RESPONSE TO DEPARTMENT OF ENERGY'S REQUEST FOR INFORMATION ABOUT PROGRESSION TO NET-ZERO EMISSION PROPULSION TECHNOLOGIES FOR THE RAIL SECTOR

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To: GreenRail@ee.doe.gov

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1. What is your view of zero-emission, or net-zero emission, rail propulsion technologies in the next 5 years? 10 years? 30 years? In your response, please include which rail propulsion technologies for line-haul and railyard operations do you see developing most promisingly. Please provide as many details as possible e.g., battery chemistry for batteries, charger type for electrification, fuel cell vs combustion, feedstock source, etc.

It is important to have a clear understanding of the "zero-emission, or net zero emission" goal as it applies to railroads. Because all environmental impacts are critical, emissions produced by production and delivery of electricity, hydrogen or diesel fuels must be evaluated along with rail 'at wheel' emissions by motive power for railroads.

An examination of the various propulsion technologies shows the total 'input-to-wheel' energy efficiency for five types of railroad motive power:[1]

- Electric catenary wire = 90%
- Hybrid catenary & battery power = 86%
- Battery electric power = 77%
- Green hydrogen power (fuel cell & battery) = 39%
- Diesel-electric power (engine & alternator) = 36%

ELECTRIC CATENARY WIRE (often called an "overhead contact system" [OCS]), directly draws power from the electric grid, and provides the most energy efficient propulsion system for moving freight or large numbers of people on land.[2] The locomotive receives energy from the electric power grid that goes directly to the train's traction motors; regenerative braking of the train returns power to the grid. There are virtually no emissions at the point of use and the electricity can come from any variety of sources including solar panels and renewables; there is no need to stop periodically to refuel. The electric motors have few moving parts, are dependable and easy to maintain.

HYBRID CATENARY & BATTERY POWER could enable electric locomotives to rely on batteries for power on trackage segments that lack overhead catenary wires.[3] There may be gaps in catenary wire due to tunnels or bridges with low overhead clearances, or gaps may exist on

[1] https://www.railwayage.com/mechanical/locomotives/follow-the-megawatt-hours-hydrogen-fuel-cells-batteries-and-electric-propulsion/

[2] Some electrified railroads have third rail power rather than OCS, however these tend to be urban mass transit systems which are entirely grade separated or in tunnels, usually un-connected to the national rail network.

[3] https://www.railwayage.com/mechanical/locomotives/battery-electric-tender-for-modern-railway-propulsion/

parts of a right-of-way during the construction of a catenary wire system. Batteries could also be carried on tender cars for modified diesel locomotives that have been equipped with a pantograph.[4] Hybrid OCS & battery power would be slightly less energy efficient than all-electric catenary motive power, but it could extend the operating life of existing diesel locomotives.

BATTERY ELECTRIC POWER provides locomotives with a range that is quite limited when compared to diesel locomotives of the same size. The batteries must be recharged frequently, and batteries have inherent losses from charging and discharging. A 2021 hybrid battery experiment using battery and diesel propulsion in a combined freight consist in California demonstrated less than a 12% reduction in diesel emissions.[5] Caltrain has purchased a battery powered Stadler passenger trainset for testing on a route between San Francisco and Gilroy; the batteries are to be charged while running under catenary wire north of San Jose.[6] Projects to convert switching locomotives from diesel to battery power have been under way for several years, and railroads are gradually starting to introduce battery powered switch engines.[7]

HYDROGEN POWER appears to be only slightly more energy efficient than diesel power.[8] Hydrogen gas has been used successfully to eliminate pollution from buses, and recently to power some trucks.[9] However, very little "green" hydrogen is currently available, due to its high cost.[10] Stadler hydrogen multiple-unit passenger trains have been purchased for use on a 9-mile segment of track in San Bernardino County, California.[11] Hydrogen powered locomotives are being tested for freight service in France, but European freight trains are relatively short, so applications to freight service in the U.S. may not be understood for some time.[12] Cold weather may be a problem; hydrogen powered passenger trains suffered breakdowns during the 2022-23 European winter.[13] An Alstom hydrogen passenger trainset recently operated during the summer months in Canada.[14]

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[4] The use of battery tenders has been largely abandoned in recent decades and would need to be reestablished. For a battery to fully power a diesel locomotive, modifications of the circuitry may be required.

