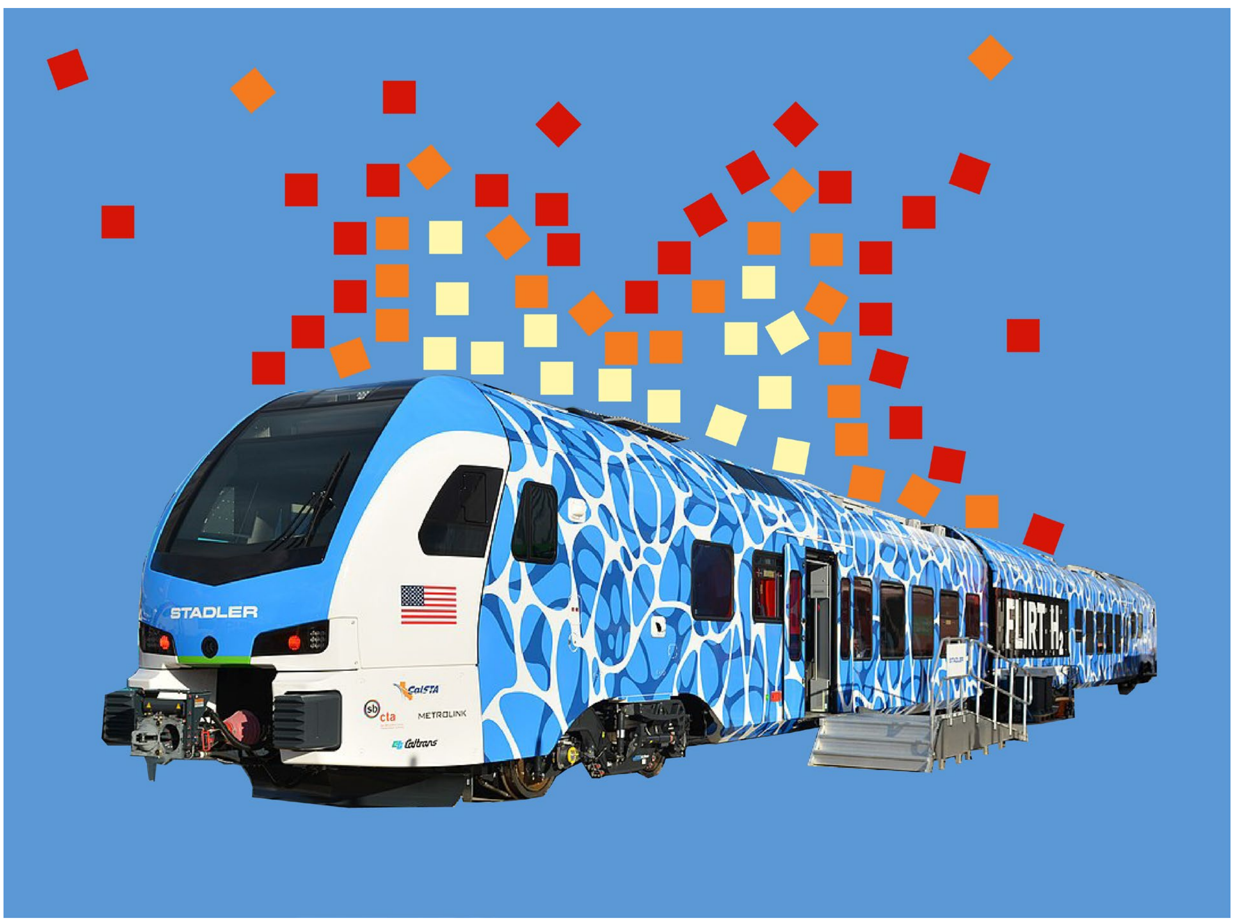
Running on Fumes: A Critical Analysis of Caltrans' 'Colored Squares' Justifications for Hydrogen Rail

Caltrans shows a few colored squares on a chart to justify hundreds of millions of tax dollars being spent on dubious, unproven hydrogen rail technology

Californians for Electric Rail

July 2025



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In 2023 and 2024, Caltrans ordered a total of 10 hydrogen-powered Stadler FLIRT trains at a cost of $207 million - an average of nearly $21 million for each - with the option to further purchase 19 more[1]. This purchase was made before a single one of the hydrogen FLIRTs was even demonstrated and operated in the state of California. In early 2023, Caltrans released a draft state rail plan that largely dismissed overhead wire electrification and proposed hydrogen as the state's preferred zero-emissions rail propulsion technology (with no real justification given). It appeared that California was committed to a hydrogen train future.

Thankfully, in response to outcry from advocates, the 2024 final California State Rail Plan changed course considerably and now calls for 1500 miles of overhead electrified rail by 2050, including Capitol Corridor, much of Metrolink, and a new high speed rail line to Arizona (though notably does not include electrification of LOSSAN coastal rail corridor all the way to San Diego). However, the state rail plan still aims to use hydrogen fuel cell trains as a "bridge" technology before the full overhead wire network is built out. The final plan (p. 9) still makes this claim without evidence: "Since hydrogen fuel cell and battery technologies can be deployed faster and cheaper than overhead electrification, these demonstration projects help Caltrans and Caltrain deploy zero emissions service faster". Therefore, we still need to be skeptical about what Caltrans claims about hydrogen-powered rail. In the short term, after the initial Arrow pilot service of a Stadler hydrogen-powered FLIRT train between San Bernardino and Redlands, the next rail line slated to receive hydrogen trains is the Valley Rail service in the Central Valley.

California rail passengers are significantly affected by the choice of hydrogen versus electric trains. As has been argued countless times before by Californians for Electric Rail, Rail Passenger Association of California and other rail industry insiders and experts, the hydrogen units are significantly more expensive upfront than an equivalent-sized electrical multiple units, they cost more to maintain, more to operate, and hydrogen trains simply cannot perform as fast and reliably as all-electric trains. Conventional rail electrification, using an overhead contact system (or OCS, most typically an overhead catenary wire), is more environmentally friendly and reliable than hydrogen propulsion in almost every respect.

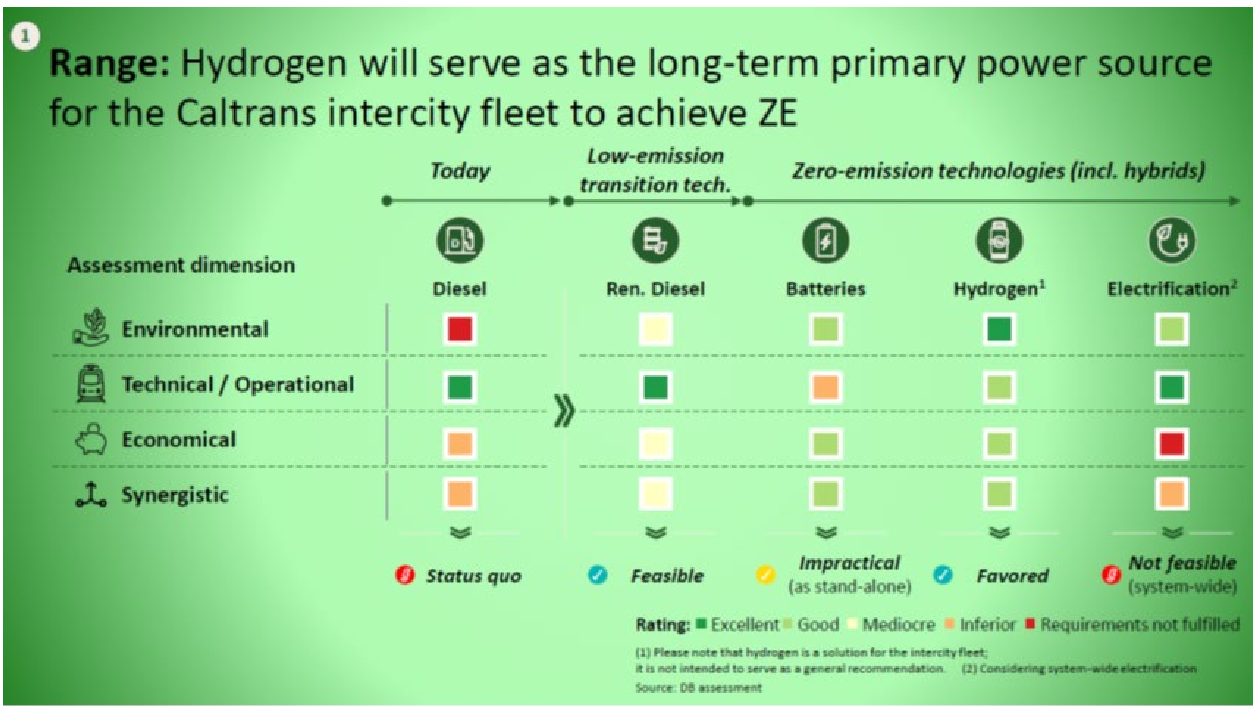
So what was California's justification for high-profile hydrogen train investments? As it turns out, there was little substance to it.

[1] "California Continues to Expand Hydrogen-Powered Passenger Rail Fleet" – Caltrans, February 2024 https://dot.ca.gov/news-releases/news-release-2024-007; "Arriving Soon in California: First Intercity Zero-Emission, Hydrogen Passenger Trains in North America", Caltrans October 2023. https://dot.ca.gov/news-releases/news-release-2023-034

Debunking Caltrans' Justification for Hydrogen

Some simplistic graphics are the only public justification given for Caltrans spending over $200 million on hydrogen trains

What evidence does Caltrain give to justify hundreds of millions of California state tax dollars on an unproven technology? Apparently, just a few misleading presentation slides with colored squares. Below is a slide from a presentation titled "FLIRT H2 Multiple-Unit Trainset Procurement Updates", from the Office of Assets and Equipment from Caltrans Division of Transportation Planning[2]. It was shown at the 2024 Next Generation Equipment Committee Annual Meeting. This graphic boldly proclaims, in big letters at the top, that "hydrogen will serve as the long-term primary power source for the Caltrans intercity fleet to achieve ZE". The only justification given for the determination is some colored squares on several charts, and a dozen or so one-sentence (or sentence fragment) explanations.



This slide is too simplistic, patronizing and misleading. This may be Caltrans' latest presentation on 'zero-emissions' rail, but they have showed versions of this slide since 2021, never providing any solid evidence for why the squares are colored other than the same, repeated one or two fragments of a sentence. No numerical data is presented to justify why a certain square is a particular color.

