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LIQUID HYDROGEN AS ATTRACTIVE ENERGY STORAGE SOLUTION FOR RAILWAY APPLICATIONS

DIPL.-ING. M. EIBÖCK, DDIPL.-ING. DR. P. LOIDOLT,
DIPL.-ING. D. JEITLER, DIPL.-ING. DR. T. STEPAN,
SAG - SALZBURGER ALUMINIUM GRUPPE, ÖSTERREICH

Abstract

Large parts of the world's railway network are not electrified. In order to achieve decarbonization of this part of the transportation sector, which is powered mostly by fossil fuels, CO2-neutral energy storage and drive train solutions have to be employed. The use of liquid hydrogen as an energy carrier for railway vehicle is both a technically feasible and economically viable solution – similar to commercial vehicles.
This publication begins with an assessment of the global railway network to identify where the conversion from conventional diesel engines to liquid hydrogen powered fuel cells or combustion engines offers the greatest potential for emissions reduction. Subsequently, the energy storage of liquid hydrogen and competing technologies such as battery-electric and high-pressure hydrogen storage systems are compared in terms of storage density, costs and safety in the context of a potential use case in the railway industry.
As a transition to hydrogen is highly dependent on the accessible infrastructure, synergies between on-road commercial transport, railway and industrial hydrogen demands are an economic necessity.

Introduction

The railway sector plays a pivotal role in the global effort to reduce carbon dioxide (CO2) emissions and combat climate change. As a highly energy-efficient mode of transportation, railways offer significant potential for reducing greenhouse gas emissions compared to road and air transport. Nevertheless, further reductions of CO2 emissions are needed towards the goal of zero emission.

In Germany, the national railway company, Deutsche Bahn, has set ambitious goals to achieve climate neutrality by 2040 [1]. Key milestones include a 50% reduction in specific CO2 emissions by 2030 compared to 2006 levels, an 80% share of renewable energy in the rail power mix by 2030, and a complete transition to 100% green electricity by 2038. These targets underscore Germany's commitment to transforming its railway system into a sustainable and environmentally friendly mode of transport.

The European Union has established comprehensive climate targets that encompass the railway sector as part of its broader Green Deal initiative. The EU aims to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and achieve climate neutrality by 2050 [2]. These targets are designed to promote the adoption of cleaner technologies and the integration of renewable energy sources across the transportation sector, including railways.

In the United States, efforts to reduce CO2 emissions in the railway sector are aligned with the national goal of achieving a 50-52% reduction in greenhouse gas emissions by 2030 compared to 2005 levels and reaching climate neutrality by 2050 [3]. The focus is on enhancing energy efficiency, increasing the use of renewable energy, and encouraging the shift of freight and passenger transport from road and air to rail.
The electrification of rail transport is a pivotal aspect of global efforts to reduce CO_2 emissions since it allows the usage of energy from renewable sources as solar energy, wind energy and hydro energy. The electrification of the rail network differs very strong for different countries.
Germany has made significant strides in electrifying its rail network over the past decades. By 2023, approximately 62.3% of the tracks were electrified. The federal government aims to increase this share to 75% by 2030 [4].

In Europe, the degree of electrification varies considerably among different countries. In 2021, an average of 57% of railway networks in Europe were electrified . Countries like Switzerland and Belgium achieve electrification rates of up to 100% and 86% respectively, while others lag significantly behind [5].

In contrast, the degree of electrification in the USA is very low. Less than 1% of the approximately 225,000 km long rail network is electrified [6]. This is mainly due to the size of the network, traffic density, and financial as well as economic constraints.

The electrification of the full railway network is no option due to the immense cost and effort needed to create the infrastructure. Furthermore the electrification of the railway transport is only a sustainable solution in case of sustainable production of the electricity. Hence, a variety of other approaches is considered to replace diesel-powered trains on non-electrified sections of the rail network.

Hydrogen fuel cells are an emerging technology that produces zero emissions at the point of use. Countries like Germany and the UK are pioneering the deployment of hydrogen trains, which offer a clean and efficient alternative to diesel engines [7]. Battery-powered trains, another viable option, can operate on non-electrified tracks and are particularly suitable for short to medium distances. These trains can be charged at stations or short electrified sections of the tracks reducing the need for extensive infrastructure [8].

E-fuels could be an alternative for diesel-powered vehicles in areas that are not economically feasible to electrify with catenary lines. Converting existing diesel engines to e-fuels could also allow the use of existing fuel infrastructure, thereby reducing adaptation costs [7].

However, there are also challenges. The overall efficiency (Well-to-Wheel) of e-fuels is currently around 13 percent due to the numerous conversion steps [9]. Additionally, the production of the raw materials still causes environmental impacts.

The focus of this paper are hydrogen fuel cell based systems and battery based systems which are benchmarked compared to systems with catenary lines. For hydrogen fuel cell based systems gaseous high pressure storage cGH2 and liquid hydrogen storage LH2 are differentiated. High pressure storages are the most widespread storage system for hydrogen in train applications so far. However, liquid hydrogen storage systems have been proven e.g. for heavy duty truck applications and seem to be a suitable solution also for train application.