[5] https://www.trains.com/trn/news-reviews/news-wire/wabtec-bnsf-conclude-initial-tests-of-battery-electric-locomotive/ https://www.theguardian.com/us-news/2021/sep/16/battery-electric-freight-train-wabtec-rail-transport-emissions

[6] https://www.trains.com/trn/news-reviews/news-wire/caltrain-orders-battery-electric-trainset-for-trial-operation/

[7] https://cleantechnica.com/2023/11/07/u-s-steel-pioneers-battery-powered-locomotives-1st-in-north-america/

[8] https://www.railtech.com/rolling-stock/2022/11/03/german-state-baden-wurttemberg-finds-battery-to-be-best-solution-for-diesel-alternative-trains/ https://www.hydrogeninsight.com/transport/will-no-longer-be-considered-hydrogen-trains-up-to-80-more-expensive-than-electric-options-german-state-finds/2-1-1338438

[9] https://www.actransit.org/sites/default/files/2022-06/0105-22%20Report-ZETBTA%20v3_FNL.pdf

[10] https://www.iscaninfo.com/article/10109517/Lex-in-depth--the-staggering-cost-of-a-green-hydrogen-economy https://www.canarymedia.com/articles/hydrogen/chart-which-countries-are-leading-the-green-hydrogen-race WlctzKJ6lQ_ohOX76f8iq0zjZ41ekmomay1Zm9mH4jKloiXChMC9hZU5IS7Mxi3XwdhnAMb4hwq7WTJE2eFgdPQ https://manhattan.institute/article/green-hydrogen-a-multibillion-dollar-energy-boondoggle

[11] https://railway-usa.com/news/73015-more-hydrogen-trains-for-the-state-of-california

[12] https://www.alstom.com/press-releases-news/2022/11/2025-nestle-waters-france-will-use-first-hydrogen-powered-freight-train-through-innovative-solution-developed-alstom-and-engie

[13] https://www.trains.com/trn/news-reviews/news-wire/hydrogen-powered-trains-struggle-with-winter-weather/

[14] https://railway-news.com/alstom-concludes-demonstration-of-first-hydrogen-train-in-north-america/

DIESEL-ELECTRIC POWER serves most of the rail systems in the United States, but the climate crisis requires abandonment of fossil fuels.[15] In many other parts of the world, catenary electric power has been dominant for decades, and is expanding to replace diesel locomotives. It can take many years for railroads to shift from one technology to another, so plans to reduce greenhouse gas emissions should be based primarily on the catenary equipment that has been in service for decades.

BY THE YEAR 2029, every railroad should have well-developed plans, and agreements with government entities, electric power grid operators, catenary equipment manufacturers, and construction companies for transitions to zero emission operations.[16] Construction should have been initiated on the most important catenary rail segments; existing diesel locomotives should be in the process of conversion to operate with pantographs on the track segments that will have catenary power; and acquisition of electric locomotives to replace retired diesel motive power should be initiated. The priorities that state and national regulators give to establishment of "net-zero" standards, and the availability of public funding to assist in the transition will play a large role in reaching these goals.

The Sierra Club recommends that the Federal Government establish a program with the nation's electric utilities and railroads to implement rail electrification nationwide. Electrified rail in heavily polluted 'nonattainment' areas where trackside communities have been most affected by diesel locomotives, should be a priority for a national rail electrification program.[17] It should also be widely understood that movement of goods by rail propulsion is three to four times more energy efficient than trucking, and it is important for the transition and funding arrangements to keep freight rail service strongly competitive.[18]

The initial projects should test the costs and efficiency, as well as the reliability of railroad battery tenders, battery power, and green hydrogen power in various climates and topographies. Robust planning for catenary electrification of the most active segments of the rail network should be completed, and arrangements for funding should be made.[19] Passenger rail operators in California can help meet the State's target for a 25% reduction per capita in automobile driving by the year 2030; the target for a 30% per capita reduction in driving is 2045.[20]

BY THE YEAR 2034, railroads should have received the needed funding, and should have completed the installation of catenary power on the most active segments of their rights of way. The use of battery-tenders should be widely demonstrated. The benefits of railway electrification should be evaluated with a full understanding of the human and economic costs of the greenhouse gas emissions that would result from less effective tactics to reduce emissions from the rail network. While lightly used segments of track may justify the use of battery propulsion, electrification of much of the rail system will provide significant long-term benefits.

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[15] https://www.cnn.com/2023/12/06/climate/fossil-fuel-phase-out-cop28/index.html

[16] https://www.railwayage.com/freight/rail-fleet-decarbonization-opportunity-what-does-it-mean-for-you/

[17] https://www.sierraclub.org/sites/default/files/2023-08/Rail%20Report%20FINAL.pdf

[18] https://www.aar.org/facts-figures#2-fuel-efficiency

[19] https://www.railwayage.com/mechanical/locomotives/managing-technology-nine-misconceptions/

[20] The reduction is from a 2019 base-year. See, https://ww2.arb.ca.gov/sites/default/files/2022-11/2022-sp-appendix-e-sustainable-and-equitable-communities.pdf p. 4

BY THE YEAR 2054, catenary power should serve at least 80% of all core network trackage in the United States, and diesel propulsion should be used only in emergency situations.

2. What efforts are you aware of to decarbonize rail transportation, including ways to reduce diesel fuel use? Are you aware of intermediate decarbonization milestones for rail transportation? Are you aware of longer term decarbonization goals for rail transportation? If so, describe how those goals might be met, including whether low- carbon biofuels will play a role.