This analysis (source of which is credited at the bottom of the slide as "DB assessment") is seriously flawed and flies in the face of evidence from around the world that electrically powered

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[2] FLIRT H_2 Multiple-Unit Trainset Procurement Updates, 2024 NGEC Annual Meeting https://www.ngec.org/wp-content/uploads/2024/05/1100-ZEMU-NGEC-2024-Caltrans-Fleet-Updates_final.pdf

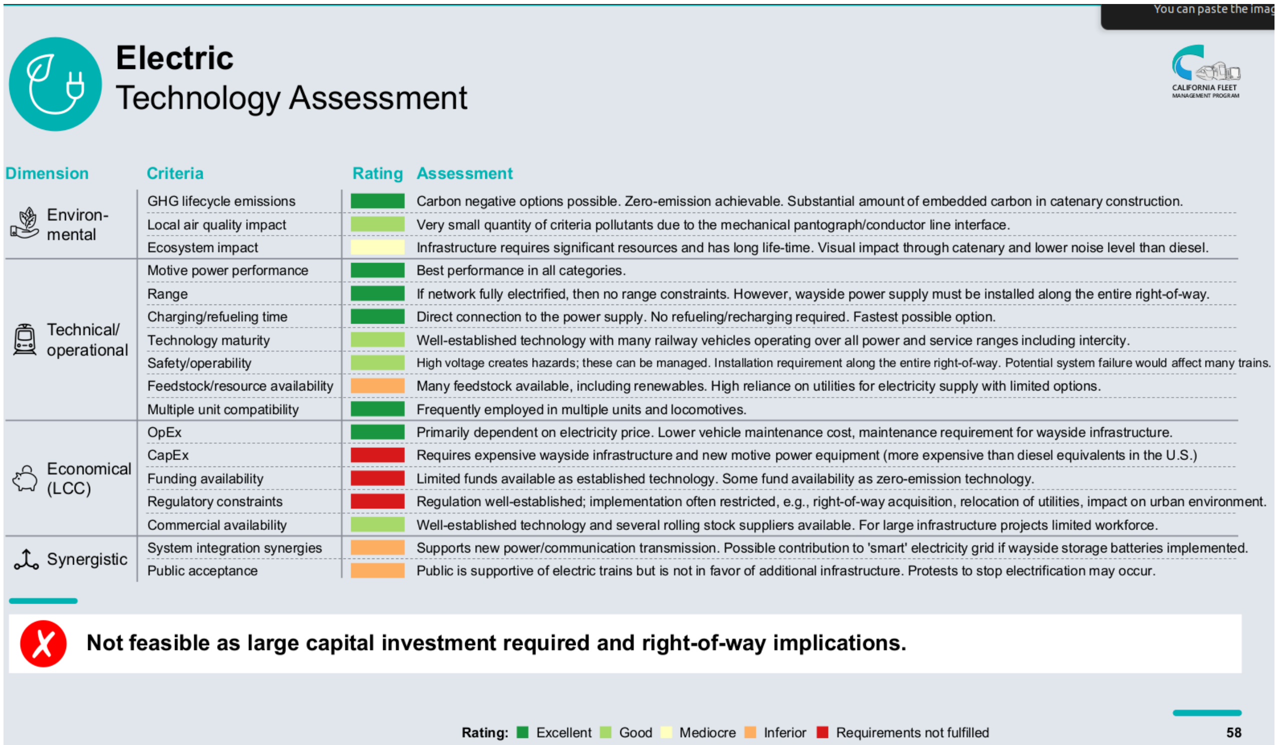
trains are superior in terms of performance, speed, reliability, lower maintenance and lower total life costs, including the cost of installing the catenary infrastructure. All of the squares in the hydrogen column should be solid red. Caltrans needs to be pressed on the evidence basis they used to justify their selection of hydrogen propulsion.

Electrification is judged to be "not feasible (system wide)" with the only justification being a note saying "considering system-wide electrification". Advocates for rail electrification in California are not even saying all railroad tracks in the state should be electrified with overhead wire, but we *are* saying it's time to take a serious look at the busiest mainlines as a start. Advocates' suggestions were ultimately adopted in the final 2024 state rail plan, which calls for a phased, system-wide approach, further demonstrating the ridiculousness of this unjustified claim.

Note one disclaimer at the bottom: "Please note that hydrogen is a solution for the intercity fleet; it is not intended to serve as a general recommendation". This slide is in fact making a "general recommendation" that hydrogen power both intercity passenger (state-supported corridors) and regional services (Valley Rail, Metrolink/SBCTA Arrow). Stating that conventional electrification is "not feasible systemwide" also sounds like a "general recommendation". The state-supported Amtrak routes of the *San Joaquins*, *Capitol Corridor* and especially the *Pacific Surfliner* (with CHSRA slated to provide overhead wire between Burbank, LA and Anaheim), are in fact prime for catenary electrification. This would especially be true with long-overdue increases in service frequency.

Life cycle costs (LCC) as shown on the chart as solid red ("requirements not fulfilled") for electrification, while hydrogen is dark green, flies in the face of actual upfront costs and operating experience of hydrogen trains around the world.

This slide from a previous presentation on the California Fleet Modernization Program goes into slightly more detail:



Dimension	Criteria	Rating	Assessment
Environ-mental	GHG lifecycle emissions	Excellent	Carbon negative options possible. Zero-emission achievable. Substantial amount of embedded carbon in catenary construction.
	Local air quality impact	Good	Very small quantity of criteria pollutants due to the mechanical pantograph/conductor line interface.
	Ecosystem impact	Mediocre	Infrastructure requires significant resources and has long life-time. Visual impact through catenary and lower noise level than diesel.
Technical/ operational	Motive power performance	Excellent	Best performance in all categories.
	Range	Excellent	If network fully electrified, then no range constraints. However, wayside power supply must be installed along the entire right-of-way.
	Charging/refueling time	Excellent	Direct connection to the power supply. No refueling/recharging required. Fastest possible option.
	Technology maturity	Good	Well-established technology with many railway vehicles operating over all power and service ranges including intercity.
	Safety/operability	Good	High voltage creates hazards; these can be managed. Installation requirement along the entire right-of-way. Potential system failure would affect many trains.
	Feedstock/resource availability	Inferior	Many feedstock available, including renewables. High reliance on utilities for electricity supply with limited options.
	Multiple unit compatibility	Excellent	Frequently employed in multiple units and locomotives.
Economical (LCC)	OpEx	Excellent	Primarily dependent on electricity price. Lower vehicle maintenance cost, maintenance requirement for wayside infrastructure.
	CapEx	Requirements not fulfilled	Requires expensive wayside infrastructure and new motive power equipment (more expensive than diesel equivalents in the U.S.)
	Funding availability	Requirements not fulfilled	Limited funds available as established technology. Some fund availability as zero-emission technology.
	Regulatory constraints	Requirements not fulfilled	Regulation well-established; implementation often restricted, e.g., right-of-way acquisition, relocation of utilities, impact on urban environment.
	Commercial availability	Good	Well-established technology and several rolling stock suppliers available. For large infrastructure projects limited workforce.
Synergistic	System integration synergies	Inferior	Supports new power/communication transmission. Possible contribution to 'smart' electricity grid if wayside storage batteries implemented.
	Public acceptance	Inferior	Public is supportive of electric trains but is not in favor of additional infrastructure. Protests to stop electrification may occur.

Let's review all the poorly-rated colored rectangles on the above slide about overhead wire rail electrification, which is concluded to be "not feasible as large capital investment required and right-of-way implications".

Environmental

On the above slide comparing propulsion alternatives, under 'Environmental' hydrogen is ranked dark green (excellent) and electrification light green (good). This is ridiculous. Conventional rail electrification, using an OCS , is more environmentally friendly than hydrogen propulsion in almost every respect:

- *Energy efficiency* - Hydrogen trains are inherently far less energy efficient than all-electric trains powered by OCS, due to the fundamental physical properties of the gas, and fundamental physics of converting hydrogen to/from electrical energy. Using electricity from the grid to produce hydrogen power for rail applications has very poor overall energy efficiency of 25% ("grid to wheel") at best, compared to an overall energy efficiency ranging ~72-77% for an electric train using an overhead wire[3]. Even if the electricity used to produce the hydrogen comes from green sources, a train would require three times the amount of overall energy compared to an electric train connected directly to the grid[4]. That means that using all-electric trains with

[4] "Freight Railroad Decarbonization & Energy Efficiency: The Dual Challenge for Railroads (Version 2)" Mike Iden, UIUC Hay Seminar, September 27, 2024 https://railtec.illinois.edu/wp/wp-

pantographs will always have at least three times less energy consumption impact on the environment than those using hydrogen. Two-thirds of the energy used to produce the hydrogen is wasted. Hydrogen fuel cell trains are even less efficient than diesel hybrid drivetrains.[5]

- *Fossil fuel sources and greenhouse gas emissions* - Most of the handful of hydrogen trains in use today get their hydrogen from fossil fuel sources. Until someday in the future, when hydrogen will primarily be from renewables via electrolysis, fossil fuels will continue as the energy source for hydrogen powered trains. At present, renewably-produced green hydrogen is far more expensive compared to hydrogen sourced directly from fossil fuels, and this is likely to remain true in the future[6]. Green hydrogen costs actually increased from 2023-2024 despite policy intended to bring it down.[7] Hydrogen production plants that are entirely reliant on dirty fossil-fuel sources are currently being built in California with public money[8], and recent guidelines for hydrogen tax credits will subsidize hydrogen production that may increase fossil fuel usage[9]. Hydrogen itself is also an indirect greenhouse gas[10], with significant climate risks that are only beginning to be understood[11]. Hydrogen leaked into the atmosphere prolongs the life of atmospheric methane emissions (an especially potent greenhouse gas), and fossil fuel extraction, which fossil hydrogen prolongs the life of, is a major source of methane emissions[12]. The water vapor emitted by fuel cells is also not as harmless as hydrogen proponents claim – it in fact rises into the stratosphere and

content/uploads/UIUC-Hay-Seminar_Iden_20240927.pdf; "Why Rail Electrification Report", UK Rail Industry Association, 2021. https://www.riagb.org.uk/RIA/Newsroom/Why_Rail_Electrification_Report.aspx

[5] "Comparative analysis of alternative powertrain technologies in freight trains: A numerical examination towards sustainable rail transport", Aredah et al., *Applied Energy, 2024.* https://www.sciencedirect.com/science/article/pii/S0306261923017750

[6] "Green Hydrogen Pricier than Projected", *The Harvard Gazette*, October 2024 https://news.harvard.edu/gazette/story/newsplus/green-hydrogen-far-pricier-than-projected/

[7] "The billion-dollar US green hydrogen boom ended before it ever began", *Canary Media*, June 2025 https://www.canarymedia.com/articles/hydrogen/green-industry-trump-tax-credits/

[8] "A California Port Gambles on Dirty Hydrogen", *Heatmap News*, September 2024. https://heatmap.news/economy/hydrogen-port-stockton-bayotech

[9] "There's Something for (Almost) Everyone in the Hydrogen Tax Credit Rules", *Heatmap News*, January 2025 https://heatmap.news/climate/final-45v-hydrogen-tax-credit

[10] "Switching to hydrogen fuel could prolong the methane problem" Princeton University, March 2023 https://acee.princeton.edu/acee-news/switching-to-hydrogen-fuel-could-prolong-the-methane-problem/

[11] "A multi-model assessment of the Global Warming Potential of hydrogen" Sand et al. *Nature Communications Earth and Environment*, 2023 https://www.nature.com/articles/s43247-023-00857-8; "How Much Does Hydrogen Leak And How Much Does It Matter?" *Clean Technica*, October 2024. https://cleantechnica.com/2024/10/21/how-much-does-hydrogen-leak-and-how-much-does-it-matter/

[12] "Methane Tracker 2021: Methane and climate change" *International Energy Association*, 2021. https://www.iea.org/reports/methane-tracker-2021/methane-and-climate-change

creates its own greenhouse effect[13]. Transporting hydrogen by pipelines or trucks has proven to have significant leakage of hydrogen, with the resulting waste, greenhouse gas effects, and safety issues even for "green hydrogen".