Comparison of hydrogen and battery-based fuel storage for railway applications

The following section evaluates gaseous and liquid hydrogen storage, along with battery-electric storage systems, based on their gravimetric and volumetric energy densities, service life requirements and limitations, as well as the costs associated with each storage system and the required infrastructure for train applications. The obtained results are benchmarked with the current diesel storage solution.

Weight and Volume of fuel storage systems

Gaseous Hydrogen Storage

Gaseous hydrogen storage systems typically use high-pressure tanks, such as those rated at 350 bar or 700 bar. These tanks are relatively heavy due to the need for thick walls to withstand the high pressures involved. The weight efficiency of these systems is around 3,4 – 6,9%, which translates to a gravimetric storage density of 1,14 – 2,32 kWh/kg. There is a correlation between filling pressure and gravimetric storage efficiency – 700 bar systems tend to be on the lower side, due to their thicker carbon wrapping in comparison to 350 bar systems. In terms of volumetric energy density, reported values range from 15 – 23 g/l (0,5 – 0,77 kWh/l), the correlation to storage pressure being reversed – 700 bar systems have an advantage over lower pressure systems [10].

Liquid Hydrogen Storage

Liquid hydrogen storage involves cryogenic tanks that keep hydrogen at -253°C. These tanks are, in general, lighter than high-pressure gaseous tanks because they operate at lower pressures below 20 bar. The weight efficiency of liquid hydrogen storage are reported to be between 4,5 and 15% (although high efficiencies can only be achieved at low maximum pressure, which comes with downsides like decreased dormancy time) [11, 10]. Current SAG liquid hydrogen storage systems manufactured from stainless steel feature a gravimetric energy density of approximately 2.6 kWh/kg, with the potential to improve this value by changing to a lighter material, i.e. aluminium. This way the storage density can be improved to at least 4 kWh/kg, with further potential for reduction by decreasing operating pressure and therefore the wall thickness. Due to the higher density of the hydrogen in liquid form, volumetric energy density is higher compared to high pressure hydrogen tanks with reported values of 4,5 – 10 g/l (0,93 - 2kWh/l) [10]. The volumetric storage density of the SAG storage system is already optimized, featuring a volumetric energy density of ~ 1.4 kWh/l [12].

Battery Systems

There are many types of battery chemistries with a potential use in railway applications – for this comparison, lithium titrate oxide (LTO) batteries were chosen for the comparison, because various studies [13, 14] came to the conclusion that LTO batteries represent a good compromise between energy density, cycle life, charging speed, life-cycle-cost and various other factors. The gravimetric energy density of those batteries is lower compared to hydrogen storage at 60 – 120 Wh/kg [15]. Batteries also require significant space - their energy density by volume is substantially lower than that of liquid hydrogen with reported volumetric energy densities of up to 229 Wh/l [16, 17]. This can be a constraint in railway systems where maximizing energy storage within limited space is crucial.

Diesel tanks

Conventional Diesel tanks are relatively lightweight compared to hydrogen storage systems and batteries – for example, a standard SAG diesel tank with a capacity of 550 l weights 32,8 kg. On a system level, this means a gravimetric energy density of 11,8 kWh/kg. This has been one of the reasons for its widespread use in railway systems. In terms of volumetric efficiency, diesel tanks are also superior to hydrogen and battery solutions – the same exemplary SAG diesel tank has an energy density of 10,5 kWh/l.

Service life requirements and limitations

Hydrogen Storage Systems

Following international regulations, most notably the Global technical regulation 13 (GTR 13 phase 1) the service life of gaseous hydrogen storage systems typically used in passenger cars or commercial vehicles is currently limited to 15 years, based on the number of tested pressure cycles during type approval. This number was chosen based on the expected maximum number of cycles during service life and contains a safety margin.
Liquid hydrogen storage systems also have a service life limited to 15 years according to GTR 13 Phase 1, although the rational for limiting the service life is different. Recent updates in GTR 13 Phase 2 have introduced new data suggesting that the number of pressure cycles in qualification tests (up to 11,000 cycles) does not exceed the expected number of cycles during service, even in severe cases. This data supports the rationale for potentially extending the service life of hydrogen storage systems to 25 years. It stands to reason that railway specific standards, such as the DIN EN IEC 63341 for Germany or the ISO 19887-2, will adapt design and testing requirements, to allow for an extended service period common in the railway industry. Revisions of these standards are currently underway and will be publicly available in 2026.

The limited service life of hydrogen storage systems can be attribute d to different factors:

Material Fatigue: Repeated pressurization and depressurization cycles during filling and extraction cause stress on the vessel, leading to fatigue and eventual failure. This is a particularly crucial design consideration for compressed gaseous storage cylinders, as they operate across a much larger pressure range compared to LH2 systems (350-700 vs. 3-20 bar). Conversely, due to the comparable low number of pressure cycles over the service life (< 15000 cycles) and the lower operating pressure, metallic LH2 storage containers can be considered fatigue resistant.