The most effective world-wide method of decarbonizing rail transportation is to rely on overhead catenary wire electrification (OCS). The International Energy Agency strongly endorses OCS as a strategy to reduce fossil fuel consumption.[21] All main lines in China are now electric, and India expects to complete electrification of mainlines by the end of 2024. The world's longest railroad, the 6,000-mile Trans-Siberian, has long been all OCS. More than half of the railways of Russia, Germany, France, South Africa, and Finland are OCS. Japan, Korea, Spain, Norway, Sweden, and Italy have electrified over 60% of their rail networks. Switzerland, Laos, Armenia, Ethiopia, and Djibouti are over 98% OCS.

Direct electrification with overhead wire is the most energy efficient and economical means of achieving zero emission rail propulsion for high and medium density rail lines. A 2021 report by the UK Railway Industry Association concludes that battery and hydrogen locomotives are only practical for light density routes and yard/industrial switching operations.[22]

Electrification is a long-term investment with positive impacts on operations costs. Research by the American Railway Engineering and Maintenance of Way Association (AREMA), conducted in the 1970s, suggests that after 30 years, the total annual operating costs (including energy costs) of an OCS system would be approximately one-third that of a system that relies on diesel locomotives. After six years of electrification, the operating cost of an OCS system is equal to that of a diesel propulsion system.[23]

Railroad rights-of-way have also been identified as ideal routes for the high-voltage power lines that need to be added to the nation's grid. For example, the SOO Green Transmission Line Project is constructing a buried high voltage DC (HVDC) transmission line alongside a railroad track between Mason City, Iowa, and Chicago. Having this power source available, railroad electrification will be simplified. Large-scale electric energy storage systems can also be co-located with the grid-connected 'traction power substations' which power electric rail lines, benefiting the reliability of both the power grid and the electric trains.[24]

Reliance on petroleum for fuel entails long-term risks like price volatility, and the likelihood that extraction of oil will decline. Oil prices are set by global markets and can be very volatile. The diesel supply chain can become entangled in issues of foreign policy and energy independence. Conversely, electricity prices are likely to fall especially with the increasing use of renewable

[21] https://www.iea.org/energy-system/transport/rail

[22] https://riagb.org.uk/RIA/Newsroom/Publications%20Folder/Why_Rail_Electrification_Report.aspx

[23] https://scag.ca.gov/sites/main/files/file-attachments/crgmsais_-analysis_of_freight_rail_electrification_in_the_scag_region.pdf

[24] https://www.nema.org/docs/default-source/technical-document-library/benefits-of-rail-electrification-final.pdf

energy sources such as solar. Electric-powered trains are also much more energy-efficient overall than those powered by diesel or hydrogen.[25]

Unfortunately, in the United States less than 1% of our national rail system is OCS.[26] The Northeast Corridor between Washington, D.C. and Boston is electrified for 457 miles. This includes the Keystone Corridor between Philadelphia and Harrisburg, parts of the SEPTA system around Philadelphia, New Jersey Transit, Metro North, and the Long Island Railroad. The Chicago area is served by two regional OCS rail lines: the Metra Electric and the South Shore Line. Denver RTD has a 25-kV OCS regional rail system that is over 54 miles in length. The 39-mile, OCS 50 kV Deseret Power Railway in Colorado and Utah carries coal from a mine to a power plant, isolated from the national rail network. The total length of these mainline electrified trackage is only about 1,500 miles. The Milwaukee Road operated an all-electric passenger and freight service over the Cascades and Rocky Mountains from 1914 until 1974.

To eliminate the greenhouse gas emissions from railroads, catenary electrification, starting with the most heavily used railroad tracks is essential. Catenary power eliminates air pollution and noise impacts to communities alongside tracks and railyards. Also, an increase in passenger train ridership is often obtained following electrification because the trains have rapid acceleration, a quiet, smooth ride without exhaust smells, and fewer breakdowns.

The use of battery powered locomotives over long distances is not a practical alternative to OCS infrastructure due to their limited range. Countries all over the world have started and expanded vast electrified rail networks economically without use of battery powered trains. A major advantage of an external source of electricity is that the train does not expend energy carrying heavy fuel or batteries as an on-board energy source.

Hydrogen-powered fuel cells alone cannot provide enough instantaneous power to rapidly accelerate a train, so an onboard battery pack is needed in addition to the hydrogen tanks, taking up more space and adding weight. A relatively few full-sized hydrogen powered passenger trainsets have ever been built, and no one knows how long they will last in service.

To achieve near zero GHG emissions and eliminate pollution from rail operations, neither battery nor hydrogen trains are a substitute for OCS power. Battery powered switch engines can complement catenary electrification for freight yard switching, and hybrid battery tender power can serve short sections of track as well as lightly-used branch lines that lack overhead wire.

Hydrogen and battery motive power will continue to be more expensive than catenary motive power, which has fewer components. There are also many experienced vendors, and manufacturers around the world to provide reliable and economic electric rail equipment, while there are only a handful of hydrogen and battery rail vendors.

