TØI report 1737/2019

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Battery Electric and Fuel Cell Trains

Maturity of Technology and Market Status

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Tittel: Batteri elektrisk og brenselcelle tog: Teknologisk modenhet og markeds status

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Sammendrag:

Selv om over halvparten av jernbanelinjene i Europa er elektrifisert enten via en tredje strømførende jernbaneskinne eller via overhengende kabler, er det ikke nødvendigvis kostnadseffektivt å elektrifisere de gjenværende linjene. I disse tilfellene kan alternativer til dieseltog være batteri- eller brenselcelle drevne tog. Den teknologiske utviklingen til batterielektriske- og hydrogen (brenselcelle) tog har kommet langt de siste årene, og flere produsenter investerer nå i utviklingen av batterielektriske- og/eller brenselcelletog. Dette har ført til at både batterielektriske- og hydrogentog nå er i bruk, både for testing men også i kommersiell drift. Endringer i driftsmetode er ikke mulig uten omfattende planlegging og tilrettelegging. Dette er særlig viktig for brenselcelle tog, fordi hydrogen til transportformål ikke er under masseproduksjon enda. Men med økt fokus på innføring av batterielektriske- og brenselcelletog i Norge og ellers i Europa, ser fremtiden lys ut for disse null-utslippsteknologiene.

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Summary:

Although most trains in Europe are powered by electricity from a third rail or overhead line, it is not always cost effective to electrify rail lines. In these cases, alternatives to diesel train population are batteries and fuel cells. Battery electric and hydrogen fuel cell technologies have developed significantly in recent years and multiple manufacturers are now investing in the development of battery electric and hydrogen fuel cell trains. Resultingly there have been an increasing number of these trains in operation, both for trials and commercial service. Changes in rail transport are not possible without the support of an adequate network, which must be highly planned. This is particularly important for hydrail, since no mass production of hydrogen for transport applications is yet in place. Nonetheless, with current focus on further implementation both in Norway and across Europe, the future is bright for these zero emission propulsion technologies.

Language of report: English (with Norwegian summary)

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Preface

As with all sectors, emission reductions are needed in the transport sector to reach national greenhouse gas targets. Emission mitigation in the transport sector is particularly important since its contribution towards the total has increased over the past decades, representing 14 % and 21 % of the EU28 greenhouse gas total[1] in 1990 and 2017, respectively. Although railways are only responsible for a small proportion of these, preparing them for zero emission is key since the EU Transport White Paper identifies long distance overland freight and medium-distance passenger travel as segments where a greater share for rail is required, to help decarbonise other transport segments.

TØI carried out this report under the Mobility Zero Emission Energy Systems (MoZEES) research centre, as part of a planned case study on zero emission trains. The main focus is to investigate the status of zero emission train solutions, summarising the status globally as well as in Norway, as a basis for further work in RA4. The project leader at TØI is Erik Figenbaum. Writing was performed by Rebecca Thorne (contributed to all sections), Astrid H. Amundsen (contributed to sections 2, 4, 5 and 6) and Ingrid Sundvor (contributed to all sections). Thanks are due to Federico Zenith (SINTEF), Ragnhild Wahl (Jerbanedirektoratet) and Stephen Oommen (Jerbanedirektoratet) for useful comments.

The bulk of the work was carried out spring 2019, and updated again spring 2020 to account for the main findings of the NULLutslippsløsninger For Ikke-elektrifiserte Baner (NULLFIB) report publication, from Jernbanedirektoratet. We have thus now reflected the findings of the NULLFIB report and the current direction of the Norwegian railway in the report, along with any other research around the issue.

Oslo, December 2019, revised May 2020
Institute of Transport Economics

Gunnar Lindberg
Managing Director

Jardar Andersen
Research Director

[1] Including international aviation

Content

Summary

Battery Electric and Fuel Cell Trains
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Whilst hybrid train solutions have been in regular operation for some time, the past decade has seen huge growth in the development of trains powered by standalone batteries or hydrogen fuel cells. Across Europe, commercial passenger service of these trains has begun, and the next years will no doubt see large-scale uptake of these technologies for stretches of rail where traditional electrification is not an option.

Zero emission trains for non-electrified lines

The majority of trains in Europe today are powered by electricity from a third rail or overhead line, which requires a catenary system and contact with a pantograph. Although electrification of main rail lines is progressing in line with emission reduction targets, it is not always cost effective, particularly for low-density passenger and freight lines. In addition, it can be difficult to fully electrify freight lines across national borders due to interoperability issues. For these lines, viable zero emission alternatives to diesel propulsion are hydrogen fuel cells or rechargeable energy storage systems such as batteries.

The technology and market is developing in Europe

Battery electric and hydrogen fuel cell technologies have developed significantly in recent years, and have seen growing application in the transport sector. Multiple manufacturers are investing now in the development of battery electric and hydrogen fuel cell trains, and there have been an increasing number of these trains in operation (for trials and commercial service).

Currently, all zero emission train projects relate to passenger trains, with (to the authors' knowledge) no dedicated battery electric or hydrail solutions for freight trains yet used. Whilst there are several examples of battery electric trains in small-scale passenger commercial service in Asia, these trains have so far mostly been in a testing period in Europe. However, Stadler is now production ready with the Flirt Akku (with over 50 commissioned in Germany) and other battery electric trains produced by Bombardier and Vivarail have been successfully tested and continue to be developed for launch. Regarding fuel cell trains (hydrail), a passenger fuel cell train manufactured by Alstom was launched in 2018 for commercial service in Germany and there are plans to additionally implement passenger fuel cell trains in other countries. Experience from these battery electric and hydrail projects so far is positive.

Infrastructure is needed

Changes in rail transport are not possible without the support of an adequate network, which must be highly planned. This is particularly important for hydrail, since no mass production of hydrogen for transport applications (and associated infrastructure) is yet in place. Key infrastructure considerations for both battery electric and hydrail technology include cost effectiveness, shareability with other types of vehicle and sustainability. The latter is a particularly key issue since the energy source and technology used to produce the electricity and hydrogen will heavily influence the overall (lifecycle) greenhouse gas reduction potential. Renewable energy sources, possibly in combination with carbon capture, are therefore required.

Partial electrification solutions to be prioritised in Norway for non-electrified lines

No fuel cell or battery electric trains have yet been tested in operation in Norway, but the Norwegian Railway Directorate (Jernbanedirektoratet) has worked through their project NULLutslippsløsninger For Ikke-elektrifiserte Baner (NULLFIB) to find zero emission train solutions for stretches of line such as the Nordland line that are difficult to fully electrify. The conclusion of this project was that partial electrification involving battery operation was the most favourable solution at the current time for use on the currently non-electrified lines in Norway, including the Nordland line.

However, the question of which zero emission train solution is best is not clear cut, and other work looking to the future performed by SINTEF found that whilst in the 2020s, battery electric technology may be most attractive in Norway, from the year 2030 hydrail may be the best overall option. Differences in these results reflect inherent uncertainties and differences in scope, methodology and assumptions.

In summary, it has now been decided by Jernbanedirektoratet to move ahead with a solution involving battery operation and partial electrification for non-electrified lines, and not proceed with any hydrogen train project. This decision has now been validated by the Ministry of Transport.

Conclusion

The European rail sector has seen significant developments in battery electric and hydrail train technology and availability in recent years, and both technologies have the potential to be technologically mature in the next decade. With current focus on implementation of part electrification involving battery operation in Norway and implementation of both battery and hydrail solutions across Europe as a whole, it is clear that this trend is set to continue.

Sammendrag

Batteri elektrisk og brenselcelle tog
Teknologisk modenhet og markeds status

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Selv om hybrid tog har vært i drift i flere år, har det i løpet av de siste ti-årene vært en stor teknologisk utvikling i tog som driftes enten med batterier eller av brenselseller. I Europa er allerede passasjertog med disse teknologiene satt i kommersiell drift, og i løpet av de neste årene kan vi forvente å se stor-skala introduksjon av disse teknologiske løsningene på jernbanestrekninger der tradisjonell elektrifisering ikke er aktuelt..

Null-utslipps tog for ikke-elektrifiserte jernbanestrekninger

De fleste togene i Europa drives i dag av elektrisitet fra en tredje strømførendeskinne eller overhengende kjøreledning, noe som krever et ledningssystem og kontakt med en pantograf. Selv om elektrifisering av hovedjernbanelinjene utvikler seg i tråd med målene for utslippsreduksjon, er videre elektrifisering ikke alltid kostnadseffektivt, spesielt for passasjer- og godstog med lav trafikktetthet. I tillegg kan det være vanskelig å elektrifisere godstransport som skjer over landegrenser, på grunn av interoperabilitetsproblemer. For disse linjene er brenselceller eller ladbare energilagringssystemer som batterier mulige nullutslippsalternativer til dieselframdrift.