Corrosion: Exposure to corrosive environment, typical for on-road applications, , can cause corrosion of the storage materials. However, since the most common materials used for gaseous and liquid hydrogen storage in mobile applications are vessels manufactured from carbon fiber composites, and stainless steel or aluminum, respectively, this degradation mechanism can be controlled by employing a suitable design of the outer shell, i.e. avoiding crevice corrosion or galvanic corrosion by matching the wrong materials.

Thermal Cycling: The temperature variations during hydrogen storage and release can cause thermal stress, leading to material degradation. These fluctuations can result in micro-cracking and other forms of damage, which may compromise the integrity of the storage system over time. It is important to differentiate between compressed gaseous and cryogenic liquid hydrogen storage here. Whereas for cryogenic storage vessels the initial cool down is the main source of thermally induced strain – tubes and container at ambient temperature get in contact with liquid hydrogen – cylinders for gaseous storage experience thermal cycles during every filling, due to rapid compression of the gas resulting in significant temperature increase. This is the main reason precooling of the supplied hydrogen is required, in order to enable fast refueling of 350 and 700 bar cylinders.

Hydrogen Embrittlement: This phenomenon happens when hydrogen atoms diffuse into a material‘s crystal lattice, causing it to become brittle and lose its ductility. High-strength metals, such as martensitic steels are particularly susceptible to embrittlement, which can result in sudden and catastrophic failure under load. As a consequence, metallic storage container for hydrogen are usually manufactured from austenitic stainless steel, in particular of the 316L family, or aluminum alloys. Their face-centered cubic lattice structure is largely resistant to hydrogen embrittlement. While the effects of hydrogen embrittlement are typically more pronounced at high temperatures and pressures due to the increased diffusivity of hydrogen, material selection for cryogenic storage systems should aim to prevent the formation of strain-induced martensite, which is promoted at low temperatures. Metallic containers for LH2 are considered to have a very high resistance against hydrogen embrittlement, if the formation of strain-induced martensite formation is prevented [18].

Contamination: In order to avoid premature failure of the storage system, relevant both for gaseous and liquid hydrogen, the fuel quality has to be tightly controlled. For instance particle contamination might result in failure of system components, such as valves if the amount of particle contamination in the fuel is too high (i.e. 1 mg/kg is the current max. allowed for type I/II grade D hydrogen used for fuel cell applications according to ISO 14687). In an effort to reduce maintenance costs, storage systems should be designed with the aim to withstand unforeseen particle contamination, in example by utilizing filters in front of critical components.

Battery Storage Systems

Depending on the use case, different battery chemistries may be chosen, such as sodium-ion for cost-effective applications or solid-state batteries for high-performance needs. In case of railway vehicles considered in this work, Lithium Titanate batteries (LTO batteries) were chosen, due to their longevity, fast-charging and high discharge capacity and high safety. For batteries the most common way of estimating service life is the amount of charging cycles, defined as the number of cycles until the original capacity is reduced to 80%. Depending on application, environmental, charging and discharging conditions the range of cycle life varies significantly. According to Hall et.al. [19], 10000 cycles can be achieved without significant loss of capacity, although the capability of fast-charging degrades with higher number of cycles. On the other hand, Han et.al. [20] investigated cycle life under harsh conditions, observing significant capacity loss already after 1000 cycles. Without actual data of the performance of LTO batteries in railway applications, a reliable evaluation of service life is not possible, however assuming appropriate battery management and moderate loads during service 10000 cycles will translate to an approximate service life of 10-15 years, which is in agreement to the numbers provided in [21]. Based on this number of expected charging cycles, at least one replacement of the battery pack might be required over the service life of a railcar or locomotive. In addition, LTO batteries typically experience a capacity fade of about 10-20% over their service life.

Over time, the battery‘s capacity to hold a charge decreases due to the degradation of active materials. The loss of capacity over service life has to be offset by installing higher capacity on the train, resulting in higher capital invest, more weight and volume of the storage system. The underlying mechanisms are explained in detail in literature, the following summarizes key findings from [22]:

Impact of SOC Intervals: Degradation increases significantly when the batteries are cycled within lower SOC intervals or with lower cut-off voltages.

Impact of Discharge Voltages: Lower discharge cut-off voltages exacerbate degradation, while higher cut-off voltages help mitigate it.

Depth of Discharge (DOD): Thermodynamic degradation is more significant at 20% DOD, while kinetic degradation dominates at 100% DOD.

Lower SOC Intervals and Lower Cut-off Voltages: These conditions lead to higher capacity loss due to accelerated degradation.

Higher SOC Intervals and Higher Cut-off Voltages: These conditions help reduce capacity loss and extend the battery‘s lifespan.

Figure 1 shows the capacity loss as a function of charging and discharging cycles [22]. The capacity loss is significantly more pronounced when cycling the battery at low state of charge and when discharging to very low cut-off voltages.

