Feasibility Analysis: Zero Emission Train from the Port of Los Angeles to Barstow

Staff analyzed the feasibility of using current battery electric and hydrogen fuel cell zero emission (ZE) locomotive technologies from the Port of Los Angeles (POLA) to Barstow, a high-traffic freight route in California. For a train to complete a trip from POLA to Barstow, there must be sufficient power and energy supplied from the locomotives throughout the trip.

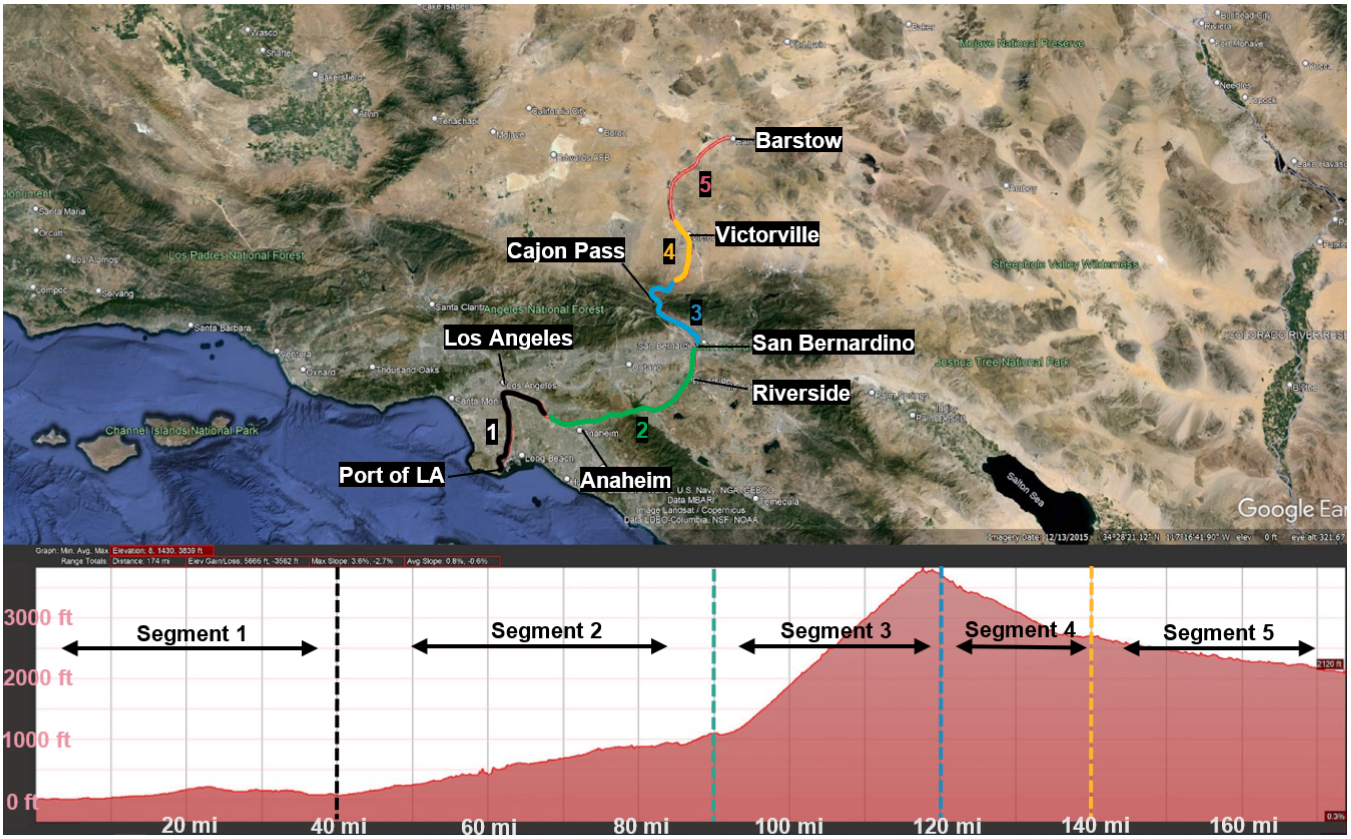
To determine the number of currently available ZE locomotives required to pull 283 containers on 130 railcars from POLA to Barstow, the power and energy required to complete the trip were calculated accounting for length of trip, track grade, rolling resistance, and drag. Once the power and energy requirements were calculated, staff were able to determine the minimum number of ZE locomotives required to supply the power and energy needed. The ZE locomotive models evaluated in this analysis are Wabtec's FLXdrive Heavy-Haul battery electric locomotive, Progress Rail's SD70J-BB and SD70J battery electric locomotives, and Canadian Pacific Kansas City's (CPKC) hydrogen fuel cell locomotive with a tender car to carry hydrogen fuel. These models were chosen because they are rated for line haul operation and can be used by a Class I railroad, who is the primary operator type traveling between POLA and Barstow. Staff estimates between four to nine ZE locomotives (depending on model) are required to complete a trip from POLA to Barstow and fewer locomotives are required when using discontinuous overhead catenary systems (OCS).

