MEMORANDUM

TO	Association of American Railroads
FROM	T. Bruce Tsuchida, Long Lam, Kailin Graham, Sylvia Tang, Megan Diehl
SUBJECT	**Review of CARB's Proposed Regulation**
DATE	April 22, 2024

On October 27, 2023, the California Office of Administrative Law approved the "In-Use Locomotive Regulation," a new regulation proposed by the California Air Resources Board (CARB). This proposed regulation aims to reduce emissions from locomotives and railyards in California by phasing out higher-emitting locomotives and ramping up adoption of zero-emissions (ZE) locomotives. CARB indicates that operators may rely on battery-electric, hydrogen fuel cell, or overhead catenary technologies to comply with the proposed regulation.[1]

In this memo, we focus primarily on the potential costs and feasibility implications of complying with the proposed regulation in California using battery-electric locomotives as the ZE technology of choice. However, the impacts of this proposed regulation will not be limited to California; CARB envisions that railroad companies will need to convert their entire North American locomotive fleets to comply with the regulation.[2] While quantifying the additional costs outside of California is beyond the scope of this analysis, our findings should be considered as part of the larger context of the nation-wide impacts of CARB's proposed regulation.

[1] California Air Resources Board. (2023). *Final Statement of Reasons for Rulemaking, Including Summary of Comments and Agency Response*, page 37. Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/fsor2.pdf

[2] California Air Resources Board. (2022). *Proposed In-Use Locomotive Regulation Standardized Regulatory Impact Assessment (SRIA).* Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appb.pdf, page 35 ("To account for operators' current fleet management patterns and the interchangeability of locomotives within each fleet, staff assumed that each operator's entire fleet would comply with the Proposed Regulation, allowing all locomotives to operate as needed in California.").

Battery-electric locomotive technologies are in early stages of development, with deployment limited to pilots and demonstrations. This presents several significant challenges for railroad operators to comply with the proposed regulation. Because of the low energy density of current battery technologies relative to that of diesel fuel, a battery-electric locomotive would be substantially heavier than its diesel-electric counterpart. Without fundamental breakthroughs, deployment of battery-electric technologies may be limited to smaller locomotives. Even if battery-electric locomotive technologies were commercially available today, compliance with CARB's proposed regulation would require railroad operators to purchase many more battery-electric locomotives than they would need diesel-electric locomotives to service the same freight demand. This is due to longer refueling (or recharging) schedules. Further, heavier battery-electric locomotives may exceed limitations of existing railway infrastructure. The increased number of locomotives could surpass the existing capacity for locomotives at railyards, and operators in turn would need to incur additional costs to expand or construct new railyards.

Beyond investments in the locomotives and in necessary charging and servicing facilities, compliance with CARB's proposed regulation would also require investments in upgrades to power grid infrastructure. We estimate that the adoption of battery-electric locomotives in the most conservative case will require $15–$16 million per year of power grid infrastructure investments in California by 2035 (including investments in generation, transmission, and distribution capacity).[3] By 2050, the required annual power grid infrastructure investment costs would increase to $83–$88 million per year. From 2035 to 2050 a total of $780–$830 million of power grid infrastructure investment would be required. In the case of high battery-electric locomotive uptake, the annual power grid infrastructure investment costs would increase drastically: complying with the proposed regulation using a 100% battery-electric fleet would bring power grid investment costs to $109–$116 million per year by 2035, increasing to $146–$156 million per year by 2050, totaling $2–$2.1 billion for the 2035–2050 period. Notably, because line-haul locomotives operate over the entirety of North America, the need for additional investments in the power system will almost certainly extend beyond California to accommodate charging needed for interstate operation.

Overall, we find that the railroad industry and the power industry will face major technological, logistical, and cost hurdles in complying with CARB's proposed regulation within the prescribed timeframe.

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3 All monetary values in this memo are in nominal U.S. dollars.

I. Rail Operations in California

Federally, railroads are categorized by Class, and locomotives are categorized by Tier. The Class I railroads operating in California are managed by Union Pacific (UP) and BNSF Railway; these account for 95% of the state's locomotive activity.[4] UP and BNSF operate roughly 12,000 interstate line-haul locomotives in some capacity in California each year. These locomotives (and other interstate locomotives not operated by BNSF and UP) pull freight both within California and across the entire North American continent close to 24 hours a day, 7 days a week. Line-haul locomotives account for about 85–90% of statewide PM2.5 and NOx emissions from locomotives.[5] California's greenhouse gas (GHG) emissions from locomotives today are estimated to be about 1.3 million metric tons of carbon dioxide equivalent per year.[6] For reference, California's total GHG emissions in 2021 were estimated to be 381.3 million metric tons of carbon dioxide equivalent.[7]

Locomotives with lower Tiers (Tiers 0 to 2) face less stringent emissions standards than Tier 3 and Tier 4 locomotives (Tier 4 locomotives are the least emitting).[8] In addition to line-haul locomotives, approximately 600 switch locomotives or "switchers" account for an additional 5% of California's locomotive emissions, and operate over short distances within railyards.[9] Rail freight volumes and, therefore, line-haul and switcher locomotive activity in California are projected to continue to grow at an expected rate of about 2.2% per year.[10]

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4 California Air Resources Board. (2022). *CARB Fact Sheet: Class I Locomotive Operators*. Retrieved from https://ww2.arb.ca.gov/resources/fact-sheets/carb-fact-sheet-class-i-locomotive-operators.

5 California Air Resources Board. (2022). *CARB'S 2022 In-Use Locomotive Emission Inventory: Regulation Proposal and Scenarios*, p. 14. Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appg.pdf.

6 California Air Resources Board. (2023). *Current California GHG Emission Inventory Data*. Retrieved from https://ww2.arb.ca.gov/ghg-inventory-data.

7 *Id.*

8 California Air Resources Board. (2022). *CARB's 2022 In Use Locomotive Emission Inventory: Regulation Proposal and Scenarios*, p. 9. Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appg.pdf.