- *Criteria pollutant emissions* - The main environmental argument in favor of hydrogen trains is that they are zero emission at point of use, having zero tailpipe emissions that impact air quality and public health. This is of course equally true of electric trains. However, hydrogen production from fossil fuels is not zero-emission, and emits criteria pollutants including smog-forming NOx at point of production – with large uncertainties and little reporting on their true emissions.[14] Our calculations suggest that while hydrogen trains powered by fossil hydrogen do emit less NOx than diesel trains, they still have about 8x the emissions of catenary trains powered by the current grid. The 2020 EPA National Emissions Inventory suggests that passenger rail is only 13% of total *rail sector* NOx emissions (a figure that likely discounts freight switching emissions), themselves only 6% of the state's NOx emissions. The majority of California's passenger locomotives are the cleanest Tier 4, while only 10% were the dirtiest Tier 0 as of 2022[15], a number that may be near zero with the replacement of most of Caltrain's diesel fleet with electric multiple units. Are the very modest air quality improvements associated with hydrogen passenger trains worth their many other environmental impacts?

- *Water consumption* - Producing hydrogen from electrolysis requires fresh, distilled water. In dry regions like California where water is scarce, the available water supply is a serious issue. Making hydrogen from salt or brackish water requires desalination, with all the energy consumption and any local environmental impacts that entails. This process is rarely included in the total efficiency calculations, but it is nonetheless significant.

- *Embodied impacts from manufacture* - Hydrogen-powered propulsion requires both batteries and fuel cells made from several mined materials (e.g. lithium, platinum, rare earth elements). Unfortunately, the extraction, processing and shipment of these materials results in significant greenhouse gas emissions, as well as potential impacts to habitats, water quality, and water supply adjacent to mines. Directly powering a train with electricity, using an external source like overhead wire, requires far less of these materials leading to lower 'embodied' environmental impacts.

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[13] "Scientists warn a poorly managed hydrogen rush could make climate change worse" *Canary Media*, February 2024 https://energynews.us/2024/02/28/scientists-warn-a-poorly-managed-hydrogen-rush-could-make-climate-change-worse/

[14] "Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities" Sun et al., *Environmental Science and Technology*, 2019 https://pubs.acs.org/doi/full/10.1021/acs.est.8b06197?casa_token=Cv_vbAlRLLgAAAAA%3A88VLZCA1MKvQp4OHWIDEBFPf2X82wtkUHESWgt0Z8r4sSstyFCitBBd6vpojesiQxotvIh30ISXQSQ

[15] "CARB Fact Sheet: Passenger Locomotive Operators" *California Air Resources Board*, June 2025 https://ww2.arb.ca.gov/resources/fact-sheets/carb-fact-sheet-passenger-locomotive-operators

- *VMT reduction* – Perhaps the most important difference between hydrogen and overhead catenary trains are their impacts on vehicle miles traveled (VMT), an important contributor to greenhouse gas emissions. Overhead catenary trains accelerate faster and have higher maximum speeds, enabling faster trips and more frequent service. There is a demonstrated 'sparks effect' of higher ridership, and thus lower car emissions, associated with electrification.[16] It is unclear if hydrogen trains have any of the same performance benefits, and they are associated with chronic reliability issues that may suppress ridership. Further, hydrogen trains are most cost effective at low frequency[17] – so investing in hydrogen trains disincentivizes future service improvements. With no ability to improve service on their own, hydrogen investments also divert funds from projects that do improve service; for instance, in 2024 15% of state Transit and Intercity Rail Program funds[18] were spent on hydrogen fuel cell buses that do not improve ridership, rather than anything to get people out of cars.

'Ecosystem impact' for electrification is rated as "mediocre" or a yellow square. The reason given: "visual impact through catenary." Adding wires to already-established rights-of-way, already-constructed rail bed and laid track has an *extremely* small additional effect on animal and plant habitat or other actual ecosystem (biological) considerations. This is one reason why California recently enacted AB 2053, a new law that exempts passenger rail electrification infrastructure from the California Environmental Quality Act (CEQA).

In addition, a recent letter to Governor Newsom by 29 University of California professors points out that to be truly "green," hydrogen production must meet three requirements:

1. H2 production projects must be powered by new clean energy that is not currently serving the grid

2. H2 production facilities must be located within reasonable proximity to the hydrogen end-user (since transporting hydrogen consumes energy and reduces overall efficiency), and

3. The facility can only run during times of renewable energy production

[16] "Caltrain Ridership Up, Again Demonstrating 'Spark Effect' of Electrification" Streetsblog SF, January 2025 https://sf.streetsblog.org/2025/01/28/caltrain-ridership-up-again-demonstrating-spark-effect-of-electrification

[17] "Path to hydrogen competitiveness: A cost perspective" *Hydrogen Council*, January 2020. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

[18] "Transit and Intercity Rail Capital Program 2024 Awards
Cycle 7 Selected Projects" CalSTA, 2024. https://calsta.ca.gov/-/media/calsta-media/documents/tircp-cycle_7_project-award-list_2024-10-23_final_a11y.pdf

These requirements stem from the poor efficiency of hydrogen use, which would create a disproportionate burden on the utility grid, possibly causing grid operators to fire up fossil fuel-based plants to meet demand. The State of California lobbied against these requirements[19], and ultimately a severely weakened version was approved by the Biden administration, with special exemptions for California[20].

Californians for Electric Rail has put together its own side-by-side comparison of environmental, technical, and operational aspects of different rail propulsion methods, shown below in Table 1. This comparison uses California's current energy mix of approximately 50% renewable energy. It also does not include changes to land use associated with biofuels, impacts on grid energy sources associated with wide-scale green hydrogen productions, or $PM_{2.5}$ emissions from car brakes and tires, so the environmental impacts of all are likely an underestimate (see Appendix on pgs. 31-32 for methodology details). OCS rail is the clear winner, even with methodology that underestimates some of the negative impacts of hydrogen.

[19] "California's break with the holy trinity of hydrogen" *Politico*, September 2023 https://www.politico.com/newsletters/california-climate/2023/09/06/california-climate-holy-trinity-hydrogen-00114386
[20] "There's Something for (Almost) Everyone in the Hydrogen Tax Credit Rules", *Heatmap News*, January 2025 https://heatmap.news/climate/final-45v-hydrogen-tax-credit

Table 1: Side-by-side comparison of different rail propulsion methods

	Gasoline car, driving alone	Petroleum diesel train	Renewable diesel train	Battery electric train	OCS electric train	Fuel cell train, fossil hydrogen	Fuel cell train, green hydrogen
Energy efficiency		36%		56-77%	75-90%		20-39%
CO_2 emissions - grid, g CO_2/passenger-mile	400	149	63	3	1	108	3
Maximum speed	~100 mph	148 mph	148 mph	100 mph	357 mph	79 mph	79 mph
Range	403 mi	800-1000 mi	800-1000 mi	100-150 miles	unlimited	800-1000 miles	800-1000 miles
Optimal Frequency	--	--	--	< 1 train/ 30 min	> 1 train/ 15 min	< 1 train/hr	< 1 train/hr
NOx (mg/ passenger-mile)	190	1,245	1,094	2	1	8	2
PM 2.5 (mg /passenger-mile)	4	7	5	~0	~0	3	~0
Peak Travel Time, LA to San Diego	~3 hrs	2 hr 54 min	2 hr 54 min	2 hr 54 min	1 hr 40 min	2 hr 55 minutes	2 hr 55 minutes

Technical/operational

Under "Feedstock/resource availability" of electrification is ranked "inferior" because of "high reliance on utilities for electricity with limited options".

Hydrogen is going to depend on natural gas suppliers, which are a small number of large oil and gas companies. There are far fewer suppliers of natural gas in California than there are utilities that provide electricity. Currently, hydrogen must be delivered by truck and as such is highly susceptible to supply chain complications (which resulted in Shell pulling out of the hydrogen refueling retail market in 2023). All three passenger rail operators who have introduced hydrogen trains into service in Germany have encountered significant problems in securing reliable sources of hydrogen, compounding the inherent inferior operational reliability of the hydrogen-fueled trains. In all three cases, this has significantly impacted passenger rail service, as reported by this February 5, 2025 *Trains* article[21]:

> *The decision to fit large fuel tanks [on 18 Alstom iLint hydrogen trains taken out of service by Frankfurt regional transport authority RMV] also reflects problems encountered accessing hydrogen supplies. While hydrogen provider Infraserv Höchst is rail connected, the switching movements required have proven more time consuming than expected, in part because access into and out of a secure chemicals plant is involved every time.*
>
> *…The other fleet of 14 iLINT hydrogen trains in Germany, used in the northern state of Lower Saxony on the Cuxhaven-Buxtehude line west of Bremen, were the first to enter commercial service [see "World's first hydrogen trains …," Trains News Wire, July 26, 2022]. They have also suffered from reliability problems, although the main issue has been reliably obtaining supplies of hydrogen to power the trains. Industrial gas specialist Linde, which has the contract to supply the hydrogen, encountered technical problems, leading to multiple trains being cancelled or replaced by DMUs and buses in 2024….*
>
> *…In mid-December [2024], a third hydrogen fleet ordered for use in Germany, and the first built by Siemens, entered service north of Berlin. Within a fortnight, the trains had been withdrawn from service, following problems obtaining reliable supplies of hydrogen. East German regional operator Niederbarnimer Eisenbahn (NEB) introduced its small fleet of seven Siemens Mireo Plus H hydrogen-powered, two-car units alongside a larger fleet of 31 Mireo Plus B battery EMU (BEMU) versions. This was the first regular service for the Siemens hydrogen trains.*
>
> *The Berlin/Brandenburg transport authority VBB, which funds the NEB services, announced in the last week of December that the NEB hydrogen fleet would be temporarily replaced by the new BEMUs and older DMUs because of the hydrogen issues. The supplier, German energy company Enertrag, was unable to provide sufficient hydrogen to the NEB maintenance shop at Basdorf, north of Berlin, using road tankers. A hydrogen fuel storage tank system is planned longer term at Basdorf but is not yet operational. Removal of the hydrogen-powered trains led to short-notice service cancellations. These continued for several weeks until mid-January, when hydrogen deliveries became reliable enough to re-introduce some of the trains.…*

In California, San Bernardino County Transportation Authority (SBCTA), the only public transportation agency in the US currently operating a hydrogen train (albeit still in testing phase as of July 2025), recently approved a single-bid contract, with $4.8 million in cost increases[22],

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[21] "German hydrogen trains experience problems" *Trains*, February 2025 https://www.trains.com/trn/news-reviews/news-wire/german-hydrogen-trains-experience-problems/

[22] "AGENDA: SBCTA Board of Directors Meeting, March 5, 2025" Item 32, pg. 543. https://www.gosbcta.com/wp-content/uploads/2024/12/2025-03-05-Board-of-Directors-Full-Agenda-2105.pdf

due to limited options on the market for hydrogen refueling making a competitive bid infeasible. Given this situation, it's quite likely that the supply chain issues plaguing German hydrogen trains may also impact California.