Notice of Update

Staff updated several assumptions in the analysis based on feedback and new information received by industry sources. The overall methodology of the analysis remains the same. The route from POLA to Barstow, segmentation, and power and energy calculation methods remain unchanged. The following were updated in the analysis: mass of railcars and containers, mass and energy capacity of FLXdrive Heavy-Haul, depth of discharge (impacting the usable energy capacity of batteries), and speed reduction in Segment 3. The SD70J model was added into the analysis. Additional analysis was done to evaluate the use of discontinuous overhead catenary systems. To see the original published analysis (published on April 22, 2024), please contact *locomotives@arb.ca.gov*.

Route from Port of LA to Barstow

Figure 1: Typical Class I Route from Port of LA to Barstow (Google Earth Pro)



The route from POLA to Barstow is approximately 174 miles with elevation as low as 17 feet (ft) and as high as 3,800 ft above sea level. The analysis splits the route into five segments as shown in Figure 1. The five segments are defined based on significant differences in elevation change. For example, Segment 1 has no elevation change, while Segments 2 and 3 have elevation changes with hill grades of 0.6% and 2.2%, respectively. Segments 4 and 5 are downhill portions of the route. Details about each segment can be found in Table 1 below.

Table 1: Characteristics of Route Segments

Segment	Distance (miles)	Elevation Change (ft)	Grade (%)	Speed (miles per hour)
1	40	0	0	50
2	50	1,020	0.6	50
3	30	2,740	2.2	10

Segment	Distance (miles)	Elevation Change (ft)	Grade (%)	Speed (miles per hour)
4	20	-1,140	-1.55	50
5	34	-580	-0.5	50

Note: Elevation change is relative to the previous segment (i.e. elevation change of Segment 3 is the altitude at the end of Segment 3 minus the altitude at the end of Segment 2). A negative elevation change and grade indicates a downhill portion of the route. Track grades in Segments 3 and 4 were found using published data while the track grades in the rest of the segments were estimated using Google Earth Pro due to a lack of publicly available information.[1] Train speed for each segment was estimated based on speed data from BNSF Railway's Zero-and Near Zero-Emission Freight Facilities Project report and communication with industry sources that requested non-attribution.[2]

Power and Energy Requirements

The power and energy required to travel along each segment of the route from POLA to Barstow were calculated. Power (P) (Eq. 1) was calculated by finding the net force (F_{net}) required for the locomotives to pull the train multiplied by the train's velocity (v). The net forces (Eq. 2) calculated along each segment considers the force to overcome a hill against gravity ($F_{gravity}$), drag force (F_{drag}), and rolling resistance (frictional forces) (F_{rr}). Drag force calculations assumed a coefficient of drag value of 2.1 (entire train treated as a rectangular box) to simplify the calculation and due to a lack of drag coefficient data for locomotives.[3] It is important to note that Eq. 2 is used for flat ground and uphill travel only. Going downhill, the net force (F_{net}) calculation uses Eq. 3. Energy (E) requirement (Eq. 4) was calculated by multiplying power by the time (t) it takes to travel along that segment based on the train's velocity.

$$P = F_{net} \times v$$

Eq. 1

$$F_{net} = F_{gravity} + F_{rr} + F_{drag}$$

Eq. 2

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[1] Trains Magazine, Cajon Pass as you've never seen it, 2011, accessed April 12, 2024. (Weblink: https://www.trains.com/wp-content/uploads/2020/10/trnm0811_acajonpass.pdf).

