). But, where there is more than one track, catenary poles would be needed on both sides of the tracks, making relocation of the fiber optic lines nearly inevitable. Installing the catenary poles further from the track, to avoid the fiber optic lines, would be a possibility, but create other challenges, such as higher structural demands on the poles, necessitating much stronger and larger poles and foundations.

Parallel overhead power lines pose a significant challenge due to complexity of the interacting currents between the power line and OCS. Detailed analysis would be required to assess the effects and devise mitigation plans for each parallel power line.

Overhead power lines and overhead communications lines (such as telephone and cable lines) crossing perpendicularly over tracks would present a different set of challenges with the adoption of an OCS system. Because there are minimum clearances between energized conductors, generally governed by the National Electrical Safety Code (NESC) or Canadian Electrical Code (CEC) and regulatory agencies in each state and province, introducing OCS – a new set of electrical conductors – would require raising many existing facilities to provide adequate clearance to the OCS.

Power lines with voltages over 115 kV may already be located high enough to provide sufficient clearance for 25 kV OCS without any modification. However, low-voltage power lines could need to be either raised or buried underground. Since it is not typical for lower voltage power lines to be located above higher voltage lines (i.e., it would be unusual for 12.5 kV line to be located above a 25 kV line and there may be regulatory prohibitions on such configurations in many jurisdictions), those lower voltage lines would likely need to be relocated underground, below the railroad tracks. The same would be true for communications lines.

Although the 2x25 kV autotransformer system greatly reduces the need for stray current protection, some amount of cathodic protection would still be needed for metallic facilities, such as pipelines, to reduce the possibility of corrosion. Facility owners would presumably be responsible for inspecting and maintaining this cathodic protection.

4. Tree Clearing and Vegetation Removal

To prevent damage to the OCS system, removal or additional trimming of nearby vegetation would be required since even small branches entangled in the catenary could damage the pantographs on passing trains. Larger branches or trees would damage or tear down the catenary, halting rail operations until the damaged overhead wires could be repaired. While electrical relay protection devices would likely detect such faults and trip the nearest substation circuit breaker in order to prevent energized equipment from becoming grounded, an electrical outage would result. Repair crews would need to be dispatched to investigate and resolve the issue before resetting substation breakers and repairing damaged OCS.

Thus, any tree limbs or trees that are close enough to the OCS to brush against or fall upon the contact wire, feeder, static wire, or poles would need to be removed. The amount of trimming would be determined on a case-by-case basis, based in part on the regulations relating to clearance of electrical lines from grounded objects. (While trees occasionally fall

on railroad tracks today, they usually cause no damage to the track; crews can remove debris relatively quickly by hand, allowing train operations to resume with minimal delay).

The additional vegetation removal required for catenary electrification could result in a dramatic visual change to railroad corridors, particularly in areas that are heavily forested. In some cases, trees form visual barriers between the railroad ROW and adjoining properties, which property owners find beneficial. Vegetation clearing may thin or eliminate such barriers. The additional vegetation clearing might also remove animal habitat and, in some cases, impact habitat for protected species.

5. Railroad Signal Facilities

Railroad signal facilities are a major subset of infrastructure that would need to be upgraded or replaced to accommodate catenary electrification. There are two categories of signal systems affected: 1) the wayside signals that provide information about the track ahead, and 2) the grade crossing active warning devices that warn motorists, bicyclists, pedestrians, and other crossing users of approaching trains at highway-rail grade crossings (i.e., the flashing light signals, bells, and/or gates commonly seen at crossings).

This Study assumes that wayside signals could be modified, with significant additions of new equipment, to be compatible with 25 kV OCS. However, based on technical limitations of the grade crossing warning device equipment, this Study assumes that all active grade crossing warning devices would need to be replaced. Although the technical details are quite complex, the following provides a broad overview of the systems.

a. Wayside Signal Modification

Modern wayside signal systems rely on electronic equipment to transmit and receive direct current (DC) pulses via the rails. These pulses both detect the presence of trains and convey information to adjoining signals. However, with catenary electrification, the rails would serve as the return path to the substations for the 25 kV electric current; the existing system of DC circuits would not work without significant modifications.

Wayside signals on the few existing 25 kV electrified railroads in the U.S. rely on an alternating current system to operate the wayside signals. The alternating current frequencies are selected to avoid harmonics of the 25 kV, 60 hertz power in the OCS and return rails.

This Study assumes that presently available technology would be used to modify the existing wayside signal system. But, even with modifications, the maximum signal circuit length would be limited (one manufacturer suggests a maximum circuit length of approximately 6,000 feet). Based on experience and observation, the existing spacing between signal installations (and thus signal circuit length) has been assumed to be approximately two miles, much greater than the allowable distance for the modified signal equipment. Thus, this Study assumes that new signal repeater equipment would need to be added between existing signal installations, splitting the longer circuits in half, thereby reducing the circuit length to within the allowable maximum.

Another possible issue that would need to be examined on a case-by-case basis is the visibility of existing wayside signals. Wayside signals are typically positioned on masts located 10 to 15 feet from the centerline of the track. However, this is approximately the

same distance that catenary poles are located from the track centerline. As such, it may be necessary in some locations, such as curves and bridge structures, to either relocate signal masts, space certain catenary poles farther from the track (thereby increasing the cost of those catenary poles), or even install overhead cantilever structures to support the signals above the catenary to ensure a clear line of sight so train crews could see the signals.

b. Highway-Rail Grade Crossing Signal Equipment Replacement

Modern active grade crossing warning devices provide a constant warning time to motorists, meaning that the lights flash, bells ring, and gates descend typically 20 to 30 seconds before the arrival of a train at a crossing regardless of the speed of the train. To achieve this, electrical circuits are superimposed on the railroad track near each grade crossing. As trains approach a highway-rail grade crossing, microprocessor equipment analyzes changes in these electrical circuits and activates the grade crossing warning devices a constant time (e.g., consistently 20 to 30 seconds) prior to a train's arrival at the crossing.

Due to electrical interference between 25 kV OCS and existing railroad signal systems, installing catenary electrification would necessitate reconstruction of essentially all railroad wayside signals and grade crossing signal systems across North America.

Electrical characteristics of 25 kV OCS would constrain the technology that operates railroad grade crossing warning devices. As a result, warning times to motorists would become more erratic.

Constant warning time circuits are incompatible with 25 kV electrification. This is a critical issue for highway-rail grade crossings with active warning devices because constant warning time functionality would be lost.

It may be possible to configure replacement grade crossing warning device control equipment in a manner that begins to approximate constant warning times. However, the additional equipment would be expensive and complex and would still not provide the sophisticated constant warning time functionality.

Rather, these modifications to accommodate catenary electrification would result in variable warning times. While the required 20 second minimum warning time would still be provided the actual warning time would vary from one train to the next, depending upon train speed. For example, a fast train might result in the minimum 20 second warning time to motorists, while a slower train might result in 40 seconds of warning time. This drawback would be especially noticeable at highway-rail grade crossings that are interconnected with roadway traffic signals, since the traffic signal timing at nearby intersections relies on the existing constant warning time functionality, which would be lost.

Information from the FRA suggests that variability in grade crossing warning times could potentially result in an increase of undesirable motorist behavior, such as motorists failing to heed the warning devices, with a resulting increase in motorists driving into the path of

oncoming trains.³¹ This would need to be evaluated during the planning of a catenary electrification program.

c. Wayside Detectors

Existing wayside detectors that rely on track circuits, such as hot bearing detectors or high/wide load detectors, would need to be evaluated for compatibility with electrification. The performance of wayside transducers may be affected by the presence of the 25 kV currents, and equipment and electronics may need electrical insulation from the rail carrying return current. Existing landslide and rock-fall warning fences also could be subject to induced currents and may require modifications.

6. Locomotive Maintenance Facilities

Locomotive maintenance facilities would also require modifications to accommodate electric locomotives. Although electric locomotives are, in some respects, less complicated than diesel-electric locomotives, the electric locomotives would require new facilities for transformer and high voltage switch gear equipment maintenance. Additional access to the rooftop equipment (e.g., pantographs, insulators, and current limiting devices) would also be required.

If hybrid locomotives were considered (See **Section VII - Motive Power**), facilities for maintaining and storing the alternate energy supply (i.e., batteries or hydrogen fuel cells) would also be necessary.

In the case of hydrogen fuel cells, facility modifications could be extensive, due to the extremely flammable nature of hydrogen. Additional building ventilation would be required to avoid build-up of hydrogen gasses. Overhead lighting, cranes, and other systems located near the roofline of buildings may need to be modified or reconstructed to ensure spark-free operation to avoid ignition of hydrogen, which could accumulate at the highest points of a building. Piping and storage tanks would also be required to discharge a locomotive's on-board hydrogen storage tanks prior to maintenance activities. Storage areas for unused batteries or hydrogen tanks would also be required.

F. Construction Procedures and Sample Timeline

1. Construction Procedures Adjacent to Railroad Tracks

Construction around a railroad is always a complex undertaking since railroad operations must continue uninterrupted while construction progresses. There are established procedures to protect workers from passing trains and to protect trains from potentially unsafe conditions in construction zones. These procedures often require trains to reduce speed through construction zones. The resulting delays to rail traffic during a major, long duration construction project (such as a nationwide catenary electrification project) would impact railroad customers and their supply chains.

³¹ Federal Railroad Administration, Highway-Rail Crossing Handbook, Third Edition, 2019, "Unreasonable or inconsistent warning times may encourage undesirable driver behavior", p. 54. railroads.dot.gov/sites/fra.dot.gov/files/2024-10/GXHandbook2019FRAFHWA.pdf

To protect workers from passing trains, these procedures often require complete shutdown of affected track segments during construction which, necessarily, disrupts and delays train operations. Where there is more than one track in a construction area, trains may be allowed to pass on unaffected tracks but are still generally required to reduce speed through construction zones.

These procedures also require that construction activities adjacent to a track be stopped when trains are allowed to pass through a construction zone.

These procedures would be applicable to all construction activity adjacent to a track, such as foundation construction, installation of the poles, installation of cantilever assemblies, installation of the overhead contact and messenger wires, and relocation of third-party utilities.

Because construction activities would stop to allow trains to pass, or train operations would be halted to allow construction to progress, the magnitude of disruption, either to the construction activities or to railroad operations (or both) is, in part, dependent upon the frequency of train traffic. Disruptions and delays would be more significant for corridors that host more frequent train operations. It is possible that those disruptions, if severe, could have a ripple effect on train operations in other, adjacent corridors.

These construction safety procedures are not unique to an electrification project; they are mandated for all work adjacent to railroad tracks in the U.S. by 49 Code of Federal Regulations (CFR), Part 214, as well as rules established by each railroad and in Canada by Transport Canada's (TC) Canadian Rail Operating Rules and Track Protection Rules, which are implemented by each railroad.

In addition, as part of the safety procedures, all employees and contractors working for the railroads in both the U.S. and Canada would need to undergo background checks via the eRailSafe system and would need to undergo mandatory screening for controlled substances.

2. Sample Construction Timeline

To help understand the duration and impacts of construction of catenary electrification on an operating railroad, consider construction along a "representative" rail corridor. While no single corridor is truly representative of the entire Class I railroad network, the following hypothetical example assumes a 1,000-mile-long corridor, consisting of two main tracks. This example assumes the target duration for the project would be approximately ten years.

When major construction activities occur adjacent to a railroad track, either the track must be removed from service to allow construction to proceed, or the construction activities must be stopped to allow trains to pass.

Installing OCS across a 139,000-mile network would result in significant delays to both trains and to the construction activities themselves.

For this representative corridor, the quantities of major materials would include:

- Approximately 60,000 OCS poles and foundations
- Approximately 2,000 miles of messenger, contact, feeder, and static wire (8,000 total miles of wire)
- Approximately 16 traction power substations, 16 switching stations, 64 paralleling stations
- Approximately 16 utility connections and associated high voltage switching stations

The first activities would consist of design, environmental documentation, and permitting. See **Section IX - Environmental Documentation and Permitting** (and **Appendix B - Environmental Documentation and Permitting Considerations Associated with Electrification of the North American Freight Rail System**) for additional details.

Environmental documentation and permitting would precede any field construction activities. Note that some field studies of environmental resources, such as wetlands, and certain protected species, can only occur during certain times of year (e.g., during the growing season for wetlands, during of the nesting season for birds, etc.); timing this field work to avoid missing a seasonal window would be critical to avoid subsequent delays to construction.

Once the design process defines the electrical demand from the traction power system, electric utilities could begin analysis of their electric grid to determine which power lines have sufficient capacity to supply each traction power substation. Utilities would also need to initiate their own environmental and permitting processes if their construction activities would create new environmental impacts. Procurement of materials, equipment, and contractors could occur concurrently with some of these activities as soon as the scope of work was sufficiently defined.

During this time, contractual arrangements with third-party utilities in the ROW and with the electric utilities that would provide power could also be negotiated. The conceptual schedule assumes that buried utility relocations (e.g., fiber optic relocations), performed by the utility owners themselves, would progress either prior to or simultaneously with catenary pole foundation construction, but that there would need to be long enough distances of the corridor clear of utilities such that foundation crews could work efficiently.

Installation of catenary pole foundations is the construction activity upon which most other construction activities depend. Subsequent installation of catenary poles, cantilever assemblies, and overhead wire is dependent upon the foundations being in place.

An optimistic productivity rate for a foundation crew drilling the holes, placing rebar cages, and filling the holes with concrete might be six completed foundations per shift, assuming minimal interruptions from trains. This 1,000-mile, double-track corridor would require nearly 15,000 crew-shifts to construct the foundations. If there were only one crew working 250 shifts per year, this task would last approximately 40 years. Multiple crews working in parallel would reduce the overall duration; this schedule assumes approximately ten crews working simultaneously, reducing the foundation construction duration to four to five years.

Using optimistic productivity rates, the foundations alone for a 2,000-track-mile corridor might require four years of work for ten crews (i.e., 40 crew-years), assuming ideal conditions and no interruptions from trains.

The North American Class I network has about 70 times as much track – 139,000 miles – potentially requiring 2,800 crew-years.

This example assumes optimistic productivity rates. It assumes that there are no foundation drilling obstructions, materials can be staged in advance, train delays to construction are minimal, utilities are relocated in advance of the drilling crew, off-track road access is available, and experienced crews are available. Some crews may need multiple work groups to achieve this level of productivity.

Subsequent construction activities include setting the poles and cantilever assemblies, which could be accomplished with equipment working from the side of the track (though work would need to stop to allow passage of trains).

After poles are set and cantilever assemblies prepared, crews would string the messenger wire, contact wire, feeder wire, and static wire. Note that, by definition, stringing messenger wire and contact wire occurs directly over the track, requiring a complete shutdown of the track

Railroad signal modifications would also proceed simultaneously with OCS work. Often, modifications to the grade crossing signal systems and wayside signal systems must be made in concert with each other, since their respective electronic circuitry and logic systems are, in many situations, interdependent. It is assumed that these activities, while discussed here as discrete construction operations, would overlap.

Simultaneously, the traction power supply equipment would be installed at various locations along the corridor, with each set of traction power equipment comprising one substation, four paralleling stations, and one switching station, with one set of equipment spaced approximately every 60-miles along the corridor. This construction would be predicated on obtaining sufficient property for each of these installations, which are unlikely to fit in the narrow ROW characteristic of most rail corridors. The manufacturing lead time for traction power equipment would be lengthy, though presumably the equipment would be standardized into common packages for installation in the field. For example, the large transformers in the substations currently have manufacturing lead times of over one year. With approximately 16 sets of traction power equipment, multiple manufacturers would need to be engaged, and multiple crews would be needed to prepare the sites, construct foundations, and install the equipment.

The commercial power utilities could concurrently construct their facilities, including modifications to power lines, new high voltage switching stations, and feeder line extensions to connect to railroad traction power substations, with no effect on train operations.

Procurement of electric locomotives and new, specialized overhead line maintenance equipment would occur concurrent with field construction activities.

Construction would conclude with an extensive testing and commissioning process, evaluating how the OCS, railroad wayside signals, grade crossing warning devices, traction

power system, utility power, and locomotives operate as an integrated whole, before placing the electrification system in operation.

The sequence of these activities is illustrated in the conceptual construction schedule in **Figure 9**. This is a simplified schedule and assumes optimal construction conditions, minimal train delay, and no impacts from inclement weather, frozen ground, staffing constraints, or material supply constraints. This schedule indicates that the time from initiation of project design to completion of commissioning and start of electric operations would be approximately ten years for the sample corridor.

SAMPLE CONSTRUCTION SCHEDULE - IDEALIZED SCENARIO

Year:	1	2	3	4	5	6	7	8	9	10
Activity										
Traction Power System and Overhead Contact System										
Design, Environmental Documentation, Permitting, and OCS Procurement	█	█	█							
Utility Relocation (Underground and Overhead)			█	█	█					
Foundation Installation			█	█	█	█				
Pole and Cantilever Assembly Installation				█	█	█	█	█		
OCS (Contact, Messenger, Static, and Feeder Wire) Installation						█	█	█	█	
Wayside Signal Modification				█	█	█	█			
Grade Crossing Modification						█	█	█		
Signaling and grade crossings commissioning								█	█	
TPS Equipment Procurement (Substations, Paralleling Stations, Switching Stations)										
TPS Equipment Procurement (Substations, Paralleling Stations, Switching Stations)				█	█	█				
TPS Equipment Installation				█	█	█	█	█		
Substation, Switching station, Paralleling station commissioning							█	█	█	
Electric Utility Connections										
Electric Utility Connection Contracts, Design, Environmental Documentation, and Permitting		█	█	█						
Electric Utility ROW Acquisition				█	█					
Electric Utility HV Switching Station Construction, Transmission Line Upgrades				█	█	█	█			
Commission Utility network mods and new installations up to point of interconnection							█	█	█	
Vehicle and Equipment Procurement										
Equipment Procurement (Locomotives, Maintenance Equipment)			█	█	█					
Equipment Manufacture and Delivery				█	█	█	█	█		
Vehicle acceptance testing							█	█	█	
Testing, Commissioning, and Punch-List										
Testing and Commissioning of OCS, TPS, Signals, Locomotives as Integrated System									█	█

Figure 9: Conceptual Electrification Schedule for Sample Corridor

One key item to note is the number of construction crews that would be working simultaneously on and adjacent to the track. In later years (years six and seven), there could be over 30 crews working simultaneously along the track (including crews working on foundations, poles and cantilever assemblies, OCS, wayside signals, and grade crossings) along the 1,000-mile corridor. On average, one crew would be working approximately every 33 miles. Each of these crews would create some level of disruption to train operations, because their work would be close to or on the track. Even if the schedule were drawn-out to last longer than ten years, or if, after extensive experience, crews achieved higher productivity, there would still likely be 20 or more crews working along the track at any one time.

The intense construction activity would impact the capacity along the rail line. While this Study does not attempt to quantify train delays and capacity reductions associated with such construction activities, experience from construction projects along all railroads has shown that impacts to rail line capacity would be significant. It is possible that the train delays resulting from construction would require new, additional track capacity be constructed to offset the construction-related delays.

OCS construction could also conflict with railroads' ongoing maintenance activities. These maintenance activities already require careful planning and scheduling to avoid disruption to existing rail operations. Indeed, several railroads already limit their own heavy maintenance activities, such as tie and rail replacement, along key routes during seasonal peaks in traffic in order to minimize operational disruptions. A simultaneous, multi-year OCS construction project, creating its own operational disruptions, would need to be coordinated with this ongoing maintenance work.

While recent public agency-led electrification projects on passenger railroads have used complete track shutdowns to speed construction or allow on-track construction equipment, such as equipment for setting OCS poles and foundations, these passenger railroads typically have long blocks of time available at night when there are few, if any, trains operating. They also typically have two (or more) parallel tracks in each corridor, thus allowing one track to remain in operation for the few nightly trains while the other track is out of service to allow crews and equipment to work on and around that track, uninterrupted.³²

By contrast, on a freight railroad, complete track shutdowns, even for a few hours each night, would not be practical because freight railroads operate trains 24 hours per day, 7 days per week. Traffic levels are relatively consistent throughout the day and night. On a single-track corridor, the daily shutdowns over several years would create extreme disruption and delay. A two-track corridor does not necessarily reduce the construction impacts; while there might be areas where one track could be shut-down for brief periods to

³² Some electrification projects in Europe have employed trains that can set OCS foundations and poles. These trains require long blocks of time on the track and have generally been used on railroads where passenger trains are the predominant traffic. In this situation, there tend to be natural "windows" of time at night when there are few, if any, passenger trains. However, these conditions generally do not exist on North American freight main lines.

allow on-track equipment to work, with twice the number of tracks, the number of foundations would double, as would the work duration.

While it may be theoretically possible to complete a catenary electrification project on the sample corridor within a ten-year timeframe, doing so would require intense construction activity, with multiple crews working at many points along the railroad and many activities occurring simultaneously. Although, with optimistic assumptions, this may be feasible from a construction perspective, the construction activities themselves would have a significant impact on rail operations. In practice, this level of construction could affect rail customers and supply chains that depend upon the corridors in question.

For comparison, the U.S. National Blueprint for Transportation Decarbonization established a 2050 timeline for transportation sector decarbonization. To meet a 2050 timeline, and assuming construction work would commence in 2030, after several years of planning, design, and environmental documentation, installation of catenary electrification on the entire 139,000-mile Class I railroad network across the U.S. and Canada would need to proceed at a pace of approximately 7,000 miles per year.

VI. Electric Grid Infrastructure

A. Key Points and Overview

Key Points:

- Electrification of Class I freight railroads would create significant, new demands for electricity from the grid.
- Demand on the electric grid is already increasing today, both for new generating capacity and for transmission line capacity. This new demand is causing congestion on existing transmission lines.
- Electric utilities would need to make significant investments in transmission and generating capacity to meet projected demands created by freight railroad electrification; these projects have lengthy development timelines.
- If large-scale electrification makes railroads dependent upon the national electrical grids in the U.S. and Canada, railroads could also be subject to the same prioritization process when grid operators are forced to ration electricity during extreme events (i.e., weather, cybersecurity, customer loads, power generation equipment failure, and so on), jeopardizing railroad operations and impacting customers and supply chains that depend upon freight railroads.

Overview:

Previous sections have addressed the infrastructure along the rail lines necessary to support catenary electrification. The electricity to supply this infrastructure, the traction power system and overhead contact system, would need to come from the national electric grid. While it is beyond the scope of this Study to identify how, when, and where new electrical transmission and generation capacity would be developed, or who would pay for that new capacity, it is important to understand that the magnitude of electricity demand created by electrification of the rail network would exacerbate any existing electrical supply constraints.