Replacing trucks (even electric trucks) with electric freight trains to move trucks off the road would benefit public health and the environment, so the development or redevelopment of rail-served industrial areas should be encouraged along with rail electrification. In many cities,

[25] Ibid.
[26] https://cleantechnica.com/2023/02/07/europe-china-india-can-electrify-all-rail-why-cant-the-us/

pollution from freight movement is a much more significant source of pollution than passenger cars. Electrified freight rail, combined with freight mode shift away from trucks, can reduce polluting diesel truck traffic many neighborhoods.

When a route is configured for fast, frequent, reliable passenger service, the efficiency and reliability of the freight service also increases. Configuration of a route for increased passenger service prepares it for fast, reliable intermodal service over short, medium, and long distances, which also benefits freight rail. Such intermodal service is used in Europe, particularly through the Alps, to reduce the volume of truck transportation on highways. In North America, other railroad operators or transport companies who might want to offer such intermodal service should be given access to the national network owned by the largest major railroads (designated as Class I), since intermodal service is a vital climate emergency strategy.

The multi-agency *U.S. National Blueprint for Transportation Decarbonization*, released in January 2023, notes that railroads are responsible for only 2% of transportation emissions. It calls for a shift of passenger travel and freight movements to our rail infrastructure as a means of reducing emissions from trucks and automobiles. However, it fails to mention that the U.S. stands out as a notable exception worldwide in not having extensive electrified rail operations. A modern electrified rail network would act as a 'force multiplier' in terms of decarbonization at many levels.[27]

Many European countries have instituted policies to encourage rail transportation as a major emissions-reduction strategy. In Europe, a trip on an OCS intercity train has 1/4th to 1/8th the GHG emissions per passenger as flying the same distance, depending on the 'carbon-intensity' of a region's particular mix of electricity sources. As part of its climate goals, the German government has established a goal to double train passenger ridership by 2030. Towards this end, new low-cost monthly passes were introduced for unlimited rides on regional rail and bus lines across the country:

> "No other motorized transport today is as climate friendly as the rail system. In addition, no other means of transport is as electromobile – and therefore as low in greenhouse gases and pollutants – as rail, which holds the largest market share of e-mobility in Germany. No other mass transport can achieve a 100% share of renewable energies as quickly – by 2038, we will have converted our traction current in Germany to 100% ecopower. A strong rail system is therefore an essential prerequisite for meeting the climate protection targets of the Federal Government and the EU, because a reduction in emissions in the transport sector cannot be achieved without a massive shift in the mode of transport towards the climate-friendly rail system. Strong Rail is a crucial beacon of hope for our climate. In concrete terms, the shift in the mode of transport and other

[27] https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf

> climate protection measures through Strong Rail means annual savings of up to 10.5 million tons of CO_2 per year in the transport sector in Germany."[28]

The U.S. railroad network is under-utilized, and we should expect more benefits from it. Current rail policies that shortchange the public interest deny Americans the compelling energy, economic, and environmental benefits inherent in moving as much freight and passengers by rail as possible. Increasing rail and transit mode share and moving away from our current heavy emphasis on the highway and air modes of transportation, will bring many environmental, economic and social benefits.

Trains are an essential, solution to the climate emergency. The inherent energy efficiency of rail transportation means that it is the most climate-friendly form of transportation over land. Rail generates only about one-fifth to one-third of the emissions of equivalent road transportation (compared on a ton-mile basis, and often even less on a passenger-mile basis). Nationwide, road transportation is responsible for 82% of transportation GHG emissions, while rail is responsible for 2%. Electrifying railroads will further reduce their GHG emissions and more than triple their energy efficiency. The climate crisis solution lies in using rail transportation far more than we do and utilizing it in innovative ways. Rapid change in transportation priorities to favor rail transportation can be a fast and effective climate emergency response.

Biofuels are an attractive option to clean up existing diesel locomotives operations quickly and inexpensively. Unfortunately, low-carbon biofuels are still polluting, and are not a solution except for legacy diesel locomotives running on lightly used lines which would not have traffic to justify overhead wire electrification.

In recent years, railroads have been introducing new diesel locomotives, which comply with the U.S. Environmental Protection Agency's environmental standards for reduced criteria pollutant emissions. The six criteria pollutants are carbon monoxide, ground-level ozone, lead, nitrogen dioxide, particulate matter, and sulfur dioxide. Trucking is sometimes described as allegedly "cleaner" than rail based on the premise that trucking is going to Tier 4 engines faster than the railroad industry is. Of course, "cleaner" applies to criteria emissions only. Tier 4 truck standards do not reduce GHG emissions significantly, and do not change the fact that trucks will continue to have vastly greater GHG emissions (per ton-mile moved) compared to rail transportation.

3. What are the benefits and challenges of the various rail propulsion technologies as compared to the other alternatives? If possible, please provide a ranking of the alternative technologies starting with the most viable/promising option.