[2] CARB, BNSF Zero and Near Zero-Emission Freight Facilities, May, 2021, accessed April 5, 2024. (Weblink: https://ww2.arb.ca.gov/sites/default/files/2022-11/zanzeff-bnsf-belreport.pdf).

[3] The Engineering Toolbox, Drag Coefficient, 2004, accessed April 15, 2024. (Weblink: https://www.engineeringtoolbox.com/drag-coefficient-d_627.html).

$$F_{net} = F_{rr} + F_{drag} - F_{gravity}$$

Eq. 3

$$E = P \times t$$

Eq. 4

The mass of the 130 railcars and 283 containers was calculated using the methodology found in the San Pedro Bay Ports Emission Inventory Methodology Report.[4] The San Pedro Bay Ports utilize data from recent years to estimate the number and mass of railcars and containers loaded on a typical train. Each railcar and container weighs 18.1 and 12.7 metric tons, respectively, and the combined mass of all 130 railcars and 283 containers is approximately 5,950 metric tons. The total mass of the train is equal to the sum of the masses for all the railcars, containers, and locomotives.

To determine the number of ZE locomotives required to complete a trip from POLA to Barstow, a minimum energy and power requirement was determined. Staff found that Segments 1–3 require the use of energy from the locomotive, while Segments 4–5 do not. Therefore, the minimum energy required to complete the trip is the sum of the energy needed in Segments 1–3. As energy is only required in Segments 1–3 (flat and uphill track only), staff determined that regenerative braking did not need to be modeled. When braking, the locomotives can convert some of their kinetic energy back into electricity through regenerative braking to charge the batteries. This regenerative braking would only occur in Segments 4–5 (downhill track) where no energy is needed to move the train.

A minimum power requirement was found by determining the highest power required by a segment. Segment 2 has the largest power requirement due to its steep grade and speed of travel, so the Segment 2 power requirement was set as the minimum power requirement for the train to complete the trip from POLA to Barstow. Depending on the speed, Segment 3 could require more power than Segment 2, however, with a speed set at 10 mph for Segment 3, Segment 2 requires more power.

Table 2 provides information regarding estimated power and energy required for each segment of the route from POLA to Barstow. The table presents the estimated power and energy requirements as a range of values rather than fixed values to account for variability in ZE locomotive models.

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[4] Port of Los Angeles, San Pedro Bay Ports Emissions Inventory Methodology Report Version 4, August 2023, accessed July 19, 2024. (Weblink: *https://kentico.portoflosangeles.org/getmedia/2f6e4e7c-6197-493b-bf3e-e3b7ea26b6eb/SPBP_Emissions_Inventory_Methodology_v4*).

Table 2: Power Required, Energy Required, and Energy Regained in Each Segment

	Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 5**	**Total**
Power Required (megawatt (MW))	1.75 – 1.90	10.87 – 11.93	6.99 – 7.69	0	0	Not Applicable
Energy Required (megawatt-hour (MWh)	1.40 – 1.52	10.87 – 11.93	20.98 – 23.07	0	0	33.25 – 36.52

It is important to note that the power and energy requirements calculated for this analysis are estimates and not exact. More detailed data such as exact track grade throughout the route, measurement of track curvature, exact dimensions of the locomotives, and specific efficiencies of each locomotive model are required to produce a more accurate analysis. Aerodynamic drag and rolling resistance were modeled in a simple manner. Staff understand that additional refinements can be made to the aerodynamic and rolling resistance factors in force calculations, however, when compared to the force required to overcome gravity when travelling along uphill portions of the route (Segments 2–3), the effect of drag and rolling resistance is small. Therefore, refinements in aerodynamic drag and rolling resistance will not significantly impact the overall power and energy requirements.

Staff also considered the effects of track adhesion to ensure that there will not be any wheel slip from the locomotive while pulling the railcars. The coefficient of friction between the track and the wheel may be as high as 0.7.[5] However, various contamination on the track surface may reduce the coefficient of friction to as low as about 0.05, which can cause wheel slip. Sand on the tracks is a commonly used method to enhance adhesion on locomotive wheels, which can provide a coefficient of friction of up to 0.4. Staff assessed the friction between the locomotive wheel and the track assuming a coefficient of friction of 0.4 and compared it to the adhesion limit for all segments of the route. The analysis determined that wheel slip will not occur as there would be enough adhesion between the wheels of the locomotive and the track.