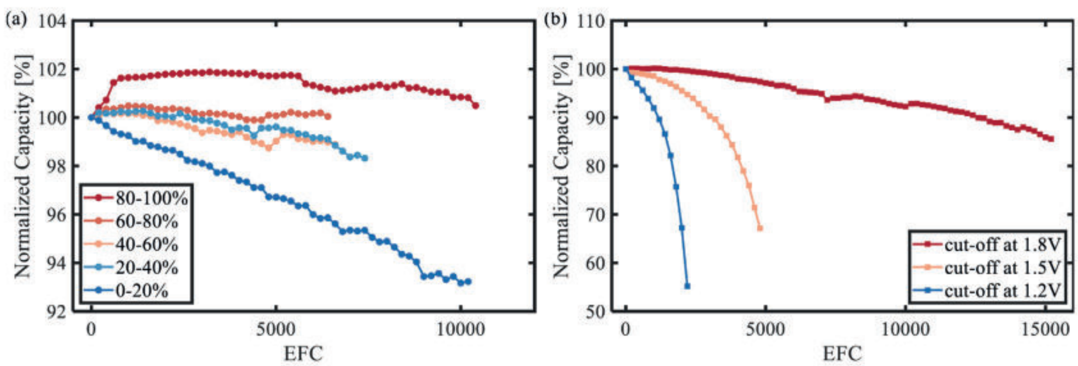

Figure 1: Capacity loss of LTO batteries as function of cycle number [22].

Diesel tanks

Standard diesel tanks made from aluminum typically feature a service life of around 20-30 years with proper maintenance. These tanks are commonly used in both automotive and railway sectors. The most common degradation mechanisms for diesel tanks are the following:

Corrosion: Diesel tanks are subject to internal and external corrosion, which can lead to leaks and structural failure over time.

Fatigue: Mechanical stress and vibrations from vehicle operations can cause fatigue and eventual cracking of the tank material.

Contamination: Water and microbial contamination in the diesel fuel can accelerate corrosion and degrade the tank's integrity.
The degradation during service life of diesel tanks can be avoided based on a proper material selection and design of the tank systems.

Cost Comparison – Storage System

In the context of railway applications, the capital expenditure (CAPEX) associated with energy storage systems is generally less critical than the operational expenditure (OPEX), which includes ongoing costs such as fuel consumption, maintenance, and idle costs due to unplanned downtime. However, with the adoption of alternative energy storage solutions, the proportion of CAPEX allocated to storage systems can be significantly higher compared to conventional diesel tanks. This allocation can influence the choice of technology depending on the specific use case. [23]

To provide a comparative analysis, high-pressure hydrogen (H2) tanks, cryogenic storage systems, batteries, and diesel tanks are evaluated based on their cost per unit of stored energy. This analysis includes identifying the primary cost drivers for each storage solution. Additionally, given that many alternative storage solutions are not yet widely adopted, the potential future cost developments for these technologies are also examined:

Gaseous Hydrogen Storage

Houchins et al. [24] analyzed different hydrogen storage solutions regarding their cost in terms of materials, components and manufacturing:

It was concluded that in terms of material costs, the carbon fibre shell, as well as the winding process for Type 3 and Type 4 vessels dominates the total system cost. It is suggested that optimizing

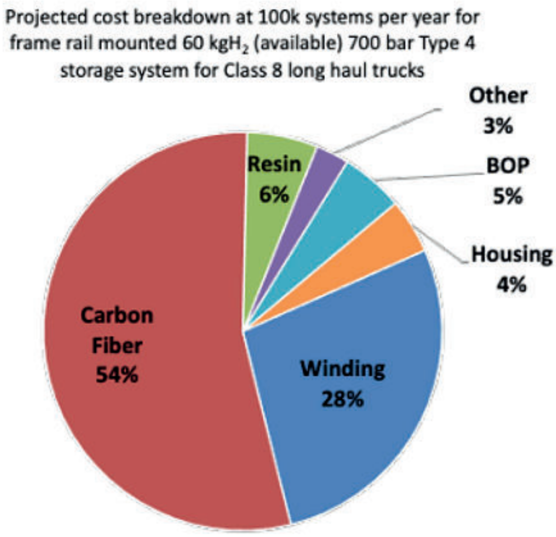

Figure 2: 700 bar Type HDV storage system cost breakdown [24]

the carbon fibre wrapping could potentially reduce production costs. For railway applications, special attention must be given to the increased lifetime and number of pressure cycles, which typically necessitate higher wall thickness and, consequently, higher material costs.

Projected storage cost was estimated at 378-392 \$/kgH2 (11,4-11,7 \$/kWh) for an exemplary 700 bar two tank configuration with a capacity of 60 kg H2 at a production volume of 100.000 tank systems per year.

Liquid Hydrogen Storage

The same DOE report [24] examined exemplary liquid hydrogen storage systems:

The total cost distribution is more evenly balanced among various components and processes in these systems compared to high-pressure hydrogen tanks (as shown in a cost breakdown in Figure 3). Significant cost drivers include valves, fittings, and tubing, as well as the Multi-Layer Insulation (MLI) and the system shell. This study assumes storage systems equipped with a pump, which constitutes a substantial portion of the total cost. Notably, in fuel cell systems, incorporating a pump is not essential, as hydrogen can be extracted through alternative methods, such as those demonstrated in the SAG tank system [25].