This section uses concerns identified on the U.S. electric grid as an example. The supply of energy to the national electric grid (generating capacity) and demand for energy from the electric grid are difficult to assess, since there are many individual entities, whose plans may change in response to government policies and commercial considerations. The following information has been sourced from recent studies from the U.S. Department of Energy (DOE) and the U.S. Energy Information Administration (EIA). In general, these studies find that there are increasing demands on the electric grid; as described by the DOE:

"Throughout the country over the next decade and beyond, increasing consumer demands, electric utility decarbonization targets, and federal and state policy are expected to drive changes in electricity supply and change the way electricity is used, including by increasing electrification of end-use technologies. These changes will put additional burden on the existing transmission system and create significant need for additional transmission investment."³³

B. Introduction

Electrifying the freight rail network would require an enormous amount of energy from the electric grid, potentially exacerbating transmission line congestion and increasing demand during high-value electricity periods. To mitigate transmission constraints and congestion, transmission system operators monitor service requests that place increased demands on the system and approve or deny those requests based on reliability limits of the transmission system.³⁴ Simply constructing an OCS system and acquiring electric locomotives does not address the underlying problem of insufficient electrical transmission and generation capacity.

Transmission line congestion could lead to potential operational concerns for railroads in a scenario where the North American rail network is powered from overhead catenary. Interconnections between regions of the transmission grid could help alleviate this issue, but the time required to approve new interconnections within the electric grid is not decreasing, but rather it is increasing, making such interconnections more challenging.³⁵ Transmission and generation constraints would need to be resolved in advance of any program to electrify freight railroads.

The following sections provide background into the constraints on the electric grid, constraints which could be magnified by the additional demands created by large scale catenary electrification.

C. Electrical Load Growth

Even if sufficient electrical generating capacity were available, one of the main factors that affects the availability of transferable energy (i.e., energy in one area that could be shifted to another, for example, to serve railroad electrification) is total load growth. The electrification of railroads represents a major new electrical load and would be included in what the DOE

³³ U.S. Department of Energy, National Transmission Needs Study (October 2023), [National Transmission Needs Study \(energy.gov\)](#), page, vi

³⁴ U.S. Department of Energy, National Electric Transmission Congestion Study (September 2020), [National Electric Transmission Congestion Study \(energy.gov\)](#).

³⁵ U.S. Department of Energy, National Transmission Needs Study (October 2023), page 48

characterizes as the “High / High” scenario, or high overall load growth above 7,000 Terawatt-hours (TWh) and high clean energy penetration above 80 percent in 2040.³⁶ The DOE estimates that to meet high future load and high clean energy growth, regional transmission would have to more than double (see **Figure 10**). In addition to the increase in transmission capacity within regional transmission organizations (RTOs) that would be necessary to accommodate the High / High scenario, transfer capacity between the different RTOs would need to increase by approximately a factor of four to support the high loads while managing congestion. As with other grid users, reliability and availability of power would be a key issue for freight railroads, since train operations would tend to require large amounts of energy on short notice.

Anticipated transmission and transfer capacity need for contiguous United States in 2035

Three different future scenario groups labeled as ___ load / ___ clean energy growth.
Median % growth compared to 2020 system shown.

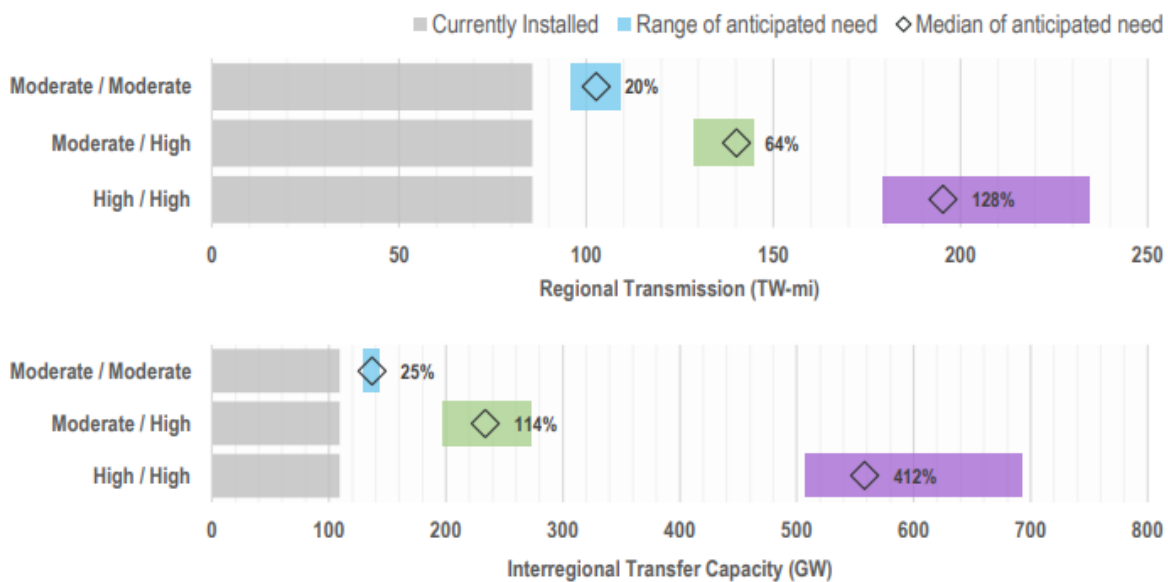


Figure 10: Anticipated Future Regional Transmission and Interregional Transfer Capacity Needs
Source: DOE National Transmission Needs Study (2023)

D. Energy Generation and Interconnections

The EIA estimates that there is currently 4.178 million GWh of electrical energy generating capacity in the U.S.³⁷ By comparison, railroad electrification could require up to 52,700 GWh

³⁶ US DOE, National Transmission Needs Study (October 2023), pages 118-119. The three scenarios identified were “Moderate/Moderate” which DOE describes as “business as usual”; “Moderate/High”, which DOE describes as the “future power system that could be enabled by current [2023] ... policies, including large investments in clean generation technologies expected to be made possible by the [Inflation Reduction Act]”; and the “High/High” scenario, which DOE describes as “only includes scenarios in which new energy policies are enacted, most notably policies that encourage high amounts of electrification and adoption of energy intensive technologies.” It is not clear whether the High-High scenario explicitly contemplated loads from large scale railroad electrification.

³⁷ U.S. Energy Information Administration, “Electricity Explained”, accessed on 2024-11-01 at: <https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php>

of energy (using the high range of estimates in this Study), slightly more than one percent of existing capacity. While one percent may seem like a small portion of generating capacity, for a system that is already experiencing capacity constraints, it would be a significant amount of additional demand. However, there are many barriers to increasing electrical generation capacity.

One example of these barriers is the long lead time for developers of generating capacity to get approval to interconnect their proposed generation sources to the existing transmission system. For example, in 2022, the lead time from initial request to operation was five years, up from less than two years in 2008.³⁸ This significant delay is leading to further challenges for RTOs in evaluating future load growth and transmission line congestion, particularly if the developers do not have a set plan for a development or ultimately withdraw their request.

Another barrier to the introduction of additional generation is the overall cost. Since there are already constraints on the grid, developers and large customers (e.g., railroads) are likely to encounter significant costs due to increased infrastructure requirements to make grid upgrades, i.e., the cost of each increment of additional capacity increases as the inexpensive capacity is often the first to be constructed. RTOs and utilities may transfer costs of overall grid improvements to the customers. In addition, the high interconnection queue withdrawal rate makes it more challenging to determine how to apportion grid upgrade costs.

When new transmission line infrastructure is required, the timeline for environmental documentation and permitting is also a constraint. Resolving ROW issues for a new power line, completing required environmental studies and documentation (such as environmental impact studies), and obtaining permits (such as water quality certifications where power line structures or construction access roads affect wetlands) can require many years.

E. Variable Energy Resource Generation

Variable energy resources (VERs) include intermittent resources like wind and solar, where generation capabilities depend on many factors and can change quickly. The variability is an increasingly important factor as the proportion of renewable energy resources increases. The unreliable nature of VERs presents a challenge. VER generation cannot be forecasted in enough granularity to be reliable, adding to the uncertainty around how the grid would be able to handle different events. VER performance during extreme weather events is also an uncertainty. Though battery storage is helping to overcome some of these short-term challenges, the buildout of bulk, long-term storage systems at a national scale is a long-term endeavor.

The intermittent nature of VERs would be particularly challenging when combined with the inherent variability of rail operations, and the often very high electrical load demands (e.g., starting a train upgrade) that are also unpredictable.

F. Extreme Event Impacts to the Grid

Extreme weather, inaccurate generation forecasts, exceptional demand, and infrastructure failures can significantly affect the transmission system, sometimes without warning. When this happens, especially in the case of extreme weather events, loads to certain customers

³⁸ US DOE, National Transmission Needs Study (2023), page 48

(e.g., population centers, hospitals, etc.) may be prioritized and lead to congestion or significant electricity pricing swings. Consequences, such as utility load shedding (forced disconnection of customers from the grid), may be felt more severely by non-priority users of the transmission system.

Unless railroads are classified as priority users for electricity, operational interruptions would accompany any load shedding event. These interruptions could cascade through the railroad network and delay delivery of essential goods, with the disruptions possibly amplified at a time of emergency.

As an example, if electric power were unexpectedly shut down on a section of steeply graded railroad, the train crews could be required to stop and secure their train by setting a significant number of handbrakes during the interruption (as will be described in **Section VII - Motive Power**, even a hybrid locomotive equipped with battery backup may lack sufficient range or charge to advance a train beyond a steeply graded section of track). This process would take a long time (particularly in areas of poor access or during inclement weather). Upon restoration of power, it would take a similarly long time to release those handbrakes.

A power outage that forces trains to stop could impact the public as well. In the event of a power outage, if trains lack an on-board battery backup (or if that battery backup was already depleted), a stranded train could result in blocked highway-rail grade crossings, delaying motorists.

G. Markets, Congestion Costs, and Coordination

The limits, factors, and costs applying to each utility upgrade and/or interconnection request would vary depending on its location. Congestion is a major issue in some markets. In addition, as energy generation shifts toward VERs, the ability to transmit this energy across markets will become even more important for efficiency, reliability, and cost. This location-dependency can be viewed by looking at wholesale electricity prices in different areas, which have strong correlation to the electricity availability and the additional transmission capacity the area possesses.

The cost of transferring energy between regions is a proxy for the amount of congestion on transmission lines. Since 2020, the price differential between regional Independent System Operators in all regions of the U.S. has increased substantially. This means that the cost of moving energy from one area to another has increased, reflecting congestion on the national electric grid. See **Figure 11**, extracted from DOE's National Transmission Needs Study (2023).

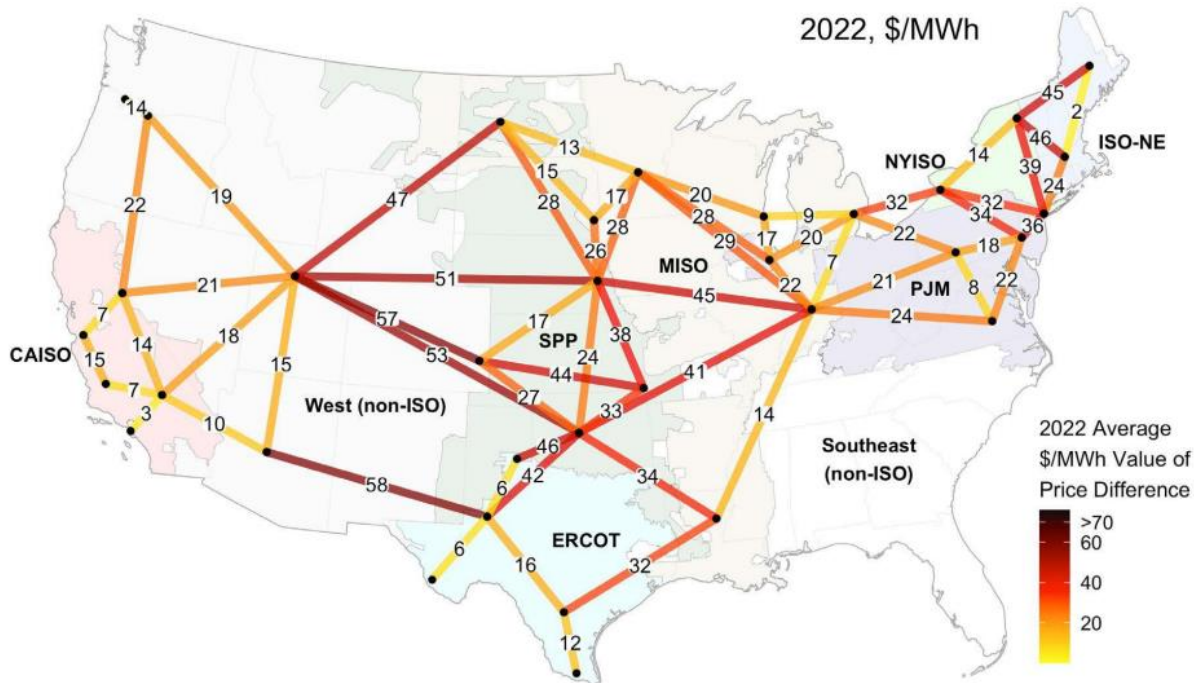


Figure 11: 2022 Schematic of Average Cost Differences per MWh within the U.S.

Source: DOE National Transmission Needs Study (2023)

An effort to improve interconnections to more effectively transmit energy between regions would reduce the cost of transferring electricity between regions. But, because reducing congestion across the electric grid is not the problem of a single user, it would require participation from many stakeholders including RTOs, utilities, private companies creating demand for electricity, as well as state, local, and federal government agencies. The number of stakeholders would likely lead to significant challenges and delays. There would also be multiple planning, design, environmental documentation studies, and permitting processes needed to gain approvals in the respective markets served.

It is important to note that the nation's electric transmission system distributes congestion costs amongst all users of a market or RTO. Thus, railroad electrification, by adding significant demand to the system, could increase congestion and, in turn, increase costs for other users.

H. Obtaining Electrical Service for Catenary Electrification

A transition to catenary electrification could only be accomplished if a secure, reliable source of grid electricity were guaranteed. This could be difficult at a time when other industries are also demanding more electricity since the ability to ensure sufficient electrical generation and transmission capacity is beyond the control of the railroad industry.

Recent projects that involve large electrical demands, such as new data centers, demonstrate the difficulty of obtaining electrical power. Some of these projects appear to

favor baseload generation over intermittent VERs.³⁹ However, these projects present a relatively known demand profile in a single location.

Conversely, large scale catenary electrification of the U.S. and Canadian railroad networks would create new demands on the electric grids in both nations. A nationwide, or even international analysis of the electric grids across both countries would be needed to assess the ability of each portion of the grid to accommodate that demand without magnifying existing grid congestion. Such an analysis would require the cooperation of grid operators across North America and would likely take several years to complete.

VII. Motive Power

A. Key Points and Overview

Key Points:

This Study evaluated several types of locomotives:

- *Catenary-electric locomotives* (or simply *electric locomotives*) that would draw power from the OCS.
 - Catenary-electric locomotives are a proven technology.
 - Designs suitable for North American freight railroad service are not currently available but could be developed.
- *Catenary-battery hybrid locomotives* that would normally draw power from the OCS but use on-board batteries to provide power to bridge gaps in the OCS.
 - No such catenary hybrid locomotives have been designed or constructed for use in the North America.
 - Even pure battery locomotives (i.e., locomotives powered solely by batteries) are a relatively unproven technology for North American service, with only a few examples being tested. The viability of battery locomotives for use in main line service has not yet been determined.
- *Catenary-hydrogen fuel cell (HFC) hybrid locomotives* that would normally draw power from the OCS but use on-board HFCs to provide power to bridge gaps in the OCS.
 - No such catenary hybrid locomotives have been designed or constructed.
 - Even pure HFC locomotives (i.e., locomotives powered solely by hydrogen fuel cells) are a relatively unproven technology for North American service, with only a few examples currently undergoing testing at the time of this Study.
 - At the time of this Study, widespread commercial hydrogen production and distribution infrastructure does not exist. The development path and cost for

³⁹ As an indication of the constrained electrical generating capacity, as this Study was being developed, Microsoft announced that it had contracted with the Three Mile Island nuclear power plant to restart a shuttered nuclear reactor to provide a dedicated energy source for Microsoft data centers. Financial Times, "Microsoft in Deal for Three Mile Island Nuclear Power to Meet AI Demand", September 20, 2024, accessed at <https://www.ft.com/content/ddcb5ab6-965f-4034-96e1-7f668bad1801>

this infrastructure are uncertain, making the feasibility of large fleets of locomotives powered with hydrogen questionable.

- Traversing an OCS gap of more than a few miles would require a hybrid locomotive to tow a large tender car to carry sufficient batteries or hydrogen to bridge the gap. Such tenders would add cost and complexity to the locomotive, add ongoing maintenance cost, and add an ongoing cost in energy to pull tenders on all trains.
- The operational complexity of managing battery tenders and their respective charge states during all operating and weather conditions, coupled with the need for a factor of safety for battery range, means that the possible length of catenary gaps would be relatively short.

Overview:

This section assesses the cost and feasibility of developing a locomotive fleet that draws electric power from overhead catenary. Included in this section is an assessment of the electric freight locomotive market; an examination of both the procurement of new electric locomotives as replacements for existing, conventional diesel-electric locomotives; the possibility of converting existing diesel-electric locomotives to work solely with an external electrical supply; and the possibility of catenary-battery hybrid and catenary-HFC hybrid locomotives.

B. Electric Locomotives

1. Electric Locomotive Performance

a. Electric Locomotive Power

Existing Class I diesel-electric freight locomotives generally produce approximately 4,400 horsepower. While catenary-electric locomotives offer the possibility to deliver more horsepower than a conventional diesel-electric locomotive, tractive effort, the force that can be exerted at the coupler, is limited by the available friction between the wheel and the rail. The ability to apply that tractive effort to pull freight trains is also limited by the strength of the couplers linking locomotives to the rail cars, and the rail cars to each other.

While high-horsepower electric locomotives have been used for passenger service, these locomotives have generally not needed to exert high tractive effort. Rather, the high horsepower has been used to achieve high acceleration and high speeds for passenger trains, speeds much faster than possible for freight trains, which are often speed-limited by the design of the freight cars.

Thus, for this Study, it has been assumed that catenary-electric freight locomotives (or hybrid locomotives) would match the 4,400 horsepower of current diesel-electric models.

b. Electric Locomotive Braking

There is the potential for catenary-electric locomotives to use regenerative braking to return energy to the OCS. However, regenerative braking would be contingent upon having another nearby train (within approximately one or two substation territories, corresponding to approximately 60 to 120 miles) capable of using that energy. This close proximity would allow the regenerated energy to be conducted via the railroad OCS system to the train needing energy.

There is a potential for regenerated power to be captured and stored in a battery on-board the locomotive. Details of this concept are discussed in **Section VII.C - Catenary-Battery Hybrid Locomotives**, but it relies on the premise that an on-board battery has available capacity to receive regenerated electricity. In other words, to receive regenerated electricity, the battery must already be in a partially discharged state, and the rate of charge via regeneration is limited to the rate at which the battery could receive a charge.

The limitations of regeneration due to infrastructure and operational constraints are discussed in **Appendix A – Train Energy Usage**.

2. Current Electric Locomotive Market

While many global freight operators currently use electric locomotives in freight applications, their approach to hauling freight is often very different from that in North America. For example, in western Europe, freight trains are limited to approximately 2,500 feet in length, whereas North American trains are typically longer. Western European freight trains are also much lighter than those in North America.⁴⁰

Outside of Europe, freight operators handle trains similar in size and weight to those that are moved by North American freight railroads. Larger and more powerful derivatives of European electric locomotives have been supplied in countries such as Kazakhstan, Azerbaijan, South Africa, and India to meet the freight hauling needs in those nations.⁴¹

There are two basic approaches to obtaining a large fleet comprising thousands of electric locomotives such as would be required for a Class I electrification program. The first option would be to attempt to convert existing diesel-electric locomotives to electric operation, while the second option would be to develop an electric freight locomotive designed specifically for the North American market.

a. Conversion of Existing Diesel-Electric Locomotives

Converting existing diesel-electric freight locomotives from alternating current drive systems to fully electric operation may offer the potential to adapt existing, FRA-compliant frames, trucks, cabs, control equipment, safety appliances, and brake systems to electric operations. These existing components have proven track records in North American service.

In theory, it would be possible to replace the diesel prime mover in a diesel-electric locomotive with a transformer and electrical switchgear. This would allow the locomotive to receive alternating current energy from overhead catenary at 25 kV and step-down the electricity to the voltage normally used by the inverters on the locomotive. Additional

⁴⁰ Community of European Railway and Infrastructure Companies, "Longer Trains, Facts and Experiences in Europe, 5th Edition", 2020. While most western European trains are limited to about 2,500 feet in length, the LKAB iron ore trains operating in Sweden and Norway are an exception, with loaded train weights approaching 9,500 tons. However, the LKAB trains are the exception. By comparison, in North America, average gross train weight (i.e., the average of empty and loaded trains) is nearly 8,500 tons, and loaded trains can weigh 15,000 tons or more.

⁴¹ International Railway Journal, "Transnet Sets New Record with 375-Wagon Train". Accessed at: <https://www.railjournal.com/freight/transnet-sets-new-record-with-375-wagon-train/>. Pulled by electric locomotives, with cars having 30 metric tonne axle loads, this test train weighed nearly 50,000 tons.

power-conditioning equipment may be required to provide energy suitable for input into existing locomotive control systems. Auxiliaries, such as the compressor for the air brake system and the dynamic brake systems, would also need to be modified. The efficacy of this approach is dependent upon the ability to reuse the existing control and braking systems, and generally reuse structural components, running gear, and the cab.

A major difference between a diesel-electric locomotive and an electric locomotive is the presence of a high-voltage, high-current energy supply, which changes many of the design requirements for such a locomotive. The high voltage (25 kV) circuits require a grounding scheme and technologies to mitigate electromagnetic interference. This grounding would be necessary to ensure the electricity is safely conducted through the systems inside the locomotive and does not also impart a dangerous level of electrical potential beyond the electrical control system and drive train. This includes the management of both touch potential and electrical interference with other systems within the locomotive, such as the Positive Train Control (PTC) system, power control systems, electronic air brakes, communications systems, and any other on-board electronic devices.

Another consideration is the necessity for an electric locomotive to use the rails as the return for the 25 kV current. This is common to all electrification systems. However, it requires reliable contact systems on the wheels and axles to avoid transmitting any current through the rolling element bearings, which would be damaged by such current. If installation of a current return system required major modifications to the locomotive trucks, it could increase the cost of the conversion.

Fire and life safety would be another important aspect of the locomotive construction that would have to be handled differently than it is in diesel-electric locomotives. The passage of electric current through the locomotive drive system generates a large amount of heat. Over time, the heat can cause insulation components to break down, which creates the possibility of arcing between components energized at 25 kV and grounded components, which could in turn lead to a fire or damage to other components. The proper insulation and isolation of various components would need to be designed into the locomotive. Another scenario would be the possibility of a downed catenary wire contacting the top or sides of the locomotive. The insulation from and isolation of potential sources of energy, as well as safety for crew members, would require careful evaluation. There are proven solutions for these considerations employed on existing electric locomotives. However, in a scenario where existing diesel-electric locomotives were converted, new methods of implementing these solutions may be required.