Teknologien og markedet er under utvikling i Europa

Batteri og brenselcelle-teknologier har utviklet seg betydelig de siste årene, og anvendelsen har økt innen transportsektoren. Flere produsenter investerer nå i utvikling av batterielektriske- og brenselcelle- tog, og det har vært et økende antall av disse togene i drift (i forsøk og i kommersiell drift).

For øyeblikket er alle nullutslippstogprosjekter relatert til persontog, og det er ingen dedikerte batterielektriske- eller hydrogen-løsninger for godstog som er i drift ennå (etter forfatternes kjennskap). Selv om det er flere eksempler på batteri-elektriske tog i småskala passasjertjenester i Asia, har disse togene hittil stort sett vært i en testfase i Europa. Stadler er imidlertid nå produksjonsklar med Flirt Akku (med over 50 bestillinger i Tyskland) og andre batteri-elektriske tog produsert av Bombardier og Vivarail har utført vellykkede tester og videreutvikles for lansering. Når det gjelder brenselcelletog (hydrail), ble et passasjertog fra Alstom med brenselcelleteknologi lansert i 2018 for kommersiell drift i Tyskland. Det er også planer om å implementere brenselcelletog for passasjertrafikk i andre land. Erfaringene fra disse batterielektriske- og hydrail-prosjektene er så langt positive.

Behov for ny infrastruktur

Endringer i jernbanetransporten er ikke mulig uten en tilstrekkelig utbygget infrastruktur, som må planlegges godt. Dette er spesielt viktig for hydrail, siden det foreløpig ikke finnes masseproduksjon av hydrogen for transportformål (og tilhørende infrastruktur). Viktige infrastrukturhensyn for både batterielektrisk og hydrail teknologi inkluderer kostnadseffektivitet, teknologisamarbeid med andre typer kjøretøy og bærekraft. Bærekraft er et viktig spørsmål siden energikilde og teknologi som brukes til å produsere strøm og hydrogen vil ha stor innflytelse på det totale reduksjonspotensialet for klimagassene i et livsløpsperspektiv. Det vil derfor kreves bruk av fornybare energikilder, muligens i kombinasjon med karbonfangst.

Delvis elektrifisering av dieselstrekningene i Norge

Brenselcelle- eller batterielektriske tog er ennå ikke testet i drift i Norge, men Jernbanedirektoratet jobber i deres prosjekt NULLutslippsløsninger For Ikke-elektrifiserte Baner ('NULLFIB') for å finne nullutslippsløsninger for strekninger som for eksempel Nordlandbanen som er vanskelige å hel-elektrifisere med kontaktledning. Konklusjonen fra dette prosjektet er at delvis elektrifisering, som involverer en kombinasjon av batteridrift og kontaktledning, var den gunstigste løsningen på det nåværende tidspunkt for bruk på de ikke-elektrifiserte linjene i Norge, inkludert Nordlandsbanen.

Svaret på hvilken nullutslippsløsning som er best er imidlertid ikke entydig. I et arbeid utført av SINTEF fant man at elektrisk teknologi vil være mest attraktivt i Norge på 2020-tallet, men at det fra år 2030 vil være hydrail som er det beste alternativet Forskjellene i disse resultatene gjenspeiler iboende usikkerheter av data og metode og forskjeller i omfang, metodikk og forutsetninger i studiene.

Det er besluttet at Jernbanedirektoratet vil fortsette med en løsning som involverer batteridrift og delvis elektrifisering, og de kommer ikke til å fortsette med hydrogentogløsninger. Dette vedtaket er godkjent av samferdselsdepartementet.

Konklusjon

Den europeiske jernbanesektoren har hatt en betydelig økt tilgjengelighet og utvikling av batterielektrisk- og hydrail-togteknologi de siste årene. Begge teknologiene har potensiale til å være teknologisk modne i løpet av det neste tiåret. Med det nåværende fokus på videre implementering av nullutslippsteknologier, inkludert del-elektrifisering i Norge og både batteri og hydrail-løsninger over hele Europa generelt, er det klart at denne trenden kommer til å fortsette.

1 Introduction

This report aims to summarise the global maturity and market status of battery electric and fuel cell technology (focussing upon regional passenger and freight rail connections), using publicly available literature sources[2]. The bulk of the report content reflects the global status as of 2019, although the report was updated in May 2020 to account for the NULLutslippsløsninger For Ikke-elektrifiserte Baner (NULLFIB) work released by the Norwegian Railway Directorate (Jernbanedirektoratet).

The aim of the report was to provide the background information for prioritizing further work within the MoZEES research center regarding feasibility studies within Norway. Battery electric and fuel cell technologies can be deployed by cities and regions to improve air quality and reduce noise where rail sections/tracks are not electrified. Such solutions can be (and are) considered to be favourable to diesel propulsion in areas where installing third rail or catenary systems are not suitable or costly. Many fossil fuel/battery electric hybrid train models exist for different applications, but in this report fossil fuel hybrid solutions and light rail (such as trams) are not presented.

As background to the topic, we first give a short introduction of the current status of the rail sector (section 2) before giving an overview of technology state of the art (section 3). An overview of the market status (and use cases) of battery electric and fuel cell trains is then given (section 4), as well as an overview of their charging and filling infrastructure requirements (section 5). Following this, the current status of rail in Norway is discussed (section 6) and finally, an outlook for the future is summarised (section 7).

[2] Only literature available in English and Norwegian has been included.

2 Current status of the rail sector

The rail transport subsector concerns the movement of goods or people by rail, using electric, diesel or (less frequently) steam and other types of trains[3]. In the European Union (EU), the rail network is mostly electrified, especially over the major lines and in urban areas (Figure 1). At the current time, around 60 % of the network is electrified, which carries 80 % of all traffic.

The majority of electric trains are powered by electricity from a third rail or overhead line, which requires a catenary system and contact with a pantograph. The latter is the dominant form of current collection for both long distance passenger and freight trains on main rail networks in the EU since they are practical, have fewer safety issues for ground users and allow the use of higher voltages (reducing line loss). Third rails are common in rapid transit rail systems such as subway and metro systems as well as in many light rail applications. Elsewhere, rail networks in the Americas, Middle East and Africa are rarely electrified (European Commission 2017).

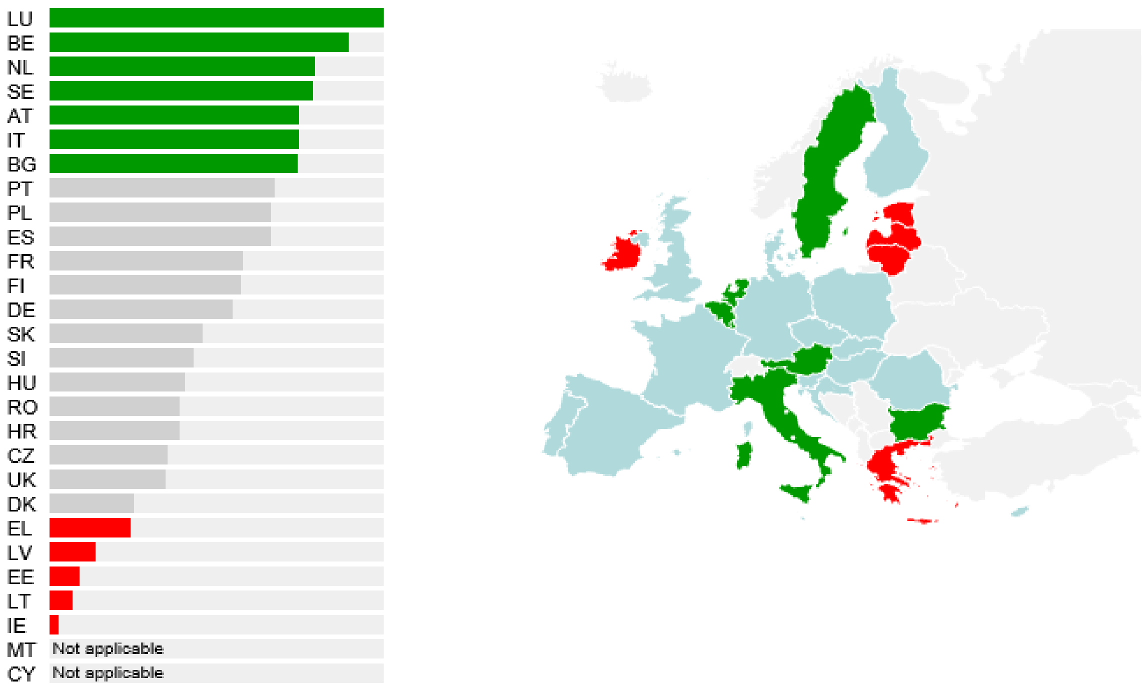


Figure 1: Percentage of electrified railway network in the EU (out of all lines in use), 2015 Source: EC (2019). The colour reflects the five countries with the highest (green) and lowest (red) percentage of railway network electrification.