I. ELECTRIC CATENARY POWER (OCS)

OCS rail propulsion technology has been proven and refined for more than a century, and its use continues to grow throughout the world. It is the most energy efficient way of rapidly moving freight or large numbers of people over land. Overhead electrification is "off the shelf"

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[28] Described by German national railway DB "Strong Rail" strategy: https://ir.deutschebahn.com/en/db-group/strategy/unsere-strategie-starke-schiene/

technology with decades of proven service and continuous technological improvements. Also, there is a large pool of manufacturers that are experienced in rail electrification technology.

The locomotive takes energy from an external source, on an as-needed basis, and the energy goes straight to the traction motors. The trains are quiet, emit no smoke and have greater energy efficiency than other propulsion technologies. The electric energy is supplied from a variety of sources including solar, and wind turbines. The trains regenerate electric power during braking and feed electricity back into the grid.

An advantage of OCS is its ability to "offload" the power source to the stationary generating facilities that support the grid. This avoids significant vehicle weight by eliminating thousands of pounds of fuel cell, hydrogen fuel, or batteries. Electric trains accelerate more rapidly than diesel-powered trains and have lower operations and maintenance costs. This enables an increased frequency of trains, and thus more capacity for each section of track. By contrast, passenger rail lines that rely on diesel-power are limited in their speed and capacity. In addition, with fewer moving parts, trains with electric power have proved to be much more dependable and economical to operate than diesel powered trains.

The "sparks effect" is the phenomenon, documented around the world, of marked increase in passenger ridership following electrification due to:

- Increased train speed and frequency due to better acceleration
- Passenger comfort (quieter, smoother ride, no smoke)
- Increased reliability (fewer train breakdowns)
- Lower equipment, O&M costs means passenger railroads can invest in more frequent service.

II. HYBRID – OVERHEAD CATENARY WIRE AND BATTERY

Rail propulsion technologies that combine the advantages of catenary and batteries may prove valuable. Using battery power on an electric locomotive, trainset, or tender car with an overhead pantograph (OCS) enables a train to move on non-electrified track (such as a tunnel or bridge) between sections of overhead wire. Various configurations that combine OCS and battery power are possible. They could eliminate the need for OCS on every section of track, whether the track provides terminal service, has low traffic volume, is a siding, connects various types of trackage, or passes through historic neighborhoods or scenic territory. Even on many busy mainlines there are existing bridges or tunnels which could constrict overhead wire clearances for these short sections.

The commercial operating experience that combines an external power source (catenary or third rail) with battery power dates back over a century and is quite limited. The Utah Copper Company rail line introduced battery-catenary hybrid electric, 75-ton locomotives in the late 1920s. They were capable of up to six hours of 'off wire' operating time. At about the same time, the New York Central was using a 'three-power boxcab' locomotive capable of being powered by either a diesel engine, batteries, overhead trolley wire or third rail.

Electrifying selected line segments, incremental electrification, combined with battery electric propulsion can potentially address many of the shortcomings of both technologies. The first step would be to target initial electrification at terminal station tracks, stations with high-acceleration requirements and the key grades of the route. This significantly reduces the cost of catenary electrification and allows electrified operation to begin with hybrid trainsets.

III. EXCLUSIVE BATTERY POWER

The size and weight of the batteries required to move trains for many miles would make sizeable battery powered trains much more costly than trains powered by overhead catenary wire, or third rail. It is practical to use battery power for switch engines that operate at low speeds and can be recharged often. Passenger trains that travel relatively short distances and lay over for sufficient time to recharge batteries may prove useful. However, batteries become depleted after a limited amount of use, and require recharging, which can take hours. The laws of physics tell us that on-board batteries (on their own) will never be light enough nor have the on-board energy storage density to power heavy freight trains nor passenger trains that travel long distances.

Maintenance trains using battery power have long been used by large urban rail transit agencies around the world, for repair work when the traction power system is de-energized. However, electric trains powered by overhead wire, or third rail became standard in the late 1800's due to the range limitations of battery power for trolleys and trains. The first electric locomotive ever built, in 1837, was a battery-powered locomotive. Lightweight railcars or multiple-unit trains were battery powered on a few lines from the early to late 20^{th} century in the US, New Zealand, Ireland, the UK and Germany. Small battery-powered trains were first used in underground mines in 1917.

IV. HYDROGEN FUEL

The energy required to produce and store green hydrogen requires three times more electricity than that needed to power an equivalent train with overhead wire from the grid. That means that using all-electric locomotives with pantographs will always have at least three times less impact on the environment than those using hydrogen.

The hydrogen supply chain, on-board storage systems and drivetrains are highly complex. These lead to more points of potential failure, and less reliability, with higher maintenance, and operating costs. Moreover, hydrogen-powered locomotives are several times more expensive than electric locomotives powered from overhead catenary. The significant capital cost of rail electrification infrastructure is often given as reason to use hydrogen power instead. However, rolling stock is also a significant upfront capital cost. Hydrogen propulsion is likely to greatly increase the capital cost of new rail fleets.

