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Road/Railway - Overview of the policy regime for the introduction of hydrogen fuel cell trains: Hydrogen trains on the rise in Europe? French region introduces hydrogen powered trains while German regions opt for battery electric trains

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【概要：Summary】

The transport sector is responsible for a quarter of the EU's total GHG emissions, and it still relies heavily on fossil fuels.

The European Green Deal's target to reach net-zero GHG emissions by 2050 also requires the decarbonisation of the transport sector and the reduction of its GHG emissions by 90% by 20250.

The EU recognizes several types of alternative fuels, including battery electric solutions, hydrogen, and biofuels.

Hydrogen-powered trains are seen as a promising solution for decarbonizing the European railway sector by replacing diesel trains operating in the non-electrified parts of the railway network with alternative propulsion. Fuel cell trains have been introduced in the German region of Lower Saxony, offering a sustainable alternative for non-electrified parts of the railway network. However, the introduction of hydrogen powered trains is meeting challenges. Notably, in the Germany, a study commissioned by the federal state of Baden-Württemberg, favoures electric or battery-powered trains over hydrogen-powered trains for economic reasons, citing the high costs for building the infrastructure and maintenance complexities of hydrogen trains. Furthermore, the German Lower Saxony region decided to introduce battery electric trains in future, rather than expanding the existing fleet of hydrogen trains, due to maintenance costs and technical complications.

In contrast, four French regions will introduce hydrogen trains and also the European FCH2Rail project, developing bi-mode demonstrator trains using hydrogen fuel cells continues with on-track testing on different routes within the Spanish National Railway Network. Moreover, also other countries including the US, Japan, China, India, and Namibia are exploring or implementing hydrogen-powered rail transport.

Overall, hydrogen trains are a promising option to reducing GHG emissions in the railway sector. The primary challenge for the deployment of hydrogen trains is the lack of infrastructure and the maintenance costs.

Ultimately, the choice of propulsion technology for trains depends on various preconditions and some of those support the operation of hydrogen-powered trains in the non-electrified part of railway networks.

【記事：Article】

1. Hydrogen propulsion as an option for decarbonising the transport sector

At present, the EU transport sector accounts for a quarter of the EU' s total GHG emissions, and the sector is still heavily dependent on fossil fuels. To achieve the decarbonisation of the EU' s mobility system and to reach net-zero emissions by 2050, all transport modes need to contribute to reduce their CO_2 emissions.

Regarding the decarbonisation of the transport sector, there are a variety of alternative fuels and power sources in discussion to replace the fossil oil sources (European Commission n.d.). Alternative fuels for zero-emission vehicles include electric propulsion, hydrogen, and ammonia. The renewable fuels include biomass fuels and biofuels as defined in Directive (EU) 2018/2001, as well as synthetic and paraffinic fuels, including ammonia, produced from renewable energy (Directive (EU) 2018/2001). The 2014 Directive on Alternative Fuels Infrastructure recognises six types of alternative fuels, including electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas, including biomethane, in gaseous form (compressed natural gas (CNG)), liquefied Natural gas (liquefied natural gas (LNG)), liquefied petroleum gas (LPG) (European Commission n.d.). The proposal for a regulation on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council (COM/2021/559 final) distinguishes between alternative fuels for zero-emission vehicles, renewable fuels, and alternative fossil fuels for a transitional phase (COM/2021/559 final). According to COM/2021/559 final, the alternative fossil fuels for a transitional phase include natural gas, in gaseous form (compressed natural gas (CNG)) and liquefied form (liquefied natural gas (LNG)), liquefied petroleum gas (LPG), as well as synthetic and paraffinic fuels.

Considering the target to reduce the transport sector' s GHG emissions, hydrogen is a promising alternative fuel option for those sub-sectors and areas, where electrification is difficult. In the early adoption phase, hydrogen is used as propulsion for local city buses, commercial taxi fleets, or on specific parts of the rail network, where electrification is not feasible.

However, currently, most hydrogen is still extracted from natural gas in a process that produces CO_2 emissions, which is not in line with the European Green Deal' s target to achieve climate neutrality in Europe by 2050.

The main precondition for an environmentally friendly use of hydrogen is its production from renewable sources. Therefore, the hydrogen production needs to shift from "grey" hydrogen, which is produced using natural gas, to "blue" and 'green' hydrogen. Blue hydrogen production relies on technologies that can capture and store carbon emissions (CCS) (Esteves 2023). However, the cleanest version is "green" hydrogen generated from renewable electricity without producing GHG emissions. However, green hydrogen is currently also the most expensive option (Esteves 2023). Therefore, the key precondition for the utilisation of hydrogen would be to reach a production, which is entirely based on renewable sources.