Electrification of EU main rail lines is progressing, not only due to various national programs to reduce environmental impacts[4], but also due to the associated low

[3] Trains are defined here as engines with locomotives or carriages.

[4] Lifecycle emissions can be reduced through use of renewables in the electricity mix.

maintenance cost, quiet operation and increased passenger comfort (Mwambeleko and Kulworawanichpong 2017). High-density passenger and freight lines have already mostly been electrified since this is the most cost-effective solution with highest carbon savings (European Commission 2017). However, the EU Transport White Paper identifies long distance overland freight and medium-distance passenger travel as segments where a greater share for rail is required; particularly through the expansion of high-speed rail lines (European Commission 2011).

Although there are no technical obstacles for electrifying remaining lines, high fixed costs are an issue (Mwambeleko and Kulworawanichpong 2017). Investment costs for new line electrification may be around several million EUR per km including power generation, transformers and transmission lines as well as the service disruption caused by the overhead wire installation (Berger 2017). This means that there are currently few cost-effective electrified solutions to replace diesel-powered trains on low-density passenger and freight lines. In addition, it can be difficult to fully electrify freight lines, partly because many freight trains operate across national borders leading to interoperability issues. This is improving with regulation (UK Transport Committee 2013).

For low-density passenger and freight lines today, and other current/future lines not suited for electrification, zero emission alternatives to diesel propulsion involve hydrogen fuel cells or rechargeable energy storage systems such as batteries (European Commission 2017). These can be used to power the traction motor or auxiliaries as a standalone power source. Hybrids and dual-mode propulsion systems, involving batteries, flywheels and super (double-layer) capacitors placed between the power source and the traction transmission system connected to the wheels, can also be used to reduce emissions and increase efficiency (Meinert et al. 2015). Surplus power source energy, or energy derived from regenerative braking, charges the storage system for higher energy efficiencies (Ghaviha et al. 2017). The power source in dual-mode hybrid trains can also be switched, to allow zero emission (and low noise) operation at stations or where it is most suited (Railway Gazette 2018c). However, only battery electric and hydrogen fuel cell trains (not hybrid) are discussed further in this report.

3 Technology

3.1 Battery electric trains

Battery electric trains replace the diesel generator with a rechargeable battery and utilise the batteries for traction power on non-electrified lines (Figure 2). Batteries may also be installed for traction power to allow a catenary based train to pass non-electrified sections of a rail network, such as narrow tunnels.

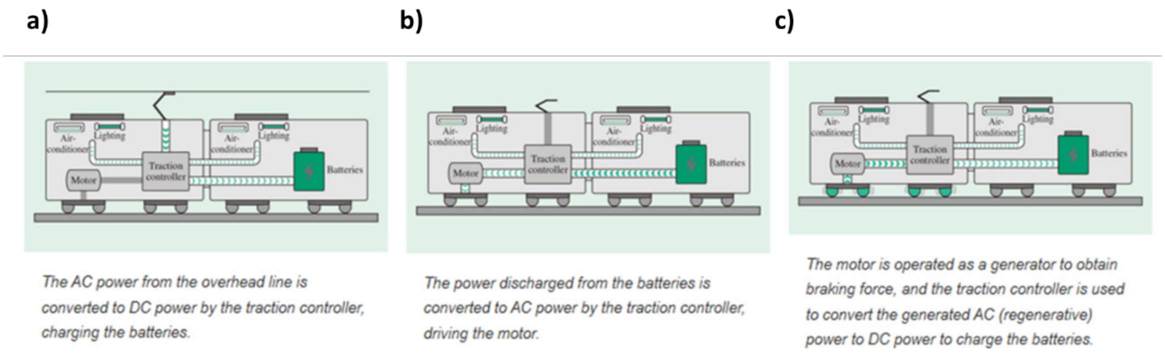


Figure 2: Operation of battery electric trains: a) Energy flow on electrified line sections, b) energy flow on non-electrified lines during powered travel, and c) energy flow on non-electrified lines during power regeneration. Source: Nagaura et al. (2017).

Much effort has been recently made to find batteries that are light weight, have small volume and are robust over many cycles[5]. Popular types include nickel-cadmium, nickel-metal hydride and lithium ion (Ghaviha et al. 2017). Nickel and lithium based batteries have a similar power density, discharge time and cost, although lithium based batteries achieve a greater average energy density, efficiency and lower self-discharge levels (Meinert et al. 2015). Lithium titanate (LTO) is a leading battery type currently being used in electric vehicles due to its high power capability, long cycle life and chemical stability, and is expected to have a successful role powering electric trains (Mwambeleko and Kulworawanichpong 2017). Other key types are lithium nickel cobalt aluminium oxide (NCA), lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) A comparison of battery types is given in Table 1, and typical battery characteristics in Figure 3.

Table 1: Qualitative assessment of different battery technologies. Source: Meinert et al. (2015).

	NCA $LiNiCoAlO_2$	SLFP $LiFePO_4$	NMC $LiNiMnCoO_2$	LTO $Li_4Ti_5O_{12}$
Cell voltage, 100%/50% SOC	4.0 V/3.6 V	3.8 V/3.3 V	4.2 V/3.7 V	2.8 V/2.4 V
Energy	+++	++	+++	–
Power	+++	++	++	+
Calendar life	+++	++	+	–
Cycle life	++	++	++	+++
Safety	+	+++	+	+++
Cost	+	+	++	–

[5] Batteries for railway applications are covered by the IEC 62620 international standard.

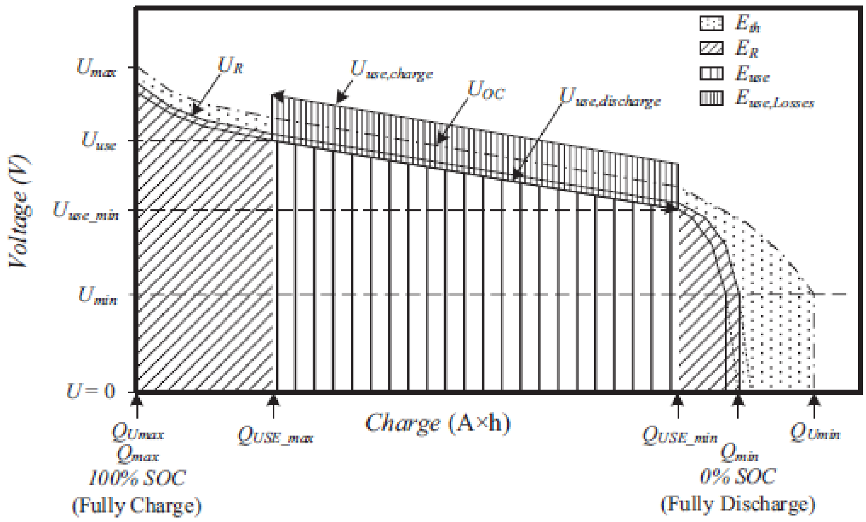


Figure 3: Definition of state of charge (SOC), useable and theoretical energy for DLC technology. Source: Meinert et al. (2015)

The choice of battery cell technology is dependent on the operating characteristics of the train. High power cells can be used with thin (high surface area) electrodes capable of large currents, but give less energy due to the large volume and weight share of foil and separator (Meinert et al. 2015). Alternatively, high energy cells can be used with thick electrodes, providing much active material and minimizing the fractional contribution of inert components to give maximized energy but at a lower power rate. This means that careful modelling is required to define the operational pattern of the train, based on its speed profile (Figure 4) or duty cycle[6]. This allows the battery characteristics and sizing to be defined, as well as its life expectation, under operational conditions.