Environmental justice and safety issues are also presented by hydrogen tanks, pipelines, and storage facilities. Hydrogen is a flammable and potentially explosive gas, that leaks easily. The risks of hydrogen leaks and explosions to crews, passengers, and trackside communities, have yet to be fully evaluated, and hydrogen leakage in tunnels could be very problematic.

The biggest danger of hydrogen, aside from its explosivity, may be the opportunity cost of the money, time and resources that will be wasted on it, compared to conventional rail electrification. While recent transportation planning has emphasized implementing advanced technology as a goal, one cautionary factor is that the pursuit of new technology could become an end in itself, resulting in a deferral of investment in proven systems. Hydrogen is bedazzling decisionmakers on U.S. transportation policy as a "shiny new thing." But new is not necessarily better. A recent report from the state of Baden Wurttemberg in Germany concluded that they will no longer consider hydrogen for rail propulsion as it is more expensive than battery or hard wire electrification by as much as 80%.[29]

4. What obstacles to rail decarbonization is the industry facing? What plans can be put in place to overcome these challenges?

The main obstacles to adopting the most efficient motive power for railroads in North America are not technical; they are financial, political, and even cultural/ideological. There is a bias against any kind of capital expenditure by private railroad companies that does not have a return-on-investment period of 5 years or less. This has not only hampered the development of electrification. It has also prevented construction of increased track capacities, new freight terminals, etc. This an arbitrary business situation, imposed largely by Wall Street, that needs fixing on the Federal policy level.

Although the reduced costs of operating electric trains will recover the construction costs for catenary power in the long run, repayments to banks or private lenders may temporarily affect profits and the market value of stocks. Because investors tend to be highly focused on maintaining low costs as measured by operating ratios, railroad managers may be wary of deviating from traditional investor expectations. However, the industry faces responsibilities that require new strategic thinking.[30] It is time to recognize that business as usual will not work.

A relatively large initial investment is needed to construct a catenary electrification system. Unfortunately, the avoidable mistakes that caused costs to balloon for the Toronto and California electrification projects have added to the obstacles.[31] It is important to learn from these projects and to find very experienced and well-qualified managers (particularly those with decades of experience outside of North America) for future electrification projects.

Other objections raised by the U.S. railroads against electrification include concerns about employee safety, clearances, and potential electromagnetic interference with signal and communication systems. These valid issues have been resolved in electrified rail operations

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[29] https://www.railjournal.com/fleet/baden-wurttemberg-rejects-hydrogen-as-diesel-alternative/ "The positives for hydrogen were: minor impacts upon introduction and during operation, and no changes required to the rail infrastructure. But the negatives were: costly filling stations; low efficiency, high energy consumption and high cost; the possible need to increase the number of trains because the range would not be sufficient for a whole day of travel; limited availability of green hydrogen; and the need to continually resupply the hydrogen filling stations."

[30] https://www2.deloitte.com/content/dam/Deloitte/us/Documents/consumer-business/us-cb-laying-track-for-the-future-success-of-freight-railroads.pdf

[31] https://www.tvo.org/article/ottawas-colossal-lrt-debacle-a-brief-ish-history and https://www.sfexaminer.com/archives/federal-monitor-warns-caltrain-electrification-project-faces-two-year-delay/article_9155ee9f-ecd0-5e44-b0c0-a7f43be6b363.html

worldwide and resistance to overhead electrification is being overcome. Railroads have long operated freight, and double-stacked container trains, under electrified wire in Pennsylvania. At least two of the BNSF-owned tracks between LA and Fullerton will be electrified as part of the California High Speed Rail project, with OCS wire designed to be tall enough for double-stacked container trains to run underneath. UP will continue to operate freight trains on the Caltrain corridor under the electric catenary wires, as well as under CHSR wires between LA and Burbank.

Sunk costs in the existing diesel-electric locomotive fleet are said to be another concern for railroads that have recently ordered new locomotives. However, existing diesel-electric locomotives can be modified to use pantographs for power.[32] Battery tenders can be added to trains that may operate on segments of track that are not electrified, and batteries might replace the diesel motors.

For the most part, the rest of the world's railroad tracks (outside of North America) are publicly owned, enabling longer-payback capital investments like electrification that are ultimately better for the railroad and society. The railroad industry must face up to the fact that actions to cope with the climate crisis need to be taken, and electrification of rail operations will take place.

It is past time for freight railroads to eliminate unhealthy diesel pollution harming people near the tracks and railyards. The environmental justice pushback to the freight railroads is picking up political and widespread popular support. People with asthma growing up next to railyards don't accept the idea that the greater energy efficiency of rail means that diesel locomotives should be allowed to continue operating forever. More elected leaders are starting to take notice of railroad pollution harming their constituents.

5. For direct electrification of rail, how do you foresee the infrastructure (such as overhead catenary) being built? Who should own and operate the infrastructure?