In general, the effort to integrate new electrical equipment into an existing locomotive would be complicated by the relative lack of homogeneity in locomotive fleets. The current locomotive fleets in North America consist largely of units made by two different manufacturers and many of those reflect different generations of a similar product. Each locomotive type would need to be evaluated to understand the exact configuration of that model. While the new equipment to be integrated into each locomotive type would be largely the same, the arrangement, fixation, and integration with existing systems will likely differ from model to model.

It is important to note that, after conversion, the resulting electric locomotive would ride on a frame and trucks and use control and brake systems that would be 10 to 30 years old. Given the high complexity of the conversion and the relative age of the reused components (e.g., control and brake systems, interior cab fittings and climate control systems, structural components, etc.), there may be greater long-term value, in terms of reliability, equipment life gain, and overall life cycle cost, in purchasing new components to replace these old components. However, in doing so, the cost of conversion would increase, and the number of original components may be further limited to items such as large fabrications or castings, such as the locomotive frame and trucks.

There is no cost history of converting North American diesel-electric locomotives to electric locomotives; the conversion cost would depend on multiple factors, such as the amount of the existing locomotive that could be retained, the cost and availability of bespoke electrical switchgear and transformers, and the amount of reconditioning that each existing locomotive frame, running gear, and control system would require.

b. Purchase of New Electric Locomotives

Most global electric locomotive suppliers have the technical capability to offer a product for the North American freight market but would need to implement significant modifications to their base designs, or develop new designs entirely, to permit operation in North America. Even heavy-haul electric locomotives in locations such as South Africa or India would require significant modification to meet the requirements of the North American market.

North American locomotive structural requirements are significantly more stringent than those in Europe (where much electric locomotive manufacturing capacity is located) or elsewhere around the globe. These structural requirements result both from North American “crashworthiness” standards, as well as the inherent strength needed to pull or push North American freight trains, which are much heavier than those in Europe.

In terms of locomotive configuration, North American locomotives have the control cabs set back from the ends of the locomotive for reasons of safety, operating crew visibility, and ease of operations. Conversely, European locomotive control cabs tend to be at the extreme ends of the locomotive, are accessed by relatively tall, steep ladders, and generally are not configured for ease of freight switching operations. Adapting an off-the-shelf European electric locomotive to North American requirements may not be practical. Instead, were European manufacturers to enter the market for electric freight locomotives, they may need to develop entirely new designs.

Existing domestic locomotive manufacturers in the U.S. and Canada could in theory offer electric freight locomotives generally configured around their current diesel-electric designs. This would require additional design effort to integrate the new electric drive system into the existing platforms and may require these suppliers to acquire additional manufacturing capabilities. The ability of North American suppliers to serve an electric locomotive market in a cost-effective manner would largely be dependent upon having an assured, contracted volume of electric locomotives such that the research and development costs, new tooling, and new supply chains, could be amortized over a large fleet size.

3. Operation and Maintenance of Electric Locomotives

Electric locomotives share some of the same equipment with diesel-electric locomotives but eliminate the diesel prime mover, which is a maintenance-intensive system, replacing it with power collection equipment, high-voltage switchgear, transformers, and power conditioning equipment. Electric locomotive power collection and conditioning equipment has few moving parts and generally requires little maintenance. However, the maintenance for control systems, brakes, and mechanical systems would be the same as for a diesel-electric locomotive. While there may be some offset in maintenance cost by the lack of a diesel prime mover and fuel system, it is important to remember that maintenance of the electrical supply infrastructure (i.e., the OCS and TPS) would be a new cost. Maintenance of the catenary and electrical supply infrastructure is discussed in **Section VIII - Catenary Infrastructure Maintenance and Safety**.

It is also important to note that the railroads' mechanical labor force would require re-training to maintain a fleet of electric locomotives. Some functions, particularly those related to prime mover maintenance, may no longer be required. Additionally, new safety training for the on-board 25 kV systems would be necessary, and, as noted in **Section V.E.6 - Locomotive Maintenance Facilities**, maintenance facilities would require new or reconfigured infrastructure to accommodate the electric locomotives.

C. Catenary-Battery Hybrid Locomotives

1. Introduction

The use of modern battery systems as an on-board source of electricity is in the early stages of development in North American in rail vehicles. While several railroads are already using or are in the process of procuring yard locomotives that operate on battery power, these are still in the testing stage, with test operations limited to controlled conditions at a few yards. While Wabtec, a freight railroad equipment supplier, has performed a pilot test of a battery locomotive operating as a short-range booster and energy recapture system, no battery electric line-haul locomotives have entered commercial main line service on a Class I railroad. Thus, the information in this section is speculative, as it is unknown how batteries would perform in the actual line-haul railroad environment; costs are also not known.

Battery technology for automotive applications is understood and many manufacturers provide automotive batteries. However, the freight rail environment is very different, both from the energy delivery perspective and the perspective of physical constraints and forces (such as impacts and vibrations) on the batteries themselves.

Batteries may offer the potential for lower maintenance compared to a diesel prime mover; however, battery systems do have several drawbacks. First is their energy capacity relative to their weight and volume. To match the energy content of diesel fuel, a lithium-iron-phosphate (LFP) battery system (the type used in pilot tests of battery-electric locomotives) would weigh many times more than the energy-equivalent weight of diesel fuel. Therefore, axle loading and space restrictions dictate that a locomotive could store much less energy in batteries than it could if equipped with a diesel engine and a full tank of fuel.

For example, a full tank of diesel fuel (approximately 5,000 gallons) offers nearly 200,000 kWh of energy stored, with the fuel providing approximately 80,000 kWh of useable energy

at the wheels.⁴² Even if a catenary-battery hybrid locomotive pulled a tender dedicated entirely to batteries, the tender might provide space for approximately 13,500 kWh of stored energy, much less than would be available in the diesel fuel. The relatively low energy density of batteries greatly limits the range that can be achieved with a battery-powered locomotive on a single charge when compared to a diesel-electric locomotive.

Battery life is another factor. The most resilient batteries available in today's market can handle between 3,000 and 5,000 charge cycles before their energy storage capacity begins to degrade. After 5,000 charging cycles, the batteries require full replacement. In a scenario where the batteries are charged only once per day, they may be able to operate for ten to 14 years before needing replacement. However, in applications where batteries see more than one cycle per day of operation, that replacement period could quickly diminish to five years or less. Charging to the full maximum charge, or completely discharging batteries can also reduce their useable life; thus, to optimize battery life, the "top" and "bottom" ends of battery capacity may not actually be accessible.

2. Catenary-Battery Hybrid Concept

Installing a battery on-board an electric locomotive (a catenary-battery hybrid) would provide an alternate source of electricity, allowing the locomotive to operate without OCS ("off-wire") to bridge gaps between electrified segments of track. For this Study, gaps in electrified track fall into two broad scenarios, "Short OCS gaps" and "Long OCS gaps," with the length of catenary gap dependent upon the size and capacity of the battery.

a. Short OCS Gaps

The short OCS gap scenario could be addressed by fitting a small battery pack to a catenary-electric locomotive. It is estimated that a battery weighing approximately 24,000 lbs. and a battery charger could be included in a catenary-battery hybrid locomotive. Such a battery could store approximately 1,600 kWh of energy, which could provide approximately 20 minutes of range of off-wire operation at full power (approximately 3.3 MW) for a freight locomotive, while allowing for some adverse weather conditions, battery degradation, internal energy losses, and avoiding complete discharge of the battery (which reduces battery life). This would permit a train to bridge a catenary gap of five to ten miles (depending upon speed, grade, train weight, weather, conditions, and amount of battery reserve desired). Such locomotives could pull trains short distances in areas where overhead obstructions would make OCS particularly expensive, such as yard tracks, tunnels, highway overpasses, customer facilities. In addition to bridging small gaps on electrified track, the batteries could also allow some limited capability to move a train to a more favorable location in the event of catenary power outage.⁴³

This approach may offer a way to reduce the particularly high cost of OCS installation at specific obstacles such as tunnels and overpasses. This Study and the accompanying

⁴² U.S. Bureau of Transportation Statistics, "Energy Consumption by Mode of Transportation", accessed on October 22, 2024, at <https://www.bts.gov/content/energy-consumption-mode-transportation> .
Converted from BTU to kWh.

⁴³ European vendors currently advertise catenary-battery hybrid locomotives with short-range battery capacity.

infrastructure cost estimate assumes that the technology to bridge short OCS gaps with on-board batteries would be feasible.

b. Long OCS Gaps

The second scenario, with OCS gaps in the range of 70 to 200 miles long, would be more challenging to address. A catenary-battery hybrid locomotive with a small, on-board battery (as discussed above) could not store sufficient energy to bridge such extended gaps. To provide sufficient power to bridge long OCS gaps, a dedicated battery tender would need to be attached to each locomotive in the motive power consist.

In this scenario, a tender car almost entirely filled with batteries would be connected via power cables to a catenary-electric locomotive. Assuming a weight of the tender car structure and battery charging and conditioning equipment to be approximately 40 tons, 100 tons of batteries could be carried on the tender car to stay within maximum axle loading limits for a four-axle freight car. For a single tender, a lithium-iron-phosphate battery (as used on the Wabtec FLXdrive locomotive) weighing 100 tons is estimated to hold batteries storing approximately 13.5 MWh of energy.

The maximum length of OCS gap would depend upon several factors, such as maximum and minimum charge states (to preserve battery life), decrease in battery range due to unfavorable weather (since the length of gap would be governed by the worst-case conditions), efficiency of the drive system, desired speed, train weight, grades, and a factor of safety on range. Additional battery capacity would be required to account for extended stops when the train would not be advancing through the gap, but the battery would still need to supply power to auxiliaries, like air compressors, electronics, communications equipment, battery management equipment, and cab temperature control equipment.

For this example, assuming a catenary-battery hybrid locomotive operates across the representative territory used for the train energy usage simulation, with no grade exceeding 0.5 percent and no net elevation gain over the territory (i.e., despite grades, the beginning and ending elevations would be the same), the maximum range is estimated to be approximately 200 miles in a best-case scenario. However, as grades over the representative territory increase to the range of 1.5 percent, the maximum gap length is estimated to decrease to approximately 70 miles. See **Appendix A – Train Energy Usage** for additional details regarding these assumptions.

The capability of a charger small enough to fit on-board a locomotive or tender and the associated recharging time would be a further limitation in the practical length and spacing of catenary gaps. Assuming an on-board recharging rate of 1 MW (the mid-range of advertised stationary locomotive recharging equipment, which may not be feasible to mount on-board a locomotive), approximately 13 hours would be required to recharge the battery (ignoring the slower charging rates that may occur as batteries reach their full state of charge). The distance available to recharge the battery is dependent upon train speed and, in this case, assuming the same train speed used to traverse the OCS gap on the representative territory, approximately 50 miles per hour, a locomotive with a discharged battery could travel as far as 650 miles under OCS (even with brief stops to change crews) before recharging its battery sufficiently to bridge a 200-mile gap in the OCS.

Based on the information above, there could, in theory, be an OCS gap in the range of 70 to 200 miles long spaced as much as 650 miles apart (in which interval the train would recharge the battery). However, the 200-mile length of gap could be achieved only in areas with minimal grade and under ideal conditions.

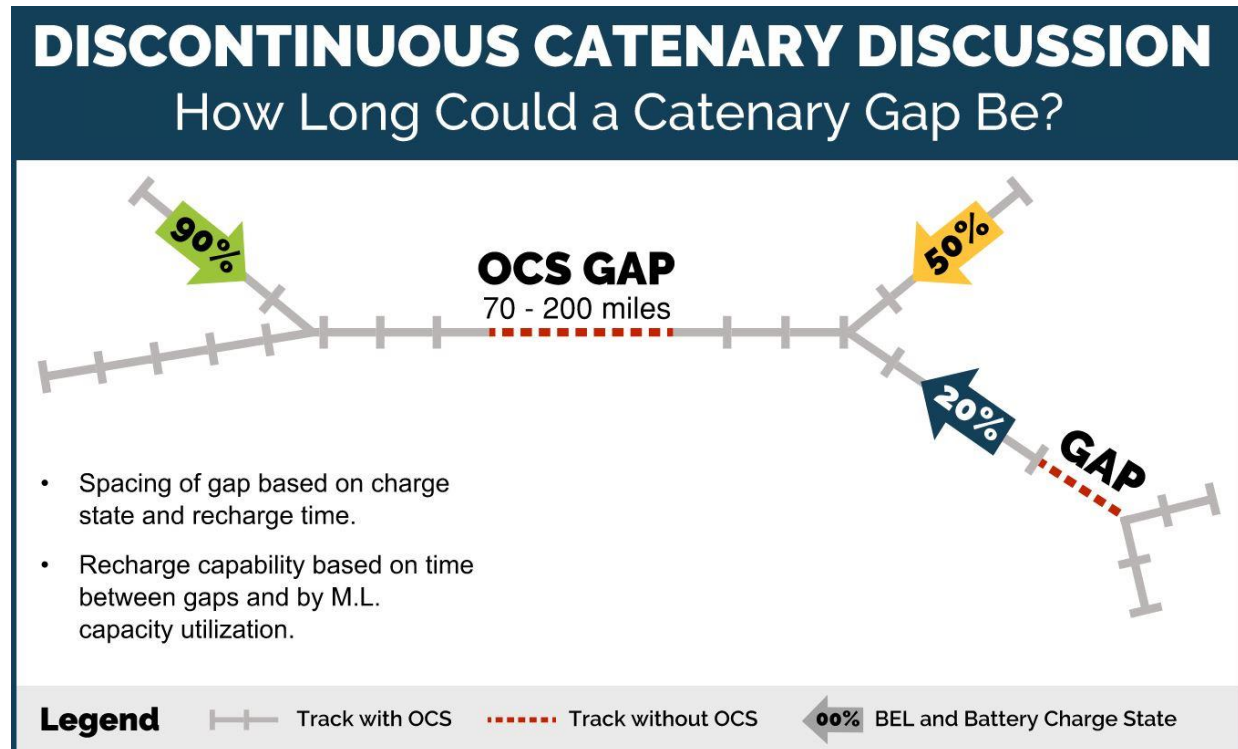


Figure 12: Maximum Length of Catenary Gap

Figure 12 illustrates the challenge of complex routings that could also limit the maximum OCS gap length because trains with varying battery charge states could approach an OCS gap from different directions or routes. There are many rail junctions across the U.S. and Canada where trains switch from one route to another on a daily basis. As illustrated in the Figure, the maximum length of gap on any one route would be dependent not only upon train speed and operating conditions on *that* route, but also upon the minimum charge state of a train entering from *another* route.

In practice, with steeper grades, heavier trains, a net elevation gain over the length of the OCS gap (meaning there may be no opportunity to regenerate braking energy back into the battery), and higher energy draw, as well as more uncertainty on the initial charge state, the practical catenary gap may be even shorter, possibly on the order of 50 to 100 miles.⁴⁴ A route-specific analysis, accounting for the physical and operational characteristics of a particular route and more data on the actual performance of battery electric locomotives,

⁴⁴ Gaps in catenary also introduce two “terminal point” substations, one on either side of the catenary gap, which add to the complexity and expense of the traction power system and eliminate the ability to transmit regenerated energy across the gap.

would be required to assess the maximum length of gap on any route, and how an OCS gap on one route affects the spacing and length of gaps on other routes.

It is also important to note that catenary battery hybrid locomotives do not reduce the amount of electrical energy needed. In fact, catenary-battery hybrids would increase power demand while operating under catenary because the locomotives would not only draw power to move their trains, but also would simultaneously draw additional power to charge their on-board batteries. As a result, surges of power demanded from the serving electric utilities could be even more pronounced than straight catenary-electric operation. The OCS and TPS infrastructure would need to be upgraded to accommodate the higher power demand, with larger wires and substations and attendant increases in infrastructure costs. This would increase the cost of these sections of OCS and TPS.

In addition, catenary-battery hybrid locomotives capable of traversing long catenary gaps would always need to pull the added weight of the tender, increasing operating costs. Each tender could take the place of one car carrying customer goods, assuming a fixed gross train weight. As an example, a train normally consisting of three locomotives, three tenders, and 100 loaded cars would need to forgo three loaded cars to accommodate the weight of the three tenders, a capacity reduction of approximately three percent per train, while simultaneously increasing the tare weight of the train.⁴⁵

The capabilities of the catenary-battery hybrid technology are still uncertain. Given the challenges of complex routings, the operational complexities of battery tenders, the resulting uncertainty in possible length of OCS gaps, and the uncertainty of costs of battery tenders, this Study does not include catenary-battery hybrid locomotives as a means to significantly reduce the amount of OCS and TPS infrastructure over long distances; the infrastructure assumptions do not include the “Long OCS Gap” scenario.

D. Catenary-Hydrogen Fuel Cell Hybrid Locomotives

1. Introduction

A catenary-hydrogen fuel cell (HFC) locomotive would store gaseous hydrogen on board the locomotive or tender car, reacting this hydrogen with oxygen from the air to produce electricity, with water as a by-product of the reaction. The electricity could power the locomotive across gaps in the OCS.

Hydrogen can store much more energy than could a similar volume of batteries. Thus, a catenary-HFC hybrid towing a HFC tender would have greater range than a catenary-battery hybrid locomotive towing a similarly sized battery tender.

Hydrogen fueling is typically faster than battery charging. From a volumetric perspective, a hydrogen fueling station capable of chilling hydrogen to approximately 5 degrees Fahrenheit (but still in a gaseous state) can fill hydrogen tanks in approximately the same time that an equal volume of liquid diesel fuel could be dispensed. However, the energy

⁴⁵ On single-track routes, train lengths are typically limited by the length of passing sidings. The length of the tender cars could displace customer cars. On railroads with two or more tracks, train lengths would not be limited in this way. However, the increase in the weight of the vehicles (i.e., rail cars, locomotives, and the additional tenders) relative to the cargo would decrease energy efficiency.

density of the resulting hydrogen would be less than that of the diesel fuel, with one gallon of hydrogen compressed at 3,000 pounds per square inch (psi) having approximately 1.9 kWh of energy, while one gallon of diesel fuel contains approximately 38 kWh of energy.⁴⁶ Note that, at higher hydrogen temperatures, refueling proceeds more slowly, and filling a tank of similar size to a conventional diesel-electric locomotive fuel tank, about 5,000 gallons, could take several hours.

The properties of hydrogen do present safety considerations. Hydrogen is a highly flammable gas that is odorless and invisible. Because of its small molecular size, it leaks through fittings and other components much more readily than other gases. For this reason, a two-pronged approach would need to be taken to mitigate the hazard from potential hydrogen leaks. First, active monitoring for hydrogen leaks would be needed, including frequent checks of vulnerable portions of the hydrogen system to ensure integrity. Second, any enclosures or enclosed spaces would need to be configured to safely vent any gas that might leak from the fuel supply system. This not only impacts locomotive design, but also the design of facilities in which hydrogen powered locomotives might be stored or operated, such as maintenance facilities and tunnels. Along with ventilation, an overlay system of flame and gas detectors would be needed.

One lesser-known safety consideration is tendency of steel (commonly used for pipelines, for example, as well as other components that require strength to withstand pressures from compressed gases) to become brittle when exposed to hydrogen, effectively weakening the steel. To avoid hydrogen embrittlement, piping and containers would need to be made of alternate materials or be equipped with liners to protect the steel from the hydrogen molecules.

Another potential concern with catenary-HFC hybrid locomotives would be the proximity of energized 25 kV catenary to the stored hydrogen. While hydrogen storage and fuel cell systems already have grounding systems, consideration would need to be given to ensuring these would function adequately in the vicinity of high voltage electricity.

2. Catenary-HFC Hybrid Concept

A catenary-HFC hybrid line-haul locomotive would require both a locomotive and tender. The locomotive itself would contain the equipment necessary to operate from overhead catenary but would have insufficient space for hydrogen fuel cells or hydrogen storage. HFC-powered locomotives also require a limited amount of battery storage capacity, which could likely be installed on the locomotive itself. The hydrogen tender would include hydrogen gas tanks, associated piping and pressure regulation equipment, fuel cells, associated cooling equipment, and electrical conversion equipment and cabling.

An additional reason to contain the hydrogen storage and fuel cells on one platform, the tender, is the increased risk of leaks and fires if gaseous hydrogen were to be routed through flexible couplings (i.e., hoses) between the tender and locomotive. By making the tender a

⁴⁶ Exact conversion factors vary depending upon source and assumptions about compression, these are based on conversion factors from the National Renewable Energy Lab, accessed at <https://www.nrel.gov/docs/gen/fy08/43061.pdf>

self-contained unit, including both hydrogen storage and the fuel cells, electric cables would be the only couplings required between a locomotive and its tender.

Maintenance of hydrogen power equipment would require, at minimum, frequent filter replacements and leak checks. Note that regulatory agencies, such as the FRA, have not identified the required maintenance tasks or intervals for hydrogen power equipment, though maintenance practices for natural gas-powered locomotives may offer some guidelines. It is assumed that inspections would need to occur at least once every six months. Additional checks and maintenance would involve inspection and testing of valves in the pressure regulator assembly and at each individual tank. Certain valves in the pressure regulator assembly would also require periodic replacement, potentially at intervals as long as three to five years, but also potentially at more frequent intervals. Major maintenance activities with current hydrogen systems involve the recertification of the hydrogen storage tanks and associated hardware, rebuild of the pressure regulation system, and occasional replacement of hydrogen tanks and fuel cells.

As with the catenary-battery hybrid concept, catenary-HFC hybrid locomotives would always need to pull the added weight of a tender, increasing operating costs.

Assuming a catenary-HFC hybrid locomotive operates across the same “representative” territory with very gentle grades considered for catenary-battery hybrids, with no grade exceeding 0.5 percent and no net elevation gain over the territory, the maximum range and OCS gap length are estimated to be approximately 900 miles. However, similar to the catenary-battery hybrid, as grades over the representative territory increase to the range of 1.5 percent, the maximum OCS gap length decreases to approximately 300 miles. See **Appendix A – Train Energy Usage** for additional details regarding these assumptions.

3. Hydrogen Availability and Logistics Constraints

The lack of availability of hydrogen constrains the potential for hydrogen-electric hybrid locomotives to be refueled, and thus constrains the number and location of possible gaps in the OCS infrastructure. Such a scenario presumes that hydrogen would be available to refuel the locomotives at terminals on each side of the OCS gap. However, there is today no widely available commercial source of hydrogen across North America.

While seven “hydrogen hubs” were selected by the DOE to enter negotiations to move to the planning, analysis, and design stage in July 2024, there is currently no plan for building-out a network of hydrogen pipelines to distribute that hydrogen to end users, or a plan for pipelines that could serve the railroad industry’s fuel needs at remote terminals.⁴⁷ The DOE notes that “further research is needed to analyze the trade-offs between the hydrogen production options and the hydrogen delivery options when considered together as a system.”⁴⁸

Hydrogen storage is another logistical consideration. Absent some amount of on-site storage at fueling facilities, fueling rates would be limited to the amount of hydrogen a pipeline could deliver, or that could be generated on-site. At a large fueling facility, with

⁴⁷ U.S. Department of Energy, Office of Clean Energy Demonstrations, Regional Clean Hydrogen Hubs Program.