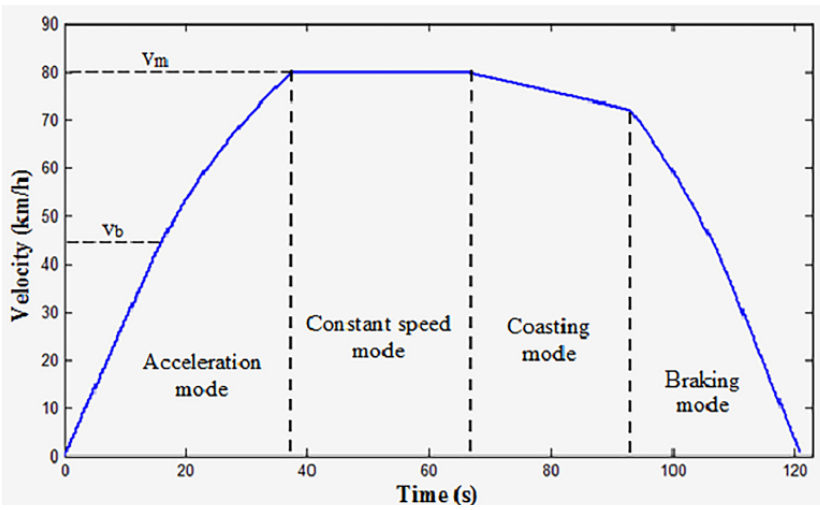


Figure 4: General train speed profile. Source: Mwambeleko and Kulworawanichpong (2017).

Battery performance is known to vary in different conditions. For example, it is well established that charging and discharging performance of batteries may vary with ambient temperature, and that power consumption varies with elevation (Sonoda et al. 2012). Tests performed by the East Japan Railway Company (JR-East) on a battery electric train found

[6] TS 50591 is standard for different types of rail operation.

that more power is consumed on an inbound (uphill) than outbound (downhill) line on the same section (Figure 5b). However, basic battery performance in summer and winter was not found to vary considerably (Figure 5a). In contrast, tests performed by Arendas et al. (2014) in an environmental chamber (controlling temperature and humidity) showed that low operating temperatures below 20 °C greatly diminished battery capacity. Evidence also suggests that temperature related performance varies with battery type, and that e.g. nickel based batteries allow a higher level of performance when placed under extreme temperatures (Meinert et al. 2015). Passenger trains are more likely to be highly influenced by ambient temperature than freight due to the energy needed to heat/cool the passenger wagons (if energy for this is sourced from the battery).

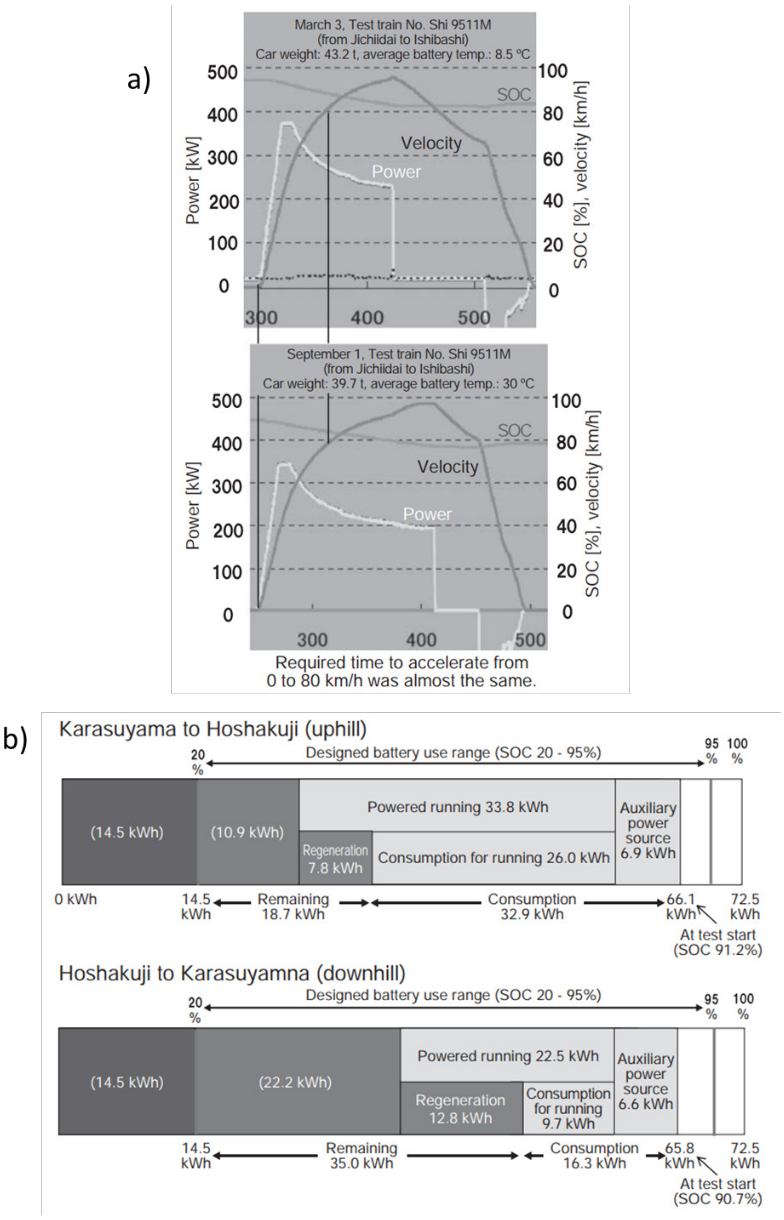


Figure 5: Comparison of powered running performance of a battery modified New Energy Train in a) summer and winter, and b) on the uphill and downhill line. Source: Sonoda et al. (2012).

Another main limitation of batteries is their power intensity – the rate at which the battery can be charged. A battery can often not accept all of regenerative braking energy, meaning it is necessary to dissipate the surplus energy in resistors (as with rheostatic braking) (Meinert et al. 2015).

3.2 Fuel cell trains

Fuel cell trains replace the diesel generator with a fuel cell stack. Several types of fuel cells exist, but among these, proton exchange membrane fuel cells (PEMFC) are the most suitable for transport applications due to their low operating temperatures, high efficiencies and energy densities, and low noise and pollution emissions (Fragiacomo and Francesco 2017). Other types such as solid oxide fuel cells (SOFC) may be technically feasible, but are not thought to be competitive financially (Schroeder and Majumdar 2010).

In order for a stack to operate at continuous optimum efficiency, the hydrogen flow rate into the stack must change according to the output power of the fuel cell stack. However, since the response of a fuel cell system is constrained by response times of pumps, compressors and control loops, it is adversely affected by transient output power demands (Meegahawattea et al. 2010). Consequently, most fuel cell feasibility studies utilise an energy storage system hybrid powertrain, where an energy storage system compensates for the slow power rate of the fuel cell (Fragiacomo and Francesco 2017), see Figure 6 and Figure 7. In this way, assisted by other energy sources, the fuel cell can work in steady-state operation, improving efficiency (and fuel consumption) and lifetime. Higher fuel cell efficiencies when in steady state mode were demonstrated by Hoffrichter et al. (2014) in a prototype train, consistent with full scale experiments. Another advantage of this set up is that breaking energy can be harnessed by the energy storage/management system.

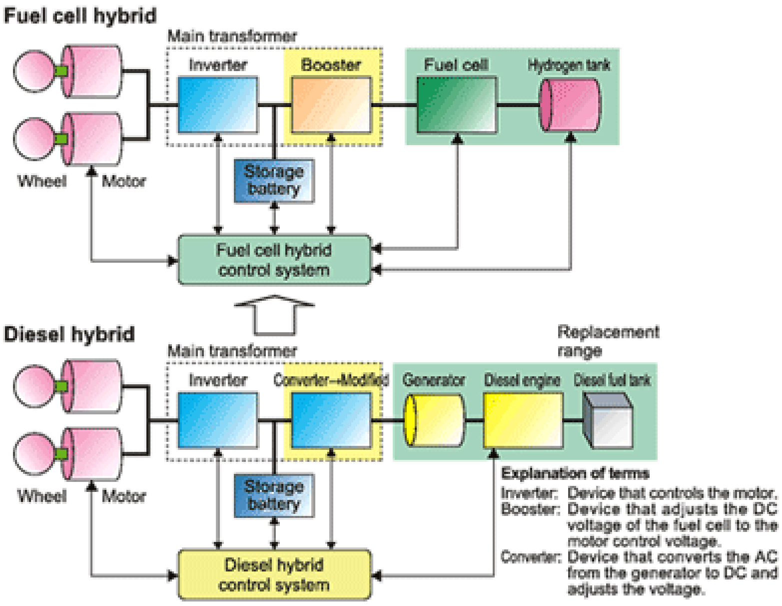


Figure 6: Overview of the first fuel cell hybrid railcar developed. Source: East Japan Railway Company (2006).