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[5] Federal Railroad Administration, A Survey of Wheel/Rail Friction, September 2017, accessed April 17, 2024, (Weblink: *https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/17468/A%20Survey%20of%20Wheel-Rail%20Friction.pdf*).

Analysis Results

Table 3 shows the minimum number of ZE locomotives required to complete the trip from POLA to Barstow for different locomotive types and models. For battery locomotives, a depth of discharge limitation was considered where only 80% of the nameplate capacity can be used in one cycle, with an efficiency value of 90% in converting stored electricity to locomotive kinetic energy.[6] Therefore, a battery electric locomotive with a nameplate capacity of 7 MWh has a usable energy capacity of 5.04 MWh. An efficiency value of 54% was used for hydrogen fuel cell locomotives (60% efficiency in converting hydrogen to electricity and 90% efficiency in converting electricity to locomotive kinetic energy).[7]

Table 3 also presents the number of locomotives required to complete the trip using typical diesel locomotives with an efficiency of 35% (converting diesel fuel to locomotive kinetic energy) to create a comparison with ZE locomotives.[8] The analysis additionally compares the number of locomotives required for different factor of safety (FOS) values to account for errors (up to 20%) in power and energy calculations. It is important to note that usable energy capacity is not determined by traction power. Usable energy capacity and traction power are independent of each other.

Table 3: Number of Locomotives Required for Different Models

Locomotive Model	**Type**	**Weight per Locomotive (MT)**	**Traction Power per Locomotive (MW)**	**Usable Energy Capacity per Locomotive (MWh)**	**Minimum Number of Locomotives Required (FOS: 1)**	**Minimum Number of Locomotives Required (FOS: 2)**
Typical Diesel Locomotive[9]	Diesel	218	3.2	65.2	4	4

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[6] Progressive Railroading, With all-battery electric locomotive purchase, Newburgh & South Shore Railroad serves as OmniTRAX's 'guineapig' in green power initiative, March 23, 2022, accessed April 5, 2024. (Weblink: https://www.progressiverailroading.com/RailPrime/Details/With-all-battery-electric-locomotive-purchase-Newburgh-South-Shore-Railroad-serves-as-OmniTRAXs-guinea-pig-in-green-power-initiative--66191).

[7] Office of Energy Efficiency & Renewable Energy, Fuel Cells, accessed March 24, 2024. (Weblink: https://www.energy.gov/eere/fuelcells/fuel-cells).

[8] Environmental and Energy Study Institute, Electrification of U.S. Railways: Pie in the sky, or Realistic Goal?, May 30, 2018, accessed April 9, 2024. (Weblink: https://www.eesi.org/articles/view/electrification-of-u.s.-railways-pie-in-the-sky-or-realistic-goal).

[9] BNSF, BNSF Locomotives, accessed April 9, 2024. (Weblink: https://www.bnsf.com/about-bnsf/virtual-train-tour/locomotive.html).

Locomotive Model	**Type**	**Weight per Locomotive (MT)**	**Traction Power per Locomotive (MW)**	**Usable Energy Capacity per Locomotive (MWh)**	**Minimum Number of Locomotives Required (FOS: 1)**	**Minimum Number of Locomotives Required (FOS: 2)**
SD70J-BB[10]	Battery Electric	245	5.7	10.44	4	4
FLXdrive Heavy-Haul[11]	Battery Electric	209	3.2	5.04	8	9
SD70J	Battery Electric	194	3.2	5.76	6	8
CPKC Line Haul (with tender car)[12,13]	Hydrogen Fuel Cell	167	3.3	50.3 (per hydrogen tender car)	4	4

Note: For the CPKC line haul hydrogen fuel cell locomotive to sustain 3.3 MW of traction power, battery augmentation would be required because the fuel cell stack itself only provides 1.2 MW of sustained power.[14] Staff determined in the analysis of POLA to Barstow that with each hydrogen fuel cell locomotive, a battery with 5.1 MWh of usable energy capacity with a FOS of 1, or 6.1 MWh with a FOS of 1.2, is needed to provide the rest of the power required to sustain 3.3 MW.