Regarding the utilisation of hydrogen fuel cells in transport, they could compete with electric batteries, but given the higher cost for producing green hydrogen and the current lack of infrastructure including refuelling stations they are not competitive considering the additional costs. The Regulation on Alternative Infrastructure intends to change this situation and improve the network of refuelling stations of hydrogen in the transport sector (COM(2021) 559 final).

2. First FCH powered passenger trains in German regional railway service

Although railways are considered being already an environmentally friendly means of transport, to further improve its carbon footprint and to achieve zero-emissions, the diesel traction needs to be eliminated in the non-electrified part of the European railway network. Regarding the railway sector, hydrogen could potentially become an energy source that could replace diesel as type of propulsion in the non-electrified part of the European railway network.

The latest developments in the field in Germany and France show that this technology could in fact complement electrification in Europe and enable the complete decarbonisation in rail (Ruf et.al. 2019). Hydrogen fuel cells are among the most practical eco-friendly alternatives for trains where electrification of the tracks is prohibitively expensive (Petzinger 2018).

On 20 September 2016, the French multinational rail company Alstom presented the first Coradia iLint hydrogen powered zero-emission passenger train (Alstom n.d.). The Coradia iLint zero-emission FCH powered passenger train has a maximum speed of 140 km/h and can cover a distance of about 800 km without refuelling. After a successful trial run of almost two years with two pre-series trains, on 24 August 2022, the world’s first hydrogen fuel cell Coradia iLint train was inaugurated in passenger service for public transportation, in Lower Saxony, Germany (Alstom n.d.). On a route between Cuxhaven and Buxtehude in Lower Saxony, it was too expensive to build the electric infrastructure to replace the diesel-powered trains with electric trains (Rathi 2018). Therefore, the Landesnahverkehrsgesellschaft Niedersachsen (LNVG) decided to replace the diesel-powered trains with hydrogen-powered trains. The 14 vehicles with fuel cell propulsion are run by the transport company EVB, the Eisenbahnen und Verkehrsbetriebe Elbe-Weser GmbH railway and bus company and the gas and engineering company Linde supplies the hydrogen to run the trains (Alstom 2022).

After the trial phase, public transport provider Eisenbahnen und Verkehrsbetriebe Elbe-Weser (EVB) started the operation of the fleet of 14 fuel cell trains with a maximum speed of 140 km per hour on the nearly 100km line running between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude in August 2022 (Rathi 2018). The necessary hydrogen refuelling facility was funded through a EUR 8.4 million grant from the German federal government’s National Innovation Programme for Hydrogen and Fuel Cell Technology.

Another important project to introduce hydrogen trains in the regional railway network was planned in the region of Frankfurt am Mian, Germany (Alstom 2022). In 2020, the Frankfurt Rhine-Main transport association RMW ordered 27 Coradia iLint fuel-cell trains from Alstom to operate in the mountainous region of the Taunus railway line, north of Frankfurt. The introduction of four hydrogen-powered train lines was scheduled for 11 December 2022 (Klevestrand 2023). This production of hydrogen is powered by the local power grid, which generates about 50% of electricity from renewable energy sources and the price for this hydrogen is considered being below market price currently quoted elsewhere (Klevestrand 2023).

However, the introduction of the fleet of 27 Alstom hydrogen trains faced several problems. Due to the trains’ production delays, only two trains went into service on 11 December 2022, just one of four routes dedicated to the operation of hydrogen trains were able to replace the diesel locomotives (Klevestrand 2023).

Even in the first half of 2023, delivery delays and technical problems plagued the operation of the hydrogen train fleet. Not only the delays in the delivery of the train sets but also the new operating procedures of hydrogen trains posed continuously technical challenges. There were difficulties with the refuelling of the vehicles at the newly built filling station for the operators of the trains. Defects in both, hydrogen and replacement diesel vehicles were "massive" and "not foreseeable" and caused the closure of the entire Taunus railway hydrogen train lines repeatedly (Klevestrand 2023). Buses had to be introduced in the rail replacement services (Klevestrand 2023).

Alstom's third contract for hydrogen trains comes from Italy where Alstom is building 6 Coradia Stream hydrogen trains in the region of Lombardy - with the option for 8 more. In 2023, the Italian ministry of infrastructure and transport allocated EUR 300 million to six projects to convert diesel trains into hydrogen trains (Bhattacharya 2023).