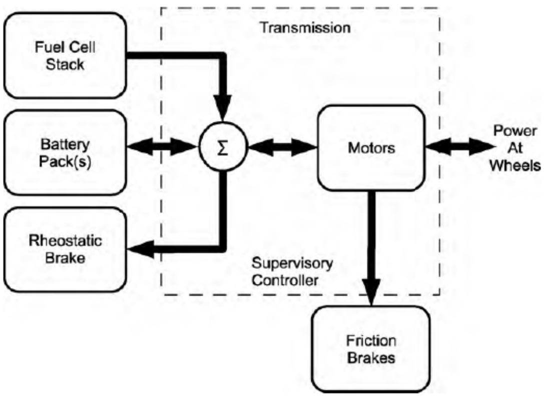


Figure 7: Hybrid (energy storage-fuel cell) energy drive. Source: Meegahawattea et al. (2010).

Where fuel cells are used in combination with batteries (a hybrid system), different energy management systems can convey varying train efficiencies (Siddiqui and Dincer 2019). A study by Torreglosa et al. (2011) investigating fuzzy logic or a cascaded energy management system (shown in Figure 8) found that using fuzzy logic provides voltages at the DC bus that are favourable to the motor inverters, expected to increase battery lifetime and convey higher efficiencies. In the study, both control systems aimed at providing optimal fuel cell operating efficiencies as well as a specified range of battery state of charge. Similarly, Hong et al. (2018) suggest that the energy management system should be based on a dynamic factor strategy with self-adaptation function for different driving cycles.

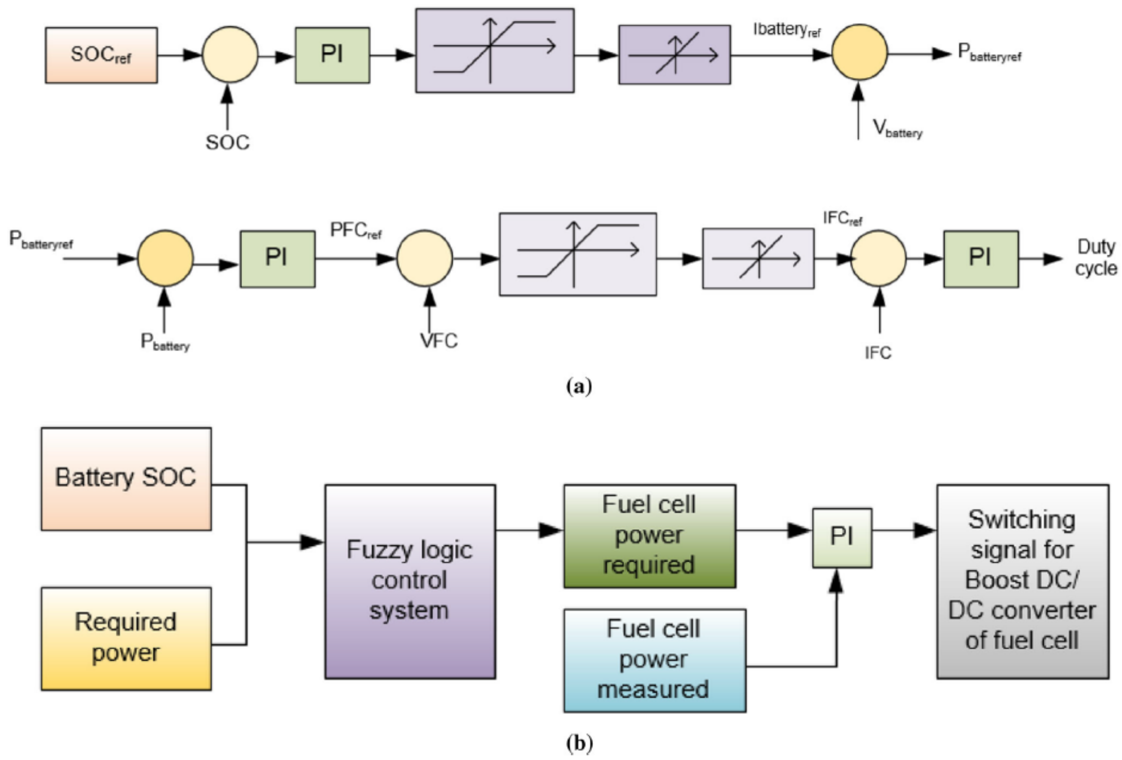


Figure 8: Control schemes for a hybrid fuel cell and battery locomotives: a) cascaded control system, b) fuzzy logic control system. Source: Torreglosa et al. (2011).

Fuel cell performance is thought to be relatively constant in different conditions, in part due to the heat produced as a by-product from the fuel cell itself. For example, tests of fuel cell vehicles showed good performance at a location where temperatures can reach -30 °C (Toyota 2014). Nevertheless, other research still shows that fuel cell performance is affected by ambient conditions including temperature (Khan et al. 2019), and as with all vehicles, there is summer and winter variation due to changes in rolling and air resistance.

4 Market development

4.1 Battery electric trains

Despite the early development of the battery electric train (Railway Technology, 2015)[7], the technology is mostly in a testing phase in the EU with limited commercial operation. Elsewhere, in Asia there are several examples in passenger commercial service already.

Currently, all projects relate to passenger trains, with (to the authors' knowledge) no dedicated battery electric solutions for freight trains yet tested. Freight trains are heavier and typically need 10 times the power (5-6 MW) of passenger trains (Sundseth et al. 2018); this means that load (capacity) and range are issues where recharging batteries at regular intervals is impractical.

Nevertheless, battery electric technology is soon to be extended to freight trains, with a battery electric freight train planned to be tested by Burlington Northern Santa Fe Corporation (BNSF) and General Electric (GE) from 2020 in the U.S. (Railway Gazette 2018a). This will be paired with diesel trains in a consist[8], will have 2,400 kWh of onboard energy storage and an energy management system, and will reduce the train's total fuel consumption by at least 10 % (Railway Gazette 2018a). Battery electric shunting locomotives, which are useful for reducing local emissions for workers and in urban areas, can also be found in commercial service (Alstom 2019).

Some recent examples of passenger battery electric train projects are given in Table 2 and described further below.

*Table 2: Overview of battery electric trains in commercial service (top) and as prototypes (lower). *Displayed range is the length of line segment operated, and not calculated (theoretical) range.*

Year	Producer	Operator	Series/Model	Development stage	Segment	Battery size (kWh)	Range (km)
2014-	J-TREC	JR-East	EV-E301	Commercial operation	Passenger	190	20.4*
2016		JR-Kyushu	BEC819	Commercial operation	Passenger	360	10.8*
2017	J-TREC	JR-East	EV-E801	Commercial operation	Passenger	360	26.6*
2015	Bombardier		Electrostar modified Class 379	Prototype	Passenger	500	50
2018	Stadler		Flirt Akku	Prototype (production ready)	Passenger		150
2018	Vivarail		Class 230 D-Train 30002 variant	Prototype	Passenger	424	64
2018	Bombardier		Talent 3	Prototype	Passenger	300	40 (100)
2018	Siemens Mobility	ÖBB	Desiro ML cityjet	Prototype	Passenger	528	
2019		JR-Central	Shinkansen N700S	Prototype	Passenger		

[7] The first model electric train was powered by zinc-acid batteries and made by Davidson in 1837, with the first experimental electric passenger train later tested in 1879 in Germany by Siemens.

[8] A sequence of connected locomotives.

4.1.1 EV-E301/E801/BEC819 Series

JR-East currently operates the EV-E301 and EV-E801 series, produced by Japan Transport Engineering Company (J-TREC), in commercial passenger service. After initial tests of a battery electric railcar from 2009, the EV-E301 series was introduced in 2014. It operates as an electric multiple unit under the 1,500 V DC overhead wire of the Tohoku Main Line, and on battery power on the non-electrified 20.4 km Karasuyama Line (Hasebe et al. 2015, Takiguchi 2015). The two-car trainsets are equipped with a total of 190 kWh lithium-ion batteries (2 x DC 630 V), and can run up to 100 km/h. The EV-E801 series two car train was later introduced on the 26.6 km long non-electrified Oga Line in Akita Prefecture in 2017 (Kyodo News 2017, Mwambeleko and Kulworawanichpong 2017). It differs from the EV-E301 series train since it is recharged from a 20 kV AC overhead supply instead of a 1,500 V DC overhead supply and has 360 kWh lithium-ion battery capacity.

Similarly, the Kyushu Railway Company (JR Kyushu) has operated the BEC819, a two car catenary and battery hybrid, in commercial service since 2016 (Mwambeleko and Kulworawanichpong 2017). The train operates a 45 km route with a 10.8 km non-electrified stretch (Wakamatsu line), and utilizes lithium ion batteries with capacity of 360 kWh.