9 *Id.* at p. 14

10 *Id.* at p. 20

II. CARB's Proposed In-Use Locomotive Regulation

CARB's "In-Use Locomotive Regulation" aims to reduce emissions from locomotives in California by phasing out higher-emitting locomotives and ramping up adoption of ZE locomotives.[11] The proposed regulation contains two elements that will impact the scale and cost of necessary power grid investment:

- **Spending Account**: Locomotive operators will be required to deposit funds into a spending account, where their deposit amounts are proportional to their operational emissions in the previous year. The funds may be used to purchase, lease, or rent low-emissions Tier 4 locomotives or ZE locomotives as well as supporting infrastructure.[12] The proposed regulation also allows for retrofitting lower-Tier (Tiers 0, 1, 2 and 3) locomotives to Tier 4 or ZE locomotives.
- **In-Use Operational Requirements**: Starting in 2030 for switcher, passenger, and industrial locomotives, and in 2035 for line-haul locomotives, all new locomotives must operate in a ZE configuration. Additionally, starting in 2030, any locomotive that is more than 23 years old cannot operate in California; ZE locomotives are exempt from this age restriction.

Figure 1 below shows CARB's projection of total line-haul locomotive activity across locomotive types (i.e., Tiers) in California out to 2050 in the agency's Proposed Regulation Scenario. The figure shows the work (in MWh) done by various locomotives. According to CARB's analysis, the total workload will roughly double from approximately 3 million MWh in 2020 to 6 million MWh by 2050. CARB's projection shows high retirement rates for the lower Tier (i.e., Tiers 0, 1, 2, and 3) line-haul locomotives around the time the locomotive age restriction comes into effect in 2030. The retired locomotives are replaced with Tier 4 locomotives. Tier 4 locomotive activity is predicted to be close to 3 million MWh in 2030—this is comparable to the activity of all locomotives today, which are largely Tier 3 or lower.

Starting in 2035, railroad operators cannot operate any new Tier 4 locomotives under the proposed regulation due to the In-Use Operational Requirements; CARB therefore anticipates that railroad operators will begin purchasing ZE locomotives at that time and continue to meet demand growth with additional ZE locomotives. CARB also presents the possibility that railroad

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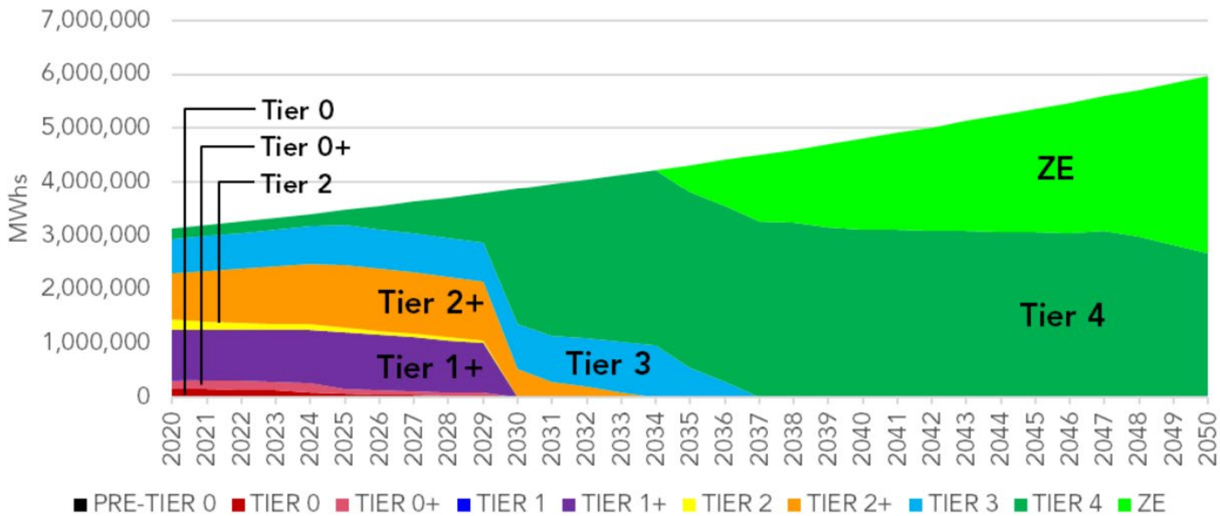
11 California Air Resources Board. (2023). *Final Regulation Order*. California Code of Regulations. Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/fro2.pdf.

12 The funds deposited into the Spending Account are calculated using a combination of the locomotives' emission factors (NOx and PM10) and annual activity measured in MWh.

companies could operate Tier 4 locomotives in a ZE configuration, but it is our understanding that current Tier 4 locomotives cannot easily be reconfigured to do so.[13,14]

In addition to the projection of line-haul locomotive activity in Figure 1, CARB makes similar projections for switch, short-line, passenger, and industrial locomotives. Across all locomotive types, CARB projects a total of 4.8 million MWh of locomotive activity by 2035 and 6.5 million MWh in 2050.[15] In these projections, CARB assumes the majority of switchers become ZE in 2030; and the majority of short-line, passenger, and industrial locomotives are ZE by 2033, 2042, and 2049, respectively.[16]

FIGURE 1: LINE-HAUL LOCOMOTIVE ACTIVITY BY LOCOMOTIVE TYPE IN THE CARB PROPOSED REGULATION SCENARIO (CALIFORNIA AIR RESOURCES BOARD, 2022)



Source and Notes: CARB's 2022 In Use Locomotive Emission Inventory: Regulation Proposal and Scenarios, Figure 7. CARB also provides similar analyses for switch, short-line, passenger, and industrial locomotives, which are accounted for in our calculations but not displayed here.

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13 California Air Resources Board. (2022). *CARB's 2022 In Use Locomotive Emission Inventory: Regulation Proposal and Scenarios*. Retrieved from https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appg.pdf.
Association of American Railroads. (2024).

14 CARB's scenario assumes that railroad operators maximize spending from the Spending Account each year. If a railroad operator has sufficient funds to purchase more low-emissions locomotives than are required to replace 23-year-old locomotives being removed from service, CARB assumes that railroad operators retire some locomotives that are less than 23 years old to make room for the low-emissions fleet. However, such a decision would result in railroad operators accepting additional stranded costs for the locomotives retired early and overlooks the possibility of operators delaying spending from their Spending Account until existing locomotives meet the 23-year mark.