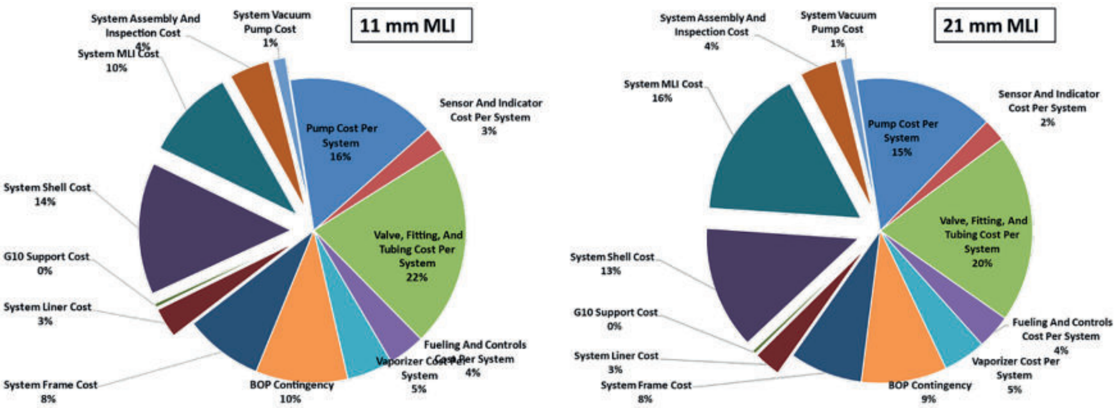

Figure 3: Cost breakdown LH2 for 11 mm and 21 mm MLI [24]

Projected storage cost for a comparable 2-tank system is projected at 215-241 $/kgH2 (6,5-7,2 $/kWh) at a production volume of 100.000 systems per year and a hydrogen capacity of 60,3-69,5 kg. Economic efficiency, e.g. cost per unit of energy stored increases with increasing size of the individual tank. In SAG experience, at present, a bulk of the total cost is distributed on specialty components like cryogenic valves, MLI, filling receptacles etc., as well as time consuming production processes like evacuation, welding and various stages of leakage tests. By optimizing the production process and increasing procurement volume of components, the cost can be reduced significantly

Battery Systems

For the same reasons mentioned in previous chapters, LTO (Lithium Titanate Oxide) batteries were chosen for comparison:

Obtaining detailed cost breakdowns for battery energy storage systems (ESSs) can be challenging, as such information is often limited or unavailable due to confidentiality. However, on a base of cell cost Oangi et al. [26] have shown, that the raw material makes up roughly 50% of the production cost for different cell chemistries, including LTO batteries and is the dominating cost factor (see Figure 4).

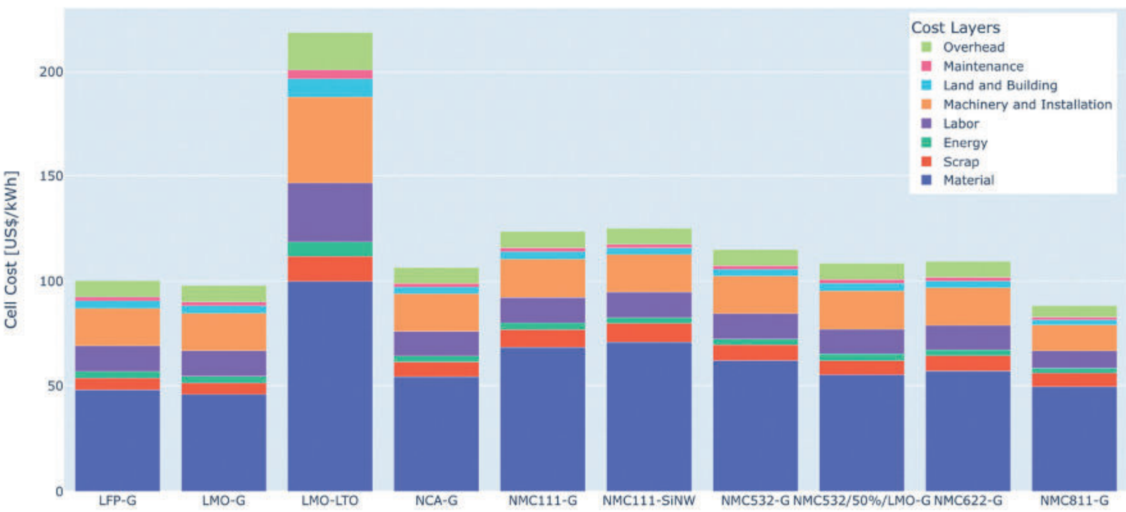

Figure 4: Sensitivity of the developed cost model to chemistries for the production capacity of 5.3 GWh per year. [26]

In 2017, IRENA [27] reported a current energy installation cost of 473-1260 $/kWh and expects a reduction to 215-574 $/kWh by 2030 (as shown in Figure 5) by means of increased production volume or more efficient cell design. The reported evaluation of current costs overlaps with the numbers given by Ritar Power [28] at 800-1200$/kWh.