⁴⁸ U.S. Department of Energy, Hydrogen Delivery, [Hydrogen Delivery | Department of Energy](#)

multiple locomotives receiving fuel simultaneously, hydrogen storage capacity would likely be needed on-site, which would be expensive and could meet resistance from neighbors. To keep tank volumes manageable, this could require additional compression (or possibly liquefaction and cryogenic) infrastructure.

Due to the significant present constraints on large-scale hydrogen production, logistics, and storage, this Study does not include catenary-HFC hybrid locomotives as a means to reduce the amount of OCS and TPS infrastructure.

VIII. Catenary Infrastructure Maintenance and Safety

A. Key Points and Overview

Key Points:

- The OCS and TPS are maintenance-intensive infrastructure.
- The OCS represents a single point of failure. A long section of OCS damaged by a tornado, flood, or hurricane has the potential to delay large numbers of trains.
- Entirely new departments for TPS and OCS maintenance and operation would need to be established. Large groups of skilled field staff would be required for maintenance. Equipment, tools, and vehicles specific to OCS and TPS maintenance would need to be procured and maintained.
- Energized 25 kV lines above the tracks represent a new safety consideration. New training and safety procedures, along with specialty equipment and tools, would be required for all field staff. These new procedures would complicate the work of other departments. Third parties, including emergency first responders, would also need to be educated about the hazards of TPS and OCS.

Overview

Electrification of the Class I network would introduce new considerations for TPS and OCS infrastructure operation and maintenance. These systems would be subjected to variabilities of geographic location, environment, climate conditions, components used, and railroad operating characteristics such as speed and train frequency. This section provides a high-level overview of these systems from an operations and maintenance perspective.

Unlike an unexpected signal system fault, which is often isolated to one specific signal location, and which might delay but not completely stop train operations, an OCS or TPS outage would disrupt the source of energy, which could stop all trains within the limits of the outage. This consideration places a premium on OCS and TPS maintenance.

B. Operation and Maintenance of the OCS and TPS

1. TPS Maintenance

The traction power facilities would be unmanned and remotely controlled and monitored. Power directors controlling the TPS would be located at a remote location, while maintenance staff would be located in the field to maintain the TPS infrastructure, such as

TPSS, paralleling stations, switching stations, feeders, gantries, cables, duct banks, circuit breakers, and electrical switches.

Typical duties for TPS maintenance personnel would include:

- **Inspections:** Checking for equipment malfunctions, overheating, breaker operations, transformer tap changer operations, relay setting and performance, or other issues.
- **Preventive Maintenance:** Regular cleaning, lubrication, rebuilding, and testing of breakers, switches, and other electrical components would be performed. Equipment suppliers would require access and supervision inside the facilities to perform testing and scheduled maintenance.
- **Corrective Maintenance:** Respond to and correct/repair equipment failures.
- **Support for Other Departments:** A trained electrician would be required to de-energize the TPS in support of other activities proximate to the TPS, such as tree trimming or operation of equipment with booms in or around TPS facilities.
- **Emergency Procedures:** Respond to power outages.

2. OCS Maintenance

Specially trained OCS maintenance personnel (linemen) would maintain the OCS and supporting systems. Due to the high voltages involved, no work could be performed on the OCS while it is energized, although, in multiple track territory, work could be performed on the OCS over one track while the OCS over the adjacent track remained energized. OCS Maintenance crews would inspect and maintain both the OCS structures (e.g., poles, auto-tensioning equipment, guy wires, etc.) as well as the contact and messenger wires, hangers, cantilever assemblies.

Typical duties for OCS maintenance personnel would include:

- **Visual Inspections to identify wear, damage, or corrosion in:**
 - Contact wire: for damage, wear, and correct position above the tracks.
 - Poles, foundations, cantilevers, insulators, clips, brackets, conductors, jumpers, and feeder connections.
 - Disconnect switches, ground connections, impedance bonds, track, and connections.
- **Preventive Maintenance:**
 - Periodic replacement of worn or damaged components, such as insulators, conductors, and hangers.
 - Tension, height, and stagger adjustments: ensuring proper tension in the catenary wires and proper height and stagger (lateral position as related to the centerline of the track) to maintain safe and optimal performance.
 - Removing accumulated dirt, debris, and vegetation that can affect contact quality and insulator effectiveness.
- **Corrective Maintenance:** Respond to and correct/repair OCS-related equipment failures.
- **Support for Other Departments and Third Parties:** A trained lineman would be required to ground the OCS system in support of other activities proximate to the OCS, such as tree trimming or operation of equipment with booms under the OCS.

- **Emergency Procedures:** Respond to OCS-related emergencies such as accidents and damaged components for isolated incidents.
- **Disaster Recovery:** A major service interruption that damages existing OCS and TPS infrastructure would need to draw upon the efforts of a comparatively small pool of qualified staff that would normally be stationed over a large area. OCS staffing levels would need to be set to accommodate emergency response and OCS restoration without causing operational delays.

OCS inspection and maintenance is particularly important because many of the components are connected via bolts and pins, all of which have the potential to loosen over time and with the vibrations of passing trains. A failed component, even a small one such as a loose catenary hanger, has the potential to become entangled in a locomotive pantograph. This could result either in the pantograph being ripped off the locomotive (damaging other rooftop apparatus in the process), the overhead wire being pulled down, or both. A side effect could be a damaged but energized 25 kV wire contacting ground, which has dangerous implications.

OCS crews would be responsible for carefully managing the geometric relationship between the track and the OCS. This is a critical activity since pantographs on top of locomotives cannot be allowed to slip off contact wire. If a locomotive pantograph were to slip off the wire, damage to the pantograph, OCS, or both would result. For example, slight cross-level variations in the track, at rail level, would cause a locomotive pantograph, approximately 24 feet above the top of rail, to rock from side-to-side. The resulting rocking motion at the rail level would be magnified at pantograph elevation. Combined with the design stagger of the wire, chording at curves, wind effects on the wire, and slight variations in track alignment, such rocking could pose a risk to the pantograph may slip off the wire if the OCS became misaligned.

Because of the hazards associated with energized 25 kV wire, work on the OCS could be performed only when the OCS is de-energized. The OCS crew members would be responsible for applying safety grounds to the OCS for themselves and other departments, such as the track department, or for third-party operations, such utility companies installing new overhead lines across the ROW. These safety grounds are typically applied at both ends of a de-energized segment and at the work site and must be applied prior to other groups commencing work and removed prior to re-energizing the OCS.

In general, from an operating perspective, the fixed catenary infrastructure required for operation of electric locomotives is sensitive to weather and other external effects. Wind and icing can affect the catenary wire and render some routes impassable for the duration of the inclement weather. Extreme weather, such as hurricanes, tornadoes, and windstorms that dislodge tree branches (or entire trees) and cause it to fall onto OCS infrastructure, or similarly entangle other wind-blown debris onto OCS infrastructure, as well, thus resulting in the potential for major damage to the OCS infrastructure.⁴⁹

⁴⁹ A Class I railroad provided an example of the frequency of weather-related operational interruptions (e.g., sleet storms, high winds knocking down trees, washouts, etc., each of which would result in enough damage to the OCS to stop trains). Extrapolating from this information, a hypothetical railroad

As described previously, ROW access roads would be necessary to facilitate OCS maintenance. Much OCS maintenance work would require crews to be elevated above the track, meaning that the OCS would be de-energized and the track would be unavailable for train operations. To minimize the amount of track occupancy time, OCS maintenance crews could perform some work using utility-style bucket trucks. On a corridor with OCS on two (or more) tracks, these trucks would need road access on both sides of the ROW.

The OCS is also susceptible to sleet storms which affect the ability of locomotive pantographs to properly contact and draw power from the OCS. The primary way to control icing on the OCS involves regular operation of trains such that frequent passage of the locomotive pantographs cuts through thin layers of ice before thicker ice layers can build-up. If no trains have operated for some time, catenary icing can become a significant problem during sleet conditions. In the event trains were not able to operate during a major sleet storm (for example, due to a utility power outage, or tree branches damaging sections of OCS), it could be hours (or days) until the accumulated ice melts off the OCS, or until pantograph-equipped locomotives (or rail cars equipped for the purpose) could be pushed by diesel-electric locomotives over the line to clear the OCS of ice.

C. Power Dispatching

A power dispatching control center would monitor and control the TPS and OCS systems. The control system would employ a SCADA system operating in a redundant configuration for maximum system availability. Power directors would control and monitor the status of the TPS and OCS equipment, including alarms, breaker operations, voltage levels, and condition of the utility supply across the entire electrified territory.

During normal railroad operations, the TPS and OCS would require minimal operational input, and the electrification system would remain energized, except for fault conditions or maintenance activities. Power directors would coordinate with the grid utilities supplying electrical power, monitor the TPS network status, and perform electrical switching operations as required to support train operations. The power directors would also be responsible for rerouting power to the OCS and different TPSS locations in the event of planned or unplanned utility power outages, coordinating power-related work in the field, energizing/de-energizing the OCS for maintenance-related work, and coordinating with field personnel to ensure safety grounding devices are applied or removed as necessary.

One power director would typically control the TPS and OCS on a geographic territory encompassing the territories of several train dispatchers, depending on the size and complexity of the respective territories. To facilitate coordination, a power director's workstation would typically be located near the several train dispatchers working the same geographic area. Because the OCS would be sectionalized into discrete electrical segments, generally matching the limits between railroad signal control points or interlockings, train dispatchers and power directors could block and de-energize, respectively, the track and OCS in the same area. The power director would do so by remotely operating the TPSS

with 10,000 track miles would, on an annual basis, experience approximately 27 outages that could damage the OCS each year.

equipment and motor-operated switches in the field to de-energize portions of the OCS for maintenance or repair activities, whereupon field staff would apply safety grounds.

Whenever a field maintenance crew (including track, signal, and structure maintenance crews) intends to operate equipment that could contact the overhead wire, the power director for that territory would need to de-energize that segment of the OCS. However, prior to de-energizing the OCS, the power director would need to coordinate with the affected train dispatcher to ensure every train has exited that segment of track, so that no trains were stranded when power was disconnected.

Unlike other railroad infrastructure, the energized OCS itself is hazardous. Touching energized OCS would have fatal consequences. Anyone in the railroad corridor would need special training and qualification testing to ensure they are aware of the hazards of the infrastructure and know the proper procedures to protect themselves from it.

Note that de-energizing the catenary would also remove the energy source needed to power the air compressors for the braking systems for any parked trains. Crews might need to secure those trains with handbrakes. As noted, the power director would also coordinate with field electricians to ensure the catenary is not only de-energized, but also has safety grounds applied if work is to be performed on the OCS or TPS within that segment.

D. Safety and Training

The introduction of exposed 25 kV conductors into the railroad operating envelope represents a new hazard for employees and third parties. Currently, track and signal maintenance forces generally do not require protection from the infrastructure they maintain. However, a 25 kV OCS system itself is hazardous, and employees must be protected from the infrastructure they are working on and around, because simply contacting energized OCS would have fatal consequences.



All staff working along the ROW would need specific safety training to be authorized to work in the vicinity of the electrified tracks. Railroads would need to develop rules, procedures, training, and testing for their own staff and for third parties (e.g., contractors) whose duties could take them into OCS territory. This training and testing would include knowledge of electrical hazard identification, minimum clearances, exclusion zones around energized equipment, and what types of equipment can and cannot be used while the OCS is energized.

For example, equipment such as excavators, cranes, backhoes, and dump trucks have components that can move or extend upward with the possibility of encroaching on the exclusion zone for energized conductors or even touching energized parts of the OCS. Such equipment would either be prohibited from operating on the track when the OCS is energized or would require installation of a locking mechanism to prevent accidental operation and contact with energized parts. These restrictions would also apply to on-track equipment, such as tie cranes, rail handling equipment, and hi-rail boom trucks.

In addition, field or mechanical personnel would be prohibited from climbing on top of most equipment while the OCS is energized. Even inspection or maintenance activities for components such as roof-mounted air conditioning units atop work equipment and locomotives would need to be restricted to prevent employees accidentally contacting energized OCS.

IX. Environmental Documentation and Permitting

A. Key Points and Overview

Key Points

- Environmental documentation is the process of identifying and disclosing to the public a project's potential impacts on human health and the physical environment. While there are multiple laws in both the U.S. and Canada pertaining to environmental documentation, the U.S. National Environmental Policy Act (NEPA) and the Canadian Impact Assessment Act (IAA) are two key laws at the federal level.
- These processes often result in changes to a project's scope or requirements to mitigate a project's impacts on the environment.
- The development of an environmental document for even a small project may require years, with larger, more complex projects typically requiring much more time. The environmental documentation process for the entire Class I railroad network would require many years, and potentially decades, of effort.
- In addition to environmental documentation, permits would be required for specific activities, such as work in wetlands, or impacts to endangered species. These permits often require years to obtain, and associated mitigation efforts may require additional time to develop.
- The impacts of catenary electrification, including visual impacts, would essentially be continuous along railroad corridors and would require environmental analysis for effectively the entire footprint of the U.S. and Canadian rail networks.

Overview

Electrifying the North American freight rail system would be a major undertaking requiring significant new infrastructure which would have a footprint on the ground and could impact environmental resources such as endangered species, cultural or archeological resources, and wetlands. Both the U.S. and Canada have established environmental documentation and permitting processes to identify such impacts. In general, these processes are highly site-specific because the environmental characteristics and a project's potential impacts at each site are unique.

Environmental documentation and permitting would also be required for the upgrades to the electric power transmission and generation systems in the U.S. and Canada. Because of the distinctions in the nature of the facilities and impacts, as well as the distinct departments and ministries responsible for such infrastructure at the policy level, an entirely separate environmental documentation and permitting process (i.e., distinct from that undertaken for

the railroad OCS and TPS) would likely be required for modifications to the electric grids in each country.

In the U.S., the Positive Train Control (PTC) mandate is illustrative of the challenges of implementing a nationwide environmental documentation and permitting effort. It required a special notification system and opportunity for comment on each individual PTC tower, comprising approximately 30,000 individual towers and foundations, which were generally spaced miles apart. Section 106 of the National Historic Preservation Act (NHPA) required coordination through over 50 State Historic Preservation Offices (SHPOs) and Tribal Historic Preservation Offices (THPOs), mainly for the potential for the excavations for each tower foundation to impact buried historic or tribal resources.

By contrast, a catenary electrification program would involve millions of individual catenary support poles and foundations, spaced approximately 175 feet apart. Each would need to be analyzed for its potential to impact resources. Catenary electrification would also require new overhead wires, substations, and utility grid upgrades, each of which would be the subject of environmental documentation. The scope of the environmental analysis would be much larger than that undertaken for the previous PTC effort.

In terms of timelines for environmental documentation, in 2020 the U.S. Council on Environmental Quality reported the average time for completion of an Environmental Impact Statement (EIS), from issuance of the Notice of Intent (NOI) to Record of Decision (ROD), was over five years, meaning roughly half of the EIS documents require more time to complete.⁵⁰

In July 2024, of the Council on Environmental Quality's (CEQ's) Bipartisan Permitting Reform Implementation Rule took effect.⁵¹ This rule includes maximum timelines to complete the NEPA process: for an EIS, it allows a maximum of two years from Notice of Intent (NOI) to Record of Decision (ROD) while for an Environmental Assessment (EA), a more abbreviated document for projects with no significant impacts or impacts that can be mitigated, allows for a maximum of one year. However, there is often a significant amount of preparatory work prior to commencement of these timelines, so completion of these documents would likely require several years, and since the Bipartisan Permitting Reform Implementation Rule is relatively new, there is no established track record of actual completion timelines.

It is important to note that the environmental documentation process would be different in the U.S. and in Canada. Additional information on this process, including an overview of the process in both nations as well as examples of the applicable laws, regulations, and permits, is located in **Appendix B - Environmental Documentation and Permitting Considerations Associated with Electrification of the North American Freight Rail System.**

⁵⁰ Council on Environmental Quality, accessed on October 30, 2024 at: <https://ceq.doe.gov/nepa-practice/eis-timelines.html> and https://ceq.doe.gov/docs/nepa-practice/CEQ_EIS_Length_Report_2020-6-12.pdf

⁵¹ Council on Environmental Quality Federal Register, accessed on November 1, 2024, at: <https://www.federalregister.gov/documents/2024/05/01/2024-08792/national-environmental-policy-act-implementing-regulations-revisions-phase-2>

X. Conceptual Cost Estimates

A. Key Points and Overview

Key Points:

- Cost estimates presented here are generalized to account for conditions across both the U.S. and Canada and are conceptual. In general, these costs are believed to be optimistic (i.e., on the lower end of the reasonable range). Refining costs would require specific study of individual corridors.
- The infrastructure cost estimates assume a "Short OCS Gap" scenario, where high-cost modifications to existing infrastructure, such as tunnels and overpasses, could be avoided. To accomplish this, it is assumed that locomotives would carry small on-board batteries storing sufficient energy to bridge gaps a few miles long, but would not need to tow battery tenders.
- Conceptual capital costs for infrastructure and equipment for electrifying the Class I network across both the U.S. and Canada are estimated to be in the approximate range of \$870 billion to \$1.1 trillion.
- Conceptual annual operating costs for the catenary electrification system would be in the approximate range of \$10 billion to \$13 billion.

Overview:

This Study developed a concept-level capital cost and annual operating cost for catenary electrification over the Class I network across the U.S. and Canada. Given the scope of infrastructure under consideration (up to approximately 139,000 track miles, depending on scenario, spanning a continent and two nations), broad generalizations regarding cost, construction conditions, and operating conditions were made to simplify the estimating process, which was based costs from comparable examples. Complexities of individual corridors or geographic areas were not considered at this high level.

However, these complexities can have an outsized effect on the final cost of a project. For example, soil conditions directly affect the design and expense of installing catenary pole foundations (as discussed in **Section V.B.1 - Foundations**); however, soil conditions vary across the continent, from soft soils where foundations would be relatively easy to install, to rocky conditions where the difficulty of hard rock excavation methods would increase the cost of foundation installation. The difficulties of constructing infrastructure adjacent to an operating railroad, where construction access is dependent upon the amount of rail traffic (as discussed in **Section V.F.2- Sample Construction Timeline**), are another area of uncertainty. While allowances have been made for these and other site-specific considerations, additional, more detailed study would be required to refine costs for any specific geographic area.

Some academic studies have shown that initial cost estimates for megaprojects often understate the final cost. In 2020, a Johns Hopkins University study evaluated seven large transportation projects in the U.S. completed between 1995 and 2015 (with final costs ranging from \$676 million to \$14.6 billion, with five of the sample projects costing more than \$4 billion) and found that overruns were a factor of 2.0 or larger, compared to initial cost

estimates. The Johns Hopkins University study notes that an earlier 2002 study found that a sample of 19 publicly funded rail projects in North America overran their initial cost estimates by 40.8 percent.⁵² While a contingency has been included in these cost estimates, based on the history of cost growth on other large projects, the actual costs for catenary electrification could increase when compared to this initial, high-level conceptual estimate.

B. Conceptual Infrastructure Capital Cost

The conceptual capital cost to add catenary electrification to the Class I railroads across the U.S. and Canada would be in the range of approximately \$870 billion to \$1.1 trillion, as shown in **Table 4**, which summarizes the key cost elements. Conceptual capital costs are expressed as a range. The low end of the range is a scenario where only those Class I routes averaging six or more trains per day would receive catenary electrification and where regeneration is available. The high end of the range is a scenario where all Class I routes would receive catenary electrification but where regeneration is not available. Yard tracks, spurs, and minor industrial leads would not receive OCS in either scenario. Note that these costs are expressed in unadjusted 2024 dollars, without accounting for inflation or discounting.

Note that these cost estimates assume that each locomotive would be equipped with a small on-board battery for operation across short OCS gaps, as described in **Section VII.C.2.a - Short OCS Gaps**. These batteries would obviate the need to modify existing infrastructure, such as overpasses or tunnels, in order to provide clearance for catenary. Such modifications to existing infrastructure would otherwise add tens of billions of dollars to the capital cost.

The conceptual costs have been rounded to the nearest \$10 billion and all costs include a 50 percent contingency. Costs are based on estimates made in 2024 U.S. dollars. Because a construction cash flow has not been developed, these cost estimates do not reflect inflation or the time-value of money. Additional detail regarding the cost estimates can be found in **Appendix C – Key Cost Assumptions**.

⁵² Edwards, Alexandria, "Cost Overruns in Infrastructure Projects: Evidence and Implications," Johns Hopkins Institute for Applied Economics, Global Health, and the Study of Business Enterprise, 2020.

Table 4: Conceptual Infrastructure Capital Cost (2024 USD)

Conceptual Capital Cost Category	Cost (with Contingency) (All Class I Routes)	Cost (with Contingency) (Omits Routes < 6 TPD)
Overhead Contact System	\$510 billion	\$400 billion
Traction Power Systems	\$150 billion	\$110 billion
Electric Utility Interconnection Costs	\$130 billion	\$100 billion
Railroad Signal and Crossing Modification Costs	\$ 80 billion	\$ 70 billion
Right-of-Way Modifications and Third-Party Protection	\$ 20 billion	\$ 10 billion
Locomotives	\$150 billion	\$120 billion
Design, Environmental Permitting, Mitigation, Procurement, and Construction Management	\$ 80 billion	\$ 60 billion
Total (Rounded):	\$1.1 trillion	\$ 870 billion

Note that these cost estimates *exclude* costs to upgrade the national electrical transmission grids in the U.S. and Canada. These cost estimates also *exclude* costs of the new electrical generating capacity that may be needed to provide sufficient electrical capacity.

Capital costs assume that the work would be undertaken and paid for by the Class I railroads, without public subsidy. This is an important assumption, since public funding would trigger a range of public contracting procedures and domestic content requirements in the U.S. and Canada, limiting the number of potential material and equipment suppliers. While there is little academic research on the matter, industry experience has shown that these provisions can increase construction costs and extend timelines for completion.

The conceptual capital costs include a 50 percent contingency to account for uncertainties at this early stage. For a program that is still being conceptualized, this is a reasonable contingency amount.⁵³ As noted above, large projects of this nature inevitably encounter complexities that are not evident during the conceptual stage, increasing costs. Since some mega-projects exceed their initial estimates by more than 50 percent, it is possible that this contingency may not be sufficient.

Assuming completion in 2050, simply averaging the \$870 billion to \$1.1 trillion cost over 25 years (excluding discounting and inflation) results in an approximate \$35 billion to \$45 billion expenditure each year. For comparison, the combined net income of the six Class I freight railroads is approximately \$24 billion per year.

⁵³ 50 percent contingencies are within the range described by Association for the Advancement of Cost Estimating, "Cost Estimate Classification System – as Applied in Engineering, Procurement, and Construction for the Building and General Construction Industries", 2020, and also as cited in "Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries."