Railroads all over the world have engaged in staged conversion from diesel to catenary electric power. Construction, enlargement, and maintenance of the infrastructure is well-understood. Railroads in the U.S. can look to the Northeast Corridor or Chicago for instruction and skilled personnel or go abroad. There are also options for electric utilities or public agencies to become the owners of rail electrification infrastructure, and if necessary, the federal government could underwrite or invest in them.

6. What collaboration with any other entities do you think will be necessary to support the decarbonization of rail transportation?

Electric utilities will be key for the electrification of rail transportation and must be involved in the planning from the outset. A single line-haul freight train can consume more than 20 MW of

[32] https://www.nature.com/articles/s41560-021-00915-5 Modifications to the diesel locomotive could mimic the dual-mode General Electric P32AC locomotive, which uses electric power (from a third rail) or its diesel engine when it is not on the electrified section of the railroad.

electric power. The utilities will need to build new substations to service electrified track, and construct or upgrade distribution and transmission lines. The electric utilities should see the new loads from freight trains as a business opportunity.[33] Utilities also would benefit from being able to transmit or distribute power using rail rights-of-way.

State and local transportation agencies will also be affected and should be involved in planning.

U.S. utilities and the DOE should consult with other countries with extensive electric rail and a high percentage of renewable energy generation, such as Germany and Spain. These nations meet more than one-third of their overall electricity needs from renewable sources (excluding large-scale hydroelectric) and have a rail system electrification rate of over 60%.

7. What are the most critical gaps (e.g., with respect to standards, regulations, supply chain, labor) that need to be filled to support acceptance of and markets for alternative rail propulsion technologies?

The catenary powered trains that might be considered ‘alternative’ by some have been an everyday experience on the Northeast Corridor and for numerous U.S. public transportation agencies for many decades. It is important to have a broad perspective when viewing passenger and freight rail investments. For example, high quality passenger rail service levels (and fast frequent freight trains) which many Americans may consider as being ‘futuristic’ or ‘unrealistic’, are, in fact, what Europe and Asia have had available for decades. There is a wealth of global experience and proven “off the shelf” technology that we can utilize to address catenary power issues for rail electrification. We don’t need to re-invent the wheel. The knowledge and providers of economical and reliable rail electrification technology are already here.

8. What infrastructure is required to support promising alternative rail propulsion technology? Are there specific routes, railyards, or network segments that would be a good candidate for alternative propulsion technologies (e.g., catenary, hydrogen fuel cells, or batteries)?

Electric grids will need to develop additional capacity along many rail lines. Substations will need to be built to deliver and receive power from the railroads.

9. What type of service testing, or de-risking, of these propulsion technologies do you think are necessary for each alternative rail propulsion technology?

Test sites for different rail propulsion technologies need to be set up around the U.S., to test a variety of rail applications and operating conditions, in different types of weather, etc. In addition, real railroad revenue operation of pre-production locomotives is needed to truly identify design or component issues and correct them. Conventional catenary technology is far lower risk than battery, hydrogen, or biofuels due to the extensive operational experience around the world. However, further experience with this established technology for freight rail

[33] Many utilities are concerned about losing revenue from more and more customers, particularly large industrial and institutional ones, investing in distributed self-generation projects such as rooftop solar.

applications is needed to develop FRA and AAR standards and best practices, for the North American freight railroad industry to fully accept overhead wire electrification.

10. What government actions do you think are necessary to help move the rail sector towards net-zero emissions?

National regulation of U.S. railroads makes Federal leadership essential for rail decarbonization. The Federal government should establish a program with the nation's electric utilities and railroads to implement rail electrification nationwide. Electrified rail in heavily polluted 'non-attainment' areas where trackside communities have been most heavily affected by diesel locomotives, should be a priority for the national rail electrification program. The new U.S.-Canada joint task force on rail electrification was announced in December 2023 at the COP28 U.N. climate change conference in Dubai. This task force should dust off existing rail electrification studies in the archives of both governments.[34]

Various models of ownership and capital project financing need to be explored to reduce the upfront costs for railroads using grants, publicly backed loans or bonds to expedite electrification.[35] Congress has been considering a National Infrastructure Bank that could be a steady funding source for electrification projects.

It would be helpful to establish policies or laws to avoid litigation that might delay rail electrification. The climate will not wait for adjudications, and rail operations should be electrified as quickly as possible.

11. Other than tax credits, what opportunities are there to incentivize transition to clean fuels, recognizing that costs are likely to be higher in the near to mid-term? (For example, vehicle consumer incentives in the on-road sector include the use of high- occupancy vehicle (HOV) lanes, free workplace charging, etc.).

The Federal government can invest in catenary infrastructure, for the same reasons that it invests in highways. Innovative financing packages involving loans and bonds can be used.

12. What type of workforce challenges are present? Are you aware of any workforce development programs that are relevant to the clean energy transition in the rail sector?