The fourth project is located in France, where four different French regions have placed orders for 12 Coradia Polyvalent hydrogen trains (Alstom 2022). Furthermore, several other countries, including Denmark, Norway, Canada, the Netherlands, and the UK are all considering the introduction of hydrogen trains (Rathi 2018). Moreover, in the US, California ordered more than 24 hydrogen trains for intercity travel (Bhattacharya 2023). In 2022, also East Japan Railway has been testing a hydrogen-powered train, aiming at starting commercial operations by 2030 (East Japan Railway 2022). In June 2023, China claimed to launch the world's most powerful hydrogen train, which is reportedly able to run for up to eight days and Namibia is set to launch Africa's first hydrogen locomotive (Bhattacharya 2023). Finally, India is preparing the introduction of 35 hydrogen trains, starting with a prototype in Haryana's Jind-Panipat route in 2024 (Bhattacharya 2023).

Besides Alstom, the Swiss company Stadler recently signed two framework agreements with the Italian railway operators Azienda Regionale Sarda Trasporti (ARST) and Ferrovie della Calabria (FdC) to supply the world's first hydrogen-powered narrow-gauge trains (Parks 2023). Stadler is expected to supply ten locomotives for ARST in Sardinia and 15 for FdC in Calabria (Parks 2023). Furthermore, Stadler is also entering the US market with its hydrogen locomotives, where the distances covered gives hydrogen-powered trains some significant advantage over battery-electric equivalents.

3. Competition between battery electric and hydrogen trains

Currently, the cheapest way to produce hydrogen is from natural gas (grey hydrogen), but to produce hydrogen from fossil fuels defeats the purpose of reducing CO_2 emissions (Rathi 2018). However, once the utilisation of hydrogen becomes widespread it could also make the production of green hydrogen cheaper, using renewable electricity coming from wind, solar, or nuclear power (Rathi 2018).

In this respect, the first goal should be to produce green hydrogen at the same or cheaper price than grey hydrogen to meet the target to reduce CO_2 emissions and to make the trains' energy usage truly carbon neutral. The other main problem of using hydrogen trains is the lack of a network of hydrogen infrastructure and refilling stations and the costs related to their introducing it in the regions where hydrogen trains should run.

Whereas in case of the introduction of hydrogen trains on four routes in the Frankfurt region in Germany seems to continue despite the delays and technical problems, the first adopter of commercial hydrogen trains in regional train transport in Germany, the Lower Saxony LNVG, has already decided to discontinue the use of hydrogen trains – only one year after the start of full commercial operation of the hydrogen trains (Bhattacharya 2023). The LNVG had invested EUR 93 million into the 14 Alstom Coradia iLint hydrogen trains and started commercial operations in August 2022 (Bhattacharya 2023). However, on 26 July 2023, the LNVG announced that as of 2029 it would gradually introduce 102 train sets with battery electric propulsion and replace all diesel-powered trains (LNVG 2023). The basis for the purchase of the new battery-powered trains was a market survey of alternative drive systems conducted by LNVG, which compared trains with hydrogen drive and rechargeable battery powered trains (LNVG 2023). LNVG's survey came to the conclusion that battery-powered trains are cheaper to operate (LNVG 2023, (Collins 2023).

However, also before the LNVG's final decision to choose battery-powered trains over hydrogen trains, was that the hydrogen trains required retrofitting with new hardware and software for their routes, and there were troubles at the hydrogen refuelling station in winter among other reasons (Bhattacharya 2023). Therefore, only one year after the commercial launch of operation of hydrogen trains, the Lower Saxony state ministry abandoned ideas for future hydrogen trains, arguing that battery-electric trains were cheaper to operate (Bhattacharya 2023, Focus Transport 2023). Therefore, in future, hydrogen trains will no longer be considered as a possible replacement for diesel locomotives.

According to the Lower Saxony state's Ministry for Economic Affairs, Transport, Building and Digitisation, battery trains can be powered by overhead electricity lines (i.e., catenary systems), or by so-called "charging islands" that can operate without constant contact with the overhead cables and this solution is found to be cheaper than hydrogen alternatives (Hill 2023, Collins 2023). Therefore, the regional transport authority LNVG will replace its remaining diesel fleet with 102 battery electric multiple train units, which are expected to be put out to tender later this year (Geerts 2023).