4.1.2 Electrostar modified Class 379

Bombardier developed and tested a modified version of the Electrostar Class 379 train that is equipped with lithium iron magnesium phosphate (LFMP) batteries (Figure 9). The prototype train entered traffic in Essex, England, for trial passenger traffic in 2015 (Railway-technology 2015). The goal was to create a 185-ton, four wagon train that reaches speeds of 120 km/h for at least 50 km without having to re-charge (Bombardier 2015). To do this it was calculated that the batteries needed a capacity of 500 kWh. The train was reported to set a battery range record when it successfully completed a 41.6 km catenary-free test-run in 2015 (Mwambeleko and Kulworawanichpong 2017).

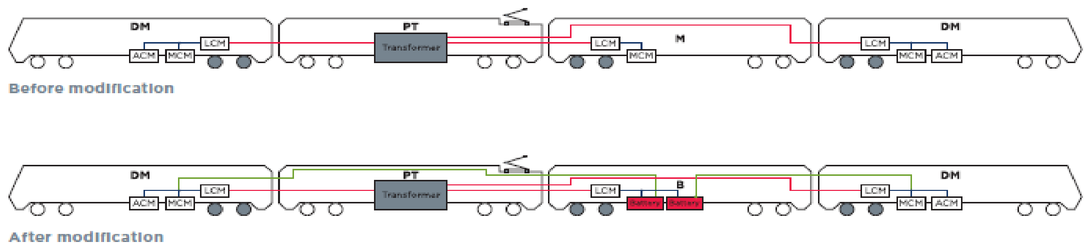


Figure 9: The Electrostar train, before and after modifying to battery-driven mode. This is called by Bombardier the Independently Powered Electric Multiple-Unit (IPEMU). Source: Bombardier (2015).

4.1.3 Flirt Akku

Stadler unveiled and trialed in October 2018 a prototype version of its electric multiple-unit trains, equipped with a battery and approved for passenger operation (Railway Gazette 2018b). The design is production ready, with 55 Flirt Akku commissioned by the Schleswig-Holstein public transport association to replace diesel trains in North Germany (Global Railway Review 2019). As part of this, Stadler will also provide 30 years of maintenance service. Stadler has also estimated that the units could be used to operate on 80 % of non-electrified routes in Germany, as well as in the United Kingdom (UK), the Netherlands and Italy (Railway Gazette 2018b).

4.1.4 D-Train

The manufacturer Vivarail launched a two-car battery electric production train approved for passenger service in October 2018 (Vivarail 2018a, Vivarail 2018b). These Class 230 D-Train 230002 variants have four lithium ion battery packs each with a capacity of 106 kWh (and a lifetime of seven years), offering a range of 64 km, and require a minimum power of 750 V to operate (Figure 10). Due to the modular power system of the Class 230, any Vivarail train can convert to battery power. The D-train was trial operated in Scotland over three days in an event supported by Transport Scotland and ScotRail, and is expected to be in service again in the near future. Vivarail has now confirmed a long term supply of batteries with Hoppecke, ensuring sustained production (Vivarail 2018b).

Figure 10: Position of batteries on a 2-car D-Train unit. Source: Vivarail (2018a).

4.1.5 Talent 3

A Bombardier Talent 3 catenary-battery hybrid prototype passenger train was introduced at Henningsdorf in September 2018 (Bombardier Transportation 2018), with the project currently in a testing and homologation phase approved for passenger service. The current prototype is equipped with four traction lithium-ion MITRAC batteries with a range of 40 km, and total capacity of 300 kWh (Figure 11) (Jin and Dubrau 2018). Bombardier estimate that total costs of ownership are currently around 50 % lower than a fuel cell train, and that energy costs are reduced by 35 % compared to diesel and fuel cell technologies (Bombardier 2019).

The next generation of the train is expected to be able to cover about 100 km on a non-electrified railway line (Bombardier Transportation 2018). According to plans, a commercial test run operation is planned to begin by end of 2019 and Deutsche Bahn will start a 12-month trial run with passengers in Germany (Bombardier 2019).

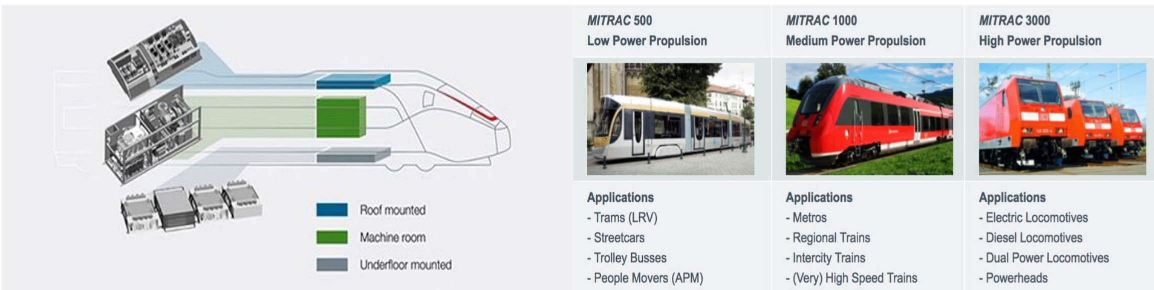


Figure 11: The Talent 3 has a Bombardier Talent 3 MITRAC powertrain which can be configured with different electric motors and battery packs. Source: Electrek (2018).

4.1.6 Desiro ML Cityjet

Austrian Federal Railways (ÖBB) and Siemens Mobility launched a battery electric train in September 2018 – the Cityjet eco – which has now been approved for passenger service. According to planned activity, passenger operation began in September 2019 (Urban

Transport Magazine 2019). The battery system is comprised of three battery containers, two DC/DC converters and a battery cooler (Figure 12). LTO batteries are utilized with a total capacity of 528 kWh (Urban Transport Magazine 2019).

The German state of Baden-Württemberg has announced plans to award Siemens a contract for 20 battery electric commuter trains to operate on Ortenau Network 8 (expected to enter service 2023), as an alternative to diesel trains (International Railway Journal 2019). As part of this, Siemens will provide maintenance.

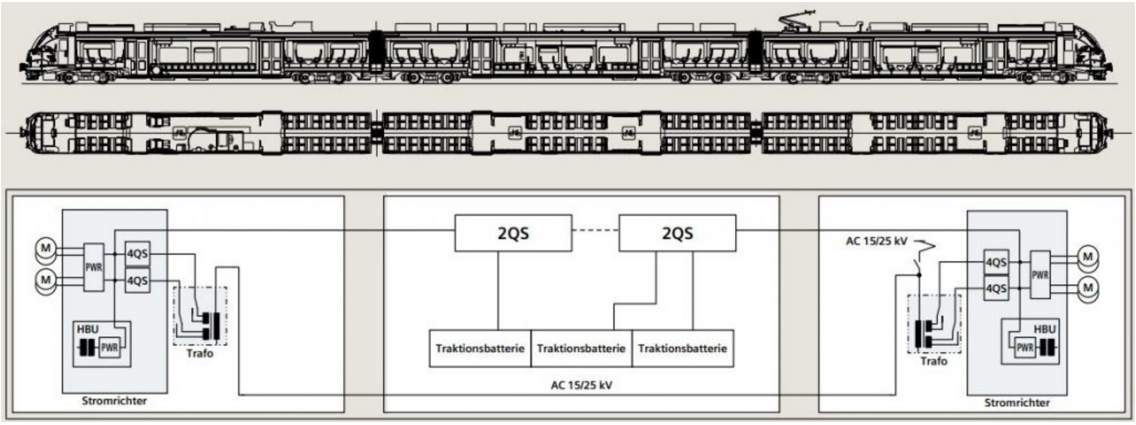


Figure 12: Mechanical and electrical schematics of the Siemens Desiro ML battery train. Source: Urban Transport Magazine (2019).

4.1.7 Shinkansen prototype

In 2019 Central Japan Railway Company (JR-Central) demonstrated a next-generation Shinkansen high speed train (N700S) under lithium-ion battery power (Rail journal 2019). The N700S fleet is due to enter service in the Tokaido Shinkansen in 2020. Although a high-speed train has high power and energy requirements, the batteries are intended for emergency use that may otherwise leave trains stranded during an extended power outage.

4.2 Fuel cell trains

Fuel cell trains (hydrail) are a relatively recent development[9] (East Japan Railway Company 2006, RailEngineer 2018, Siddiqui and Dincer 2019). Although there are fewer examples of hydrail demonstrations today than battery electric trains, a commercial passenger fuel cell train has recently been launched in Germany and there are also plans to develop passenger fuel cell trains in other countries. For example, the Austrian Zillertal Railway has plans to implement hydrail from 2022 as an alternative to electrification of a 32 km stretch of the Jernbach - Mayrhofen line (Reidinger 2018)[10], and major studies are being performed to determine its favourability elsewhere (Metrolinx 2018).