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[10] Progress Rail, EMD Joule Battery-Electric Locomotive, accessed April 5, 2024. (Weblink: https://s7d2.scene7.com/is/content/Caterpillar/CM20231020-d404c-92873?_gl=1*h81skd*_ga*MjA0MTg3Nzc2Ny4xNzAwMDAxOTQ5*_ga_FMYNPMTMYT*MTcxMjMzNjEwOC4zMC4wLjE3MTIzMzYxMDguNjAuMC4w&_ga=2.139680507.955966259.1712179450-2041877767.1700001949).

[11] Wabtec, FLXdrive Battery-Electric Locomotive Technology, accessed April 5, 2024. (Weblink: https://www.wabteccorp.com/FLXdrive-Battery-Electric-Locomotive?inline).

[12] CARB, Appendix C Technical Support Document: Zero Emission Locomotive Conversion, accessed April 5, 2024. (Weblink: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/15dayappc.pdf).

[13] Railway Age, Zero/Low-Emission Locomotive Global Roundup (Updated), June 7, 2023, accessed April 5, 2024. (Weblink: https://www.railwayage.com/mechanical/locomotives/zero-low-emission-locomotive-global-roundup/).

[14] See reference 12, p. 15-16.

Key Takeaways

The limiting factor that impacts the number of locomotives required to travel from POLA to Barstow is energy capacity. Due to the inclines along Segments 2 and 3, a locomotive with more energy capacity is favorable. The analysis concludes that for a train consisting of 130 railcars and 283 containers, between four to nine line haul battery electric locomotives (depending on model and FOS) are required and four hydrogen fuel cell locomotives with one hydrogen tender and battery augmentation are required to complete the trip from POLA to Barstow.

Higher traction power and energy capacity is favorable to complete the trip, such as the SD70J-BB battery electric locomotive which requires the least number of locomotives (four locomotives) to travel from POLA to Barstow. Although this eight-axle model is not marketed in North America, the locomotive demonstrates the technological capability of battery electric locomotives. If operators would like to use larger locomotives that provide more traction power and battery capacity, they may upgrade their track infrastructure. When using typical BNSF diesel locomotives, four locomotives are required to complete the trip.

Staff estimates that the analysis result is scalable to heavier or lighter trains. That is, a 50% increase in the number of railcars and containers will result in up to 50% more locomotives required for all four ZE models (when FOS is 1 and not including combinations of different types of locomotives within a train). While the relationship between train mass and number of locomotives needed is not exactly linear, the trend generally holds. The weight of railcars and containers contributes most to the power and energy required to complete the trip, thus affecting the number of locomotives needed.

Hydrogen fuel cell locomotives, such as the CPKC hydrogen fuel cell locomotive, has similar traction power to the FLXdrive Heavy-Haul and SD70J models, however, the total range that hydrogen fuel cell locomotives can travel is considerably more. Hydrogen is more energy dense than current batteries and a fuel cell locomotive utilizing a hydrogen tender car can carry even more hydrogen along its route to extend the locomotive range. Hydrogen fuel cell locomotives utilizing a tender car can carry more than four times the amount of usable energy of a battery electric locomotive. Utilizing a hydrogen fuel cell locomotive with a tender car may be beneficial to some operators if they intend on traveling distances further than Barstow and do not want to stop to refuel, or recharge, in the case of battery electric locomotives.

Operators may choose to utilize existing diesel locomotives in a ZE configuration by connecting them to battery tenders or battery electric locomotives. This would result in 100% tailpipe emissions reductions and diesel fuel savings by using energy from the batteries rather than the diesel generator. Once beyond the California border, operators could then choose to power the locomotives with diesel. Operators may also choose to use the battery electric locomotives with diesel locomotives in a hybrid configuration outside the California border which can reduce fuel consumption and emissions by up to 30%.[15] New lithium ferrous phosphate battery technology can allow for a 14 MWh battery with a usable energy capacity of about 10.1 MWh to reside within a single boxcar.[16] Staff estimates that four diesel locomotives with four battery tenders are required to complete the trip emission free from POLA to Barstow when FOS is one, and five diesel locomotives with five tender cars when FOS is 1.2. Additionally, operators may also choose to use battery locomotives with battery tenders to reduce the number of locomotives needed. For the FLXdrive and SD70J models on the route of POLA to Barstow, four battery locomotives with two battery tenders are needed when the FOS is one, and five locomotives with two battery tenders are needed when the FOS is 1.2.