Note that the very large quantities of materials, labor, services, and equipment required for large scale catenary electrification could be large enough to shift the markets for these items. If this occurs, further cost escalation could result, which has not been included in the conceptual capital cost.

C. Conceptual Annual Operating Cost

The chief elements of operating cost are the cost of electricity, and the cost of a labor force needed to maintain and operate the OCS and TPS. These have been expressed as an annual cost in **Table 5**. The cost for electric power was derived from the energy model. A 50 percent contingency has been included in the range of maintenance staff costs. No contingency has been included in the cost estimate for electric power.

Table 5: Conceptual Annual Operating Cost (2024 USD)

Conceptual Operating Cost Category	Annual Cost
Electric Power	\$4 billion - \$5 billion
OCS and TPS Maintenance Staff	\$6 billion - \$8 billion
Total (rounded):	\$10 billion - \$ 13 billion

The cost of electricity is expressed as a range. The low end of the range is a scenario where only those Class I routes averaging six or more trains per day would receive catenary electrification and where regeneration is available. The high end of the range is a scenario where all Class I routes would receive catenary electrification but where regeneration is not available. Yard tracks, spurs, and minor industrial leads would not receive OCS in either scenario. As described in **Section V - Railroad Infrastructure for Catenary Electrification**, regeneration is only feasible under specific operating conditions, and so the range reflects an assumption that, at times, minimal or no regeneration would actually be possible. As also explained in **Section V** of the Study, there appears to be a low probability of selling excess regenerated power back to the utilities and, as such, it is assumed there would be no financial credit to the railroads for regeneration.

Note that identifying possible reductions in existing railroad cost structures was beyond the scope of this Study. However, at a qualitative level, while there may be some reductions in locomotive maintenance and diesel fuel costs (since catenary-electric locomotives do not have a diesel engine), it's possible that these could be offset by the need to establish and staff entirely new departments for maintenance and operation of the catenary electrification system.

XI. Summary

A. Summary of Findings

Catenary electrification of the Class I freight rail network across the U.S. and Canada is technically feasible, but construction of such a network would cost on the order of \$870 billion to \$1.1 trillion. The construction activities would last decades and be disruptive to existing railroad operations. The resulting system would be susceptible to single-points-of-failure, and the system would create significant new demands on electrical utility grids.

Table 6 summarizes broad categories of considerations related to a freight railroad catenary electrification program.

Table 6: Major Considerations for Catenary Electrification

Consideration	Description
Resiliency	<p>Catenary electrification is susceptible to single points of failure; train operations would be dependent upon the catenary system for energy. Disruptions to the OCS or TPS, including utility power outages, could halt train operations. Even with some amount of on-board battery back-up, trains could be stranded by an OCS or TPS outage unless they had a sufficient battery charge to operate to the nearest section of energized catenary.</p> <p>Severe weather events (such as hurricanes or tornadoes), or even falling trees could damage the OCS and TPS and result in train delays while those components were restored. Sufficient personnel would be needed to respond to such events.</p>
Adaptability	<p>The electrical capacity of the catenary electrification is relatively fixed. Unless the OCS and TPS were initially over-built, large increases in train traffic in any corridor could exceed the capacity of the OCS and TPS. This could affect a railroad’s ability to handle surges in traffic due to detours, maintenance work, or changing supply chains</p>
Environmental Effects	<p>Installation of OCS and TPS across the entire Class I network would have an expansive footprint across the U.S. and Canada. This would result in significant environmental impacts in many areas. The process for environmental documentation and permitting would be extensive, requiring years or potentially decades to complete.</p>
Cost	<p>Conceptual capital cost estimates of catenary electrification would range from approximately \$870 billion to \$1.1 trillion.</p> <p>Conceptual annual operating cost estimates for energy and maintenance staff would range from approximately \$10 billion to \$13 billion.</p>
Timeline	<p>This Study assumed implementation of catenary electrification by 2050. To accomplish that much construction in a relatively short timeframe could increase demand for construction labor and for specific materials and equipment (such as copper, transformers, or new locomotives) so much that the cost increases could be felt beyond the railroad industry. The pace of catenary installation would need to exceed 7,000 miles per year, assuming construction commenced in 2030.</p>

A summary of the findings for infrastructure, motive power, environmental documentation and permitting, energy, and costs follows.

1. Infrastructure and Operations:

a. Overhead Contact System and Traction Power System

Installing catenary infrastructure would be both complex and disruptive to ongoing railroad operations. Because much of the construction work, particularly installation of the OCS (including foundations, poles, and overhead wires) would occur immediately adjacent to or over a track, construction would need to stop any time a train passed by a construction area or, conversely, train operations would need to stop to allow construction to proceed. Construction of the entire system along the entire Class I network would require decades to complete, with construction impacts on various corridors for the entire duration. During this time rail customers and their supply chains would be impacted by operational delays resulting from the construction effort.

The TPS distributes electrical energy to the OCS. The TPS equipment would need to be connected to the electric grid which itself would need to be modified to facilitate the new connections. Connections to the electrical grid would be complex and expensive, as not every existing power line would be capable of providing electricity to the TPS. Redundant power feeds to the electrical grid would also need to be established in order to achieve operational reliability and resiliency.

Other infrastructure would need to be modified or built new. Examples include major modifications to the railroad signal system, as well as potential modifications or relocations of third-party utilities that occupy railroad corridors.

b. Catenary Infrastructure's Effect on Operational Resiliency

Catenary electrification represents a potential single point of failure for railroad operations. Existing diesel-electric locomotives each have their own independent energy supply, offering redundancy and operational resiliency. Conversely, if a catenary infrastructure, serving as a train's primary (or only) source of energy, were damaged, for example, by severe weather rail operations may have to cease on the affected corridors, impacting customers and supply chains.

In addition, the capacity of catenary electrification to power trains is fixed at the time of construction, based on the capacity of substations and sizing of electrical conductors. Shifts in power demand from railroads, such as large numbers of detouring trains (e.g., resulting from construction activities or service interruptions), or longer-term shifts in supply chains and customer demand, could be difficult to accommodate, unless the electrical system were initially overbuilt. If overall track capacity in a corridor were to be increased, expensive modifications to the OCS and TPS infrastructure (as well as potential modifications to the electric utility connections) would also be required.

2. Motive Power

Class I freight railroads currently use diesel-electric locomotives, a mature technology with a relatively long range due to the high energy density of diesel fuel. Diesel fuel is widely available and is relatively simple to handle, transport, and store.

This Study considered technologies for locomotives that would receive electrical energy from one of three sources: catenary-electric locomotives receiving energy from overhead catenary, catenary-battery hybrids that would receive energy from overhead catenary or an on-board battery storage (which itself would be charged by the catenary), or catenary-hydrogen fuel cell hybrid locomotives that would receive energy from overhead catenary or on-board hydrogen fuel cells, powered by on-board hydrogen storage tanks (which would be refilled at terminals).

a. Catenary Electric Locomotives

Existing electric locomotive designs, mostly developed for international rail operators, would require significant modification to be suitable for the North American market. Alternately, it may be possible to convert existing diesel-electric freight locomotives to operate from catenary power, but the required modifications would be extensive. Alternately, new locomotives suited for the North American freight service would need to be designed and manufactured, though this capability exists.

b. Hybrid Locomotives

For this Study, hybrid locomotives were assumed to be able to draw energy from either overhead catenary or from an on-board energy source, either batteries or hydrogen fuel cells. Hybrid locomotives could potentially reduce the amount of OCS required. Three hybrid locomotive scenarios were considered:

- Catenary-battery hybrids for short OCS gaps:** One possible hybrid approach would be to include a small battery on-board an otherwise standard catenary-electric locomotive. This small battery would store just enough energy to allow the locomotive to bridge short gaps (potentially as long as 10 miles) in the OCS. These gaps may be necessary at specific overhead obstructions (such as overpasses or tunnels) to avoid the very high capital cost of reconstructing such existing infrastructure to provide clearance for the OCS. This approach was deemed feasible and was one of the assumptions upon which the conceptual capital cost estimate was based.
- Catenary-battery hybrid locomotives for long OCS gaps:** This approach assumes each locomotive would pull a tender full of batteries to allow the locomotive to bridge longer gaps in the catenary. However, due to the uncertain capabilities of battery technology in the freight railroad environment, the operational complexities associated with ensuring locomotives had sufficient charge time to bridge a long gap in the OCS, the need to pull battery tenders, the comparatively short lengths of OCS that might be avoided relative to the overall OCS requirements, and the uncertain cost and maintenance requirements of the catenary-battery hybrid, this scenario was not considered for the conceptual capital cost estimate.
- Catenary-hydrogen fuel cell hybrid locomotives:** Although these hybrid locomotives could offer comparatively long range, the technology is still in the

testing stage. Because this technology would require development of hydrogen production, distribution, and storage infrastructure (which presently does not exist across North America in widescale), catenary-hydrogen fuel cell locomotives have not been considered for the conceptual capital cost estimate.

3. Environmental Documentation and Permitting

Both the U.S. and Canada have laws and regulations which are intended to both protect the environment and inform the public about actions the respective governments are taking. A program as large as catenary electrification across the U.S. and Canada would require dozens, or even hundreds of separate environmental documents and hundreds or potentially thousands of permits, likely separated by geographic region, jurisdiction, and applicant. While there is no analogous program that would have a nationwide physical footprint, history of environmental documentation and permitting efforts on linear transportation projects suggest a nationwide effort could require years or potentially decades to complete.

4. Energy

Catenary electrification of the Class I railroads would create new demand for a large amount of electrical energy. This Study has evaluated potential energy usage based on publicly available data, and with different scenarios based upon whether regeneration of braking energy into the catenary would be feasible. The range of energy used would be approximately 41.4 TWh to 52.7 TWh per year, which represents new demand on the electric grid. New additional electrical generating capacity and electric transmission line capacity could be necessary to accommodate the energy demand from catenary electrification, though the costs of upgrades to the electric grid are not included in the conceptual capital or operating cost estimates.

5. Conceptual Cost Estimates

The conceptual capital cost for installing catenary electrification on the Class I freight railroad network across the U.S. and Canada would range from approximately \$870 billion to \$1.1 trillion. Such a program would also require multiple decades to complete.

The conceptual operation of the catenary system would also create new annual costs, both for electricity and for additional staff required to maintain the OCS and TPS. These costs (which do not account for potential offsets, such as possible reductions in diesel fuel cost) would be approximately \$10 to \$13 billion per year.

Appendix A – Train Energy Usage

This appendix outlines the approach to estimate, at a conceptual level, train energy usage, including various factors such as train counts, operating grades, train make-up and characteristics, and train operating patterns. These items were used to develop energy calculations for various scenarios.

A. Overview

The major relevant factors for train energy usage are train weight, grade, and speed. The key data inputs were a detailed route map of the North American Class I railroad network, elevation data for North America, and train frequencies along main lines and branch lines.

This information was combined to generate a map of the railroad network divided into thousands of discrete segments, each with elevations, grades, and the number of tracks. Train frequency data was superimposed onto each segment. Using an average weight for each train, the number of tons on each route was determined, and with the grade information, the amount of energy to move trains over a given route was approximated using software designed to analyze railroad electrification projects.

The major considerations included in the train energy usage conceptual analysis are identified below.

B. Data Used to Develop Train Energy Usage

The data sets came from multiple sources. The key sources were:

- Federal Railroad Administration (FRA) track map GIS data set
- FRA highway-rail grade crossing GIS data set.
- United States Geological Survey (USGS) digital elevation model (DEM) data sets.
- Transport Canada (TC) track map and grade crossing GIS data set.
- Canadian DEM data sets.

The track map data sets include several categories of track: yard, industrial leads, major industrial leads, other, main line, and siding. The track maps also identify the railroad subdivision for each track segment. The main line and siding tracks for the six Class I railroad members of the AAR were considered for this analysis. Inputs regarding operating patterns from the Class I railroads were also used to support this analysis.

1. Numbers of Trains

The track map was combined with information from the FRA and TC highway-rail grade crossing databases. The grade crossing databases include train counts at each crossing, as well as characteristics of each crossing, such as whether the crossing has active warning devices, and latitude and longitude information. This information is stored as individual points with a single latitude and longitude for each crossing. A spatial join was used to create a buffer around each of the crossing points. Any track segments within the buffer had the train counts from the grade crossing assigned to the track data set.

This resulted in highway-rail grade crossing information, including train counts from the highway-rail grade crossing database, being assigned to the nearest track segment. The track segments and associated train counts were then organized by subdivision.

Since each subdivision was represented by many track segments with many associated grade crossing points, there were many different train counts (which came from the publicly available, FRA and TC grade crossing data) that could be associated with the subdivision. Given the large number of individual crossings, and the fact that data at each crossing is typically updated over intervals measured in years, there was variability in the train counts. To smooth this variability, the higher of the mean or median of the train counts that was associated with the subdivision was assigned to the entire subdivision. A check for reasonableness was performed, and several Class I railroads made train count recommendations for specific subdivisions based on recent data (as opposed to the grade crossing data, which, based on a five-year update cycle, could be several years old at some locations). Where the calculated total ton-miles for a specific railroad was different from the railroad's STB reported ton-miles, the results for each segment were scaled by the ratio of STB ton-miles divided by the calculated ton-miles.

To manage the amount of data to be processed, the train counts grouped into 8 categories. The lowest category had the fewest trains per day, up to five trains per day. This relatively small grouping was intended to capture relatively light density routes, which comprised approximately 24 percent of mileage (based on the above methodology). This threshold was employed to filter out long but low energy use sections of track, as will be described later.

2. Grades

The GIS track map was also used to assess grades on the North American Class I railroad network. Grades are simply the change in elevation between two points divided by the distance between the two points. The elevations were determined by importing digital elevation models (DEMs) for the U.S. and Canada. These DEMs provide topographic representations of the ground surface. Several DEM resolutions were investigated.⁵⁴ Due to limitations on processing power, after several trials on limited geographic areas, it was determined that 30-meter DEMs would strike a reasonable balance between resolution and processing time. The elevations of the DEM points on the grid closest to the track were assigned as the elevations for the track.

Because 30-meter resolution implies that a point on the track could be as much as 15 meters (50 feet) from the track, measured perpendicularly, some error in track elevations as assigned from the DEM points was possible. In other words, a DEM point that sampled the ground elevation up to 50 feet from the track may not have the same elevation as the track itself. Even in generally flat terrain, there may be river valleys, large drainage ditches, or other topographic features that are a large distance (vertically) from the track. If a DEM point

⁵⁴ Digital elevation models (DEMs) are networks of points based on a uniform, square grid over the area in question. One elevation (z-coordinate) is provided at each intersection of the grid lines (which is represented by x,y coordinates, or latitude/longitude coordinates). The resolution of a digital elevation model refers to the spacing of the grid lines, and thus the points and elevations of each point. A 30-meter resolution means that the grid lines are 30 meters (about 100 feet) apart.

samples the ground at one of these features, the sampled elevation could be different from the track elevation. The same would be true of DEM points sampled in mountainous terrain.

To address the difference between actual track elevation and the elevation at the nearest sample points (known as the “delta”), multiple sample distances were trialed. A three-mile sample distance was selected as the basis for the segment length over which the track grades would be calculated as providing a reasonable representation of the grades while not obscuring too much data. This relatively long distance minimized the effects of sample point elevation delta. A comparison in **Table 7** below illustrates the effects of sample point delta on a hypothetical railroad segment 15,000 feet long (just under three miles), where the assumed actual track grade is 1.0 percent. An actual elevation difference could be as much as 150 feet, but when comparing it to sample data (or a delta), the resulting difference in grade becomes ~0.1 percent (20 feet / 150 feet) and the resulting grade plus delta is 1 percent plus 0.1 percent, or 1.1 percent.

Table 7: Diminishing Effect of Elevation Delta over Increasing Distances

Sample Distance (ft)	Actual Elevation Difference (ft)	Resulting Grade	Elevation Delta (ft)	Resulting Grade (Including Delta)	Difference from Actual Grade
500	5	1.0%	20	5.0%	4.0%
1,000	10	1.0%	20	3.0%	2.0%
5,000	50	1.0%	20	1.4%	0.4%
15,000	150	1.0%	20	1.1%	0.1%

The table shows that for very short sample distances, the effect of a 20-foot elevation delta (difference between actual track elevation and sample point elevation in the DEM) is much more significant on the overall grade compared to long sample distances. Unlike highways, railroad grades rarely exceed 2 percent, so the amount of climb or fall in a given sample distance is limited. Railroads also have historically employed relatively uniform grades.

Based on three-mile sample distances, the grades of each segment were imported into the GIS model; see **Figure 13** for a representation of the resulting grades.

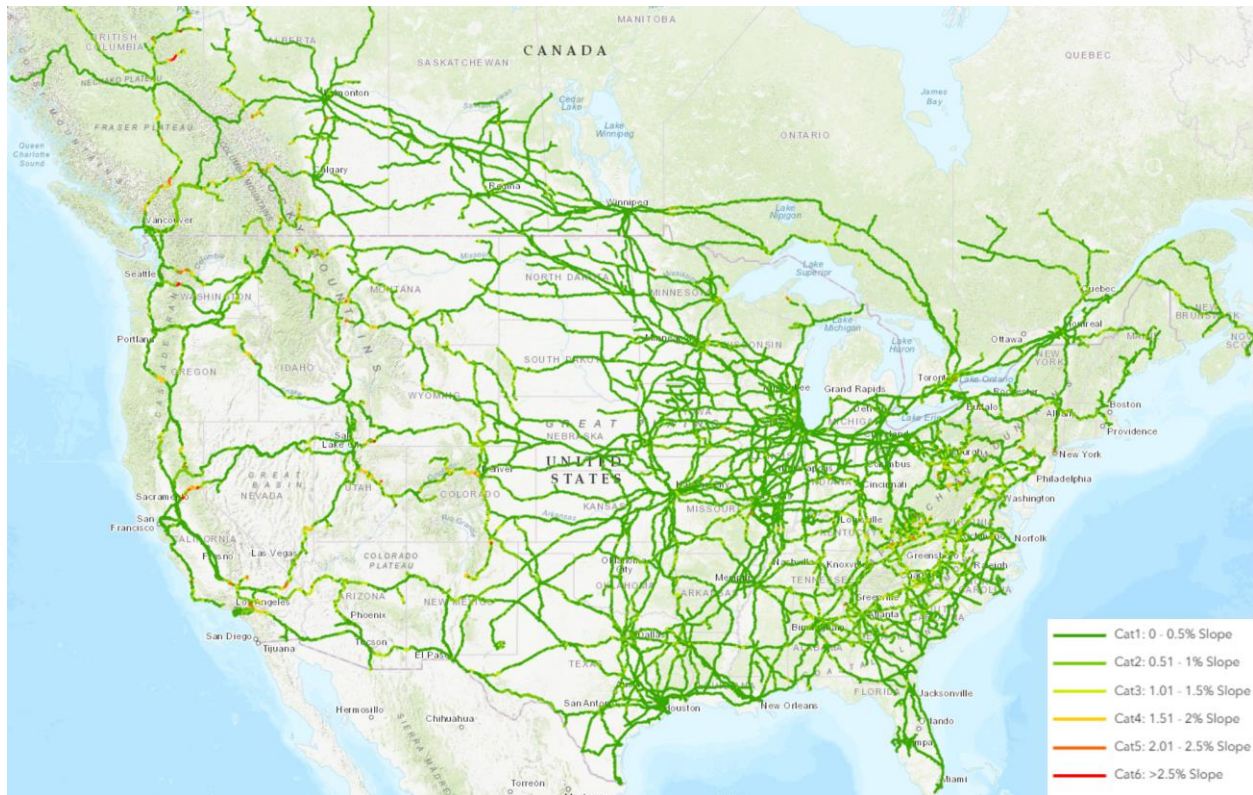


Figure 13: Map of Grades on U.S. and Canadian Network

3. Train Characteristics

Maintain Existing Train Operating Patterns

A baseline assumption is that train operating patterns for an electrified North American Class I railroad network would generally remain the same as they are today, or as expressed in the grade crossing train count data.

Alternative Train Operating Patterns

To evaluate the possibility of electrifying only part of the Class I network, while leaving other parts without catenary, an alternate operational scenario was evaluated, one in which locomotives were changed mid-trip (i.e., where catenary electric locomotives on one train were replaced with locomotives that could operate independently from catenary, such as conventional diesel-electric locomotives).

CARB studied this specific scenario and identified that changing locomotives enroute creates complexities and problems. For example, additional locomotives and crews would need to be waiting on standby for a train to arrive in order to effect the locomotive change-out. Accomplishing the locomotive change-out would also require additional track storage space, turnouts, locomotives, and staff for changing-out the locomotives at terminals. Changing the locomotives on a train would also trigger specific regulatory requirements for inspecting trains that would require additional tests and effort from crewmembers.

In addition, modern trains operate with locomotives distributed throughout the train – not just at the front of the train. This is known as distributed power, which allows the locomotive at the front of a train to remotely control locomotives distributed throughout the train via data links. When compared to a scenario where all locomotives are grouped at the front of a train, distributed power improves the way trains perform along a route and by distributing the power and braking forces along the length of a train, saves energy. Like the locomotives at the front of a train, the distributed power locomotives often operate from origin to destination, regardless of where the train begins or ends its route.

Removing locomotives from the front of a train is time consuming and complex but removing remotely controlled distributed power locomotives from the middle of a train to exchange them for electric locomotives would be an even more complicated task. At the point where locomotives were to be changed, special track configurations would be required, necessitating additional tracks and turnouts, and even more sets of locomotives and staff standing by, waiting for a train to arrive in anticipation of a locomotive change-out. Changing locomotives from the middle of a train requires uncoupling the train in the middle (where the distributed power locomotives are located) and recoupling it. This, in itself, would require additional staff standing by to exchange the distributed power locomotives, and to perform additional testing and inspection to validate that the mid-train locomotives had established data connections with the controlling locomotives at the front of the train. Overall, CARB found that changing locomotives enroute would add 1.59 to 4.29 hours of additional delay for each train at each locomotive change, with significant additional track and a large number of standby locomotives required to facilitate the locomotive exchanges.⁵⁵

Assuming implementation of catenary electrification on corridors hosting, for example, 30 trains per day, the exchange of locomotives could result in over 120 hours of operational delay each day at each exchange point. CARB found that it would result in mode shift away from railroads and towards trucks as this delay would significantly impact the supply chain. For these reasons, a partial electrification scenario was not considered.

Train Weights

Another component of the train energy usage model was train weight. To approximate train weight, AAR provide recent data for the analysis. As train operations have become more efficient, train weights have increased. A total of 8,470 gross tons, including the weight of three road locomotives, was assumed as the average train weight operating on all main lines. Note that this train weight was assumed to be representative of all trains on a given subdivision, for both directions of travel. Thus, for routes with particularly steep grades (where train weight plays an important factor in energy consumption), this may over- or under-estimate the energy consumption.