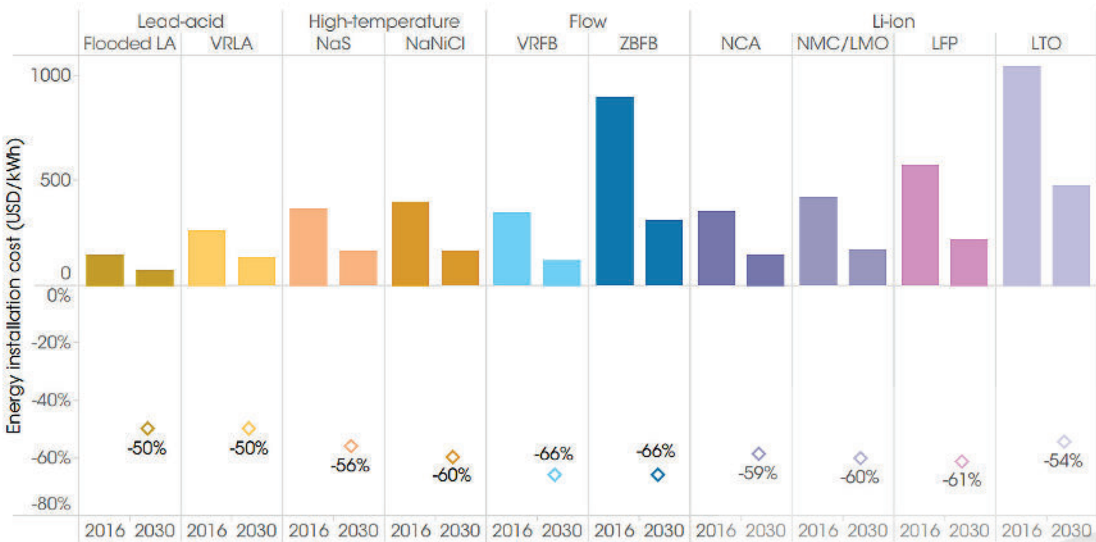

Figure 5: Sensitivity of the developed cost model to chemistries for the production capacity of 5.3 GWh per year. [26]

Diesel tanks

In comparison to battery electric or hydrogen storage solutions, the cost of diesel tanks is negligible, which precludes the necessity for detailed cost analyses. To put the ratio in perspective - empirical data from SAG indicates that the cost of standard aluminum diesel tanks is substantially lower than 1$/kWh.

Total cost of ownership and fueling infrastructure

A widely used metric for comparing the costs of trains running on alternative fuels is the total cost of ownership (TCO). The major cost drivers, which have to be considered are the CAPEX and OPEX for the vehicle and the infrastructure, the electricity costs, taxes/levies and potential income by utilizing excess heat and O2, the byproduct of green hydrogen production by electrolysis. Most TCO analyses present case studies because the boundary conditions related to location, operation, infrastructure, and further necessary assumptions differ significantly from one use case to another, making it difficult to provide universally legitimate statements [29, 30, 31]. However, a few general conclusions can still be derived:

- Complete electrification of railway tracks, while the most efficient solution from a drivetrain perspective, is not economically feasible for large countries like the United States, which has approximately 148,000 km of railways with less than 1% currently electrified. In contrast, Germany has over 60% of its railway network electrified. However, with an annual new-electrification rate of only 65 km, it would take more than 200 years to achieve full electrification of the entire network at this pace. So alternative solutions are required.
- Similar to the energy sector, the intermittent consumption of green electricity during train operation necessitates converting surplus energy into molecular energy carriers like hydrogen, which can be stored and utilized as needed.
- With increasing demands on range and power, the TCO of battery-powered trains increases in favor of hydrogen supplied vehicles. The current tipping point for multiple-unit railcars lies between 120 and 200 km, dependent on the future development of battery storage technology.
- Hydrogen-powered trains face significant challenges due to the lack of supply infrastructure and the high costs associated with hydrogen fuel. Moreover, achieving substantial CO2 emissions reduction depends on the use of green hydrogen, which currently accounts for only about 5% of global production.

With regards to the hydrogen supply infrastructure for railway production, transportation and dispensing to the vehicle must be considered. A study conducted by the National Renewable Energy Laboratory compares the levelized costs of dispensed hydrogen in two different scenarios [32]:

- Hydrogen refueling station supplied with liquid hydrogen from a tanker
- Hydrogen refueling station supplied with gaseous hydrogen from onsite production

The basic premise for the values presented in Figure 6 and Figure 7 is a hydrogen production at a scale of 100 metric tons per day and uses the median of the cost range of currently produced hydrogen in the United States (mostly by steam methane reforming). Therefore, considering the necessity of large infrastructure investments for the production of green hydrogen, the cost of production might be significantly higher than suggested in this study. Furthermore, it is assumed that the LH2-trailer covers a roundtrip of approximately 100 km, whereas for onsite production a distance of 100 m to from production to refueling station is considered. Taxes, incentives or additional profits are not considered, the provided numbers can therefore be considered minimum retail prices.

As one might expect, increasing utilization and capacity of the refueling station decreases the costs of dispensed hydrogen significantly, due to the proportionately reduced station costs. The expenditures for transport and terminal are negligible in all scenarios, whereas the share of liquefaction on the overall fuel costs increases, due to the assumption of a static hydrogen production of 100 MTPD.