Discontinuous Overhead Catenary Systems

While the route from the POLA to Barstow can be done by just battery electric locomotives alone, there are benefits to utilizing OCS compatible locomotives with battery electric locomotives in the same train. Track electrification using OCS has existed for more than 100 years and is commonly used in other parts of the world for freight transportation. Discontinuous OCS refers to the use of OCS along certain segments of a route rather than completely electrifying it. This can reduce the need for extensive electrification infrastructure and lower the initial investment and maintenance costs associated with electrification. By using discontinuous OCS, the OCS-compatible locomotives pull the train in electrified segments and the battery electric locomotives pull the train in non-electrified segments as shown in Figure 2 below.

The use of OCS along certain segments of the route from the POLA to Barstow can significantly reduce the number of locomotives required to complete the trip because the energy demand needed from battery electric locomotives would be less than if the trip were done by battery electric locomotives alone. OCS-compatible locomotives typically offer more traction power than standard line haul battery electric locomotives, which can also help to reduce the number of locomotives required to complete the trip. In addition to the energy and power advantages, when a train consisting of OCS-compatible and battery electric locomotives is under an OCS segment, the battery electric locomotives can recharge using pantographs connected to the OCS lines. This would help increase the operational range of the battery electric locomotives.

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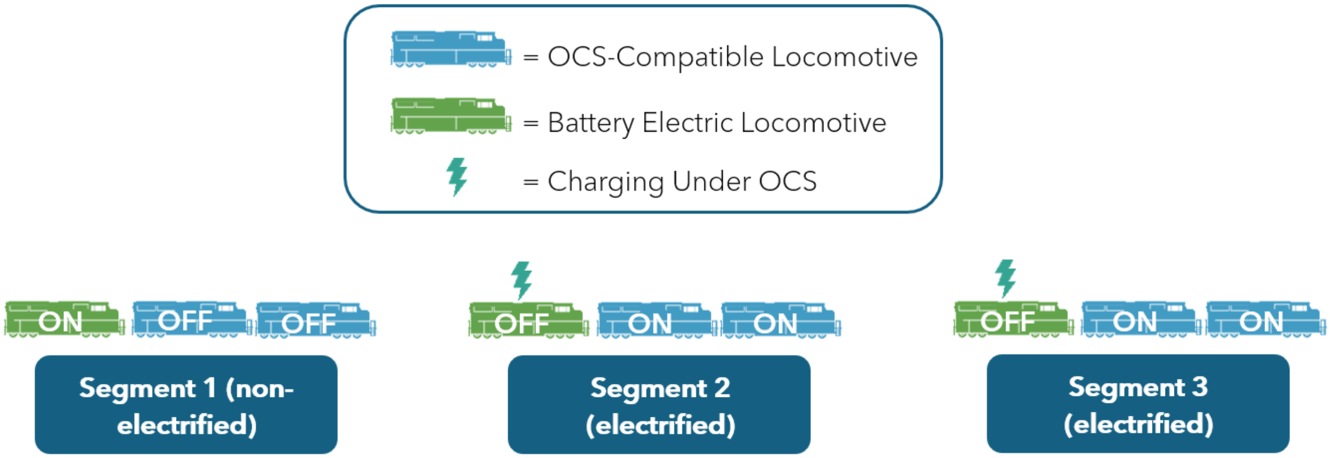
[15] Wabtec, Wabtec's All-Battery Locomotive, FLXdrive, Lowers Freight Train's Fuel Consumption by More than 11 Percent in California Pilot, May 17, 2021, accessed July 29, 2024. (Weblink: https://www.wabteccorp.com/newsroom/press-releases/wabtec-s-all-battery-locomotive-flxdrive-lowers-freight-train-s-fuel-consumption-by-more-than-11-percent-in-california#:~:text=At%20more%20than%206%20megawatt,energy%20savings%20and%20emission%20reductions.%E2%80%9D).