⁵⁵ California Air Resources Board, "Transitioning to a Zero or Near-Zero Emission Line Haul Freight Rail System in California: Operational and Economic Considerations, Final Report," University of Illinois and Urbana-Champaign, 2016

Train Resistance

The Davis Equation is an industry accepted approach for calculating train resistance and was used to assess the rolling resistance of trains. It accounts for rolling resistance of bearings, resistance of the track, weight of individual cars and locomotives, and other factors. While different railroad and industry organizations use slightly different formulations of the Davis equation, the AAR's formulation was selected for this Study.⁵⁶ Each formulation has undergone empirical testing – the AAR's formulation reflects updates to 2001.

The general formulation of the Davis equation is of the form:

$$R = A + (B \times v) + (C \times v^2) \quad \text{Equation 1}$$

Where:

- R = Rolling resistance
- A = Speed-independent rolling resistance, generally comprising a both a constant term and a weight-dependent term
- B = Coefficient for speed dependent term
- C = Aerodynamic coefficient, also incorporating a weight-dependent coefficient
- v = train speed in miles per hour

Train resistance is also affected by grades and curvature, with steeper uphill grades and sharper curves presenting more resistance to forward movement than level track, and descending grades generally helping to accelerate trains.

4. Energy Calculations

Scenarios Considered

The analysis considered eight scenarios, comprising combinations of track geometry (e.g., grades and curves, and whether the railroad had a single main track or a double main track), train frequency (e.g., high-density lines and low-density lines), and whether regeneration was a possibility.

The eight scenarios developed for the energy model are shown in **Table 8** below. Additional description of these parameters follows.

Table 8: Infrastructure and Train Frequency Scenarios

Number of Tracks	Scenario Grade	Considered Train Frequency	Regenerative Braking
Single	Gentle	Low	With Regeneration
Single	Gentle	Low	Without Regeneration
Single	Gentle	High	With Regeneration

⁵⁶ American Railway Engineering and Maintenance of Way Association, Manual for Railway Engineering, 2024, Ch. 16 Part 2, and W.W. Hay, Railroad Engineering, © 1982, Association of American Railroads, RP-548, 2001

Number of Tracks	Scenario Grade	Considered Train Frequency	Regenerative Braking
Single	Gentle	High	Without Regeneration
Double	Gentle	Low	With Regeneration
Double	Gentle	Low	Without Regeneration
Double	Gentle	High	With Regeneration
Double	Gentle	High	Without Regeneration

Energy of Motion

The preceding information was used in conjunction with the software analysis suite OpenTrack to develop a representation of the energy required to move the representative train over a representative geographic territory. Combinations of grades and curves were developed to represent gently graded territories, with grades of 0.5 percent or less and broad curves, and of more steeply graded territories, with grades ranging from 1.0 to 2.0 percent and sharper curves.

The energy used to move a train is affected not only by the train's rolling resistance and the resistance due to grades and curves, but also due to acceleration resulting from stops and starts. Because stopping and starting trains is dependent upon traffic levels and infrastructure capacity, additional scenarios were developed to represent single track territories, where trains would need to stop in sidings to allow opposing trains to pass, and two main track territories, where trains would stop infrequently.

Since the number of stops was a variable based on the number of tracks and the number of trains, scenarios were developed for both low train frequencies (e.g., one train every three hours each direction) and high frequencies (e.g., one train every hour each direction) for each of the infrastructure scenarios.

The output from the OpenTrack model was the amount of energy needed (at the point of application between the wheel and rail) to operate each train over the given territory for each scenario.

Electrical Energy

The mechanical energy to move the train (sometimes called "energy at the wheel") was the first part of the calculation. The second part of the calculation was to develop the electrical energy needed to move the train. This is different from energy of motion because it includes losses in the electrical distribution and conversion system and within the locomotive itself. These losses are themselves functions of the amount of energy used. The outputs were the electrical energy to move the representative train based on a given set of infrastructure and operating conditions and the energy at the substation bus bar, the feed point from the national utility grid to each substation, the differences accounting for efficiency losses. These efficiency losses, while small in relative terms are, in absolute terms, large amounts of electricity when considering an international railroad network.

5. Electrical Energy Usage

The characteristics of the electrical system play a major role in the overall efficiency. For the energy model a 2x25 kV AC distribution system was assumed as the basis for the infrastructure. By varying key parameters, such as conductor sizes, substation capacity, and substation spacing, a representative electrical infrastructure suite was developed.

The electrical energy and losses were assessed using the OpenPowerNet simulation software. This software suite has been used extensively to simulate alternating current electrification projects for European railroad electrifications, as well as for the comparatively few electrifications in the U.S. and Canada (such as Amtrak's Northeast Corridor). The software can account for different types of alternating current electrical systems and different infrastructure characteristics.

Figure 14 shows one of the outputs of the OpenPowerNet software, used for the initial substation sizing on a gentle grade, single track territory with trains operating on one-hour headways and making use of regenerative braking.

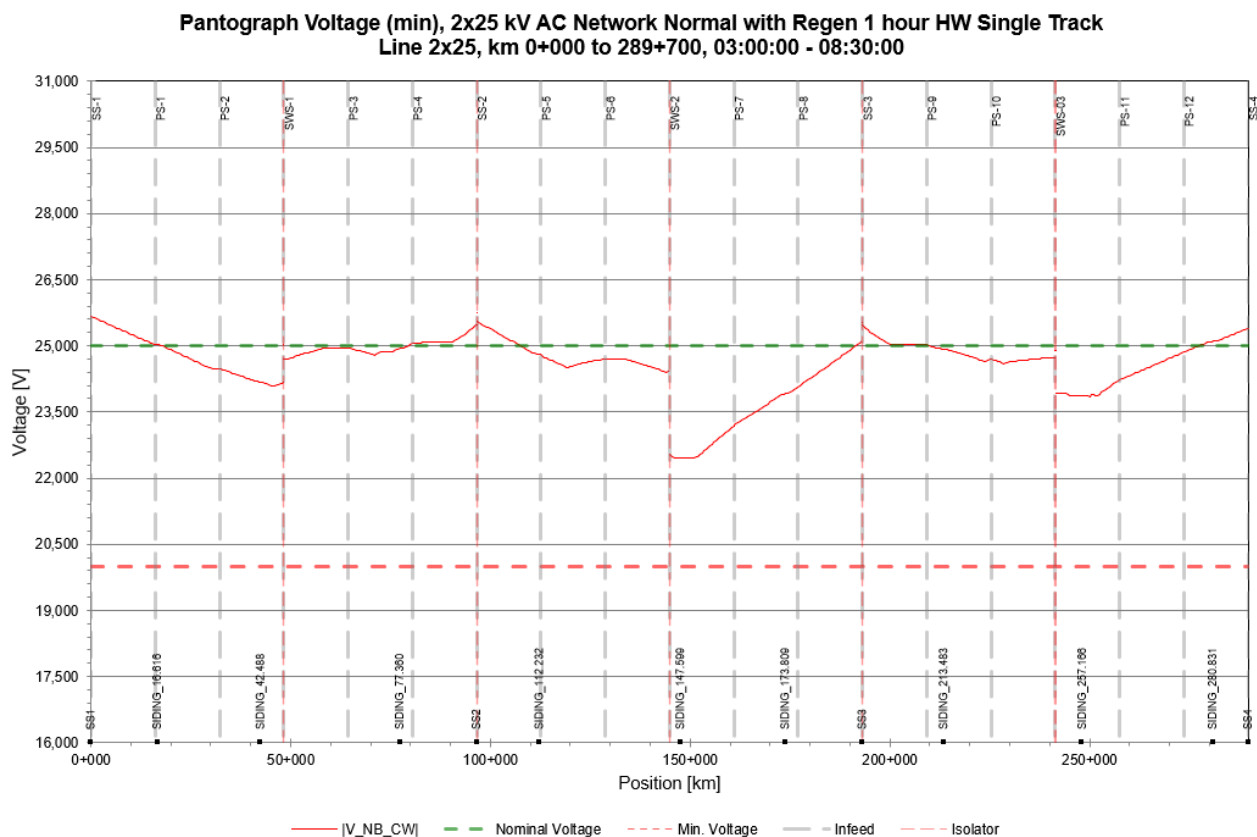


Figure 14: Pantograph Voltage Example

Potential for Regeneration

While one set of scenarios addresses only energy input to the system to power locomotives, additional scenarios were developed to account for the possibility of regenerative braking. Locomotives use electric motors to convert the energy in electricity into kinetic energy, in this case rotational energy at the wheels. The process can also work in reverse, instead

acting as alternators, the motors can turn kinetic energy at the wheels into electrical energy. The OpenPowerNet software suite can simulate the possible energy savings from regeneration.

Regeneration would occur under idealized conditions and would not always be available. Regeneration was found to play a relatively minor role for territories that had gentle grades, with the total amount of energy regenerated being as little as three percent of the total energy used under ideal conditions. This is because other losses in the system – the unavoidable frictional losses associated with heavy trains that tend to slow trains and the electrical transmission and conversion losses – would reduce the need for and efficiency of regeneration. Most of the North American Class I railroad network is comprised of track with relatively gentle grades, and regeneration plays a limited role in energy savings.

Note that electric utilities may be unwilling to accept regenerative electricity from railroads due to the randomness of regeneration, spikes in the magnitude of the regenerated energy, and the poor quality of the regenerated electricity, which typically cannot meet utility industry standards (such as supplying electricity free of harmonics) for electricity introduced onto the national electric grid. Thus, if there were no nearby train needing energy, the regenerated electricity would need to be dissipated as heat using resistor grids (referred to in the industry as dynamic braking). This would limit the actual amount of possible regeneration.

Combining Parameters

The various parameters of grades and train frequency represent eight data points, four each for the without regeneration and with regeneration scenarios. Linear interpolation was used to characterize energy usage for intermediate scenarios between established data points (or, in the case of scenarios lying outside of the established data points, linear extrapolation) such as different combinations of train frequency, grade, numbers of tracks, and whether regeneration was in use.

This information was then mapped to the GIS representation of the network, with physical characteristics (i.e., grades, train frequencies, and number of tracks) being the determinants of the energy usage.

6. Results of Train Energy Usage

The results of the train energy usage simulations are summarized in **Table 9** which illustrate, as a range, the approximate amount of electrical energy that would be used to operate trains.

The low end of the range assumes a scenario where regeneration is available to the maximum extent possible, and that only routes with six or more trains per day would be electrified. The upper end of the range assumes a scenario where regeneration is not available, and that all Class I routes are electrified (excluding light-density tracks such as industrial spurs, yard tracks). The selection of a six train per day threshold was based on miles of route compared to amount of energy used for those miles. Track with six or more trains per day represents approximately 76 percent of mileage, and approximately 95 percent of energy.

Note that the energy usage estimates do not include any contingency; these values are based solely on ranges from different operational and regenerative braking scenarios.

Table 9: Approximate Annual Energy Usage, 2024

Average Daily Energy Usage, Gigawatt-hours	Annual Energy Usage (Terawatt-hours)
114 GWh – 145 GWh	41.4 TWh – 52.7 TWh

The data for the amount of energy was then combined with average state and provincial energy costs reported by the U.S. Energy Information Administration (either the industrial cost, or, in states reporting transportation costs, the average of industrial and transportation costs) or the Canadian Centre for Energy Information (using the average selling price for “Other industries”).

C. Hybrid Locomotive Concepts

Several concepts for hybrid locomotives were evaluated to assess the possible range they could operate “off wire,” across gaps in the OCS, assuming they would pull one tender of batteries or hydrogen fuel cells for energy storage. Four axle tenders were assumed.

1. Catenary-Battery Hybrid

This scenario assumes a catenary-battery hybrid, three locomotive consist, with each locomotive pulling one battery tender (three tenders total). Each tender would have a gross weight on rail of 286,000 lbs., leaving a net capacity of 200,000 lbs. of lithium-iron-phosphate batteries remaining after the allowing for the assumed additional weight of heavy-duty structure of the tender and battery charging and conditioning equipment.

See **Table 10** for the characteristics of Catenary-Battery Hybrid locomotives.

Table 10: Catenary-Battery Hybrid Characteristics

Parameter	Value
<i>Weight of Batteries</i>	200,000 lbs. / 90,719 kg
<i>Energy Density of Batteries</i>	150 Wh/kg
<i>Maximum Energy Storage per Tender</i>	13,608 kWh
<i>Maximum Allowable Charge State</i>	90%
<i>Minimum Allowable Charge State</i>	10%
<i>Working Range (Max. Charge – Min. Charge)</i>	80%
<i>Reduction in Capacity Due to Adverse Weather</i>	15%
<i>Useable Energy Storage</i>	9,253 kWh
<i>Locomotive Energy Efficiency</i>	90%
<i>Factor of Safety for Battery Capacity</i>	1.2

The minimum energy for the average train (including three locomotives and three battery tenders) to traverse representative territory for “gently sloping terrain” (i.e., generally flat, with grades no steeper than 0.5 percent over the sample territory approximately 120 miles long, and no net elevation gain or loss between endpoints, and an average speed of approximately 50 miles per hour), would require approximately 100 kWh per train mile of energy based on the OpenTrack_OpenPowerNet model. The caveat that there would be no net elevation gain is important because it implies regeneration into the battery would be feasible. Allowing a factor of safety of additional battery capacity of 1.2, to allow for unplanned delays (during which time the locomotive batteries would need to power their own thermal management system and power auxiliaries on the locomotive, such as the air compressor, cab climate control, computers, communication equipment, etc.). The locomotive theoretically has an additional ten percent of spare battery capacity at the “bottom” of the charging range that would normally go unused, effectively increasing the factor of safety to near 1.3, resulting in a theoretical range of approximately 205 miles under best-case conditions.

However, as grades steepen, more energy would be required to move the train. For a steeply graded section with varying ascending and descending grades up to two percent, the OpenTrack_OpenPowerNet model showed energy requirements of up to approximately 300 kWh per train mile. Under these conditions, range would be decreased significantly, to approximately 70 miles.

2. Catenary-HFC Hybrid

This scenario assumes off-wire operation with a catenary-HFC hybrid locomotive consist, with each locomotive pulling one tender for hydrogen storage and fuel cells (three tenders total). In the case of compressed hydrogen, the constraint is not weight, but rather the available remaining area of the tender to hold the hydrogen tanks. For this example, it has been assumed that the tender would be 85 feet long, with 2.5 feet at each end reserved for crew walkways and switching steps, leaving an area approximately 80 feet long and ten feet wide for energy storage.

It is important to note that there are no hydrogen fuel cell locomotives in commercial production, though several Class I railroads have invested in prototypes that are undergoing testing. The following information has been developed from publicly available sources, including reports from public agencies investigating HFC passenger equipment, the DOE, and manufacturers.

See **Table 11** for characteristics of the Catenary-HFC Hybrid locomotives.

Table 11: Catenary-HFC Hybrid Characteristics

Parameter	Value
<i>Floor Area of Fuel Cell</i>	100 sq ft
<i>Floor Area for Hydrogen Tanks</i>	700 sq ft
<i>Hydrogen Tanks per Tender</i>	212

Mass of Hydrogen per Tank	10 kg
Total Mass of Hydrogen	2121 kg
Energy Density of Hydrogen (per US DOE)	37.7 kWh/kg
Maximum Energy Storage per Tender	79,970 kWh
Fuel Cell Efficiency	55%
Locomotive Energy Efficiency	90%
Available Energy for Use	118,755 kWh
Factor of Safety for Energy Storage Capacity	1.3

As with the catenary-battery hybrid, the same OpenTrack_OpenRailNet model outputs for representative gently graded sections and steeper sections were used to represent energy used per train mile. Since the energy density of hydrogen is significantly higher than that of a battery, the range for the train with three locomotives and three tenders is greater when compared to the battery tender scenario. Allowing for the factor of safety, the range on the representative gently sloping territory was approximately 900 miles, while on the steeper territory, it was approximately 300 miles.

Appendix B – Environmental Documentation and Permitting Considerations Associated with Electrification of the North American Freight Rail System

A. Key Points and Overview

1. Key Points

- Environmental documentation is the process of identifying and disclosing to the public a project's impact on the environment. While there are multiple laws in both the U.S. and Canada requiring environmental documentation, the U.S. National Environmental Policy Act (NEPA) and the Canadian Impact Assessment Act (IAA) are two key laws at the federal level.
- These processes often result in changes to a project's scope, or requirements to mitigate a project's impacts on the environment.
- The development of an environmental document for even a small project might require years, with larger, more complex projects typically requiring much more time. The environmental documentation process for the entire Class I railroad network would require many years, and potentially decades, of effort.
- In addition to environmental documentation, permits would be required for specific activities, such as work in wetlands, or impacts to endangered species. These permits typically also require years to obtain.
- The impacts of catenary electrification, including visual impacts, would essentially be continuous along railroad corridors and would require environmental analysis for the entire footprint of the U.S. and Canadian rail networks.

2. Overview

Electrifying the North American freight rail system would be a major undertaking requiring significant investment in railroad and utility delivery infrastructure, including OCS, transmission lines, distribution lines, substations. Each of these infrastructure components would have a footprint on the ground and would result in impacts to environmental resources such as endangered species, cultural or archeological resources, and wetlands. Identifying these impacts would require following established environmental documentation and permitting processes in both the U.S. and Canada. In general, these processes are highly site-specific because the nature of the work and infrastructure proposed at a particular site varies from one site to the next and because the environmental characteristics of each site, and thus the potential impacts, are unique.

Note that this section addresses only the environmental documentation and permitting for the infrastructure associated with the railroad electrification only. It does not address the environmental documentation and permitting processes that would be necessary to upgrade the power transmission systems and build more generating capacity in both the U.S. and Canada.

B. Environmental Documentation and Permitting Framework

1. Infrastructure that Could Trigger Environmental Documentation and Permitting

Installation of electrification infrastructure in the field, the OCS and TPS, would result in impacts to the environment and trigger environmental documentation and permitting processes in both the U.S. and Canada. The OCS, TPS, and associated connections to the electric grid, as well as a range of potential environmental impacts, are summarized briefly below, and in more detail in **Section V - Railroad Infrastructure for Catenary Electrification**.

OCS

The OCS is the most obvious and, from an environmental perspective, potentially the most impactful element of a large-scale railroad electrification program. Construction of the OCS would require both excavation and placement of concrete for foundations as well as overhead structural elements (poles and contact wire systems). OCS infrastructure would cover approximately 139,000 miles of track, and over four million catenary poles with associated foundation excavations would be necessary. And, as noted in **Section V.D.1 - Access Roads**, new access roads would need to be constructed, or existing access roads improved to allow OCS to be installed and maintained. The OCS and access roads would be constructed primarily within existing railroad ROW and would impact wetlands, endangered species, cultural resources, and aesthetics, among others, within the project area.

Traction Power System and Electric Grid Connections

The second major element would be the TPS, comprising traction power substations, switching stations, and paralleling stations along the railroad ROW. The TPSS would require high voltage connections to the national electrical grids in the U.S. and Canada. The TPSS are the infrastructure elements that take high-voltage electricity delivered at approximately 115 kV to 230 kV from utility transmission lines and transform it to the 25 kV voltage needed by the OCS system to power trains. Assuming that substations would be located approximately every 60 miles along each rail line, over 2,000 substations would be required.

The substations would need to be connected, via new power lines, to the electrical transmission lines comprising the national electrical grids in the U.S. and Canada. Many of these new connections could be made where an existing transmission line crosses a railroad ROW, with the railroad substations and utility high voltage switching stations located on parcels of land adjacent to the railroad ROW. However, there would be many locations where electrical power would be required from a utility, but where there is no nearby power line with sufficient capacity crossing the railroad ROW.⁵⁷ In these situations, a new electrical connection, referred to as a feeder line, typically with a voltage between 115 kV and 230 kV would need to be constructed to link the proposed railroad substation with the national electrical grid. These feeder lines would cross overland, over properties not owned by a

⁵⁷ That a given power transmission line exists near the proposed location for a railroad substation does not guarantee that the power line has adequate capacity or correct voltage to serve the electrical load created by railroad electrification. A connection may need to be established between the proposed railroad substation and a more distant power line.

railroad, potentially for several miles. Constructing these feeder line connections would require property rights over a range of different properties, such as private properties, public lands (e.g., lands owned by municipalities, states, or federal agencies like the U.S. Bureau of Land Management), and public roads.

C. Potential Regulatory and Statutory Framework for Environmental Documentation and Permitting in the U.S.

1. U.S. Federal Government Permitting Overview

Within the U.S., NEPA is the federal legislation that requires federal agencies to consider the potential environmental impacts of their proposed actions. Under NEPA, one agency is designated to lead the environmental review process and coordinate with other agencies as required.

It is assumed that a federal mandate for railroad electrification project would trigger NEPA, and the FRA or U.S. Surface Transportation Board (STB) would likely be designated as the lead federal agency. In this case the FRA or STB processes for implementing NEPA would apply unless additional laws and regulations were passed to modify the requirements of NEPA. Since different agencies have different processes for implementing NEPA, the determination of the lead federal agency is a significant step.

Briefly, the parameters of NEPA are as follows:

"NEPA requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. The range of actions covered by NEPA is broad, and includes:

- Making decisions on permit applications
- Adopting federal land management actions
- Constructing highways and other publicly owned facilities

Using the NEPA process, agencies evaluate the environmental and related social and economic effects of their proposed actions. Agencies also provide opportunities for public review and comment on those evaluations."⁵⁸

The resulting environmental documentation would consist of a Categorical Exclusion (CE), Environmental Assessment (EA), or an Environmental Impact Statement (EIS); the latter involves a higher-level analysis and provides for more public engagement compared to an EA.

Another key factor in understanding complexity of environmental documentation is the number of different environmental documents that would be required. The entire Class I railroad network could not be covered by a single environmental document, even programmatically, as the scope of work is simply too large and the process for preparing a document and receiving and addressing public comments would be too unwieldy. Instead, it is more likely that environmental documentation would be divided into multiple parts, likely as individual phases of work along each Class I railroad. Each segment or phase of

⁵⁸ U.S. Environmental Protection Agency, accessed on October 28, 2024, at: <https://www.epa.gov/nepa/what-national-environmental-policy-act>

work would require its own separate environmental document that would need to be completed prior to initiating construction work in that segment.

2. Examples of Approvals and Permits Required

A wide range of federal laws and regulations would apply to railroad electrification. While there are numerous potential federal regulations, **Table 12** identifies some of the major laws, approvals, and permits that would be associated with a railroad electrification and pose the most challenges to schedule, cost, and design considerations, as well as the elements of the electrification infrastructure that might trigger the specific permit or approval.

As noted, NEPA is the key law that requires identification and disclosure of impacts, and sets guidelines for avoiding, minimizing, or mitigating for those impacts. While the NEPA process results in a certified environmental document, it does not result in a specific permit. There are other laws and regulations, such as the Clean Water Act and Endangered Species Act, which requires project proponents to undertake additional environmental documentation processes prior to issuing permits to affect the relevant resources.

Table 12: Examples of Approvals and Permits Required in the U.S.