In the future, the availability of hydrogen fuel assumes the construction of an expensive pipeline network that has yet to be built and poses substantial safety risks and political challenges. Meanwhile, virtually all of the state's major rail corridors have access to well-developed and accessible electric transmission and existing substations. Also, electric railroads around the world have long developed their own 'in-house' electric power generation, dating back to the Milwaukee Road and various electric transit lines over a century ago. If California decides to mass produce "green hydrogen" from our highly renewable grid, the electrolyzers connected to this grid would have the exact same supply issues as catenary systems. And to reiterate again the environmental difference mentioned above, *using hydrogen would consume three times more electricity than conventional electric trains*.

The difficulties and safety risks of hydrogen refueling will have many operational impacts. According to Stadler, it takes about 30 minutes to refill the hydrogen tanks on a FLIRT[23]. However, well beyond the time it takes for hydrogen fueling, emphasis needs to be on the physical issues that make it inherently a complex process. So much on-board equipment is involved- compressors, refrigeration, gas detectors (for leakage), high-pressure piping, proper grounding to prevent static electric discharges, etc. are all required to make the system work. With this inherent complexity, there are many potential points of failure that are not going away no matter what future technological advances /manufacturer quality improvements there are. In a state prone to earthquakes, this system seems at least as risky as a grid failure. In fact, probably more-so.

So far, the track record of hydrogen vehicle fueling station reliability in California has been atrocious[24]. In one high-profile example, hydrogen fueling problems in 2023 led to cancellation of bus services in the Coachella Valley[25]. Similar widespread hydrogen fueling station breakdowns have happened worldwide. For example, in September 2023 it was reported that about half of all hydrogen refueling stations in South Korea had broken down at some point since the start of 2022 due to technical problems[26].

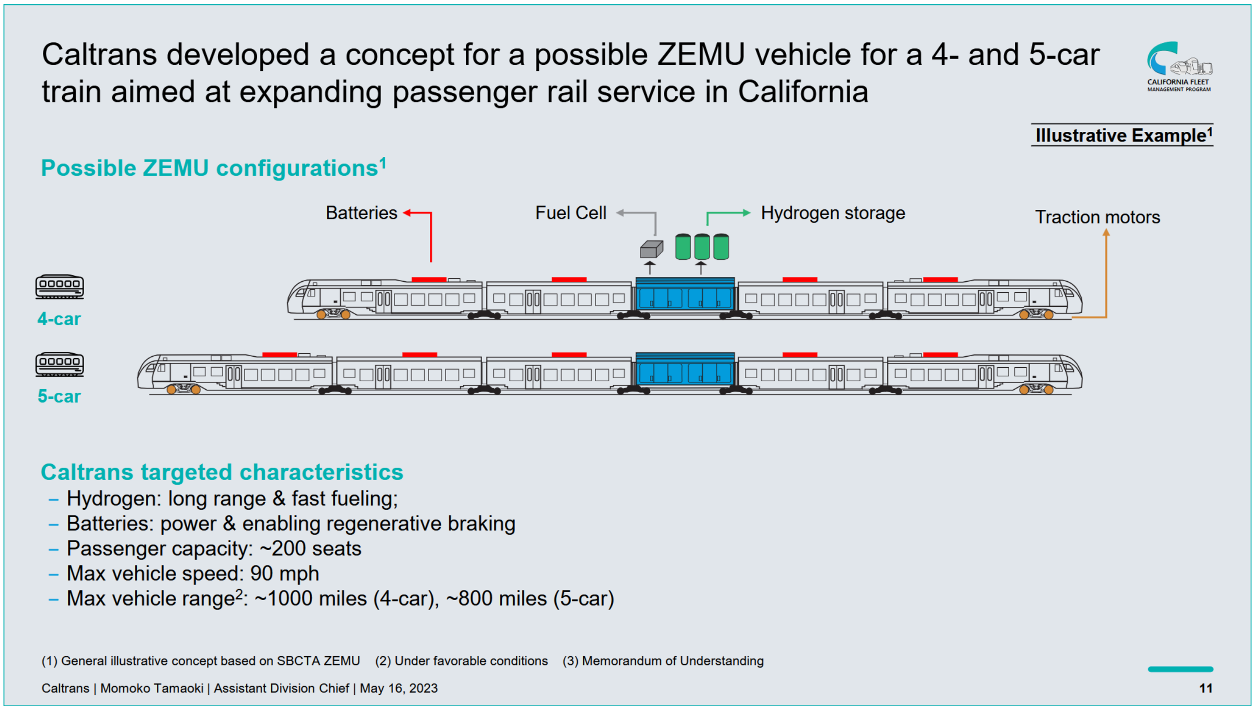
[23] "Stefan Bernsdorf, STADLER Rail, Statement and Presentation of the Flirt H2 Train", *Green Energy Center Europe*, 2024 https://www.youtube.com/watch?v=47vc2ey68ZM

[24] "California's Hydrogen Stations Being Fixed More Hours Than Pumping At 30% Capex Per Year" *Clean Technica*, March 2024. https://cleantechnica.com/2024/01/27/californias-hydrogen-stations-being-fixed-more-hours-than-pumping-at-15-capex-per-year/

[25] "For months, bus fueling problems have left SunLine routes cancelled and riders waiting", *Desert Sun*, November 2023 https://www.desertsun.com/story/news/local/2023/11/03/why-bus-routes-around-palm-springs-have-been-cancelled-for-months/71442818007/

[26] "'Inconvenience' | About half of all hydrogen refuelling stations in South Korea have broken down since start of 2022" *Hydrogen Insight*, September 2024

One important factor ignored in the technical/operational section is speed and power. Hydrogen trainsets are power limited and as a result are also speed limited. Caltrans has said they expect their FLIRT ZEMUs to be able to do 80 to 90 miles per hour. Currently they are limited to 79 mph by the FRA. Caltrans' existing diesel trains can do 110 to 125 miles per hour if the tracks would permit operations that fast – as can overhead catenary trains.



The Arrow ZEMU trainset features six (6) 100kw fuel cells along with batteries while their existing DMUs feature two (2) 520 kW Tier 4 diesel engines. The ZEMU has a continuous power rating ignoring the batteries of 600 kW compared to the 1040 kW of the DMUs. For intercity service Caltrans FLIRT ZEMUs features eight (8) 100 kW fuel cells plus batteries. DMUs bought for DART Silver line and Texrail are similar with four (4) cars but used two (2) or four (4) 520 kW Tier 4 diesel engines. The ZEMU has a continuous power rating, ignoring the batteries, of 800 kW compared to the 1040 kW or 2080 kW of the DMUs. Overall, hydrogen trains are significantly underpowered compared to existing diesel trains. Why are we investing extra into vehicles that can barely meet existing operational requirements and foreclose near-term improvements? Lower speeds also accentuate hydrogen train's limited VMT reduction and mode shift potential.

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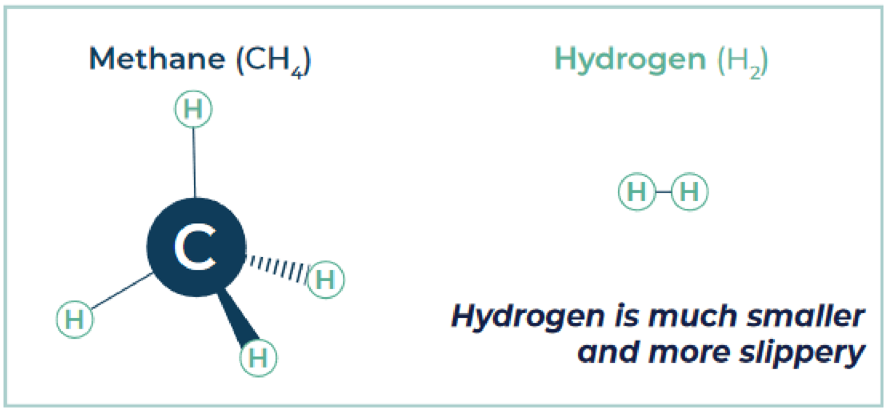
https://www.hydrogeninsight.com/transport/inconvenience-about-half-of-all-hydrogen-refuelling-stations-in-south-korea-have-broken-down-since-start-of-2022/2-1-1713793

Safety

There is no mention of safety of the different rail propulsion options in the Caltrans presentation, despite it being perhaps the most important concern. If a colored square was provided by these charts for safety, then the colored square for hydrogen would be solid red.

Leakage of hydrogen from pipelines and storage tanks is a serious problem, as hydrogen is a smaller molecule inherently more prone to leaks than natural gas. Hydrogen burns more explosively and easily than methane (natural gas)[27], creating hazards for residents living near hydrogen storage and refueling facilities. For example, the SBCTA hydrogen train fueling station in San Bernardino is less than 500 feet from homes. Delivering hydrogen to rail fueling stations with trucks also poses dangers to the wider public.



Source: Pipeline Safety Trust (2023)[28]

Compressing, transporting, and fueling with hydrogen could hardly be considered a risk-free operation. Hydrogen is a colorless, odorless, flammable gas. It diffuses in the atmosphere at high velocity, but leaks can create high temperature, essentially invisible torches, or in the case of a confined leak with oxygen present... a bomb.

Hydrogen disperses at an extremely fast rate. The RMS molecular velocity of hydrogen gas is roughly2400 m/s at room temperature, which means that it's very unlikely to reach a flammable or explosive fuel/oxygen ratio in a large, open space. The Hindenberg went up because the hydrogen was confined and then burned. Outdoor leaks will cause a nearly invisible, super hot torch, or in the case of a large leak, a giant plume of fire. If you have a leak inside a building or a confined space with poor ventilation - that's a different story. We would hope, and reasonably assume, that hydrogen fueling stations and processing facilities would be designed with ventilated/open spaces to avoid this. However, while large parts of passenger trains are

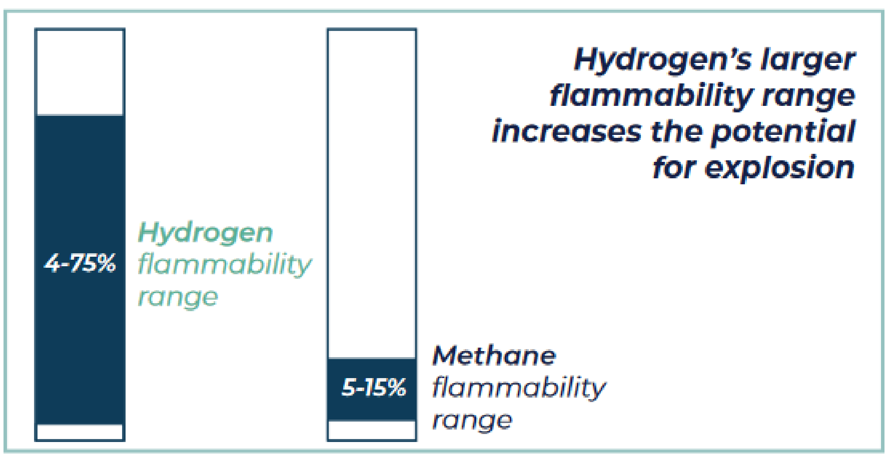
[27] "Safety of Hydrogen Transportation by Gas Pipelines", *Accufacts, Pipeline Safety Trust*, November 2022. https://pstrust.org/wp-content/uploads/2022/11/11-28-22-Final-Accufacts-Hydrogen-Pipeline-Report.pdf

[28] "Summary for Policymaker" *Pipeline Safety Trus*t, January 2023. https://pstrust.org/wp-content/uploads/2023/01/PST-Hydrogen-Summary-for-Policymakers-1.pdf

ventilated, there are all kinds of 'confined space' opportunities onboard if the leak gets into the wrong spot. Also, on existing diesel and battery-electric freight locomotives, there are all kinds of different cavernous spaces onboard without any ventilation. A hydrogen-power locomotive would have plenty of such confined spaces as well.