15 2.19 % growth is assumed for switcher locomotive activity, while activity for short-line, passenger, and industrial is assumed to remain constant out to 2050.

16 CARB assumes that all switchers below Tier 4 are phased out by 2030, despite some of them not yet reaching 23 years of age.

The projections in CARB's Proposed Regulation Scenario highlight several major compliance challenges that the railroad industry will face. First, the industry will need to rapidly ramp up the deployment of Tier 4 locomotives in six years. As Figure 1 shows, most of today's locomotives are Tier 3 or lower, with Tier 4 locomotives comprising only 6.7% of the total North American locomotive fleet.[17] Effectively, the industry is being asked to replace all existing locomotives with Tier 4 locomotives. Reaching this level of deployment at the swift pace anticipated by CARB means that the industry will have to overcome challenges related to engineering and manufacturing logistics (e.g., raw material, labor force, and expanded capacities for factories and facilities).

Second, the new Tier 4 locomotives under CARB's proposed regulation cannot be operated in California once they reach the 23 years in age. This age limit is approximately half of the 40 to 50 years of economic life commonly assumed in the railroad industry.[18] This could lead to stranded assets for the railroad companies, if not a cost increase to the services provided.[19] To minimize stranded costs, railroad operators could sell or operate Tier 4 locomotives outside of California once they reach the age limit (a decision that would present serious operational challenges) or retrofit end-of-life Tier 4 locomotives (if such retrofit technology were to be available by that time). Alternatively, if ZE locomotives were to become commercially available, railroad operators could avoid the stranded costs by directly adopting ZE locomotives and bypassing Tier 4 locomotives.

III. Technical Issues with Electric Locomotives

While CARB indicates that operators may rely on battery-electric, hydrogen fuel cell, or overhead catenary technologies to comply with the proposed regulation, battery-electric locomotive technology appears to be the leading candidate for locomotive decarbonization in certain limited applications.[20] The other two candidate technologies score lower than battery-electric locomotives on the technological readiness scale and higher on cost and infrastructure

17 Internal Brattle correspondence with AAR.

18 Engine Technology Form. (2024). *Rail | Engine Technology Forum*. Retrieved from https://enginetechforum.org/rail#:~:text=These%20reduce%20emissions%20of%20nitrogen,as%20much%20as%2050%20years.

19 For simplicity, we are assuming the cost of lease contracts, or converting older Tiers for compliance, would converge with the cost of purchasing and owning new Tier 4 locomotives.

20 California Air Resources Board. (2016). Technology Assessment: Freight Locomotives. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2020-06/final_rail_tech_assessment_11282016%20-%20ADA%2020200117.pdf.

requirements.[21] In particular, electrification via catenary line is prohibitively expensive and provides less pulling power than is necessary for Class I freight.[22] Based on these factors, we evaluate the cost and feasibility of complying with the proposed regulation assuming battery-electric locomotives as the ZE technology of choice.[23]

Even if the battery-electric locomotives were commercially available, there are several major logistical challenges for the railway industry through this transition. A typical diesel-electric locomotive with a 5,000-gallon diesel tank can provide the equivalent energy to the railroad as a battery-electric locomotive with approximately 75–80 MWh of energy storage. However, the relatively low energy density of current battery technology limits the feasible energy storage capacity of a battery-electric locomotive, due to both weight and volume constraints. Tier 4 locomotives typically weigh around 420,000–430,000 lbs and are fueled with roughly 5,000 gallons or 35,000 lbs of diesel.[24,25] Locomotives weighing more than this may not be able to operate on current railways due to weight limits for certain parts of infrastructure (e.g., bridges).[26] By contrast, a lithium-ion battery with 75 MWh of storage capacity may weigh up to 660,000 lbs on its own, or one and a half times the locomotive's weight, before accounting for the weight of the non-battery components of a battery-electric locomotive.[27] These figures far exceed the current limitations on weight that the railway infrastructure supports today.

In addition, the low volumetric energy density of battery technology means that batteries may have to be connected via tender to the locomotive—this would displace a material portion of the train's total freight load, greatly impacting revenues for railroad operators.[28] Given these constraints, without fundamental improvements in battery technology, battery-electric

21 *Id.*

22 *Id.* at p. VIII-3.

23 However, we note that there are no commercially viable battery-electric locomotives today, and developing and testing alternate technologies can take several years. As a point of comparison, Caltrain is replacing its diesel locomotives with catenary-powered locomotives, and it took almost four years for the operator to finalize the design and another four to five years for manufacturing and testing. Compared to battery-electric locomotive technology, catenary-powered locomotive technology is much more matured. This experience highlights the extremely steep challenge the railroad industry faces, having to mass produce commercially viable battery-electric locomotives within ten years. *See* Caltrain. (2024). Electric Trains | Caltrain. Retrieved from https://www.caltrain.com/projects/electrification/electric-trains.

24 Assuming a fuel density of 7 lbs per gallon of diesel.

25 Union Pacific. (2016). New Locomotives Take Clean Air Tech from Theory to Reality. Retrieved from https://www.up.com/aboutup/community/inside_track/ge-tier-4-11-17-2016.htm.

26 Internal Brattle correspondence with AAR.

27 Brattle calculation based on energy density of 250 Wh/kg for lithium-ion batteries (Thunder Said Energy, n.d.). Heavier battery-electric locomotives can also cause damage to the track infrastructure over time.