[9] The first fuel cell hybrid railcar was developed in 2006 by the East Japan Railway Company, as a modification of the NE train. With a single-car configuration, it contained induction motors (95 kW x 2 units), solid polymer type fuel cells (65 kW x 2 units) and lithium-ion type batteries (19 kWh) and could reach 100 km/h. The hydrogen tank capacity was approximately 270 L at 35 MPa. However, the primary source of power was still the diesel-powered generator in the developed train, with only a third of power obtained from the hydrogen fuel cells.

[10] New rolling stock and hydrogen fuelling, as well as production facilities, is estimated to cost €80 million.

As with battery electric trains, to the authors' knowledge there are currently no hydrail freight examples yet in operation, although plans are being made. For example, ÖBB has revealed plans for a hydrail freight train (4-6 MW) with 1.1 t hydrogen storage (ÖBB 2019). Hydrail shunting trains have also been developed. BNSF rail freight railway and the U.S. Army Corps of Engineers developed a prototype of a 130 t fuel-cell-powered switch locomotive (shunting train), which was trialled in 2010 (Miller et al. 2010, Ballard 2019). The trains had a hydrogen storage capacity of 60-70 kg at 350 bar (Miller et al. 2010, Ballard 2019), and utilised a Ballard PEM-based heavy duty fuel cell system with gross power of 300-500 kW along with a battery to meet peak loads, giving a maximum power of 1.2 MW (Ballard 2019). At a smaller scale, ÖBB has developed a hydrail switch (shunt) prototype with 30 kW fuel cells and 4 kg hydrogen storage (350 bar) (Serban et al. 2017). In addition, fuel cell mine locomotives have been developed; Vehicle Projects and Ballard collaborated in the production of five 17 kW hydrail mine locomotives for the Republic of South Africa in 2012 (RailEngineer, 2018).

Nevertheless, the technology is ready for adaptation to freight (Hydrogenics 2015) and many case studies have been performed (Isaac 2018). Hydrail may also be more suitable than battery electric for the heavier loads and longer journeys associated with freight, as well as interoperability in different countries (Ruf et al. 2019). In addition, operation with short downtime is enabled, as well as long operating hours without refuelling (Ruf et al. 2019). Nonetheless, the question of whether hydrogen can actually provide the 'pulling power' for the heaviest loads of the freight industry has not yet been directly answered, due to a lack of testing to date (Open Access Government 2018).

Some recent examples of passenger hydrail projects are given in Table 3 and described further below.

Table 3: Overview of hydrail trains in commercial service (top) and as prototypes (lower).

Year	Producer	Operator	Series/Model	Development stage	Segment	Hydrogen storage (kg)	Range (km)
2018	Alstom	LNVG	Coradia iLint	Commercial service	Passenger	89	1000
2017		JR-Group		Prototype	Passenger		
2018	BCRRE/ Porterbrook		HydroFLEX	Prototype	Passenger	20	
2018	Vivarail		Modified Class 230		Passenger		1050
2018	Siemens Mobility		Mireo Plus H	Prototype	Passenger		

4.2.1 Coradia iLint

In September 2018 two prototype Coradia iLint fuel cell trains from Alstom entered regular commercial service with Lower Saxony Transport Authority (LNVG) in Germany (Alstom 2018), the world's first approved passenger train to use hydrogen fuel cells for traction power (Figure 13). Test runs of the train were conducted in March 2017, and the train is now available on the market (serial production). The two trains are operated on the Eisenbahnen und Verkehrsbetriebe Elbe-Weser network, on a 100 km line between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude.

The iLint has underframe-mounted traction motors driven by a traction inverter. On the roof is a Hydrogenics HD200-AT power pack that packages six HyPMTM HD30 fuel cells (with common manifolds and controls) and X-STORE hydrogen tanks supplied by Hexagon xperion (RailEngineer 2018). With a polymer inner liner, covered with carbon fibres soaked in resin and wrapped in fibreglass, these tanks store 89 kg of hydrogen (on each car) at 350 bar. Also mounted on the underframe is a lithium-ion (NMC) battery pack supplied by Akasol and an auxiliary converter, to provide drive power and store braking energy (111 kWh battery system power at 800 V) (Akasol 2019). Each iLint's HD30 fuel cell has an output of 33 kW and weighs 72 kg with an efficiency of 48-55 %. At maximum power output, each railcar's fuel cells operate at 200 kW (400 kW total for train) and the battery at 225 kW. The fuel cells are designed to operate at full operation levels only when the power requirement is high and for a comparatively longer period of time (Siddiqui and Dincer 2019).

With one tank filled the train has a range of 1,000 km (Alstom 2018), similar to a diesel train. The maximum speed is 140 km/h, and kinetic energy generated during braking and surplus fuel cell energy is stored in the lithium-ion batteries. The train has seating for 150 passengers, with a further 150 standing (Railway Technology 2018). The iLint weighs 105 t comparing well with the corresponding Lint 54 (100 t) (RailEngineer 2018).

There are long term plans for the iLint. In 2015, Hydrogenics announced that it had signed a ten-year exclusive agreement with Alstom to supply at least 200 fuel cells over a ten-year period (RailEngineer 2018)). Similarly, Akasol has announced they will supply up to 500 battery systems for 250 trains in the next 15 years, and ensure their ongoing operation (replacing battery systems) (Akasol 2019). A further 14 Coradia iLint will be delivered to Lower Saxony Regional Transport (LNVG) (RailEngineer 2018), with the contract also covering maintenance and energy supply services for 30 years. Alstom has also signed letters of intent for 60 Coradia iLint to different parts of Germany (Railway Technology 2018), and according to Alstom, the UK, France, the Netherlands, Denmark, Norway, Italy and Canada are also developing Hydrail plans. The UK, for example, is looking to pilot Alstom iLint trains by 2019 or 2020 (Gtm 2018).

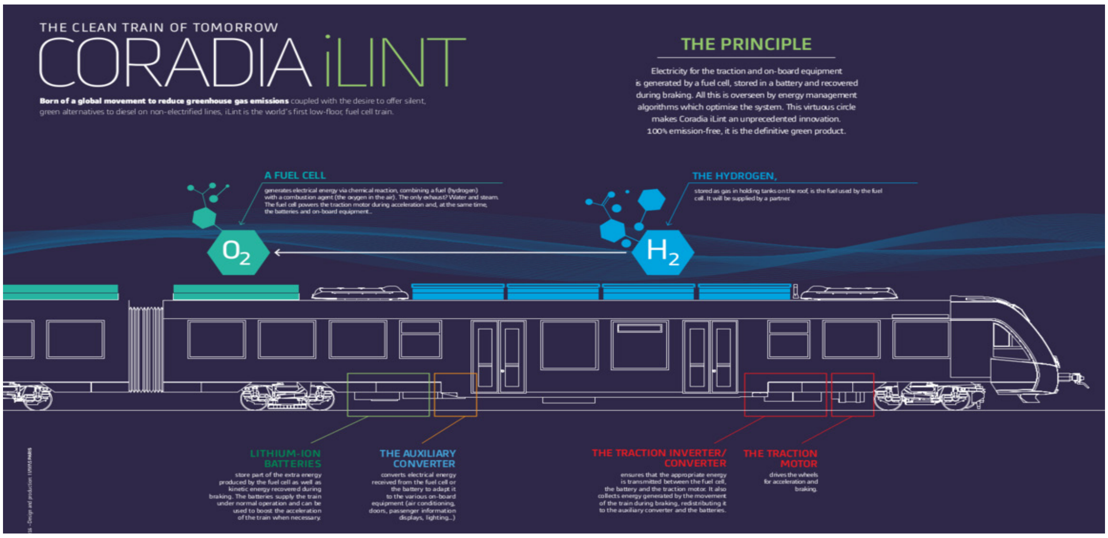


Figure 13: The technology of the Coradia iLint. Source: Alstom (2018)

4.2.2 Japan Railways prototype

In August 2017 a prototype fuel cell train was tested in western Tokyo, Japan by the Japan Railway group (JR-Group) (Iwamoto 2017). The fuel cell units are supported by lithium-ion batteries for auxiliary power. The next step is to test the train in passenger traffic.