If hydrogen were to leak into a passenger cabin, or smaller spaces within a passenger cabin like electrical/mechanical cabinets or pockets of dead space, that it could explode. The "lower explosive limit" (LEL) - the concentration of hydrogen in air where it can explode - is only 4%. The upper explosive limit is 75%, so you can get a boom anywhere from 4 - 75%. The takeaway is that you don't need much hydrogen in a confined space to cause an explosion. There are decent hydrogen detectors on the market, and it is assumed that these are part of the design for hydrogen trains, but they will need to be calibrated and tested on a regular basis.

The temperature of hydrogen tanks must be carefully controlled[29]. The cooling units, both onboard the train and at the stationary fueling station, use a substantial amount of energy. The additional safety hazards of hydrogen fueling are multitude. The hydrogen fueling nozzles are very expensive, yet have to be replaced often because they are delicate and have proved so far to have short operating lives. Cold weather hydrogen fueling has proven to be problematic, as was experienced in Germany with hydrogen iLint trains in 2023[30]. The nozzle also must sufficiently be electrically grounded upon connecting to the vehicle's fueling port, since any spark or discharge from static electricity near a leak point can ignite the hydrogen. Leaks are also a problem for greenhouse gas emissions[31].



Source: Pipeline Safety Trust (2023)[32]

[29] "Stefan Bernsdorf, STADLER Rail, Statement and Presentation of the Flirt H2 Train", *Green Energy Center Europe*, 2024 https://www.youtube.com/watch?v=47vc2ey68ZM

[30] "Hydrogen-powered trains struggle with winter weather" *Trains*, February 2023. https://www.trains.com/trn/news-reviews/news-wire/hydrogen-powered-trains-struggle-with-winter-weather/

[31] "How Much Does Hydrogen Leak And How Much Does It Matter?" *Clean Technica*, October 2024. https://cleantechnica.com/2024/10/21/how-much-does-hydrogen-leak-and-how-much-does-it-matter/

[32] "Summary for Policymaker" *Pipeline Safety Trust*, January 2023. https://pstrust.org/wp-content/uploads/2023/01/PST-Hydrogen-Summary-for-Policymakers-1.pdf

In 2023, a hydrogen bus caught fire in Bakersfield while fueling, completely destroying it and part of the fueling station[33]. Bus service was negatively impacted, with buses cancelled, as the ten hydrogen buses remaining in the fleet could not be refueled. In December 2024, two separate hydrogen filling stations in South Korea experienced explosions in the same week[34]. Given how few hydrogen buses there are operating out in the world, the fact that has happened more than once in the past three years is cause for concern[35]. To quote Michael Barnard's October 2024 article about the greenhouse gas and safety dangers of hydrogen[36]:

> *"Hydrogen is the gas that's the second-best escape artist in the universe. Helium has it by an edge because while helium is four times the mass of hydrogen per unit, it comes in atoms, not molecules. Hydrogen only comes with another hydrogen atom in the hydrogen molecule, which ends up wider as a result, even if still only half the mass. As result, they treat ordinarily airtight containers and seals as if they are mesh bags.*
>
> *...Safety studies out of Europe, where many people are taking the odd idea of replacing natural gas with hydrogen in furnaces and stoves seriously, make it clear that the risks are about four times greater, so perhaps 16,000 buildings in the USA would go boom a year. Perhaps not the right direction, especially when heat pumps and electric stoves work just fine and have approaching zero risks."*

The fundamental safety difference between conventional electric rail and hydrogen fueled trains is the physics and engineering involved. You are dealing with a high-pressure gas that also must simultaneously be cooled to low temperatures, while at the same time ensuring that a small static electric spark doesn't ignite it. The inherently greater complexity of hydrogen fueling and supply systems will always mean they will require more maintenance, be less reliable overall, and more accident-prone than OCS.

When it comes to safety, we should not be shy about mentioning the worst-case scenarios and asking what is being done to prevent them. When an OCS fails, the worst that happens is a falling wire that causes sparks or arcing which short out the system. That spark (or an electrical short) can indeed be very dangerous immediately adjacent to the OCS failure. Yet over a century of widespread operating experience of OCS around the world has shown that injuries/fatalities or big fires caused by OCS failures are extremely rare. It has happened before but is almost unheard

[33] "Fire engulfs new hydrogen bus and fueling station at Golden Empire Transit" *Bakersfield Now*, July 2023 https://bakersfieldnow.com/news/local/fire-engulfs-new-hydrogen-bus-and-fueling-station-at-golden-empire-transit-kern-county-bakersfield-fire-department-get-bus

[34] "Safety concerns grow after two explosions at South Korean hydrogen filling stations in same week", *Hydrogen Insight*, January 2025 https://www.hydrogeninsight.com/transport/safety-concerns-grow-after-two-explosions-at-south-korean-hydrogen-filling-stations-in-same-week/2-1-1759496

[35] "Hydrogen bus on fire in the Netherlands. A Solaris bus in Arriva's depot has been destroyed. Investigations are underway" *Sustainable Bus*, November 2021 https://www.sustainable-bus.com/news/hydrogen-bus-fire-arriva-solaris/

[36] How Much Does Hydrogen Leak And How Much Does It Matter?" *Clean Technica*, October 2024. https://cleantechnica.com/2024/10/21/how-much-does-hydrogen-leak-and-how-much-does-it-matter/

of- with hundreds of millions of passengers and millions of tons of freight carried around the world each day by electric trains. By contrast, a hydrogen leak from a rail fueling station (which would be much larger than a car/truck/bus fueling station) has the physical potential to level a city block, if a big enough plume spreads in confined space, then gets a spark of static electricity. It may be a cliche to bring up the Hindenburg disaster, but all it took was a small leak and a little static electricity to start the fire which consumed the entire airship in less than a minute. This does happen very rarely with natural gas facilities, and hydrogen is a much greater leak risk than methane.

Economical/ Life cycle costs (LCC)

Three squares are bright red in this category, or "Requirements not fulfilled" by electric trains:

CapEx- "Requires expensive wayside infrastructure and new motive power equipment (more expensive than diesel equivalents in the U.S.)."

The exceptionally high cost attributed to electrification, compared to the other propulsion alternatives, is not explained. The next slide in the deck says that using Caltrain costs (assumed to be $8.2 million per single-track mile) as a reference, "it would cost $6.8B to fully electrify Caltrans intercity rail". Other than that, no numbers of any kind are given (cost estimates, cost/benefit/sensitivity analysis, overall energy efficiency) in this Caltrans presentation- just colored squares, with one sentence backing up each one. Even if it did cost $6.8 billion, what would be the measurable economic benefits? $6.8 billion is less than 1/4 of California's road-dominated annual transportation budget for 2024, and would presumably be spread over many years. The experience of a wide variety of electric rail operations around the world has shown over the long-term, the upfront costs of catenary wire infrastructure are outweighed by the significant economic benefits of electrification.

It is interesting to note here that comparable regions of the world have demonstrated that it is possible to wire up routes at a fraction of the cost per track-mile of Caltrain. Legislation like AB 2503, which exempts rail electrification from CEQA and is now the law of the land, and the proposed permit streamlining bill SB 445, directly eliminate contributors to Caltrain's high costs. In addition, the whole process can be accelerated and made more cost effective by better project planning and management[37], with clear definition of the scope of the project and its implementation. Costs will drop further given the economies of scale of increased parts production, a widening array of component manufacturers, competition among vendors and contractors, and increasing skills and experience with catenary construction. Add in the use of

[37] "Project Delivery Reform for Transit and Rail: Letter To Assembly Select Committee on Permitting Reform", *Californians for Electric Rail*, December 2024. https://calelectricrail.org/wp-content/uploads/2024/12/Project-Delivery-Reform-ltr-12_16_2024-final.pdf; "Against Patchwork Funding: How Multi-Year Investment Frameworks Can Deliver Rail Service Infrastructure Cheaper and Faster", *Californians for Electric Rail*, June 2025. https://calelectricrail.org/against-patchwork-funding-how-multi-year-investment-frameworks-can-deliver-rail-faster-and-cheaper/

cost-effective long-lived components - including stronger, lighter-weight power line support masts with smaller foundations and longer spacing distances - and the long-term economics improve. Catenary electrification costs will be lowest with a "rolling program" of large-scale, continuous electrification development over a period of years.

The significant upfront 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 will greatly increase the capital cost of new rail fleets. Hydrogen trains are more expensive to purchase upfront than conventional OCS electric trains of the same passenger capacity.

As an example, Caltrans recently bought Stadler four-car hydrogen FLIRTs each costing over $20 million. This is approximately twice as expensive as a standard two-car electrical multiple unit (EMU) in Europe. Caltrain's eight-car double-decker EMUs reportedly cost about $50 million each,[38] but one must compare these (in the context of the overall number of passengers) with a four-car single-decker hydrogen FLIRT[39]. The two-car SBCTA Arrow hydrogen-powered FLIRT H2 has a published seating capacity of 116 passengers. Therefore, it follows that the four-car version of the FLIRT H2 would seat 232 passengers. If such a trainset costs Caltrans $21 million each, that would work out to approximately $90,520 capital cost per passenger seat. A single trainset of eight double-decker KISS EMU cars can carry about 800 people, which works out to $62,500 per passenger seat. These figures are only for the upfront capital cost of the rolling stock, and do not take into account the per-passenger costs of other required capital costs such as OCS/electric power or hydrogen or supply infrastructure and fueling systems, nor the O&M costs of the trains. It should be noted that EMU upfront unit capital costs tend to be lower in Europe than the cost of the Caltrain Stadler EMUs, due to the greater market for mass-production bringing down per-unit costs.

It is extraordinary that trains with such a low passenger capacity are being ordered by California taxpayers for such a high price. The existing locomotive-hauled trainsets on state-supported *Capitol Corridor*, *San Joaquins*, and *Pacific Surfliner* corridors can carry up to 500 passengers. If these were replaced with four-car FLIRTs, it would cut the number of seats per train by more than half.