28 Such a configuration may need to comply with existing regulations, such as those from the Federal Railroad Administration.

locomotive storage capacity is likely to be limited to below 20 MWh. For reference, the Progress Rail Joule Electric Locomotive, a battery-electric locomotive prototype that is not yet commercially available today, has an industry-leading battery capacity of 14.5 MWh.[29] This suggests that the railroad industry could require five times as many battery-electric locomotives to carry the same amount of work as diesel-electric locomotives, potentially leading to large cost increases.[30]

The railroad companies would also need to grapple with new complexities associated with operating battery-electric locomotive fleets, incurring significant costs to provide the same level of service. A typical diesel-electric line-haul locomotive with a 5,000-gallon tank can be refueled in approximately 20–25 minutes. By contrast, a battery-electric locomotive with 8 MWh of energy storage capacity (far below the capacity required to replace a diesel-electric locomotive) would take nearly six hours to recharge using the industry-leading 1.4 MW charger.[31] This much longer out-of-service time for charging means operators would need to purchase additional locomotives and/or modular batteries to ensure constant operations. Assuming 1.4 MW charging speeds, every three locomotive in service would require another two locomotives to be charging in order to maintain 24/7 operations.[32]

To accommodate the higher number of locomotives and necessary charging infrastructure, the railroad companies will also need to expand railyards or—more realistically—construct new railyards. Because many existing railyards have been in their current locations for decades (if not much longer), the surrounding space available for further development is extremely limited. With residential properties, commercial development, and industrial facilities already taking up much of the surrounding space, practical options for further railyard expansion may not exist.

These observations suggest that the railroad operators would have to acquire more battery-electric locomotives (beyond the number of new battery-electric locomotives needed to replace the existing diesel-electric locomotives) to ensure they can operate at the same level of service. And the railroad operators would need to make these consequential and costly

[29] Progress Rail. (2024). EMD Joule Battery Electric Locomotives. Retrieved from https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html

[30] 75 MWh / 14.5 MWh ≈ 5.

[31] Progress Rail. (2024). EMD Joule Battery Electric Locomotives. Retrieved from https://www.progressrail.com/en/Segments/RollingStock/Locomotives/FreightLocomotives/EMDJoule.html

[32] Based on an average in-service tractive power of 0.9 MW, obtained from operational data from the BNSF ZANZEFF project. BNSF Railway. (2021). BNSF Zero- and Near Zero-Emission Freight Facilities Project: Battery Electric Locomotive Consist. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2022-11/zanzeff-bnsf-belreport.pdf.

business and strategy decisions at a time when the technology is not fully ready. Furthermore, fleetwide adoption of battery-electric locomotives may require material expansions of railyard capacity to accommodate the extra battery-electric locomotives that charge between services. These are major costs to consider; however, we have not assessed their magnitude.

IV. Electric Energy and Power Requirements for Compliance with CARB's Proposed Regulation

The exact strategy the railroad industry may take to comply with the proposed regulation is uncertain at this time, and will depend on the relative economics, technological progress, and supply chain readiness of Tier 4 and ZE locomotives in the future. Furthermore, the proposed regulation does not prescribe the rate at which operators must adopt ZE locomotive technology. CARB's Proposed Regulation Scenario in Figure 1 anticipates growth in Tier 4 locomotives initially, with ZE locomotive growth beginning in 2034. However, as discussed earlier, Tier 4 locomotives are not common among all locomotives in service today. When combined with the deliverability and production challenges as well as potential stranded cost concerns, the railroad industry could choose to accelerate its adoption of ZE locomotives. These dynamics suggests two bookend futures (Futures) for ZE locomotives:

- **Future 1**: All Tier 3 and lower-tier locomotives are initially replaced with Tier 4 locomotives between 2030 and 2035, and then with ZE locomotives thereafter; this is what CARB shows in Figure 1.
- **Future 2**: All Tier 3 and lower-tier locomotives are replaced with ZE (i.e., battery-electric) locomotives immediately starting in 2030. Under this Future, Tier 4 locomotives (shown in darker green in Figure 1) will be replaced with ZE locomotives (shown in lighter green in Figure 1).

Under Future 1, the majority of post-2030 locomotive work in California is done by Tier 4 locomotives until about 2047. ZE locomotive activity is small in 2035 but grows to become the majority of locomotive activity in 2050.[33] By 2058, the last of the Tier 4 locomotives (put in service in 2035) will be retired (or retrofitted to ZE, if this becomes commercially and technically feasible) as they approach the 23-year age limit.

33 We are only discussing line-haul locomotives. However, CARB assumes that all lower-Tier switchers that are phased-out in 2030 are replaced with ZE switchers, with no increase in Tier 4 switchers past 2030.

Accommodating the charging of battery-electric locomotives would necessitate upgrades to power grid infrastructure, in proportion to the amount of power for charging that is required. Assuming ZE locomotives will be battery-electric locomotives, we estimate 872 GWh of electricity will be needed by 2035 to energize all ZE locomotives in California (including line-haul, switchers, short-line, passenger, and industrial locomotives) in Future 1. This corresponds to 100 MW of charging capacity. For comparison purposes, 100 MW is roughly equal to the power requirement of two to three mid-sized airports.[34] In 2050, the annual energy and power requirements grow to 4,799 GWh and 548 MW, respectively.[35] The magnitude of charging infrastructure requirements may be greater, depending on battery charging times and operational schedule.[36]

In Future 2, the electrical energy and charging capacity requirements are much greater. We estimate that in this Future, about 6,300 GWh of electrical energy and 720 MW of charging capacity would be needed by 2035 in California, increasing to 8,456 GWh and 965 MW by 2050, respectively. For reference, the total amount of electricity consumed by the 1.1 million households in San Diego County in 2022 was 7,440 GWh.[37] The exact impacts and feasibility of having the necessary charging infrastructure in place to support any transition to battery-electric locomotives would also depend on the distribution of the charging infrastructure, i.e., whether charging would be concentrated in a specific region (centralized charging) or dispersed throughout the state or region. We describe the cost impacts of the necessary infrastructure and related feasibility challenges in the sections below.

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[34] International Air Transportation Association, "Energy and New Fuels Infrastructure, Net Zero Roadmap," p. 7, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/energy-and-new-fuels-infrastructure-net-zero-roadmap.pdf

[35] We generate these estimates using the locomotive activity data provided here by CARB, an assumed diesel locomotive engine efficiency of 38% (Dick, 2016), an assumed efficiency ratio of 2:1 between battery-electric and diesel-electric locomotives (Popovich, et al. 2021, Phadke and Tasar 2019) and assuming 8,760 hours of operation per year.