[16] Natalie D Popovich, et al. Nature Energy, Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric, November 11, 2021, accessed April 12, 2024. (Weblink: https://www.nature.com/articles/s41560-021-00915-5).

Figure 2: Example of Using Battery Electric and OCS-Compatible Locomotives with Discontinuous Catenary



The OCS-compatible locomotive evaluated in this analysis is the Siemens Vectron locomotive. This commonly used European freight locomotive provides up to 6.4 MW of traction power.[17] The FLXdrive Heavy-Haul and SD70J models are the two battery electric locomotives analyzed with the Siemens Vectron OCS-compatible locomotive.

The implementation of OCS along the route from the POLA to Barstow is explored in the three scenarios shown in Table 4. The implementation of OCS in Segment 1 was excluded due to the low power and energy requirements which can easily be handled by battery electric locomotives. OCS implementation in Segment 2 was excluded as the analysis found the number of locomotives required would be similar to just using battery electric locomotives. This analysis is meant to provide a high-level estimate of the number of OCS-compatible and battery electric locomotives needed to complete the trip from the POLA to Barstow if OCS is implemented along the route with a FOS of one.

Table 5 presents the number of battery locomotives needed between the FLXdrive Heavy-Haul and SD70J as well as the number of Vectron OCS locomotives needed to complete the trip from the POLA to Barstow.

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[17] Siemens, Vectron AC/DC/MS – the locomotive that's forging new paths, accessed April 5, 2024. (Weblink: https://www.mobility.siemens.com/global/en/portfolio/rolling-stock/locomotives/vectron/ac-dc-ms.html).

Table 4: Scenarios of OCS Implementation from POLA to Barstow

Scenario	**Description**
OCS in Segment 3	Battery electric locomotives pull the train in Segments 1 and 2. OCS-compatible locomotive pulls the train in Segment 3.
OCS in Segments 2 and 3	Battery electric locomotives pull the train in Segment 1. OCS-compatible locomotive pulls the train in Segments 2 and 3.

Table 5: Number of Locomotives Needed with OCS Implementation by Scenario

Locomotive Type	**Number of Locomotives Needed with OCS in Segment 3**	**Number of Locomotives Needed with OCS in Segments 2 and 3**
Battery Electric Locomotives	4	1
OCS-Compatible Locomotives	1	2

The results presented in Table 5 show the implementation of OCS along the route from the POLA to Barstow can reduce the number of locomotives required to complete the trip. Implementing OCS in Segment 3 requires a total of five locomotives and OCS implementation in Segments 2 and 3 requires three locomotives. Implementation of OCS along Segments 2 and 3 requires the least number of locomotives because the OCS-compatible locomotives offer more traction power and are not limited by energy capacity like battery electric locomotives are.

Operators may also take advantage of dual-mode locomotives such as the FLXdrive eHybrid which operates in battery or OCS mode.[18] The battery has a usable energy capacity of 1.66 MWh and when in battery only mode, the locomotive has 1.3 MW of traction power. When under OCS mode, the locomotive is assumed to have 4.2 MW of traction power. If OCS is implemented along Segments 2 and 3, only three FLXdrive eHybrid locomotives are required to pull the train from the POLA to Barstow (no other battery locomotives are needed.) The three FLXdrive eHybrid locomotives have enough power and energy capacity between them to operate in battery mode in Segment 1.

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[18] See Reference 11.

Conclusion

The use of ZE locomotives along the route from the POLA to Barstow is feasible with the ZE rail technology available today. Staff estimate between four to nine ZE locomotives (depending on model) are required to complete the trip from the POLA to Barstow and fewer locomotives are required when using discontinuous overhead catenary systems (OCS). There are multiple technology pathways available so that an operator may choose the pathway best suited for their business. The results highlight the advantages of combining multiple ZE technologies together. The integration of battery electric locomotives and tenders with other ZE technologies such as hydrogen fuel cell and OCS locomotives presents a pathway that provides better performance and operational flexibility than using a single ZE technology alone. This integration can also reduce the need for extensive infrastructure development while also reducing the number of locomotives required to complete the trip from the POLA to Barstow.