Meanwhile in the near term, the much-hyped "ZEMU" FLIRT H2 slated to soon run on the Arrow line between San Bernardino and Redlands, the first hydrogen train to run in California, has had delays and dramatic project cost increases. As described by San Bernardino County Transportation Authority (SBCTA) May 9, 2024 Transit Committee agenda packet[40]:

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[38] "Approval of Resolution Authorizing to Exercise Stadler Contract Option for Rail Vehicle Procurement" *Caltrain*, July 2023. https://www.caltrain.com/media/31269/download
[39] "FLIRT", *Stadler*. https://www.stadlerrail.com/en/flirt-h2/details/
[40] "AGENDA, SBCTA Transit Committee Meeting May 9, 2024", Item 7, pg. 200 https://www.gosbcta.com/wp-content/uploads/2024/05/Transit-Committee-Agenda-5.9.24.pdf

> *"ZEMU conversion of three Arrow Service DMUs – When the State initially awarded a $30 million Transit and Intercity Rail Capital Program grant to develop the ZEMU technology, the State requested SBCTA convert the three DMUs procured for the Arrow Service. The 2021 Update included a project to convert all three DMUs to meet the goal of operating the entire Arrow Service corridor as a zero or low emission revenue operation. However, conversion of the vehicle will not be possible and purchase of new vehicles will be required, which significantly increases the cost of this initiative. The Board allocated $9.2 million of Zero Emission Transit Capital Program funds to this project, which when combined with the $7.5 million of existing funds will allow for the purchase of one vehicle, leaving an estimated unfunded need of $26.5 million."*

Costs for starting up service of the hydrogen-powered Stadler ZEMU are spiraling out of control, and the hydrogen rail pilot project is severely over budget. At the December 4, 2024 SBCTA Board of Directors meeting, it was reported that the total program cost for the one pilot ZEMU two-car multiple unit, fueling station and associated infrastructure and operations of nearly $64 million, more than double the original estimate – and service introduction delayed at least a year after the promised 2024 start[41]. Given the fact that the two-car FLIRT hydrogen unit can seat 108 passengers, this works out to a cost of over a half million dollars per passenger seat of capacity. The dramatic cost increases of the SBCTA hydrogen rail program demonstrates how hydrogen trains are an unproven, high-risk and very expensive technology.

Mike Iden, in the article cited above, estimated that building a hydrogen fueling station for BNSF at Belen, New Mexico (sized to replace all existing diesel locomotive fueling at the same site) would have a capex of roughly $7.5 billion. A hydrogen fueling station network for the entire BNSF Railway would cost well over $100 billion. Who knows what it would cost for all of North America? These figures don't even include the cost of a new hydrogen locomotive fleet or the continuing costs of providing the fuel itself.

As previously mentioned, the hydrogen supply chain, on-board storage systems and drivetrains are highly complex. That means more points of potential failure, less reliability, higher equipment capital, maintenance and operating costs. These points of failure include:

- Fuel cell (expensive, must be replaced in 3-10 years[42], although real-world operating experience of hydrogen trucks has shown the fuel cells degrade in as little as two years[43])

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[41] "AGENDA: SBCTA Board of Directors Meeting, December 4, 2024" Item 21 pg. 280 https://www.gosbcta.com/wp-content/uploads/2023/12/2024-12-04-Board-of-Directors-Full-Agenda-2086.pdf

[42] "Hydrogen will 'almost always' lose out to battery-electric in German rail transport: train manufacturer" *Hydrogen Insight*, August 2023. *https://www.hydrogeninsight.com/transport/hydrogen-will-almost-always-lose-out-to-battery-electric-in-german-rail-transport-train-manufacturer/2-1-1504868*; "FAQs" *Hydrogen Fuel Cell Partnership*, https://h2fcp.org/faqs

[43] "EU Spent €1.2 Billion On Hydrogen Transportation, Asked for More to Compete With Batteries" *Clean Technica*, March 2024. https://cleantechnica.com/2024/03/08/eu-spent-e1-2-billion-on-hydrogen-

- Battery pack (expensive, must be replaced in 8-10 years, based on current industry standard warranties for EV batteries)

- Hydrogen tank (must have pressurization and cooling system- all complex, expensive and energy-consuming)

- Leak detection systems

These complexities have consequences. The evidence to date from both electric and hydrogen trains -- in actual revenue service -- has shown that the O&M costs are much higher for hydrogen, and studies increasingly suggest that the total lifecycle cost for hydrogen is higher than for electric trains. This was the conclusion of a study by the German state of Baden-Württemberg, which found hydrogen trains to have 80% higher costs[44] than electrification; the Austrian state of Tyrol came to similar conclusions, as did real-world experience by the German transit agency LNGV. Even a 2020 study by the Hydrogen Business Council, which was bullish on hydrogen overall, concluded that overhead catenary is still more cost-effective than hydrogen for high-frequency rail[45]. It should be noted that the 2020 study was done before the last few years of real-world operating experience for hydrogen trains in Europe.

There is no track record to indicate how much a comprehensive green hydrogen infrastructure would cost, especially over the long term. It is important for public transportation and infrastructure policy to acknowledge this fact, and not waste time and money exploring technological dead-ends when our precious, public resources could have been spent on what is proven to work. A rail system with conventional electrification as its backbone (with catenary-battery hybrids for relatively short unelectrified sections) is a well-proven commodity.

transportation-asked-for-more-to-compete-with-batteries/

[44] "'Will no longer be considered' | Hydrogen trains up to 80% more expensive than electric options, German state finds" *Hydrogen Insight*, October 2022. 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

[45] "Path to hydrogen competitiveness: A cost perspective" *Hydrogen Council*, January 2020. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

Funding availability

"Limited funds available as established technology".

This is likely a veiled reference to the federal Hydrogen Hubs program[46], created by the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (IIJA) which allocated $7 billion for hydrogen infrastructure and market development, with no equivalent set aside for rail electrification. Hopefully future climate bills will not favor inefficient, immature technology over proven climate solutions. California's hydrogen hub, ARCHES, has been a major driver of hydrogen policy.

However, on day one of his second term, President Trump froze all undisbursed funding from the IIJA and IRA, putting California's entire hydrogen hub program in jeopardy[47]. In May 2025, the House has approved a bill that would end the clean hydrogen tax credit by the end of 2025[48], though the Senate version passed July 1, 2025 and ultimately approved and signed by Trump extends that to 2028[49]. While the of the Hydrogen Hubs have so far escaped complete destruction, given the Trump administration's penchant for ignoring congressional direction and its hostility to California and renewable energy, the fate of ARCHES remains uncertain. In 2025, the funding environment no longer disproportionally benefits hydrogen and Caltrans' funding assessment is no longer relevant.

Regulatory constraints

"Regulation well-established. Implementation often restricted e.g. right-of-way acquisition, relocation of utilities, impact on urban environment."

Hydrogen pipelines, storage tanks, electrolysis or other production facilities, and fueling facilities require all of the above, and will have to go in a lot of people's backyards.

Rail electrification schemes seldom require purchase of additional property along the rail right-of-way, since the catenary poles are placed very close to the tracks. Railroad rights-of-way in California for the most part are not particularly constrained, even in urban/suburban areas. Light rail and streetcar lines also have had no insurmountable problems accommodating overhead wires in dense urban and suburban areas throughout the state. In fact, street-running streetcars and

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[46] "Regional Hydrogen Hubs", *US Department of Energy*, archived June 28, 2025. https://web.archive.org/web/20250628143017/https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0

[47] "Trump freezes funding under Inflation Reduction Act and infrastructure law" *Canary Media*, January 2025. https://www.canarymedia.com/articles/policy-regulation/trump-orders-freeze-on-inflation-reduction-act-infrastructure-law-funding; "How the GOP Bill Will Reshape American Energy" New York Times, July 2025. https://www.nytimes.com/2025/07/03/climate/congress-bill-energy.html

[48] "The House's 11th Hour Cuts to Clean Energy Tax Credits, Explained" *Heatmap News*, May 2025. https://heatmap.news/politics/house-passed-budget-bill

[49] "The Senate's Harsh Compromise on Clean Energy Tax Credits, Explained" *Heatmap News*, July 2025. https://heatmap.news/politics/senate-big-beautiful-bill

light rail lines are far more impacted by the urban environment (and vice versa) than regional or intercity rail lines.

Additionally, the California Legislature passed a bill in 2024, as mentioned above, AB 2503, which exempts passenger rail electrification projects on existing right of way from the California Environmental Quality Act (CEQA). Governor Newsom signed this bill into law on September 27, 2024.

"Synergistic"

"System integration synergies" for overhead wire electrification is ranked as "inferior", despite the reasons given: "supports new power/communication transmission. Possible contribution to 'smart' electricity grid if wayside storage batteries implemented". This also ignores the major investments California has already committed to in overhead electrification, particularly for its high speed rail network. Caltrain regional rail and high speed rail – California High Speed Rail Authority (CHSRA) and Brightline West – will use the global standard of 25 kV overhead wire electrification. So 'synergy' with global manufacturers and standards of 25 kV means that a wide range of vendors from around the world can provide electric rail technology to California. Rolling stock interchangeability with 25 kV electrification between Caltrain, CHSR, and Brightline West and other lines would be very 'synergistic'. The 2024 California State Rail Plan even acknowledges this (p. 9, and Figure 4 below)[50]:

[50] "California State Rail Plan", *Caltrans*, January 2025. https://dot.ca.gov/-/media/dot-media/programs/rail-mass-transportation/documents/california-state-rail-plan/2024-ca-state-rail-plan-a11y.pdf

Caltrain completed the Peninsula Corridor Electrification Program in September 2024, heralding a new era of electric railroad operations in California. Their 51 miles will contribute to approximately 440 miles of electrified railroad that will be constructed in the state by 2034. By 2050, California envisions 1,500 miles of electrified railroad. Routes slated for eventual overhead wire electrification will do so with multi-billion-dollar corridor investments that are coupled with high-speed and/or very high service frequencies. These include the statewide high-speed rail system, extension of electrified rail service from San Francisco to Sacramento through a new transbay tunnel, trains from the Los Angeles Basin to Las Vegas, and the extension of electrified operations north of Merced to Sacramento.

The zero-emissions mainline rail technology that is seeing the most miles of advancement is in fact conventional OCS electrification. Caltrain electrified service has already begun, (51 miles compare to 9 miles hydrogen unit for SBCTA Arrow planned by 2026), meanwhile construction will begin soon on a combined length of about 350 miles of OCS between California HSR and Brightline West. Either testing or actual service for either project may begin in 2028 – 350 miles of overhead wire total for the two HSR lines vs. 119 miles of hydrogen for Valley Rail+SBCTA.

It should also be noted that BNSF has recently agreed to 125 mph electric passenger trains on tracks shared with its freight trains on a BNSF-owned corridor between LA and Fullerton, along with allowing 25 kV overhead catenary wire, with BNSF double-stack container freight trains passing under them. This is the result of negotiations and agreements with the CHSRA and other California public agencies (at state and county level). This 22-mile segment currently sees an average of over 100 trains per day (about split between passenger and freight), but a capacity for far more is planned. This track segment is part of the BNSF Southern Transcon between LA and Chicago, the busiest long-distance intermodal rail line in North America.

Public Acceptance

"Public acceptance" of overhead wire electrification is also ranked as "Inferior" because "Public is supportive of electric trains but is not in favor of additional infrastructure. Protest to stop electrification may occur".

It is true that the wealthy NIMBY town of Atherton successfully delayed Caltrain electrification with a frivolous yet ultimately unsuccessful lawsuit[51]. Metrolink has also said that opposition to wires in Redlands was a reason they went with hydrogen for the Arrow[52]. However, public support for eliminating pollution from diesel sources, including trains, is very high. Policy reform at the state level, like the aforementioned AB 2503 legislation, can mitigate the power of local municipalities and property owners to block electrification projects with substantial and wide public benefits of reducing pollution and noise. Judging by the crowds who showed up to ride the first Caltrain electric trains, the public is *very* supportive of overhead wire electrification.