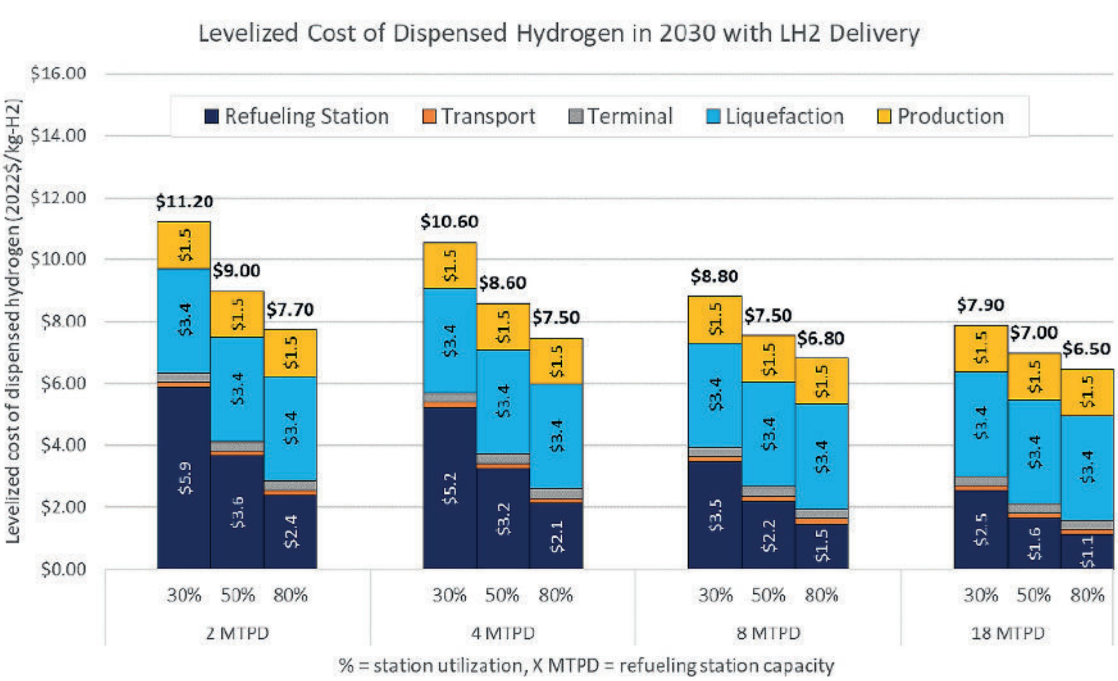

Figure 6: Costs of dispensed hydrogen with LH2 delivery as a function of dispensed fuel quantity (in metric tons per day, MTPD) and fueling station lifetime utilization rates [32]

For the refueling station employing onsite hydrogen production the impact of station utilization and capacity is similar but even more pronounced due to the majority of fuel costs being attributed to the station equipment. Although the presented results favor onsite production and supply of gaseous hydrogen over liquid supply by trailer, it must be noted that onsite production is not feasible for every refueling station and liquid on-road transport is much more cost-effective than gaseous distribution (4tLH2/trailer vs. 1tGH2/trailer). In addition, optimization of the liquefaction process may reduce energy demand and consequently costs significantly (7 kWh/kgH2 according to [33] vs. ~ 10 kWh/kgH2 assumed in this study [32]).

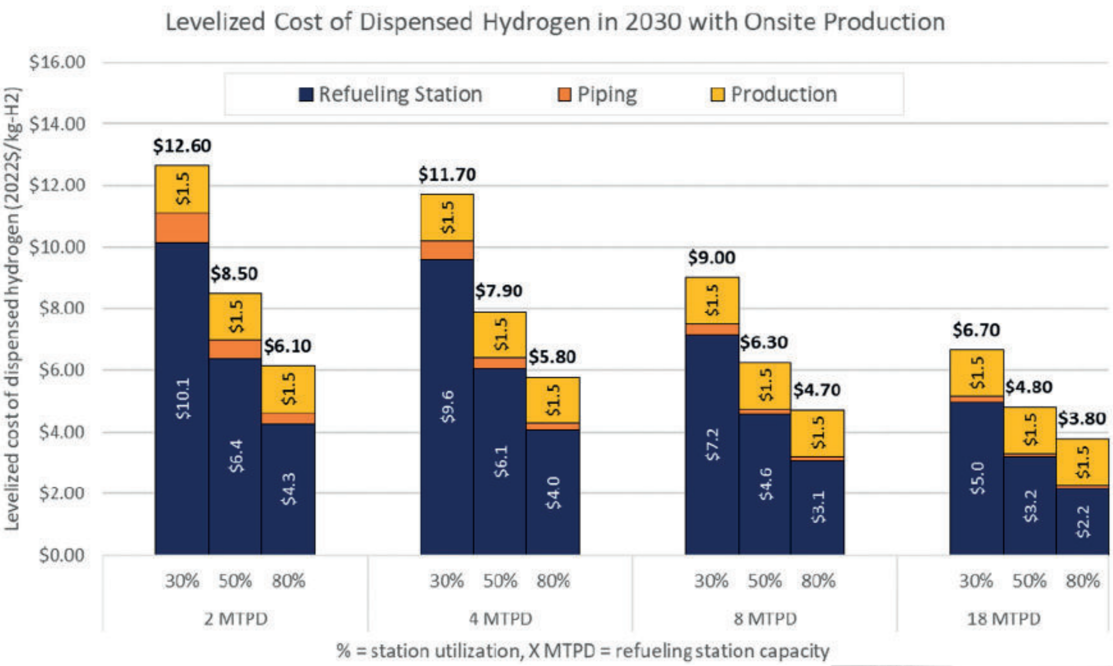

Figure 7: Costs of dispensed hydrogen with onsite production as a function of dispensed fuel quantity (in metric tons per day, MTPD) and fueling station lifetime utilization rates [32]