The LVNG's decision to switching to a battery electric solution confirms the results of a study commissioned by the German federal state of Baden-Württemberg, which concluded that hydrogen trains would be 80% more expensive in the long run, compared to electric options (Ministerium für Verkehr Baden-Württemberg 2022). The study concludes that overhead electricity lines or battery hybrid trains would be far more economic over a 30-year period (TTK 2022, Ministerium für Verkehr Baden-Württemberg 2022, Focus Transport 2023). According to the consortium TransportTechnologie-Consult Karlsruhe GmbH (TTK), komobile GmbH (Vienna) and other partners, which conducted the study Bericht SteFanS on alternative options for 16 non-electrified route sections in Baden-Württemberg in question showed that in most cases, a battery hybrid train solution would be the best option (Ministerium für Verkehr Baden-Württemberg 2022). While the diesel propulsion on the railways must be discontinued, and while the construction of overhead lines would take too long and would sometimes be too expensive, trains with alternative drives are the means of choice on some railway lines (Ministerium für Verkehr Baden-Württemberg 2022).

Regarding the 16-line sections in question, infrastructure scenarios were developed for the various drive technologies, the costs incurred were determined and possible route-specific synergy effects were investigated. In addition, vehicle-related parameters such as production costs, maintenance costs, the energy requirements of the vehicles and CO_2 emissions were examined and taken into account in the evaluation (Ministerium für Verkehr Baden-

Württemberg 2022). Considering the three options of full electrification of a line, the introduction of hydrogen trains and battery electric trains, in contrast to the hydrogen option, the electric drive has turned out to be the best alternative (Ministerium für Verkehr Baden-Württemberg 2022). Decisive for the evaluation were economic aspects, but also supplementary strategic aspects, such as the closing of gaps between existing lines with overhead contact lines, possible functions in freight traffic or the option for diversionary traffic. (Ministerium für Verkehr Baden-Württemberg 2022).

The Bericht SteFanS study 's final recommendation concludes that the operation of hydrogen hybrid trains is not further considered in the near future, due to various operational and economic disadvantages (Ministerium für Verkehr Baden-Württemberg 2022).

However, the three options of full electrification of a rail track, the battery electric train solution or the hydrogen train solution are considered to be options for different environments, and they are differently suited in different environments. It cannot be entirely excluded that the one or other solution is unsuitable for certain environments but the best choice in others. Consequently, there is no competition between battery electric trains, hydrogen powered trains or conventional electric trains, as they are each the best choice for certain environments.

However, one significant limiting factor for the hydrogen powered trains solution is the fact that for the operation of hydrogen hybrid trains, it needs a corresponding infrastructure of filling station or production sites for green hydrogen (TTK 2022). In addition, vehicle-related parameters such as production costs, maintenance costs, the energy requirements of the vehicles and CO_2 emissions need to be taken into consideration (TTK 2022). Therefore, when considering the economic aspect of the choice, hydrogen will almost always lose against the battery electric solution on routes of a limited length (TTK 2022). The study 's final recommendation concludes that the operation with hydrogen hybrid trains is not further considered due to various operational and economic reasons (TTK 2022). In a direct comparison, hydrogen train propulsion was not able to assert itself on any of the examined routes in Baden-Württemberg due to the infrastructure and operational characteristics. In addition, hydrogen fuel cells require significantly more maintenance than a batteries alone and hydrogen trains also require a battery for back-up power (Parks 2023). The only time hydrogen trains usually win tenders in Germany is when hydrogen models are specifically requested (Parks 2023). Instead, if the tenders are open to all technologies and the only condition is a potentially CO_2-free drive, the battery powered trains almost always prevail over hydrogen trains (Parks 2023).

The main reason for this result in favour of the battery electric trains is that in Central Europe, there are rarely routes with a distance of more than 80km from a station with an overhead charging line, which can be used to recharge the batteries of a battery electric train (Parks 2023). This effectively eliminates one of the main advantages of hydrogen trains, which would be to operate on routes without recharging infrastructure for travels of 500-600km (Parks 2023). Therefore, in countries like the US, where the distances to be covered without recharging options are much larger, hydrogen-powered trains have a significant advantage over battery-electric train equivalents. Accordingly, it will highly depend on the preconditions and the distance to be covered if hydrogen-powered trains have an advantage over battery-powered trains (Parks 2023).