Let's look at the very real possibility that communities may *not* supportive of hydrogen. In whose neighborhoods are you going to put hydrogen production facilities, pipelines, storage tanks and fueling stations? The real estate footprint required for hydrogen infrastructure will be significant, and would necessarily have to be right next to large numbers of people. Residents of industrial-adjacent fenceline communities in California are already voicing concerns about the public safety risks of such large amounts of pressurized, flammable hydrogen. The secretive nature of even publicly-funded hydrogen hubs is already sowing public distrust of the hydrogen industry[53].

The source of the hydrogen for the SBCTA Arrow pilot hydrogen train has not been publicly disclosed, and one can only assume that it comes from dirty fossil fuel sources. All we do know is that it will be delivered by diesel-powered trucks. Regular risky shipments of pressurized or liquefied hydrogen to the fueling station in San Bernardino by diesel truck will be necessary.

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[51] "How Environmental Law Holds Back Cleaner & Better Rail | Part 2: Atherton vs. Caltrain Electrification" *Californians for Electric Rail*, April 2024. https://calelectricrail.org/how-environmental-law-holds-back-cleaner-better-rail-part-2-atherton-vs-caltrain-electrification/

[52] "SFA Happy Hour ft. Darren Kettle – August 2023" https://youtu.be/C6DKVzh9b70?si=AbxnRNRg2yjO5IY0

[53] "One year in, US clean hydrogen hubs face questions — and have few answers" *Canary Media*, October 2024. https://www.canarymedia.com/articles/hydrogen/one-year-in-us-clean-hydrogen-hubs-face-questions-and-have-few-answers

Safety issues of hydrogen train operation, storage, transportation and production are still unresolved. As described above, the worst-case scenarios of what can happen with such large amounts of a compressed, flammable gas could be catastrophic.

Reliability and performance of hydrogen trains in the real world

As stated above, the 'colored squares' slide stating "hydrogen will serve as the primary long-term power source for the Caltrans intercity fleet" says "Source: DB assessment", at the bottom. This refers to the North American consulting wing of DB (Deutsche Bahn), the national railroad of Germany. DB should know better. The majority of Germany's railroad tracks are electrified: as of 2022, 55% of track in the Federal Republic of Germany (over 14,000 miles) was electrified with overhead catenary wire. More track in the nation is being electrified.

Too often California public agencies and elected officials think that somehow we in the Golden State are the first people in the world to ever consider zero-emissions trains, and first to ever study and compare hydrogen vs. battery technology, etc. However, Germany in particular is ahead of the U.S. on the hydrogen rail experimentation curve, as well as rail electrification on a mass scale, so the German hydrogen rail experiences of the last couple years are perhaps a glimpse into the near future on at least a couple regional rail lines in California.

The real-world operating experience of actual, hydrogen-powered, revenue passenger service in Germany has been plagued by very high operating costs, poor reliability and breakdowns, and half the range as promised. All of this has significantly harmed passenger service[54]. In two German states, actual regular hydrogen train service has been a major fiasco, and at least two other states have intensively studied the hydrogen option but rejected in favor battery power combined with more catenary wires.

The EVB regional railroad in Lower Saxony, Germany was the first in the world to introduce a fleet of 14 hydrogen-powered Coradia iLint trains in 2022. Along with train breakdowns and teething problems causing severe strains on the railroad's finances and staff, a major cost factor was that as a result of market forces (supply/demand/market speculation), the price of hydrogen skyrocketed just as these trains were introduced, due to the sourcing of much hydrogen in Europe at the time from Russian gas. Lower Saxony's public transportation authority LNVG announced in 2023 that no more hydrogen trains will be pursued, and that the remainder of the diesel fleet will

[54] "'Chaos and massive disruptions' | World's largest hydrogen train fleet suffering teething problems in Germany" *Hydrogen Insight*, February 2023. https://www.hydrogeninsight.com/transport/chaos-and-massive-disruptions-worlds-largest-hydrogen-train-fleet-suffering-teething-problems-in-germany/2-1-1403982

be replaced with electric trains that use batteries combined with overhead wires[55]. In September 2024, it was reported that the hydrogen trains had to cut back operation in Lower Saxony due to hydrogen fuel supply bottlenecks, leading to the reintroduction of diesel-powered trains[56].

In southwestern Germany, the state of Baden-Württemberg has come to the same conclusion, rejecting hydrogen rail propulsion, after an extensive study, as mentioned above[57]. Passenger service on the RMV regional rail line in the state of Hesse (Frankfurt region) deteriorated so badly due to the recent introduction of new hydrogen trains, that the railway offered free travel to passengers in April and May 2024 to regain public trust[58]:

> *"The RB15 line in the Frankfurt region, one of the four railways on the mountainous Taunus network, has faced a host of problems since it was supposed to make the switch from diesel to hydrogen in December 2022, resulting in the cancellation of 19% of its scheduled trains in 2023...There has never been such a failure in the performance and reliability of a regional train line," said Knut Ringat, managing director of the RMV, the public body responsible for planning, organising and financing transport in the region. Ulrich Krebs, the chairman of RMV's supervisory board, admitted: "The start of the hydrogen trains was a complete failure. "As compensation for the people in the [region], the use of the Taunusbahn will be completely free of charge in April and May." It is the first time such a move has been made in the entire German public transport system, according to the RMV. "We want to regain the trust of customers with this campaign," added Ringat."*

In November 2024, RMV announced that 18 of its 24 Alstom Coradia iLint hydrogen multiple-units will be withdrawn from service in early 2025, following repeated technical issues with the

[55] "German hydrogen pioneer opts for battery trains for remainder of fleet" *Railtech*, September 2023 https://www.railtech.com/rolling-stock/2023/08/09/german-hydrogen-pioneer-opts-for-battery-trains-for-remainder-of-fleet/?gdpr=accept

[56] "German hydrogen train network runs dry" *Electrive*, September 2024. https://www.electrive.com/2024/09/11/german-hydrogen-train-network-runs-dry/

[57] "'Will no longer be considered' | Hydrogen trains up to 80% more expensive than electric options, German state finds" *Hydrogen Insight*, October 2022. 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

[58] "Hydrogen-only railway line will provide free travel to all passengers for two months as compensation for 'complete failure'" *Hydrogen Insight*, March 2024. https://www.hydrogeninsight.com/transport/hydrogen-only-railway-line-will-provide-free-travel-to-all-passengers-for-two-months-as-compensation-for-complete-failure/2-1-1613792;
"Blamage für die Brennstoffzelle/Embarrassment for the fuel cell" *Spiegel* (in German), January 2024 https://www.spiegel.de/auto/hessen-blamage-fuer-die-brennstoffzelle-a-1ff2d6e9-d936-4a39-ae12-8f52e2d273b8

hydrogen fuel cells which power the fleet[59]. They will be replaced by diesel multiple-units, as described by *Trains* in the February 5, 2025 article[60]:

> *"In mid-December 2024, train manufacturer Alstom —first to build hydrogen-powered passenger trains with its iLINT design, launched in 2014 at the InnoTrans trade fair in Berlin — had to withdraw most of the largest fleet it has supplied in Germany for urgent rework and upgrades. The fleet of 27 iLINT trains, known as Class 554, in Germany were bought as part of a 2019 contract worth over $500 million for use on the Taunus network of regional routes north of Frankfurt am Main. The contract included the supply of hydrogen to power the trains; Alstom's share for the trains was around $350 million.*
>
> *The iLINT trains have been in regular service since 2023, but intensive use has demonstrated that they do not offer the expected reliability. Alstom has attempted to improve reliability by producing additional spare parts but now intends to completely overhaul each train. The entire fleet will be partly rebuilt at Alstom's expense, with more powerful hydrogen fuel cells and additional hydrogen storage being fitted. Eighteen of the 27 trains will be withdrawn initially for repairs, with nine remaining in use on the RB12 Königstein-Frankfurt route. Six of the hydrogen trains are scheduled to work daily. A replacement fleet of 16 leased older LINT diesel multiple-unit trainsets, funded by Alstom, will operate other routes in 2025 while the iLINT fleet is overhauled.*
>
> *… Frankfurt regional transport authority RMV, which owns the fleet and funds the operation, has been publicly highly critical of Alstom. The authority says the two years of experience with the hydrogen fleet has 'done a disservice to [public] trust in new traction technology'."*

Rail passenger advocates in Bavaria are vocally opposing hydrogen, and supporting electrification instead[61]:

> *"The most important meaning of hydrogen for mobility in Bavaria is the opportunity for photo ops for politicians, distraction from the essentials and the waste of tax money," said Lukas Iffländer, chairman of Pro Bahn's Bavarian regional association, commenting on a recent appearance of the state economics minister Hubert Aiwanger — a strong proponent of H_2 in transport — at the IAA motor show in Munich earlier this month.*
>
> *…"Only with a lot of tax money can 'pilot projects' be carried out, which no longer have any meaning other than enabling expensive photo ops," Iffländer added.*
>
> *Pro Bahn pointed out that in technology-neutral tenders for public transport by other German states, electric drivetrains using a combination of overhead lines and batteries have generally won out over hydrogen fuel cells.*

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[59] "Technical issues force withdrawal of Alstom hydrogen trains" *International Railway Journal*, November 2024. https://www.railjournal.com/fleet/technical-issues-force-withdrawal-of-alstom-hydrogen-trains/

[60] "German hydrogen trains experience problems" *Trains*, February 2025. https://www.trains.com/trn/news-reviews/news-wire/german-hydrogen-trains-experience-problems/

[61] "'A waste of taxpayer's money' | German passenger group slams hydrogen trains as a distraction from need to electrify" Hydrogen Insight, September 2023. https://www.hydrogeninsight.com/transport/a-waste-of-taxpayer-s-money-german-passenger-group-slams-hydrogen-trains-as-a-distraction-from-need-to-electrify/2-1-1516761

> *This echoes recent comments by German train manufacturer Stadler, which noted that not only are battery-electric models appropriate for the range of most of the 500 routes still served by diesel stock, but these have lower operation and maintenance costs than fuel-cell trains.*
>
> *"For the railways in Bavaria, we carried out a concrete analysis of all Bavarian local transport lines, with the result: Complete electrification is possible at short notice and with little effort," Iffländer said.*
>
> *Pro Bahn's analysis recommends deploying battery-electric trains as an immediate measure while overhead lines are installed along railways, with the easiest-to-electrify routes and junctions prioritised.*

In February 2024, the states of Bavaria and Baden-Württemberg announced a conventional electrification plan for currently un-electrified lines[62]. A passenger railroad in Austria also recently ditched hydrogen rail plans in favor of overhead wire electrification[63].

Germany is moving on from its failed experiments with hydrogen passenger trains, as concluded by *Trains* in the February 5, 2025 article[64]:

> *All three German hydrogen train orders (placed 2017-2022) – which in total represent 48 two-car trains — were supported indirectly by substantial additional federal government funding, which has since ended. Since the initial funding was used up, no further hydrogen-train orders have been received from German operators, and some German state governments which had signed "in principle" agreements to buy them have decided not to (e.g. Baden Württemberg).*
>
> *The operating difficulties to date, plus the substantially higher cost of buying hydrogen trains in the first place, has probably given battery power a clear advantage as operators in Germany and across Europe look to get rid of diesel-powered passenger trains. Several hundred battery EMU trains have been ordered for use in Germany from Stadler, Alstom, Siemens, and CAF. Multiple trains are in service, with many more due in 2025-26 from all four manufacturers; similar BEMU trains are also on order for use in other European countries. As in Germany, there have been no further orders for hydrogen-powered passenger trains elsewhere in Europe, although a small number of hydrogen-powered switching locomotives are on order.*

If California has any sense, we will follow their example and move on from the hydrogen experiment.