[36] The charging capacity calculated here assumes charging schedules are fully optimized to minimize the capacity needs. In reality, optimizing the charging scheduling may not be possible because of operational constraints. Further, there may be needs to take charging facilities out of service, such as for maintenance needs. The charging capacity needs will increase when these factors are considered.

[37] California Energy Commission. (2022). Electricity Consumption by County. Retrieved from https://ecdms.energy.ca.gov/elecbycounty.aspx.
U.S. Census Bureau. (2024). U.S. Census Bureau QuickFacts: San Diego County, California. Retrieved from https://www.census.gov/quickfacts/fact/table/sandiegocountycalifornia,sandiegocitycalifornia,CA/PST120222.

V. CARB's Proposed Regulation Will Result in Higher Power System Costs

The power grid infrastructure needed in California to comply with CARB's proposed regulation and associated costs across the two Futures will depend on how chargers are distributed across the state. We develop and evaluate three hypothetical charging configurations (Configurations) to capture how the ZE locomotive charging facilities might be planned and operated across the state:

1. **Centralized**: battery-electric locomotive charging is concentrated where there is currently the most railyard activity
2. **Semi-distributed**: battery-electric locomotive charging is spread across three high-traffic regions
3. **Fully distributed**: battery-electric locomotive charging is spread across all existing California railyards

To calculate the power grid infrastructure investment costs, we first determine the additional capacity required for the charging of battery-electric locomotives, then calculate the costs of the power grid infrastructure upgrades utilities would have to make to accommodate this capacity.[38]

We determine the charging capacity required in each region under these Configurations based on amount of switcher activity in railyards in each California Air Basin.[39] Table 1 below summarizes the charging facilities' share by California's air basins across the three Configurations. In the Centralized Configuration, all charging facilities are located in the South Coast air basin, where most railyard activity is concentrated. In the Semi-distributed Configuration, charging facilities are located in the three busiest regions—South Coast, San Joaquin Valley, and the San Francisco Bay Area—proportionally to the region's railyard activity. In the Fully Distributed Configuration, charging facilities are located in all six air basins, proportionally to the region's railyard activity. We then map the six air basins to the three major California investor-owned utilities: Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E).

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[38] We assume that all additional capacity required for charging will necessitate utility infrastructure upgrades.

[39] California Air Resources Board. (2020). 2020 Locomotive Emissions Inventory. Air Quality Planning & Science Division Public Workshop. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2020-09/CARBlocoinvwebinar2020.pdf.

TABLE 1: CHARGING DISTRIBUTION BY REGION UNDER DIFFERENT CHARGING CONFIGURATIONS

Air Basin	Utility	% of Charging Located in Each Region		
		Centralized	Semi-Distributed	Fully Distributed
Mojave Desert	SCE	-	-	8%
Sacramento Valley	PG&E	-	-	8%
San Diego	SDG&E	-	-	2%
San Francisco Bay Area	PG&E	-	11%	9%
San Joaquin Valley	PG&E	-	18%	15%
South Coast	SCE	100%	71%	58%

Source and Notes: Brattle's calculations using data from 2020 Locomotive Emissions Inventory (ca.gov).
The Semi-distributed Configuration divides charging capacity across regions according to relative contribution to the total railyard activity of the three busiest regions.

For each Configuration, we estimate the costs of upgrading the respective utility's power grid infrastructure needed to accommodate the charging loads. Note that these are upgrade costs to the utility's equipment, and do not include costs associated with the charging facility that the railroad operator has to install. At a high level, there are three major cost categories associated with expanding the respective utility's power system:

- Generation capacity costs: the amortized cost of building additional generation resources to meet the additional electricity demand. The 2024 value ranges from $94/kW-year for PG&E to $136/kW-year for SDG&E.[40]
- Transmission capacity costs: the cost of expanding or reinforcing the transmission system to accommodate new load. The 2024 value ranges from $19/kW-year for SCE to$165/kW-year for SDG&E.
- Distribution capacity costs: the cost of upgrading distribution circuits, substations, and sub-transmission. The 2024 value ranges from $5/kW-year for SDG&E to $29 for SCE.[41]

For our calculations, we use the marginal generation and marginal transmission and distribution capacity cost data from each of the three Californian utilities.[42] We estimate the total system

40 Marginal generation costs are based on the capacity of a four-hour standalone utility scale, lithium-ion battery.

41 Marginal capacity costs are expected to escalate with inflation, with the exception of long-term marginal distribution capacity costs, which are expected to escalate at a greater rate than inflation.

42 California Public Utilities Commission. (2022). *2022 Distributed Energy Resources Avoided Cost Calculator Documentation*. Retrieved from 2022-acc-documentation-v1a.pdf (ca.gov)
Doherty, A. (2022). Decision Adopting Real-time Pricing Pilot and Marginal Generation Capacity Cost Study and its Usage. Public Utilities Commission of the State of California. *Retrieved from* 496322162.docx (live.com)
California Public Utilities Commission. (2021). *Prepared Testimony Executive Summary on Southern California*

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costs needed to build out charging infrastructure in California by multiplying the charging requirements by the respective capacity costs under each Future and Configuration.

Table 2 below summarizes the annual power grid infrastructure costs incurred by 2035 for the three Configurations for Future 1 (following CARB's Proposed Regulation Projection) and Future 2 (all existing locomotives are replaced by ZE locomotives and no Tier 4 locomotives).[43] Costs by 2035 are between $15–$16 million per year under Future 1, but drastically increase to $109–$116 million per year if complete electrification via batteries is considered (i.e., Future 2). The Fully Distributed Configuration has higher costs, primarily because it places additional charging in the service territory of PG&E and SGD&E, which respectively have higher generation and transmission marginal costs. Table 3 below displays the summary of annual power grid infrastructure costs incurred by 2050, and Figure 2 displays the cumulative power system investment needed between 2035 to 2050. From 2035 to 2050, a total of $780–$830 million of power grid infrastructure investments are needed under Future 1, and $2–$2.1 billion of investments are needed for Future 2.