Permit/ Approval	Authorizing Agency	Permit Trigger	Applicable to Electrification
National Environmental Policy Act (NEPA) (42 USC 4321; 40 CFR 1500-1508)	Lead federal agency (likely the FRA)	Any federal permit or federal approval would trigger NEPA; siting work on federal lands; accessing federally owned transmission system; receipt of federal grants or funds. For electrification, federal funding or oversight designated by Congress would trigger NEPA.	Federal funding or oversight designated by Congress would trigger NEPA.
Rivers and Harbors Act of 1899, Section 14 (Section 408) (33 USC 408)	U.S. Army Corps of Engineers (USACE)	Modification of a USACE-authorized project, including modification of USACE-authorized flood reduction projects, such a levee system including its interior drainage system.	Installation of catenary/electrification equipment on or across a levee could result in additional engineering analysis, coordination, and permitting with affected USACE Districts and local governing bodies.
Rivers and Harbors Act of 1899, Section 10 (33 USC 403; 33 CFR Part 322)	USACE	Work in or over navigable water, including transmission or electrical lines.	Placement of transmission or electrical lines over a navigable waterway may require authorization under Section 10.

Permit/ Approval	Authorizing Agency	Permit Trigger	Applicable to Electrification
Clean Water Act Section 404 (33 USC. 1251 et seq and 33 USC 1344; 33 CFR 320-331 and 40 CFR 230)	USACE	Discharge of dredged or fill material in Waters of the U.S. (WOTUS).	While much (but not all) OCS equipment could likely avoid WOTUS, substations or access roads would likely affect WOTUS. Where electrification infrastructure cannot avoid WOTUS then a Clean Water Act Section 404 permit may be required.
Clean Water Act Section 401 - Water Quality Certification (33 U.S.C. 1341(a)(2))	State agency	Applying for a CWA Section 404 permit or for an activity that might result in discharge into jurisdictional waters to ensure water quality is maintained from the impact to WOTUS.	Required as part of the CWA Section 404 permit process. State specific requirements affecting design or construction could be imposed by 48 different state agencies in the contiguous U.S.
Federal Endangered Species Act (ESA) (16 USC 1531-1544)	U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS)	Any federal agency issuing a permit or an approval must comply with the federal ESA under Section 7. Actions undertaken in the absence of a federal nexus must comply under Section 10 of the ESA if listed species are present or potentially present in the project area. The ESA applies to public and private land and activities.	Since listed species exist throughout the U.S., ESA compliance considerations would be required regardless of a federal nexus for the activities. Timing restrictions for in-water work or tree clearing may be imposed as part of the consultation.
Bald and Golden Eagle Protection Act (50 CFR §§ 13, 22 Eagle Permits)	USFWS	Construction and operation of a facility within 660 feet of a bald or golden eagle nest.	If infrastructure improvements are within 660 feet of an observed nest a disturbance permit would be required and may result in time of year restrictions for construction and maintenance near the nest.
National Historic Preservation Act (NHPA), Section 106 (16 USC 470; 36 CFR 60 and 800)	State Historic Preservation Office (SHPO)	Projects receiving federal funding, license, or permit requiring review for cultural resources. The Rail Program Comment applies to historic properties within the ROW and disturbed areas within the ROW that have not been identified as an archeological resource. Activities outside the ROW, known archaeological sites, and undisturbed areas in the ROW are not covered by the Program Comment.	Coordination would be required with multiple State Historic Preservation Offices (SHPO) and Tribal Historic Preservation Offices (THPO) regarding the application of the Rail Program Comment. Installation of OCS, which involves significant below-grade disruption/installation in undisturbed areas, and any work outside the ROW, such as construction of the high voltage switching stations by the electric power utilities, would not be covered by the Program Comment and would

Permit/ Approval	Authorizing Agency	Permit Trigger	Applicable to Electrification
		<p>Programmatic agreements (PA) are the most commonly used program alternative for large, complex projects and may be an option for this program. A program that has undertakings with similar or repetitive effects on historic properties can avoid the need for individual reviews for each project. PAs can also formally delegate Section 106 decision making responsibilities to non-federal parties, such as state departments of transportation.</p>	<p>require coordination through 50+ SHPO/THPOs, leading to numerous interpretations and stipulations. Multiple rail lines pass through sovereign tribal lands. Even if the railroads own the ROW through the lands, sovereign nations typically manage the energy/grid systems.</p>
<p>Section 4(f) of the U.S. Department of Transportation Act (23 CFR 774)</p>	<p>Lead federal USDOT agency (likely the FRA)</p>	<p>Protects publicly owned parks, recreational areas, wildlife and waterfowl refuges, and historic sites from being used for transportation projects without meeting certain conditions.</p>	<p>Catenary is visibly obtrusive and not congruous with natural environments. This could lead to significant visual impacts, especially to sensitive areas such as national parks, state parks, and other designated scenic corridors. Visual impacts are typically challenging to mitigate and equate to “use.” Under Section 4(f) must be avoided if feasible and prudent.</p>
<p>Migratory Bird Treaty Act of 1918 (16 USC 703-712)</p>		<p>The Migratory Bird Treaty Act prohibits take (including killing, capturing, selling, trading, and transport) of protected migratory bird species. An approval or permit is not issued but compliance in the form of timing restrictions for construction are mandated under the Act.</p>	<p>The installation of OCS energized at 25 kV, as well as new power transmission lines energized at over 115 kV feeding railroad substations, present a hazard to protected migratory bird species.</p>

While the above table identifies regulatory requirements that would affect implementation of railroad electrification, a critical point for regulatory permitting is whether a federal nexus would be based on the possibility of federal funding, or mandated as congressional oversight. This could be similar to the development and implementation of Positive Train Control (PTC), discussed below, where the FRA was given oversight responsibilities, with other federal agencies (such as the Federal Communications Commission (FCC)) having regulatory authority over certain infrastructure requirements.

3. Ability to Use Preemption

Many states have their own statutes and regulations pertaining to environmental protection and documentation. It is possible that some of these would be preempted under 49 USC 10501 for activities at railroad facilities or within the railroad ROW. For example, California and

Washington have state analogs to NEPA, the California Environmental Quality Act and the Washington State Environmental Policy Act, respectively.

Within the U.S., railroads are generally exempt from state and local permitting on their own facilities and ROW.⁵⁹ It is assumed that these state environmental requirements would be preempted and would not affect activities occurring within the railroad ROW.

If preemption is not applicable, then state and local regulations would be required for the proposed work; this could lead to conflicting interpretations or standards for design, construction, and maintenance.

With preemption in place, states and localities are generally able to exercise regulatory authority over railroads with respect to safety considerations. Of particular interest with respect to railroad electrification would be the authority of the state public utility commissions regulatory authority over power line clearances, voltages, and design considerations. It is conceivable that a patchwork of different state regulations pertaining to electrical construction would need to be reconciled in order to provide a standard for railroad OCS construction.⁶⁰

Also note that preemption would possibly not apply to new electrical connections established between railroad substations and existing transmission lines. These are essentially “new customer” connections, would be located outside of the railroad’s facilities and ROW, and would likely need to be constructed under the authority of the respective state public utility commissions related to acquisition of ROW and easements, road crossings, etc. In some cases, condemnation proceedings may be required to obtain the necessary ROW or easements for these new feeder lines. Additionally, new substations and feeder lines may trigger additional state processes regulated by state energy boards/councils. These are not present in all states, but many have requirements and processes similar to NEPA.

4. Previous Industry Experience with Positive Train Control

Positive Train Control (PTC) was a nationwide mandate that required new infrastructure construction along most Class I railroad corridors. While not perfectly analogous to the scope of electrification, the manner in which the PTC program was implemented provides some context for the implementation of a nationwide suite of railroad infrastructure.

⁵⁹ Per 49 US Code §10501(b), “The jurisdiction of the US Surface Transportation Board over... the construction, acquisition, operation, abandonment, or discontinuance of spur, industrial, team, switching, or side tracks, or facilities, even if the tracks are located, or intended to be located, entirely in one state, ...is exclusive. Except as otherwise provided in this part, the remedies provided under this part with respect to regulation of rail transportation are exclusive and preempt the remedies provided under federal or state law.”

⁶⁰ In California, for example, California Public Utility Commission (CPUC) General Order 95, regulates, among other things, power line design, construction, and minimum safety clearances. CPUC undertook a lengthy, multi-year process of modification and supplementation of their regulations to account for the different (generally reduced) clearances needed for 25 kV railroad electrification for the California High Speed Rail Authority and Caltrain projects. Other states that have similar safety regulations, but which have not yet contemplated the unique characteristics of railroad electrification, would presumably need to undertake similar rulemaking activities.

The Rail Safety Improvement Act of 2008 (RSIA) mandated installation of PTC across a significant portion of the Class I main line network. Implementing PTC required upgrades to portions of railroad signal systems, new communications equipment, significant investments in hardware for locomotives, design of entirely new back-office data management systems,

While the PTC system involved tens of thousands of radio towers, each of which triggered the possibility of environmental review, railroad electrification would require literally millions of catenary support poles and foundations – orders of magnitude more infrastructure and more potential impacts – that would be subject to the environmental documentation and permitting process.

and dispatching system upgrades. The new communications equipment included radio towers (used for data transmission) that were installed in the field, adjacent to many existing railroad signal locations along the Class I network. While the network architecture varied depending upon railroad and site conditions, it is estimated that Class I railroads installed approximately 35,000 PTC radio towers around their systems.⁶¹

The new radio towers were the major component of the PTC system that required environmental documentation. These towers had underground foundations up to 15 feet deep and construction methods that were somewhat similar to those of the foundations that would be needed for a catenary electrification system. The FCC was the lead agency for environmental review of this work and required compliance with NEPA and NHPA, and, in particular, Section 106 of the NHPA, which requires consultation with SHPO and Tribal Officials.⁶²

Due to the scope of the PTC work, the Advisory Council on Historic Preservation (ACHP) issued a “Program Comment” that, in some circumstances, provided the FCC with a somewhat more streamlined process for compliance with Section 106. However, each individual tower needed to be assessed for compliance with the Program Comment or an alternate mechanism for compliance, and notification to SHPOs and THPOs was still required. As a result, SHPOs and THPOs had the opportunity to comment on any specific PTC tower or group of towers. Because there were a discrete number of PTC towers with potential environmental impacts only at specific points along railroad corridors, a database,

⁶¹ Advisory Council on Historic Preservation, “Program Comment to Tailor the Federal Communications Commission’s Section 106 Review for Undertakings Involving the Construction of Positive Train Control Wayside Poles and Infrastructure”, accessed on October 28, 2024 at: https://www.achp.gov/sites/default/files/program_comments/2018-07/Positive%20Train%20Control%20Program%20Comment.pdf

⁶² “The federal agency implementing the project or providing assistance, licenses, permits, or approvals for a proposed project is responsible for consulting with stakeholders and completing Section 106 prior to making a final decision. Consultation is the cornerstone of the Section 106 process and should be initiated in the early stages of project planning. Agencies work closely with state and Tribal officials in Section 106 reviews. Appointed by each state governor, the SHPO coordinates the state’s historic preservation program and consults with agencies during Section 106 review. Agencies also consult with federally recognized Indian Tribes and Native Hawaiian Organizations (NHOs) when historic properties of religious and cultural significance to them are involved.”, Advisory Council on Historic Preservation, “Section 106 Review”, accessed on October 28, 2024 at https://www.achp.gov/sites/default/files/whitepapers/2024-10/2024_Section%20106_Final.pdf

the Tower Construction Notification System (TCNS), was established to notify all affected parties of the proposed locations for PTC towers.

Experience through the PTC program demonstrates that, even with the expedited process, the installation of some 35,000 PTC radio towers resulted in a significant amount of environmental documentation. Although the PTC program was initiated in 2008, environmental documentation for individual towers (such as new towers) continues as this document is written, in 2024, since every new tower constructed still requires evaluation for its potential effects on the environment. This is illustrative in terms of the scope of environmental documentation needed for an electrification program.

A key distinction between the environmental process used for PTC and the process that would need to be followed (or established) for an electrification program is the physical footprint and potential environmental impacts of an electrification system. Whereas PTC installed towers only at discrete locations and allowed for use of the TCNS for those specific locations, a railroad electrification program would install catenary poles every few hundred feet along one or both sides of the railroad ROW, along with access roads, substations, etc. An electrification effort would be several orders of magnitude larger than the PTC program.

5. Timeline for Environmental Documentation and Permitting in the U.S.

The environmental documentation and permitting process for the entire Class I network in the U.S. would be lengthy, requiring years or possibly decades based on existing regulations and processes. A conceptual timeline for a sample corridor, comprising approximately 1,000 miles of ROW, over 30,000 catenary poles and foundations, and approximately 35 new substations, with new transmission line interconnections, would take several years to prepare environmental documentation and permits based on current policies. Even the baseline resource studies (which in some cases can be performed only during certain timeframes during the year) for a 1,000-mile-long corridor would take a year or more to complete based on the very large project footprint. Impacts on historic, archaeological, and cultural resources; wetlands; endangered species; migratory birds, and a host of other resource categories, would be inevitable, requiring consultation with other agencies, complicating and lengthening the documentation and permitting effort.

In 2020, the Council on Environmental Quality (CEQ), an advisory council created by NEPA and residing in the U.S. Executive Branch, reported on recent timelines and document length for Environmental Impact Statements under NEPA. For the years 2010 to 2018, the average time for the FRA to complete an EIS was 5.16 years, with average document length of 517 pages.⁶³

It is important to note that the approximate five-year timeline was an average of previous environmental documents, with some documents requiring less time, and other documents requiring more time. Complex environmental documents could require substantially more time than the average. Railroad electrification would be a complex document and would be expected to require more time. As an example of a large corridor project, the environmental

⁶³ Council on Environmental Quality, accessed on October 30, 2024 at: <https://ceq.doe.gov/nepa-practice/eis-timelines.html> and https://ceq.doe.gov/docs/nepa-practice/CEQ_EIS_Length_Report_2020-6-12.pdf

documentation for the California High Speed Rail Authority's (CHSRA) project to construct a new railroad, approximately 500 miles long linking northern and southern California, required over a decade to complete.⁶⁴ While CHSRA's project required a significantly larger footprint (because it was mostly on newly acquired, greenfield ROW), the same process for conducting baseline studies and assessing and documenting impacts would apply to a railroad electrification project on existing railroad corridors.

In July 2024, CEQ's Bipartisan Permitting Reform Implementation Rule went into effect⁶⁵, which includes maximum timelines to complete the NEPA process and establishes two years from Notice of Intent to ROD for an EIS and one year for an EA. With this in place, agency timelines may be reduced from the average 5.16 years noted above. However, there are still activities that would need to be completed before this "official clock" starts (such as baseline studies and conceptual engineering) that would mean the actual timelines would extend well past two years for the full process. In addition, there are situations where environmental review for a long corridor would be broken-down into shorter sections, each with its own EIS, possibly proceeding sequentially, rather than in parallel, meaning that the documentation for a long corridor might take substantially longer than two years. As this permitting reform has only just taken effect, the actual reduction in duration for environmental documentation times has yet to be seen.

Also note that, although an EIS (or EA) for an individual segment of electrification that is not environmentally complex might be completed within the average timeframe or the new guidelines, environmental documentation for electrification of the entire U.S. Class I railroad network, likely comprising dozens (or hundreds) of individual environmental documents, would likely require a substantially longer time, and some documentation would by necessity, need to occur sequentially.

It is also possible that there would be legal challenges (for reasons such as applicability of preemption, visual impacts, construction impacts, adequacy of environmental documentation that was performed, ROW takings, etc.) in multiple jurisdictions. These could require additional years to resolve, further delaying implementation.

D. Potential Regulatory and Statutory Framework for Environmental Documentation and Permitting in Canada

There are numerous environmental regulatory considerations associated with the development of freight rail electrification infrastructure within Canada. The focus of the following discussion is on the environmental permitting regulatory requirements for the OCS and electrical connections between the national electrical grid and the railroad substations.

⁶⁴ California High Speed Rail Authority, accessed on October 30, 2024 at: <https://hsr.ca.gov/programs/environmental-planning/>

⁶⁵ Council on Environmental Quality Federal Register, accessed on November 1, 2024 at: <https://www.federalregister.gov/documents/2024/05/01/2024-08792/national-environmental-policy-act-implementing-regulations-revisions-phase-2>

Given the wide range of options of how the OCS and traction power system and electric grid connections are designed and constructed, environmental documentation and permitting may include a combination of:

- Federal environmental assessment(s) under the *Impact Assessment Act* (IAA).
- Provincial review and permitting required for work outside the railroad ROW.
- In some instances, it is possible that no permits would be required as long as all Federal Acts and best management practices are adhered to for work within the ROW on federal lands.

A detailed analysis would be required to understand the specific permitting needs for each specific proponent or project, location, province, environmental and social needs. Power delivery and rail infrastructure in Canada requires levels of provincial and federal regulatory permitting, with environmental assessment approvals requiring coordination between multiple regulatory jurisdictions. Development of transmission lines, electrification infrastructure, and rail infrastructure usually requires the validation of the need for the line, as well as a high-level reviews of engineering, land use, socio-economic, and environmental constraints. An overall, nationwide program of electrification would likely not be reviewed as a singular "Project" of freight rail electrification; each Class I railroad would be required to undergo their own permitting process.

The electrification of infrastructure within Canada can be assumed to require multiple environmental assessments (federal and/or provincial levels), with the required infrastructure of and for each power company and railroad being reviewed individually as a Project. Further complications of jurisdiction of land ownership can trigger differing levels of federal or provincial permitting, First Nations land use agreements/sharing, and consultations. The environmental permitting pathways would be connected to land ownership, jurisdiction, the components of the Project (size, structures, and processes) and the environmental and social settings.

1. Canadian Federal Government Permitting Overview

Within Canada the IAA came into force on August 28, 2019, creating the new Impact Assessment Agency of Canada and repealing the *Canadian Environmental Assessment Act* (CEAA) 2012. Projects that are subject to IAA include designated projects described in the Physical Activities Regulations ("Project List") or other projects that the Minister may designate, based on factors set in the legislation.

It is important to note that on June 20, 2024, the Budget Implementation Act, 2024, received Royal Assent and brought into force amendments to the IAA. These changes were made in response to the Supreme Court of Canada's 2023 decision on the constitutionality of the IAA. As such the IAA procedures, policy and guidance documents are still being updated to reflect these legislative changes.

Electrifying the Canadian freight rail system could fall under several of the triggers of designated projects within the Physical Activities Regulations of the IAA. There are two types of project-level impact assessments for designated projects: those led by the Agency and those led by an independent review panel. Both types are also supported by other federal departments and agencies, which are required to provide their specific expertise for project

assessments, including scientific expertise about potential effects. The Act also includes provisions for regional and strategic assessments, including with Provinces. While the Government of Canada outlines "one project, one assessment" in impact assessment with cooperation and coordinated action between jurisdictions, the federal government still makes the final decision on whether the project is in the public interest based on the Minister's recommendations following an analysis of the impact assessment report and all other relevant information obtained during the impact assessment process, and the Minister still issues a decision statement with enforceable conditions.

The triggers for designated projects within the Physical Activities Regulations of the IAA can vary for each proponent that would be involved with electrifying the Canadian freight rail system, in terms of location, size thresholds and/or exemption criteria. Within the Physical Activities Regulations (commonly known as the Project List), the following may trigger, or be used in part by the Minister to trigger, the IAA process:

- For areas within Canadian National Parks and Protected Areas, the construction, operation, decommissioning and abandonment in a wildlife area, as defined in section 2 of the Wildlife Area Regulations, a migratory bird sanctuary, as defined in subsection 2(1) of the Migratory Bird Sanctuary Regulations or a protected marine area established under subsection 4.1(1) of the Canada Wildlife Act, of a new electrical generating facility or electrical transmission line or a new railroad line.
- For the construction, on land that is managed or administered by the Parks Canada Agency, of a new physical work, if the construction is contrary to the management plan for that land that is tabled in each House of Parliament under subsection 32(1) of the Parks Canada Agency Act, subsection 11(1) of the Canada National Parks Act, or subsection 9(1) of the Rouge National Urban Park Act, or to a similar plan for the land that is approved by the Minister responsible for the Parks Canada Agency.
- The construction, operation, decommissioning and abandonment, in a national park, of a new railroad line.
- The construction, operation, decommissioning and abandonment of either of a new international electrical transmission line with a voltage of 345 kV or more that requires a total of 75 kilometers (km) or more of new ROW or a new interprovincial power line designated by an order under section 261 of the Canadian Energy Regulator Act.
- The construction, operation, decommissioning and abandonment of either of the following a new railroad line that is capable of carrying freight or of carrying passengers between cities and requires a total of 50 km or more of new ROW, or a new railroad yard with a total area of 50 hectares (ha) or more, or the expansion of an existing railroad yard, if the expansion would result in an increase of its total area by 50 percent or more and a total area of 50 ha or more.

Given that there would be thousands of miles of OCS along the Class I main lines in Canada crossing provinces, new acquisition of ROW land for substations and electrical connection may be needed (including within Federal National Parks), and an increase in the overall footprint of the ROW that may exceed the 50 km and or 50 ha thresholds, several of the above Physical Activities Regulations could be, or are close to being, triggered.

It can be assumed that the components of the Project that meet the descriptions of the above triggers, combined with the Minister's ability to designate any project not described in

regulations to undergo the IAA process, would require at a minimum an Initial Project Description that includes the information prescribed by regulations.

If the Initial Project Description conforms with the Project List and regulations, the federal Impact Assessment Agency of Canada (the Agency) would work with the provincial governments, other federal departments/agencies, the public, and Indigenous groups in the planning phase to prepare a summary of issues for a possible impact assessment. Depending on the size, location, impacts of the works, environmental and social considerations, there may be individual projects within a larger program of electrification of the Canadian freight rail system that do trigger a full Impact Assessment, and those that do not trigger one at all.

If the Agency determines an Impact Assessment is required, they provide Tailored Impact Statement Guidelines specifically for a Project. Proponents use these guidelines to identify and assesses the impacts of the Project, along with the measures proposed to mitigate those effects, in the creation of an Impact Statement submission. The Agency leads a coordinated review amongst departments and other jurisdictions such as the provinces, of the Impact Statement and issues the Decision Statement with their reasons for the determination and conditions.

From conducting the environmental baselines and assessments needed to write and prepare an IAA Impact Assessment to the determination, typically takes three to five years for the full process given the timelines listed above of 180 days and 300 days for the government review alone.

2. Examples of Approvals and Permits Required

Within the IAA assessment process there are several primary Federal Departments and Agencies with associated environmental regulations that grant authorization and or permits that may be required for new infrastructure projects. Examples include, but are not limited to, the list below:

- Fisheries Act.
- Species at Risk Act.
- Migratory Birds Convention Act.
- Canada Wildlife Act.
- Canadian Environmental Protection Act.

Examples of additional permits and approvals required are shown in **Table 13**.