Ehrhart et al. investigated the feasibility of different configurations of refueling infrastructure for hydrogen rail applications [34]. The study focused on equipment cost and design of refueling stations for multiple unit (MU) trains, passenger and freight locomotives of various sizes and examined gaseous hydrogen dispensing for MU trains and passenger locomotives and liquid filling for freight trains, respectively. All configurations were evaluated assuming the supply of liquid hydrogen by trailer. The results are summarized in Table 1.

Design	Dispensed State	Capacity (kg/day)	Component Cost ($\times$\$1,000,000)	Lot Size ($\times$1,000 ft^2)
Multiple Unit Direct-Fill Cryopump 15-Minute	GH_2	2,600	1.7	12.8
Passenger Locomotive Direct-Fill Cryopump	GH_2	20,000	7.1	30.4
Small Freight	LH_2	37,500	4.6	20.2
Medium Freight	LH_2	375,000	30.1	62.9
Large Freight	LH_2	1,500,000	117.4	158.5

Table 1: Design configurations of refueling station based on different railway applications [34]

For gaseous filling the direct fill cryopump design wins out, both over the direct fill by compressor and the cascade fill design. This can be attributed to the significantly lower costs of the cryopump compared to the compressor, whereas the cascade design, aiming to reduce the max. supply rate on compressor and heat exchanger, is very expensive due to the high number of tanks required to enable cascade filling. For liquid filling the components costs are even further reduced, since the cryopump only shifts liquid hydrogen at low pressure from the refueling station to the train, without the need for compression, or a chiller at the dispenser to enable fast gaseous refueling. As a consequence, the component costs for LH2 dispensing for small freight trains are smaller than for direct fill of a passenger locomotive, even though the capacity is almost twice as high. Normalizing the equipment costs to the capacity of hydrogen per day, the refueling station for gaseous refueling is nearly 3-times as expensive. Based on this finding we recommend the application of liquid hydrogen refueling instead of gaseous refueling. As long as liquid hydrogen is supplied to the fueling station, the lower equipment costs justify the liquid hydrogen storage for MU and passenger locomotive trains as well.

Conclusion

In conclusion, the use of liquid hydrogen as an energy carrier for railway vehicles presents a technically feasible and economically viable solution for decarbonizing non-electrified sections of the global railway network.

The comparison of the different systems show advantages and disadvantages for every system:

- Gaseous Hydrogen: Heavy and voluminous, with low volumetric energy density, less efficient for space-constrained applications.
- Liquid Hydrogen: Lighter and more volume-efficient, with higher volumetric energy density, better suited for railway systems if space is limited.
- Battery Systems: Heavy and voluminous, with lower energy density compared to hydrogen, but suitable for electric trains as renewable energy storage.
- Diesel Tanks: Lightweight and highly volume-efficient, with high energy density, but not a clean energy source.

Each storage system has its advantages and disadvantages, and the choice depends on the specific requirements and constraints of the railway system. For instance, hydrogen storage (both gaseous and liquid) offers a cleaner alternative to diesel but comes with challenges related to weight and volume. Battery systems are suitable for electric trains but have lower energy densities compared to hydrogen and diesel – they have lower gravimetric and volumetric storage efficiencies, but can be a viable solution if space and range requirements allow for those limitations. This is especially true, if only parts of the railroad network are not electrified and are bridged with batteries – in this case, the existing powerlines in electrified sections can be used to charge batteries.

In use cases that require comparatively high ranges, volumetric energy density can be a significant key specification, especially if space is critical – i.e. in multiple units (trains without dedicated locomotives), in which space occupied by energy storage leads to decreased space for passengers. Liquid hydrogen storage systems are the best green solution for those specifications, due to their high volumetric energy density. It has to be mentioned that in case of fuel cell powertrains, a battery is needed to buffer peaks of power demand/transient power demand – in this case, limitations of the battery systems must be addressed. In comparison to exclusively battery electric systems, the reduced size of the battery facilitates easier management of associated limitations.

The viability of railway vehicles with liquid hydrogen storage is highly dependent on the availability of liquid hydrogen in the future energy systems. If liquid hydrogen is used to distribute hydrogen via ships, trains and trucks then the TCO of liquid hydrogen storages is lower compared to gaseous storages. However, in case of distribution of gaseous hydrogen via pipeline the additional step of liquification might lead to an substantial increase of the TCO in case of liquid hydrogen storage.

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SAG New Technologies GmbH

A - 5651 Lend 25
+43 6416 65000
aluminium@sag.at

www.sag.at