TABLE 2: ESTIMATED ANNUAL POWER SYSTEM COST BY 2035 BY FUTURES ($MILLION PER YEAR)

	Future 1: CARB Proposed Scenario	Future 2: 100% ZE Scenario		
		Centralized	Semi-Distributed	Fully Distributed
Generation Capacity Cost	$10	$75	$73	$73
Transmission & Distribution Capacity Cost	$5–$6	$34	$41	$43
Total	**$15–$16**	**$109**	**$114**	**$116**

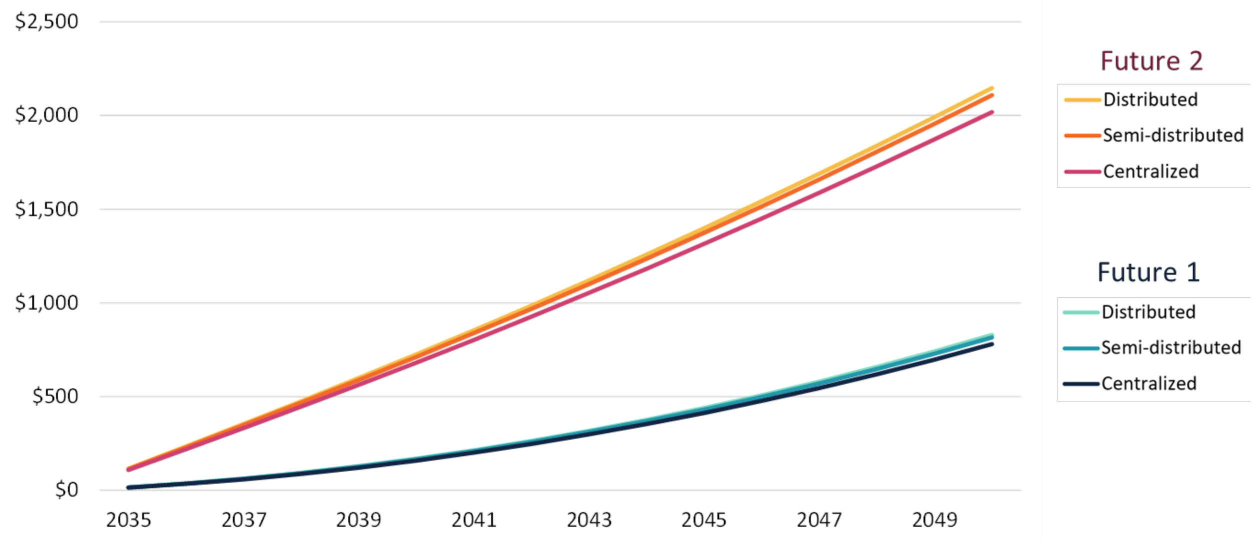
TABLE 3: ESTIMATED ANNUAL POWER SYSTEM COST BY 2050 BY FUTURES ($MILLION PER YEAR)

	Future 1: CARB Proposed Scenario	Future 2: 100% ZE Scenario		
		Centralized	Semi-Distributed	Fully Distributed
Generation Capacity Cost	$55-$57	$100	$98	$98
Transmission & Distribution Capacity Cost	$26-$33	$46	$55	$58
Total	**$83-$88**	**$146**	**$153**	**$156**

Edison's 2021 General Rate Case, Phase 2. Retrieved from 485618386.PDF (ca.gov)
SDG&E. (2023). *Revised Prepared Direct Testimony of Jeff De Turi on Behalf of SDG&E. Public Utilities Commission of the State of California.* Retrieved from Microsoft Word - 2024 GRC Phase 2 - REVISED Chapter 5 (DeTuri-Commodity) Redline (sdge.com)

43 Annualized costs are amortized over 20 years. California Public Utilities Commission. (2022). *2022 Distributed Energy Resources Avoided Cost Calculator Documentation*. Retrieved from 2022-acc-documentation-v1a.pdf (ca.gov).

FIGURE 2: CUMULATIVE POWER SYSTEM INVESTMENT COSTS FROM 2035 TO 2050



We note that, for several reasons, the above cost figures are conservative estimates and likely represent the lower bound of power grid infrastructure costs that would be incurred in California to facilitate the necessary charging.

First, the marginal cost data used in our analysis is based on studies conducted by California's utilities as of 2024. However, these marginal costs are likely to increase over time as California, in its pursuit of an economy-wide electrification strategy, continues to add considerably more load and demand for electricity. As more load interconnects to the power system, it becomes more constrained. Consequently, more costly upgrades to the grid will be required. Rapid growth in electricity demand therefore increases the marginal costs of building out generation, transmission, and distribution.[44] Therefore, if large charging loads such as those required under Future 2 interconnect to the grid, the costs to add an additional MW of load may be much higher than those used to derive the figures above.

Second, the location of the charging facilities within each air basin (and utility region) will also impact the actual infrastructure costs. The costs reported in the utilities' marginal cost studies represent the average marginal cost across the entire service territory of each utility. The actual marginal cost of providing extra capacity will vary depending on the state of the power system and the feasibility of upgrading it at a given location. Transmission or distribution system

[44] For example, serving the same amount of energy through intermittent renewable resources that are typically located far from population centers where power is consumed, oftentimes require more transmission capacity (to account for the intermittent nature) and length (to account for the distance between the resource and load it serves), leading to larger investments. Integrating larger amounts of intermittent renewable resources will also likely require more operational flexibility, such as those provided by battery storage, and again leading to larger investments.

upgrades in an urban, densely populated area will likely differ significantly from those in a rural area. Such considerations need to be balanced with the logistical and scheduling considerations of railroads when anticipating the most suitable locations within California for charging infrastructure.

Third, investments in the power system are lumpy, or discrete in size, and cannot be built exactly to size. This characteristic requires the utility to overbuild its system to serve the customer. For example, assume a utility is planning to serve a new 60 MegaVolt-Amp (MVA) load. If the transfer capabilities of available transmission lines are either 50 MVA with lower cost or 70 MVA with higher cost, the utility will have to build using the higher cost 70 MVA line to serve the 60 MVA load, resulting in a 10 MVA overbuild. The calculation based on marginal cost ignores this reality and assumes one could build incrementally to the exact size needed.