Table 13: Examples of Approvals and Permits Required in the Canada

Federal Act	Federal Authorizing Agency/Department	Project Relevance	Applicable to Electrification
<p><i>Impact Assessment Act (IAA)</i> (S.C. 2019, c. 28, s. 1)</p>	<p>Impact Assessment Agency of Canada</p>	<p>The Agency and Act would be the federally governing body and process leading any federal impact assessments for the Project.</p>	<p>Physical components, construction works, and access, would be governed by the <i>Impact Assessment Act</i> and may require a federal impact assessment and decision statement. Physical Activities as defined in the text above (commonly known as the Project List), may trigger, or be used in part by the Minister to trigger, the IAA process.</p> <p>The Acts and Authorizing Agencies below, would also be involved within the coordinated IAA process.</p>
<p>Fisheries Act</p>	<p>Fisheries and Oceans Canada (DFO)</p>	<p>The <i>Fisheries Act</i>, and subsequent Regulations made under the Act, defines DFO’s responsibility for the conservation and protection of fish and fish habitat including preventing pollution, the management of fisheries and the protections of fisheries waters in Canada.</p>	<p>Given that fish species and fish habitat exists throughout Canada, compliance considerations with the <i>Fisheries Act</i> and/or <i>Fisheries Act</i> Authorizations, and/or Letters of Advice would be required for all physical components, construction works, and access that may impact fish or fish habitat or cause the death of fish, such as construction or access roads that could affect fish habitat. This analysis would also be part of the coordinated IAA process.</p>
<p>Species at Risk Act (S.C. 2002, c. 29)</p>	<p>Environment and Climate Change Canada Fisheries and Oceans Canada</p>	<p>The Species at Risk Act (SARA) provides legal protection of wildlife species and their habitat. A SARA permit can be issues under Section 73 of SARA, to authorize a proponent to engage in an activity affecting a listed wildlife species, and any part of critical habitat or residence.</p>	<p>Given that SARA species exist throughout Canada, compliance considerations with SARA, and permits where compliance is not possible, would be required as a result of construction activities, particularly for the OCS system. This analysis would also be part of the coordinated IAA process.</p>
<p>Migratory Birds Convention Act, 1994 (MBCA)</p>	<p>Environment and Climate Change Canada</p>	<p>Migratory birds in Canada are protected under the <i>Migratory Birds Convention Act, 1994</i> (MBCA).</p>	<p>Given that migratory bird species and their habitat exists throughout Canada, compliance</p>

Federal Act	Federal Authorizing Agency/Department	Project Relevance	Applicable to Electrification
		Together with the Migratory Birds Regulations (C.R.C., c. 1035)] and the Migratory Birds Convention between Canada and the USA, included migratory birds and their habitat are protected. Other bird species would fall under the relevant Wildlife Acts of the provinces and territories.	with the Act is required for all physical components, construction works, and access that may impact migratory birds, such as construction of the OCS and new power line connections. This analysis would also be part of the coordinated IAA process.
Canada Wildlife Act (R.S.C., 1985, c. W-9)	Environment and Climate Change Canada	The Wildlife Area Regulations allows for permits to be issued for activities that would otherwise contravene the Act with activities that could be harmful to species and to their habitat. The Canada Wildlife Act is responsible for wildlife areas in Canada, including the creation, management, and protection of the areas.	Portions of Class I railroads that pass through National Wildlife Areas in Canada would require review and/or permitting under the Canada Wildlife Act (R.S.C., 1985, c. W-9). This analysis would also be part of the coordinated IAA process.
Canadian Environmental Protection Act, 1999 (S.C. 1999, c. 33) (CEPA)	Environment and Climate Change Canada	The Act is responsible for pollution prevention and the protection of the environment and human health. Compliance with the Act would be required during construction and throughout the lifetime of the rail.	CEPA permits are not anticipated to be required. Railroad electrification would be presumed at a high level to adhere to the Act. This analysis would also be part of the coordinated IAA process.

If a full impact Assessment is not required, the above Acts would still apply and permits and authorizations would be required through individual Acts and the Federal Government departments and or agencies that enforce those acts. For example, a permit is required to conduct an activity, such as construction access through wetland habitat, which could affect a wildlife species at risk listed on schedule 1 of the Species at Risk Act (SARA) as extirpated, endangered, or threatened, its residence or any part of its critical habitat. Individual authorizations from the Federal Government departments and or agencies that enforce those acts can take anywhere from two months to two years to obtain depending on complexity of the works and environmental requirements.

Work which relates to the core of the federal jurisdiction over railroads (such as the structure of the undertaking of the construction, repair, alteration, and management of the railroad), generally do not require provincial permits. Any components that fall outside the ROW limits, go beyond the core of the federal jurisdiction over railroads, or require the use of private or Provincial Crown lands may trigger provincial permits even if they are part of the same Project and proponent. It is possible that a combination of provincial permitting with specific Federal permits may be obtained if the full Impact Assessment is not required.

3. Canadian Provincial Government Permitting

Components of an electrification program on non-federal lands outside of railroad ROW limits can be subject to Provincial permitting processes if they were to trigger a specific province's permit applications or environmental assessment processes. Provincial governments would also participate in the IAA assessment process administered by the federal government.

Because each Province and Territory has their own discrete environmental permitting and environmental assessment process and relevant Acts, it is possible that the development of freight rail electrification infrastructure may trigger permitting in some provinces, but not in others. Timelines for provincial permitting can vary from two weeks for straightforward permits to several years for more complex environmental assessments. The effort could involve provincial-level environmental assessments or impact statements (in addition to federal documentation) as well as provincial permitting.

Appendix C – Key Cost Assumptions

A. Introduction

This Appendix summarizes a range of rough order of magnitude costs for installing catenary electrification (OCS and TPS) on the Class I freight railroad network in the U.S. and Canada, including up to 139,000 miles of track, depending upon scenario. This includes sidings and major branch lines, but excludes tracks in yards, spur tracks, and industrial lead tracks.

This conceptual estimate assumes that catenary-electric locomotives would be equipped with a small on-board battery with sufficient energy to move the locomotive and train several miles, across short gaps in the OCS. This means that overhead infrastructure that might otherwise be too low to accommodate energized OCS (e.g., overpasses, through truss bridges, tunnels, inside customer facilities etc.) could remain, largely unmodified, with significant cost savings. Similarly, in this scenario, locomotives could operate into yard receiving and departure tracks without the need for OCS.

This Appendix is organized by categories of costs organized by items that are estimated by Track Mile, Centerline Mile (Route), Cost per Each (or Location), Additional Costs for Right-of-Way Modifications, Environmental Costs, and Locomotive Costs. This estimate focuses on costs that were significant contributors to overall capital costs.

This Appendix also includes an assessment of the conceptual staffing levels and energy costs needed to operate and maintain the OCS and TPS.

This Appendix also highlights other factors that can influence costs, such as corridor occupancy, replacement costs, and skilled labor.

B. Approach to Developing Costs

This Study assumed that Class I railroads would implement the program, including developing designs and environmental documentation, constructing OCS and TPS systems, procuring the motive power fleet, training and developing staff, etc. This means that costs would not be affected by domestic preference laws.

It is important to note that complexities of individual corridors or locations can have an outsized effect on the ultimate cost. For example, soil conditions directly affect the expense of installing catenary pole foundations (as discussed in **Section V.B.1 - Foundations**); however, soil conditions vary across the continent, from soft soils where foundations would be easy to install, to rocky conditions where the premium expenses of hard rock excavation methods would significantly increase the cost of foundation installation. The difficulties of constructing infrastructure adjacent to an operating railroad, where construction access is dependent upon the amount of rail traffic, are another area of uncertainty. While allowances have been made for these and other site-specific considerations, additional, more detailed study would be required to refine costs for any specific geographic area. To address such uncertainties, a 50 percent contingency has been applied to all costs.

C. Costs per Track Mile

1. Overhead Contact System (OCS) for a Single Track

Elements for OCS would include but not be limited to:

- Pole and foundations spaced at an average interval of 175 feet along main tracks and sidings.
- Drilled pier foundations (with a rebar cage), assumed to be 3 feet in diameter by 15 feet deep (these dimensions were based on recent examples; detailed design was not performed).
- The poles are assumed to be approximately 35-foot tall I-beams with insulators, cantilever assemblies to support the contact and messenger wire, supports, and bonds/grounds.
- 300MCM OCS contact wire.
- ACSR (aluminum conductor steel reinforced) messenger wire, and hangers.
- 556 MCM ACSR negative feeder wire.
- 4/0 Static Wire.
- Auto-tensioning system.
- Phase break switches.
- Survey.
- Tree clearing and vegetation removal.
- Access road construction and/or improvements.

Labor hours for OCS installation on high-density lines can be twice those of lower density lines due to the need to stop work for trains. The Study defined high-density lines as having more than 12 trains per day (TPD) on a single-track route and more than 22 TPD on a double track route.

High cost of living areas (like urbanized centers along the coasts and in major cities) are also a factor and can increase construction costs when compared to standard construction costs. The U.S. Department of Defense (DOD) Area Cost Factors were used to determine which states were considered “high cost.” All track miles within each of these states was considered to be high cost when the DOD Area Cost Factor exceeded 1.05.

Base OCS costs for areas where construction would be simple and there would be only minimal interruptions from trains would be on the order of \$2.5 million per track mile. With contingency, the cost would increase to \$3.8 million per track mile.

On routes with extremely high train traffic, over 26 trains per day for single track or 48 trains per day for double track, an additional 20 percent was added to the cost due to reduced construction productivity. In urban areas, where obstructions (such as utilities and other buried infrastructure) could be more frequent and ROW tends to be more constrained, foundation installation could be more difficult and an additional \$200,000 per track mile was added to the cost. These costs would be in addition to the base cost.

The result of these additions would be a range of costs, from the base OCS cost in areas where construction costs would be lowest to the cost along corridors with both many trains and in urban areas, where construction costs would be highest. This range would be approximately \$3.8 million to \$4.7 million per track mile, including contingencies.

Note that alternative foundation configurations were considered, such as driven steel piles, or wood poles. Driven steel piles were assessed to be more expensive than drilled piers. The experience of other long electrification projects, each of which elected to use drilled piers, reinforces that assumption. Wood poles, by contrast, might be feasible and possibly less expensive, but would have less strength and be subject to fire, rot, and would have substantially shorter lifespan than drilled pier/concrete foundations. Moreover, harvesting sufficient trees to furnish 4 million poles could create significant environmental impacts that would need to be evaluated.

2. Electric Utility Interconnection

High-voltage interconnections from the national utility grid would be needed to supply power to the TPS. The cost of adding new services can vary widely due to the available capacity of nearby power lines.

It is important to note that railroad substations cannot always be connected to the nearest utility power line. Utility power lines must be of the correct voltage and be able to accommodate the additional electrical load from the railroad, as well as the nature of the load. Moreover, to achieve redundancy and provide operational reliability in case of a power outage, adjacent TPSS should not connect to the same utility circuit, meaning that feeder lines may need to be constructed from more distant utility lines. Recent passenger rail electrification projects have encountered this issue, which could result in the need to either upgrade utility infrastructure to establish connections for power, or to develop new feeder lines. Higher train density corridors would require higher capacity, thus more expensive connections.

Costs to account for these items range relative to train volume:

- High Density Corridor: \$0.9 million per route mile before contingency.
- Low Density Corridor: \$0.7 million per route mile before contingency.

3. Signal (Wayside and Grade Crossing) Upgrades

Class I railroad signal infrastructure largely consists of coded, direct current track circuits. Most of this technology would be incompatible with 25 kV electrification and would require modifications. It has been assumed that most existing signal locations are spaced approximately two miles apart (nearly twice the practical length in 25 kV territory) and most existing signal locations would require modifications but could remain in-service. New signal repeaters would need to be installed between existing signal locations to keep track circuits within maximum length limits for 25 kV territory.

Additionally, sight distance of existing wayside signals could be impacted by the new catenary poles. Relocation of some signal masts or installation of new signal bridges would be required in certain instances. It has been assumed that most control points would not need reconstruction. This is a key assumption, and, if incorrect, could add significantly to the

cost. It has been assumed that only routes with six or more trains per day and routes that have multiple main tracks would have wayside signals.

The constant warning time circuits at highway-rail grade crossings are incompatible with 25 kV electrification. There are additional complexities at many highway-rail grade crossing locations, such as crossings within control points, crossings interconnected with traffic signals, and crossing approaches that include other track appliances and circuits that would affect the cost of new grade crossing circuits.

This assumed combined cost for wayside signal modifications and grade crossing signal replacement has been estimated at approximately \$0.5 million per track mile before contingency, and \$0.7 million per track mile with contingency. As noted, these costs assume many existing wayside signal locations would require modification but could otherwise remain in-place. If entirely new wayside signaling were required, costs could increase substantially.

D. Costs per Route Mile (Centerline Mile)

1. Traction Power System (TPS), including gantries

This item includes civil and electrical works for TPSS, switching stations, and paralleling stations

- TPSS footprint of 0.75 acres each.
- Switching Station footprint of 0.35 acres each.
- Paralleling Station footprint of 0.25 acres each.

Civil works would include site preparation, excavation, foundation pads/slabs, prefabricated buildings, road rock, a parking/access road, and chain link fence with gates.

Electrical works would include high voltage switchgear switch, circuit breakers, transformers, gantry tie ins for incoming high-voltage utility power and outgoing traction power, insulated bus ducts, electrical cabinets, switchboards, panels, relays, batteries, conduits, feeders, impedance bonds, SCADA systems, and data and communication equipment.

For every 60 route miles, the assumed equipment for a 2x25kV Electrification System would be:

- One (1) TPSS with two (2) high voltage transformers,
- One (1) switching station
- Four (4) paralleling stations

Additional ROW easements would be needed to extend overhead high-voltage utility power lines to the TPSS.

The estimates cost per centerline mile for TPSS would be \$0.7 million per mile before contingency, or \$1 million per route mile with contingency.

E. Additional Costs for Right-of-Way Modifications

Costs associated with protection or relocation of third-party facilities have been included in the cost estimate. Although, in some cases, these costs may be passed-on to the third-party facility owners, these would nonetheless be costs associated with electrification.

1. Utility Protection (Metallic Pipelines Only)

Although the 2x25 kV autotransformer system greatly reduces the need for cathodic protection, some amount of cathodic protection would still be needed. It has been estimated that approximately 11 percent of the total route miles to contain parallel, metallic pipelines that would need protection.

2. Fiber Optic Relocation

It is possible that existing fiber optic and telecommunications lines would be impacted during the construction of OCS. It is assumed that 5 percent of route miles would require fiber relocation.

3. Raising Power Lines at Highway-Rail Grade Crossings

Existing electric power transmission and distribution lines crossing above the OCS may need to be raised to increase vertical wire-to-wire clearance between the OCS and power line. This Study assumes that any utility lines energized at less than 230 kV would need to be either raised to provide adequate clearance above the OCS, or buried underground, to pass under the track, while lines energized above 230 kV would typically already have higher clearances and would not need to be raised.

GIS data was used to identify high voltage crossings below 230 kV, and it was assumed that 25 percent of those would need to be raised due to insufficient wire to wire clearances between the high voltage power line and OCS. Information on low voltage distribution lines, below 60 kV, was not available from the GIS databases and these were not counted.

4. Fencing (Right-of-Way)

Metallic fences and gates that are within the limits of the electrified railroad would be subject to induced currents. These fences would need to be upgraded to be electrically continuous between grounding locations and have additional grounding added.

The study assumed new three-strand barbed wire fence (since older fences may have isolated sections of wire that could pick-up current), gates, and grounding (including demolition and disposal of existing fencing) only in rural areas.

5. Vegetation Removal/Tree Trimming

Vegetation adjacent to OCS infrastructure must be cleared to prevent trees or limbs falling on the OCS, and to reduce the amount of nearby flammable material in the case of an arc or spark from the OCS. This would involve selective clearing to remove trees from within the ROW or OCS maintenance limits. It was assumed that the incremental additional amount of vegetation clearing to provide clear space for the OCS would be a ten-foot strip along each side of the track (totaling of 20 feet per track foot), with a potential area of clearing amounting to 2.5 ac per track mile.

It is assumed that urban areas would not require selective clearing.

6. Total Additional Costs for Right-of-Way Modifications

The estimated cost per centerline mile for right-of-way modifications would be approximately \$0.1 million before contingency, or approximately \$0.2 million including contingency.

F. Environmental, Permitting, Mitigation, Design, and Construction Management

There would be a significant cost for developing environmental documentation to satisfy NEPA or IAA. In addition to completing the environmental documentation, a separate permitting process would be required, since permits would be required for activities, such as work in wetlands; this process may also result in requirements to mitigate impacts.

There would also be costs associated with design of the OCS and TPS, procurement, construction management and field inspection, coordination between railroad departments during design and construction, overall program management efforts, coordination with third parties, design costs for utilities to analyze of their networks and design of their portions of new facilities, etc.

Together, these costs have been estimated to be approximately 7 percent of the total cost.

G. Locomotive Costs

There are no examples of electric freight locomotives manufactured for the North American market. Assumed costs for electric locomotives were based on publicly reported costs for locomotives in the European market, with those costs converted to USD.

In Europe, the cost of a four-axle electric freight locomotive, with 5,000 to 6,000 horsepower, is reportedly in the range of €4 to €5 million, based on published sources.⁶⁶ As this Study is written in 2024, the current exchange rate is €1.00 to USD \$1.08. The equivalent cost in U.S. dollars would be approximately \$4.3 to USD \$5.4 million.

However, new or substantially modified designs would be needed for the North American market. North American line-haul freight locomotives are typically 6-axle and, to pull heavier loads, and weigh more than European locomotives. These characteristics could increase the cost when compared to the European locomotives. Similarly, the need to include small on-board batteries and chargers (that have been assumed to be present on all locomotives to enable them to bridge short gaps in the OCS) could also increase the cost. Conversely, U.S. locomotives could be rated at lower horsepower than European models, and the economies of scale associated with large orders may result in a reduced unit cost.

⁶⁶ Railway Supply, "Alstom has delivered the Traxx DC3 Electric Locomotive to Italy", May 5, 2024, <https://www.railway.supply/en/alstom-has-delivered-the-traxx-dc3-electric-locomotive-to-italy/#:~:text=The%20first%20of%20twenty%20ordered,transport%20news%20portal%20Railway%20Supply> and RailMarket News, "France in the Spotlight: Railpool also Orders Alstom Traxx Universal Locomotive", July 24, 2023, <https://railmarket.com/news/rolling-stock/6964-france-in-the-spotlight-railpool-also-orders-alstom-traxx-universal-locomotives>

If approximately 25,700 line-haul locomotives in the current Class I fleet were replaced with electric locomotives, the assumed cost would be approximately \$100 billion, before contingency. If only routes with 6 or more trains per day were equipped with OCS, it has been assumed that the number of required locomotives would be reduced and the cost of electric locomotives would also be reduced, to approximately \$80 billion before contingency.

H. Conceptual Capital Costs

Table 14 summarizes rough order of magnitude costs for the potential infrastructure and ancillary features needed to implement catenary electrification. This conceptual estimate includes a 50 percent contingency due to uncertainty in scope of work, quantities, unit cost ranges, and technical complexity. Two scenarios were developed, representing upper and lower ends of a range of costs, based on the amount of track to be equipped with OCS. The amount of track considered in each scenario was based on the average number of trains operating on that track. The method to determining the number of trains is described in **Appendix A – Train Energy Usage**.

For a scenario where catenary electrification was installed on all Class I routes, approximately 139,000 miles of main line, siding, and major branch lines within the U.S. and Canada, the conceptual capital cost would be approximately \$1.1 trillion, including contingencies.

For a scenario where catenary electrification was installed only on those routes with 6 or more trains per day, approximately 105,000 miles, the conceptual capital cost would be approximately \$870 billion, including contingencies.

For comparison, these costs, which include locomotive, design, environmental, and construction management costs, are lower on a track mile basis than other recent U.S. electrification projects, which had costs of approximately \$9 million per track mile for OCS and utility infrastructure.

Table 14: Summary of Conceptual Capital Costs (in billions 2024 USD)

Conceptual Capital Cost Category	Cost (with Contingency) (All Class I Routes)	Cost (with Contingency) (Omits Routes < 6 TPD)
Overhead Contact System	\$510 billion	\$400 billion
Traction Power Systems	\$150 billion	\$110 billion
Electric Utility Interconnection Costs	\$130 billion	\$100 billion
Railroad Signal and Crossing Modification Costs	\$ 80 billion	\$ 70 billion
Right-of-Way Modifications and Third-Party Protection	\$ 20 billion	\$ 10 billion
Locomotives	\$150 billion	\$120 billion
Design, Environmental Permitting, Mitigation, Procurement, and Construction Management	\$ 80 billion	\$ 60 billion
Total (Rounded):	\$1.1 trillion	\$ 870 billion

As noted, the cost estimates assume that private entities (e.g., the Class I railroads) perform construction with private funding. Should portions of these improvements transition to the public sector to develop and construct, there would be additional factors to consider, such as public contracting and domestic content requirements. Experience has shown that these factors could increase costs and lengthen the schedule.

I. Conceptual Operating and Maintenance Expense for Electrification

The annual operating and maintenance cost for the OCS and TPS systems would depend upon many factors. For this conceptual study, staffing and energy have been assumed to be the key cost drivers. Assumptions about the number of field staff have been made, and overall staff costs include a contingency of 50 percent, intended to account for uncertainties at this high level, as well as the costs to support the field staff. These support costs would include functions such as management support, material control, human resources, contract support, and maintenance equipment.

Field staffing levels are described below.

- TPSS maintenance crews are assumed to include three staff – one foreman and two electricians – and cover approximately 120 route miles. As the system ages, additional crews may be required for the increased maintenance associated with older cabling and switches. Some heavy maintenance or repair of equipment may also be contracted to the equipment manufacturers.
- OCS maintenance crews are assumed to include approximately 20 staff for 100 miles. However, as the system ages, additional staff would be required to repair minor issues. OCS maintenance crews must accomplish a comparatively large amount of work in a short amount of time because work near energized components requires that the OCS must be de-energized and grounded prior to commencing work, thus interrupting train operations. To keep these interruptions at a minimum, crews would need to be sized accordingly.

The workforce required to maintain the OCS and TPS infrastructure would range from approximately 19,000 to 25,000 staff, depending upon scenario, resulting in a labor cost of approximately \$6 to \$8 billion per year.

The Study developed approximate energy costs ranging from \$4 to 5 billion per year. See **Appendix A – B.6 - Results of Train Energy Usage** for the estimated annual amount of energy used from the grid and a description of the process of developing those estimates.

The combined cost of operating and maintaining the catenary electrification system, including the electricity and the additional staff required to maintain the OCS and TPS, would result in a cost range of approximately \$10 to \$13 billion per year.

Note that identifying possible reductions in existing railroad cost structures was beyond the scope of this Study. However, at a qualitative level, while there may be some reductions in locomotive maintenance and diesel fuel costs (since catenary-electric locomotives do not have a diesel engine), it's possible that these could be offset by the need to establish and staff entirely new departments for maintenance and operation of the catenary electrification system.