Railroad training and education are weak in the U.S. Our focus on highways has caused much of the expertise in railroad design, construction, and operation to be lost. For example, state and local departments of transportation are overwhelming staffed with engineers skilled in road building, but few if any with experience in rail construction and operations. The maintenance and furthering of technical expertise require an educational pathway to allow young people to enter the field, and academic institutes where innovation and research can be nurtured. The U.S. has only three specialized university railroad transportation and engineering programs (University of Illinois, Michigan Technological University and Penn State) and the programs are

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[34] For example, freight rail electrification studies from the 1970s, resulted in the U.S. electric coal-hauling railroads at the time and BC Rail's Tumbler Ridge from the 1980s. Many of the technical principles of this work are relevant for North American rail operations today.

[35] An example is the publicly owned electrification infrastructure over tracks that are privately-owned in the LA-Fullerton electrification proposed by CHSRA on the BNSF-owned section of LOSSAN.

relatively limited in compared to their European or Asian counterparts. A few railroad courses exist at other U.S. universities, ranging from one to six classes. In contrast, the European Union has nearly forty university programs in railroad transportation and engineering. Similar railroad programs are offered in India, Russia, China, Taiwan, and Australia. A full-scale railroad transportation and engineering program should be initiated in colleges and universities throughout the U.S. Short line railroads could be used in conjunction with a comprehensive technical training and apprenticeship program in railroad trades (operation, track and signal maintenance, vehicle maintenance, supervision, and management).

13. Are you aware of any goals for Total Cost of Ownership (TCO) willingness to pay for advanced technologies? Recognizing that DOE and industry are driving to cost parity with diesel in the long term, what do you think the goals should be regarding reasonable extra costs over the diesel baseline in the near term?

The costs of installing and maintaining catenary wire, and other options, should be measured against their significant health and environmental benefits. The fewer parts in electric locomotives reduce maintenance costs 40%-50% compared to diesel-electric locomotives, and electric locomotives have longer operating lives, with less down time.

14. In your opinion, how do certain technologies (e.g. battery) compare for different use cases (e.g. line haul, switching)?

Overhead catenary wire (OCS) is a proven technology, used successfully by freight and passenger rail operations in most of the world. For routes that have low tunnels or bridges, various techniques have been developed (insulated tunnel conductor bars w/ surge arresters), or battery-OCS hybrid configurations can power through the non-electrified sections. Standard OCS electrification will prove more economical when transportation policy encourages a scaled-up modal shift to rail transportation.

Hydrogen and batteries are much less efficient than OCS. According to a recent study by Deutsche Bahn (DB), the 'sweet spot' for battery or hydrogen train would be on lines with light traffic and moderate speed, without electric power. The number of watt-hours of energy consumed per seat-mile on a passenger train was estimated to be 20.5 for electric (w/ overhead wire), 43.6 for battery power and 46.2 for hydrogen propulsion. The energy density of hydrogen, stored onboard at 350 bar, has a volumetric energy storage density 1/12th that of diesel, and current battery technology only 1/20th. Factoring in the overall energy efficiency, the volumetric energy density of hydrogen powering a train is less than ¼ that of diesel, and battery about 1/10th that of diesel.[36]

Trains powered by hydrogen or batteries cannot be a viable solution for long-distance freight and high-speed passenger rail, due to the laws of physics. The range of a hydrogen or battery powered locomotive will be a small fraction of the 800 to 1,000 miles for conventional locomotives. This range could be extended somewhat with tender cars, but this adds costs and complexity. A freight locomotive must be able to pull up to 100 more times its weight. Therefore, the onboard power plant must be at least an order of magnitude larger in size, along

[36] https://www.hsrail.org/events/zero-emissions-rail-propulsion-electrification-batteries-or-hydrogen/

with the magnitude of energy stored onboard. The battery locomotives for 'yard switching,' and hydrogen passenger train sets have a very limited range, and are likely to be more expensive to purchase, operate, and maintain compared to conventional all-electric locomotives.

15. In your opinion, what percentage of overall locomotives could reasonably be expected to be zero-emission locomotives between now and 2050? How do you think production might scale up over time?

By 2050, virtually all diesel motive power should be eliminated. The body and frame of many existing diesel locomotives can feasibly be converted to electric power and equipped with pantographs as OCS expands. Diesel-engine-alternators can be removed and replaced with a transformer and possibly with a supplemental battery pack. Existing locomotives can then be gradually replaced by electric locomotives with higher power capability at a ratio of two to three. The pace of the transition depends entirely on sources of funding.

16. How do you think power needs should be estimated for the rail industry over time? E.g. number of locomotives or switchers?

World-wide practices assign rail motive power to a variety of railroad situations and economic conditions. Consultations with international experts are essential. US DOE and/or DOT should provide research grants to universities to identify how many locomotives would be needed to handle the modal shift to rail, in lieu of further highway expansion. Similar focus should be directed to identifying the rail infrastructure upgrades needed to shift road dependency to rail at scale.

17. What do you think should be the estimated global market size for net-zero emission locomotives or retrofitting technologies?

Electric locomotives have a world-wide market and have been a significant portion of the railroad industry for many decades. The International Union of Railways (UIC) should have specific information.

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