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[62] "Electrification plans for south German Regio S-Bahn network agreed" *International Railway Journal*, February 2024. https://www.railjournal.com/infrastructure/electrification-plans-for-south-german-regio-s-bahn-network-agreed/

[63] "'Technology moves on' | Austrian railway scraps plans to replace diesel trains with hydrogen-powered options" *Hydrogen Insight*, April 2024. https://www.hydrogeninsight.com/transport/technology-moves-on-austrian-railway-scraps-plans-to-replace-diesel-trains-with-hydrogen-powered-options/2-1-1620507

[64] "German hydrogen trains experience problems" *Trains*, February 2025. https://www.trains.com/trn/news-reviews/news-wire/german-hydrogen-trains-experience-problems/

Conclusions

In sum, the Caltrans/DB 'colored squares' case for dismissing proven rail electrification in favor of highly-unproven and inefficient hydrogen technology is mystifying

Worldwide, electrified rail service provides reliable, available passenger services covering a wide spectrum of applications from high density local suburban to high speed intercity applications. In practice, these systems have also proven to be readily transformable and adaptable as required to meet emergent needs. With regard to passenger trains, it is unlikely hydrogen propulsion will have the "sparks effect" phenomenon documented around the world, where electrification caused significant increases in ridership because of reduced trip times, increased frequency (in part due to lower operating costs), fewer train breakdowns, and the enhanced comfort of a quieter, smoother, smokeless ride. All the evidence, right down to the basic fundamentals of physics, is that there will never be a more efficient rail propulsion technology than conventional electric rail technology (with OCS).

A succession of consultant studies hyping battery and hydrogen trains have been used by public agencies such as CalSTA, Caltrans and CARB to distract from what really needs to happen: an incremental overhead catenary rail electrification program for California. Rather than planning zero emissions technology decisions based on service, VMT, and broader network goals, Caltrans strategy appears to be top-down imposed to suit the hydrogen industry's needs. The 2023 California Hydrogen Market Strategy, announced by the Office of the Governor in response to ARCHES, a public-private partnership, receiving $1.2 billion from the federal Hydrogen Hub program, explains Caltrans's choices far better than their own stated reasoning. The document, which calls for coordination across CARB, Caltrans, and many other executive-level agencies, calls on the state to:

> *Leverage state assets to increase access to hydrogen fueling by transit and public users. Identify opportunities for the state to use clean, renewable hydrogen that simultaneously increase access for the public.*

The state's hydrogen strategy is to place the burden of developing the market and technology for industrial and freight uses on transit riders – sacrificing transit service and reliability for the sake of industry. The hackneyed logical gymnastics involved in justifying its hydrogen train investments are downstream of this. Green hydrogen is undoubtedly important for greenhouse gas emissions reductions in the industrial sector as chemical feedstock – but many of its biggest uses, like steelmaking, are not major parts of the California economy, while others, like oil refining, can be reduced alongside fossil fuel consumption. And transportation emits more greenhouse gases than industry in California[65], so prioritizing industrial emissions at the expense of transportation makes no sense. The results of this coordination can be seen across agencies – for example, CARB's In-Use Locomotive Rule included hydrogen trains as "zero emissions rail" over the protestations of environmentalists, despite its questionable environmental benefits.

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[65] "Current California GHG Emission Inventory Data" *California Air Resources Board*, https://ww2.arb.ca.gov/ghg-inventory-data

Rail riders or the environment do not benefit from California's hydrogen strategy, but who does? The fossil fuel industry. Sempra, the parent company for several natural gas utilities, was the top donor to California politicians in 2023[66] and one of the top lobbyists[67], and they have repeatedly attempted to spend ratepayer money on hydrogen projects[68]. Given the industry-driven logic behind California's hydrogen strategy, and the lack of public discussion and rigorous evaluation behind the state's hydrogen train purchases, there are many reasonable questions for the public to ask:

- Where, exactly, will all the hydrogen to power these trains come from, and what will the fuel cost?
- Why did Caltrans purchase 10 hydrogen FLIRT multiple units from Stadler, with an option to buy 19 more, before the first one had ever been delivered and tested in the state?
- What if the Stadler hydrogen FLIRT multiple units turn out to be expensive failures, like the Alstom iLints have been in Germany? Will Caltrans admit failure or double-down and throw good money after bad?
- Why is Caltrans "betting the farm" on this one model of train?
- Does the massive amount of pro-hydrogen lobbying in Sacramento by the oil and gas industry have anything to do with the decision of CalSTA and Caltrans to choose hydrogen as the only zero-emissions option for intercity passenger trains in the whole state?
- Who will monitor the actual greenhouse gas release of the hydrogen supply chain and ensure that the entire "energy source-to-wheels" system is pollution-free?
- Will a true, long-term analysis follow this development and compare the costs of hydrogen-powered trains to catenary over a 30 year lifetime?

California's hydrogen train strategy demonstrates a remarkable level of statewide coordination in service of hydrogen market development. Coordinated statewide planning, regulation, and deployment of state staff are needed to bring down costs and rapidly deploy green, cost-effective, synergistic overhead electrification around the state. Let's hope that as the hydrogen hype fades, the state will deploy similar levels of coordination in service of holistic climate goals and public transportation needs instead.

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[66] "This year's top contributor to California campaigns is an unexpected fossil fuel giant" *The Sacramento Bee*, September 2023. https://www.sacbee.com/news/politics-government/capitol-alert/article279486729.html

[67] "A record amount went to lobbying California's government. Who were the biggest spenders?" *CalMatters*, February 2024. https://calmatters.org/politics/2024/02/california-lobbying-state-government/

[68] "Landmark Rate Case will Save Southern Californians from Paying Tens of Millions for Dead-end Hydrogen Projects and SoCalGas' Climate Obstruction Efforts" *Earthjustice*, December 2024. https://earthjustice.org/press/2024/landmark-rate-case-will-save-southern-californians-from-paying-tens-of-millions-for-dead-end-hydrogen-projects-and-socalgas-climate-obstruction-efforts

Appendix: Assembly methods for Table 1 calculations

1. Efficiency from Christeller, Reinhard, 2023 "Hydrogen - but not in Transport", Urban Transport Magazine and Iden, Michael, 2023, "Follow the Megawatt-Hours" Railway Age.
2. Car CO2 emissions from "Greenhouse Gas Emissions from a Typical Passenger Vehicle", EPA
3. Diesel and renewable diesel carbon dioxide emissions calculated from standardized g CO2/MJ value that incorporates differences in energy density between the two fuels. Values taken from Jeswani et al. (2020) based on soy-based biodiesel not incorporating land use change (figure 3). Actual emissions are likely higher when accounting for land use changes triggered by mass adoption. This was converted using the average energy intensity for US commuter rail in 2019 (which includes some electrified trains; pure diesel value would be higher) taken from Table 7.03 of the US Dept. of Energy Transportation Energy Data Book, Edition 40.
4. Battery, Catenary, and Green (electrolytic) hydrogen electric train emissions calculated using the WH/seat-mile calculated in a Deutsch Bahn study. Converted using the CO2 intensity of the California grid as of 10 am, 2/15/24: 0.069 T CO2/WH. This approach does not include the emissions from large-scale hydrogen production inducing additional natural gas combustion, which could be 2x the emissions per kg of gray hydrogen according to a study by Energy Innovation.
5. Gray hydrogen emissions calculated based on the 10 g CO2/kg value for steam methane reformation (gray) hydrogen from the 2023 Energy Innovation study, using 0.2 kg/mile from an RSSB study, and the passenger capacity of a Stadler H2 FLIRT assuming a 4 car run as will be done on the SBCTA arrow.
6. Top speed for hydrogen based on the Stadler H2 FLIRT. This is what the train is currently certified for, and may not represent its theoretical maximum. https://www.stadlerrail.com/en/flirt-h2/details/
7. Optimal operating frequency for battery and hydrogen from the Hydrogen Council's 2020 study *Path to Hydrogen Competitiveness: A Cost Perspective*
8. Car NOx emissions calculated from the Bureau of Transportation Statistics data using 2023 numbers, assuming a 50/50 mix of cars and light trucks (SUVs/pickups).
9. Emissions for diesel and renewable diesel locomotives calculated from CARB's 2021 report from a Tier 3 locomotive operating on line-haul cycle (Table 8). Diesel = cert (EPA diesel standard), Renewable = R100 (100 percent renewable diesel from used cooking oil). Converted from g NOx/bhp-hr to g NOx/MJ using EPA conversion factors. This was converted using the average energy intensity for US commuter rail in 2019 (which includes some electrified trains; pure diesel value would be higher) taken from Table 7.03 of the US Dept. of Energy Transportation Energy Data Book, Edition 40 . Note that passenger rail in Southern California uses cleaner Tier 4 engines.
10. NOx emissions for catenary, battery, and electrolytic hydrogen trains calculated based on NOx from electricity generation calculated using baseline (non-heatwave) daily emissions from gas plants in 2022 from Regenerate California's 2023 report and the average power output of gas plants in 2022 (annual total energy mix, GHW/365) from the California Energy Commission. Does not include 12,712 GWH of power from coal, oil, biomass that produce NOx but were not included in emissions in the first source. Emissions per seat-mile calculated as per note 4.

11. NOx emissions for gray (steam methane reformation-derived) hydrogen calculated based on mg/MJ averages for US production from Sun et al 2019, converted to NOx/kg using the 120 MJ/kg energy density of hydrogen from the Rocky Mountain Institute. Emissions per seat-mile calculated as per note 5.
12. Car PM 2.5 emissions calculated from the Bureau of Transportation Statistics data using 2023 numbers, assuming a 50/50 mix of cars and light trucks (SUVs/pickups). Calculation includes exhaust and tire wear PM 2.5 but not brake wear for fairer comparison with the CARB data which did not include brake emissions.
13. PM 2.5 for petroleum and renewable diesel locomotives calculated as per Note 8.
14. PM 2.5 emissions data for the CA energy grid were unavailable, presumably because natural gas combustion, the main combustion source of energy in the grid, does not produce substantial PM 2.5.
15. PM 2.5 emissions for gray (steam methane reformation-derived) hydrogen calculated based on mg/MJ averages for US production from Sun et al 2019, converted to NOx/kg using the 120 MJ/kg energy density of hydrogen from the Rocky Mountain Institute. Emissions per seat-mile calculated as per note 5.
16. Diesel, renewable diesel, and battery electric travel time based on current scheduled Surfliner travel time.
17. Catenary travel time based on Alon Levy's 2017 calculations "A High-Speed Train From San Diego to L.A. Is Possible Even Without High-Speed Rail", Voices of San Diego
18. Additional minute of travel time for hydrogen trains assumes train travels at 79 mph between Solana Beach and Oceanside rather than current Surfliner top speed of 90 mph.