Finally, the costs estimated above cover the power grid infrastructure investments needed in California to comply with the proposed regulation. Because line-haul locomotives that operate in California do not stay in the state but travel across the entirety of North America, similar investments in the power system will be needed outside of California to support interstate operation. Switching diesel-electric locomotives to battery-electric locomotives would require charging infrastructure to be installed across the country. Therefore, our findings for California should be considered in the context of these additional cost and feasibility challenges.

VI. Feasibility and Logistics

A partial or full transition to battery-electric locomotives in California would represent a major electrification project, not dissimilar to interconnecting a large industrial load to the power system. Such interconnections are subject to a range of complex and lengthy planning, permitting, and construction requirements. Below, we describe the form these processes might take. As the discussion highlights, developing large-scale electricity infrastructure does take time, oftentimes in the range of five to ten years. This observation suggests that the timeline outlined in the proposed regulation (i.e., only ZE locomotives are allowed after 2035, which is only a decade away) to be unrealistic.

A. Planning

Whenever a large electric load is seeking interconnection to the electricity system, the new load and the utility serving the new load will go through a planning process to ensure that the new interconnection does not impact the reliability of the power grid. The level of extensiveness of this process depends on the size and characteristics of the load, the location of interconnection (e.g., whether it is seeking interconnection to the distribution or transmission system, or where within the transmission or distribution system), and how much additional infrastructure upgrades are needed to facilitate the interconnection. Upgrade needs could include large-scale infrastructure components—such as high-voltage transmission lines or substations—as well as distribution and site-level infrastructure components.

In California, each major utility is responsible for interconnecting load to their transmission and distribution system. While the exact planning processes vary across utilities, generally, once a party requests to interconnect load to the transmission or distribution system, the utility will conduct studies to determine whether it would need to modify or upgrade its system to facilitate the interconnection. For example, if an entity seeks to connect to the PG&E distribution system, the initial application needs to include information such as load profile, load breakdown, five years of monthly historical load data and five-year load forecast. [45] Other information requested include electrical, civil, architecture drawings, and equipment.[46] The interconnecting party is typically required to cover the costs of the studies as well as the costs of upgrading or modifying the power system.

B. Permitting

The permitting process for large loads is evaluated on a case-by-case basis and depends on the scale of the project. Required permits for charging infrastructure itself (excluding associated grid infrastructure) could include construction and building permits, as well as an Environmental Impact Report demonstrating compliance with the California Environmental Quality Act (CEQA).[47] Supporting power system infrastructure may be exempt from these permitting requirements if the proposed facilities are adequately described in the project's

[45] PG&E. (Accessed 2024). Wholesale Distribution Tariff Application Review and Checklist. Retrieved from https://www.pge.com/assets/pge/docs/about/doing-business-with-pge/wdt-checklist.pdf.

[46] The initial application requires the location of the points of delivery, site plan, building elevation plans, switchgear elevation view, single line diagram, meter and relay diagrams, three-line diagrams of required protective device. Construction details such as switchgear and meter section specs/cut sheets, control diagrams including direct current tipping circuit and full-size phase and ground coordination curves showing full coordination with the utility's system are required as part of the design and engineering process.

[47] City of San Jose. (2016). Initial Study/Mitigated Negative Declaration for the Equinix Data Centers (SV-12, SV-13, SV-14) and Santa Teresa Substation. Retrieved from https://www.sanjoseca.gov/home/showpublisheddocument/26217/636691074137830000.

other permitting documents, particularly the CEQA review—PG&E provides guidance on navigating this process in its transmission and distribution interconnection handbooks.[48]

Recent growth in the construction of data centers in California presents a relevant case study for the permitting process that railroad operators could face when connecting large charging load to the power system. In San Jose, California, three large datacenters recently interconnected to the power system.[49] The initial study on the data centers was performed in 2016 and was later revised and re-submitted with Addendum in 2019. PG&E submitted its proposal to construct the Santa Teresa Substation and related facilities on July 29, 2019. Seven months after submitting the proposal (February 27, 2020), the California Public Utilities Commission's Energy Division determined the construction of the facilities was exempt from a Permit to Construct.[50] This four-year process may have taken longer if more intervenors joined the regulatory process.[51]

C. Construction

The construction process is also unique to each project. For example, the Automated People Mover (APM) in Los Angeles, a 2.25-mile elevated guideway that would connect Los Angeles International Airport (LAX) with public and private transportation, is now estimated to take more than seven years to complete.

The APM project uses design-build-finance-operate-maintain (DBFOM), a public-private-partnership contracting model. The developer is responsible for the design and construction of

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48 PG&E. (2023). Transmission and Distribution Interconnection Handbooks. Retrieved from https://www.pge.com/en/about/doing-business-with-pge/interconnections/handbooks.html.

49 Tostado, M. (2022). Builds Substation in Silicon Valley to Provide Reliable Power to Data Centers, Improve Operating Flexibility in South San Jose. Retrieved from https://www.pgecurrents.com/articles/3395-pg-e-builds-substation-silicon-valley-provide-reliable-power-data-centers-improve-operating-flexibility-south-san-jose.

50 PG&E. (2019). Staff Disposition of Pacific Gas and Electric's (PG&E's) Advice Letter 5601-E and PG&E's Supplemental Advice Letter 5601-E-A on Notice of Construction, pursuant to General Order 131-D, for the Construction of the Santa Teresa Substation in the City of San Jose. Public Utilities Commission. Retrieved from https://www.pge.com/tariffs/assets/pdf/adviceletter/ELEC_5601-E.pdf.