4. New projects for introducing hydrogen trains in Europe

Whereas in Germany, some regions are already distancing themselves from introducing hydrogen powered trains into their regional transport network, due to the high maintenance, operational and refuelling infrastructure costs, four French regions have ordered twelve Régiolis hydrogen trains. The four French regions Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Grand Est and Occitanie have ordered the dual-mode trainsets powered by electricity and hydrogen. These trains will partly replace diesel units, which still represent 26% of the TER fleet's energy consumption and 77% of its CO_2 emissions (SNCF 2023). The new dual-mode hydrogen trains will have a range of 600 km and carry 220 passengers at speeds of up to 160 km/h and they are expected to start their trials in 2024 (SNCF 2023).

Furthermore, the European FCH2Rail (Fuel Cell Hybrid Power Pack for Rail Applications) project, which is developed by a consortium of companies including CAF, DLR, Toyota, Renfe, Adif, CNH2, IP and Stemmann-Technik, started in January 2021 and will continue until December 2024. It is a bi-mode demonstrator train with hydrogen fuel cells (CAF 2023). At the heart of the FCH2Rail project is a hybrid, bi-modal drive system that combines the electrical power supply from the overhead line with a hybrid power pack consisting of fuel cells and batteries that is independent of the overhead line, so it can serve on both the electrified and the non-electrified parts of the rail network (FCH2Rail n.d.).

The project FCH2RAIL has the objective to combine the advantages of electric traction with overhead catenary and fuel cell hybrid powertrain for non-electrified tracks in a Bi-mode multiple unit (Cordis 2019, FCH2Rail n.d.). The intention is to replace the polluting diesel powertrains currently used on non-electrified tracks by a Fuel Cell Hybrid PowerPack (FCHPP) (Cordis 2019). This FCHPP is expected to reduce GHG emissions significantly and still can use the highly efficient catenary-electric powertrain in the same multiple unit. According to Cordis (2019), the main tasks and results of FCH2RAIL project are to develop, build, test and homologate a Fuel Cell Hybrid PowerPack (FCHPP) (Cordis 2019). This scalable, modular, and multi-purpose energy source shall be applicable for new vehicles in different rail applications (Multiple Unit, Mainline and Shunting Loco) and should be also suitable for retrofitting existing trains (Cordis 2019). The demonstrator train is based on an existing Renfe train, in which CAF has installed a new power generation system using hydrogen fuel cells and batteries. This new power system has been integrated into the vehicle's existing traction system (CAF 2023). After the static testing phase at the CAF's plant in Zaragoza, the dynamic tests began in mid-2022 on a closed track, and the current testing phase takes place on representative lines of the Spanish Railway Network (CAF 2023, Cordis 2019). The test scenarios include running under different climatic and operating conditions. Where energy is available from overhead lines, the train continues to run on it. Where there are no overhead lines, the energy comes from the fuel cell battery system, the "Fuel Cell Hybrid Power Pack" (FCH2Rail) (CAF 2023, Cordis 2019).

The success in the development of this project is expected to confirm the commitment of the companies in the FCH2Rail consortium to developm environmentally friendly mobility solutions like the Fuel Cell Hybrid Power Pack (CAF 2023).

5. Conclusion

When it comes to decarbonisation of transport, hydrogen-based fuel cells propulsion can be one of the favoured options to replace the fossil-fuelled diesel trains running on the non-electrified parts of railway networks.

However, as the German examples show, it is just one option out of some alternative mobility-related options of propulsion. As the introduction of hydrogen trains in some German regional railway networks or the decision against it show, it highly depends on the preconditions of the regional railway network if hydrogen trains are the advantaged over other train types. The suitability of hydrogen vs. battery-electric trains depends on various factors, regional rail network conditions, the distance to be covered in the non-electrified railway network and the costs of maintenance and infrastructure.

While some regions in Germany are moving away from hydrogen-powered trains due to high maintenance and operational costs compared to battery electric options, four French regions are introducing hydrogen trains.

Overall, hydrogen trains represent a promising eco-friendly option for reducing GHG emissions in railway transport, especially when using green hydrogen as energy source and on non-electrified routes of a medium distance of 500 to 1000km. In fact, the advantage of hydrogen trains depends on the trains' range and the distance they need to cover.

However, there could be also space for hybrid solutions like the hydrogen-electric propulsion as tested under the European FCH2Rail project.

Ultimately, the choice of propulsion technology like hydrogen or battery electric solutions will depend on various factors, and since there is no single fuel solution for the future of low-emission mobility, all main alternative fuel options are likely to be suitable for certain preconditions and distances to be covered.

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