51 The key project-related approvals, agreement, and permits for the project included: Grading Permits, Building Permits, Use Permits, Tree Removal Permits, Permit to Construct (to be obtained from the California Public Utilities Commission for Substation), Permit to Construct (to be obtained from Bay Area Air Quality Management District for diesel-fueled generators), and Occupancy permits and Permit to Operate for Generators (to be obtained from Bay Area Air Quality Management District. City of San Jose. (2016). Initial Study/Mitigated Negative Declaration for the Equinix Data Centers (SV-12, SV-13, SV-14) and Santa Teresa Substation. Retrieved from https://www.sanjoseca.gov/home/showpublisheddocument/26217/636691074137830000

the APM System, including the operating system (vehicles & operating technology) and fixed facilities (stations, guideway, infrastructure). Construction began in 2018 and was originally planned to be completed by 2023. However, it was later postponed to 2024, and recent updates suggest that it may not be ready until late 2025.[52]

On the power infrastructure side, LAX recently updated its infrastructure to address persistent power reliability, redundancy, and capacity issues. LAX constructed a new power receiving station (Receiving Station X or RS-X) in cooperation with the Los Angeles Department of Water and Power (LADWP). The contracted builder started to perform design, pre-construction, and construction services in November 2019 and completed them in May 2022. In addition to the new receiving station, design and installation of new 34.5-kV distribution feeder duct banks will connect to the existing distribution system to the Automated People Mover train system.

D. Bulk Power and New Resources

If the new load is to interconnect directly to the transmission system, investments in the transmission system may be needed. Building out transmission typically represents a hefty investment that needs to be phased in over lead times of five to 10 years or more. For example, it took LADWP 8 years to develop the Barron Ridge Renewable Transmission Project, which provided customers access to approximately 1,000 MW of wind and solar power.[53]

Similarly, adding new resources to serve the new load (which are likely renewable resources in California) will require time. New utility-scale resources that are interconnecting to the transmission grid go through a series of interconnection studies. The Lawrence Berkeley National Laboratory estimates that a typical project built in 2023 took nearly 5 years from the interconnection request to commercial operation.[54] The lengthy generation interconnection process is now being reviewed by the various system operators and utilities.

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[52] Shalby, C. (2024). *"LAX's long-promised rail link, the People Mover, likely delayed until late 2025"*. Los Angeles Times. Retrieved from https://www.latimes.com/california/story/2024-03-29/lax-people-mover-likely-delayed-until-2025.

[53] LADWP, (2016). *"The Barron Ridge Renewable Transmission Project cost $300 million"*. LADWP News. Retrieved from *Corrected* Barren Ridge Project Brings Renewable Energy Home (ladwpnews.com).

[54] Rand, J. et al. (2024). *Queued Up: 2024 Edition Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023*. Lawrence Berkeley National Laboratory. Retrieved from https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_1.pdf.

Interconnection for new resources on the distribution system have different processes.[55] For example, PG&E offers three study pathways for interconnection of distribution-level (60 kV or lower) projects, depending on different project scales and impacts on the electrical system: Fast Track, Independent Study, and Cluster Study.[56] The Fast Track process, which aims at projects with minimal system impact, takes about three months to complete and includes a series of 10 screening steps. If a project fails these screens, further analysis via Independent or Cluster Studies may be necessary. The Independent Study, suitable for "electrically independent" facilities up to 20 MW, ranges from six to 12 months to complete, depending on project complexity.[57] The Cluster Study, for projects not electrically independent and impacting the system collectively, occurs once annually in March with a completion timeline of 18 to 20 months, encompassing both Phase 1 and Phase 2 studies to evaluate system-wide impacts and facilitate cost-sharing for necessary upgrades.[58]

VII. Conclusion

CARB's In-Use Locomotive Regulation represents a dramatic shift in operations, infrastructure, and logistics of the railway sector, not just in California but across North America. In this document, we evaluate the cost and feasibility implications of the proposed regulation on the California power system. First, we find that compliance with the proposed regulation while maintaining the same level of service will likely require railroad operators to acquire far more battery-electric locomotives than what their fleet size today would suggest. This is due to longer refueling (or recharging) schedules and weight limitations the railroads may have.

Second, this increased number of locomotives may exceed existing railyard capacity, presenting an additional challenge of expanding and/or developing new railyard infrastructure. Third, we calculate the cost of upgrading the utilities' assets to accommodate the railroad operators' charging facilities for the battery-electric locomotives. This cost calculation considers solely upgrades to California's power system and does not include that for the actual charging facilities.

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55 Resources that are eligible to interconnect at lower voltage systems will be much smaller in size (i.e., capacity).

56 PG&E. (2024). *Understand PG&E Distribution Qualifications*. Retrieved from https://www.pge.com/en/about/doing-business-with-pge/interconnections/understand-pge-distribution-qualifications.html#accordion-d4b55bbcb5-item-799cda4966.

57 SDG&E. (Accessed 2024). *Generator Interconnection Procedures (GIP) Attachment H*. Retrieved from https://www.sdge.com/sites/default/files/WDAT%20%20Generator%20Interconnection%20Procedures%20-%20Attachment%20H.pdf.

58 Given the power requirements, charging infrastructure supporting battery-electric would likely require an Independent Study or a Cluster Study.

In performing this analysis, we considered two Futures for the industry in compliance with the proposed regulation: one which follows CARB's projections of a phasing out of emissions-intensive locomotives in favor of Tier 4 and eventually battery-electric locomotives, and one in which railway operators endeavor to meet demand for locomotive activity with solely battery-electric locomotives. In 2035, the annual power and capacity needs for California to charge battery-electric locomotives are 872 GWh and 100 MW under CARB's projected Future and 6,300 GWh and 720 MW under the 100% battery-electric Future. This corresponds to $15–16 million and $109–116 million, respectively, of annual power system capacity costs by 2035 for the infrastructure needed to support locomotive charging, depending on the charging Configuration across the state assumed. Between 2035 and 2050, the total cost of power grid infrastructure investments under the CARB's projected Future is $780–$830 million, and $2-$2.1 billion for the 100% battery-electric Future. Importantly, these costs cover only those incurred from expanding California's power system; given that line-haul locomotives travel across all of North America, the proposed regulation would almost certainly require the industry to shift to battery-electric locomotives, impacting power systems throughout the country.

Overall, we find that the railroad industry will face very significant barriers to complying with this proposed regulation within the prescribed timeframe.

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