4.2.3 HydroFLEX

A UK hydrail train prototype (HydroFLEX) was developed by fitting a hydrogen fuelcell powerpack supported by lithium-ion batteries to an existing Class 319 train (Figure 14). 100 kW FCveloCity-HD fuel cells were supplied by Ballard, hydrogen storage tanks by Luxfer (20 kg total), and traction batteries by Denchi (Ballard 2019, Green car congress 2019). After successful proof of concept, Porterbrook and the University of Birmingham's Center for Railway Research and Education (BCRRE) announced in June 2019 that it will be tested on the mainline railway for passenger service (Green car congress 2019).

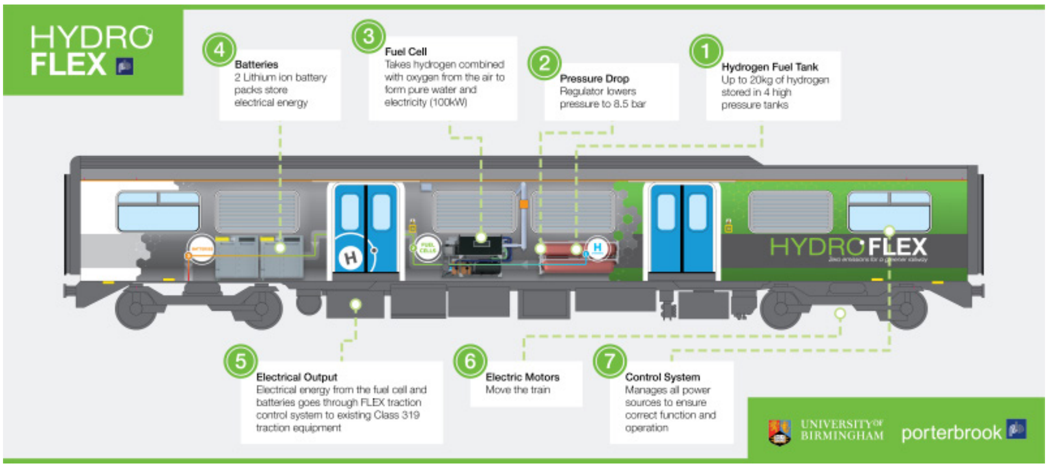


Figure 14: UK HydroFLEX train. Source: Green car congress (2019).

4.2.4 Vivarail prototype

Vivarail is currently developing a prototype modular hydrogen train (based on the Class 230) to be tested by the end of 2019 on their tracks in the UK (The engineer 2019). The train is planned to have two driving motor cars powered by Hoppecke batteries, and two carriages housing fuel cells and hydrogen tanks (~1050 km range). Since Vivarail claims that they have built their trains such that they can be modified, trains sold as diesel units or diesel-battery hybrid units can at some point also be converted to run on hydrogen.

4.2.5 Mireo Plus H

Siemens Mobility is developing a hydrail prototype – the Mireo Plus H, which will use a fuel cell drive developed by Siemens together with Ballard. The technology is planned to be integrated by 2021 (Railway-technology 2019).

Compared to the iLint, the Mireo Plus H is more powerful (1.7 MW vs. 0.4 MW), and consequently has a different target market.

4.3 Possible complementarity

In practice, there will likely be a degree of complementarity between fuel cell and battery technologies, as in other transport segments (Hovi et al. 2019, Alstom 2020). For example, hydrail can offer a large range and can be potentially better adapted for long-distance and high energy-requiring freight trains, whilst battery trains may be used for shorter stretches of non-electrified rail (such as those partially electrified with catenary systems). Hence, fuel cell trains may also be more relevant for cross-border freight transport, although this would depend on the possibility to refill hydrogen in countries across the line, which in turn will depend on international cooperation.

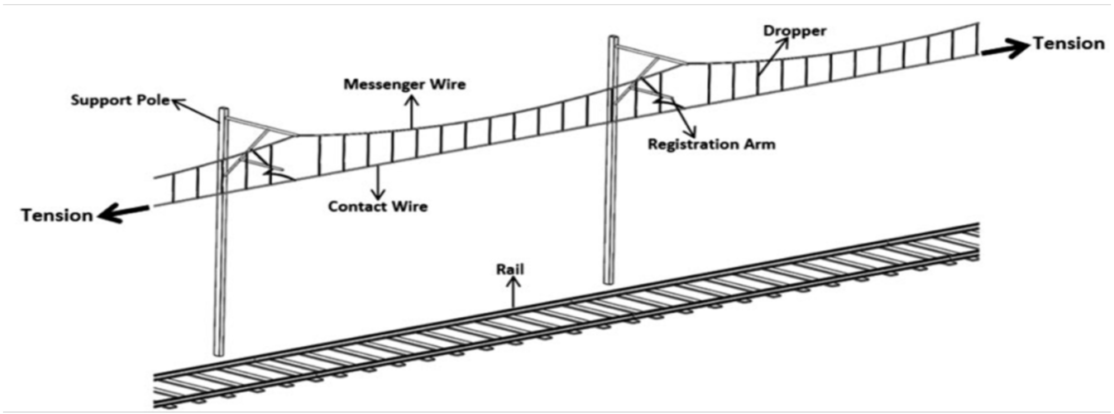
5 Charging and filling infrastructure

5.1 Battery electric trains

Battery electric trains can utilise available electricity (and infrastructure) when on electrified lines and battery power when on non-electrified lines (Figure 15). Thus, in electrified sections, cars can raise their pantographs and run on electric power from overhead contact lines like ordinary electric trains. If the state of charge (SOC) of batteries is low, railcars may also charge batteries dynamically with power both from overhead contact lines and regenerative energy at breaking. For example, the Japanese Series EV-E301 railcar uses a DC/DC converter to lower the 1,500 V from overhead contact line to 630 V battery voltage (Takiguchi 2015). If running on non-electrified sections, the cars lower their pantograph and run on batteries alone, charging batteries with regenerative energy from breaking only (Figure 16). Similarly, the Talent 3 train can be charged from the 15 kV 16·7 Hz overhead line or using regenerated braking energy (Bombardier 2015), as can the Electrostar (Bombardier Transportation 2018) and D-Train (Vivarail 2018a).

Special charging facilities may also be utilised to recharge batteries when the train is stationary. For example, the Series EV-E301 railcar utilises fast charging at railside facilities. Here, the railcars raise their pantographs and reinforced contact strips allow for contact with overhead rigid wires at the charging points (Takiguchi 2015). Vivarail has similarly launched a fast charge system for its Class 230 battery trains (Vivarail 2019), which comprises short sections of third and fourth rail that connect to the train via carbon ceramic shoegear. Previously, Vivarail had described an automatic charging point for use with their D-train on non-electrified lines, with an electric supply of 11 kV or 33 kV (Vivarail 2018a). The rate of charge was identified by the on-board power electronics, and the power source was connected without human intervention. A static battery bank may be used instead to provide an energy reserve at the charging points, which may then be recharged overnight at a low rate. Vivarail cite charge time as 7 minutes (to convey a 60 mile range). Similarly, Bombardier cite charge time for their Talent 3 trains of 7 to 10 minutes (Bombardier 2019), with only terminal stations required to be electrified.

a)



b)

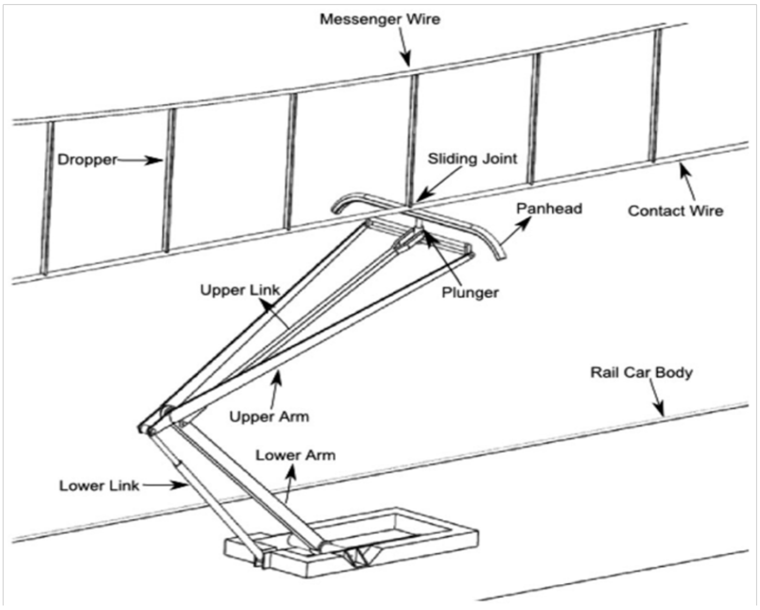


Figure 15: Example a) catenary system, and b), pantograph and catenary system combined. Source: Pappalardo et al. (2015).

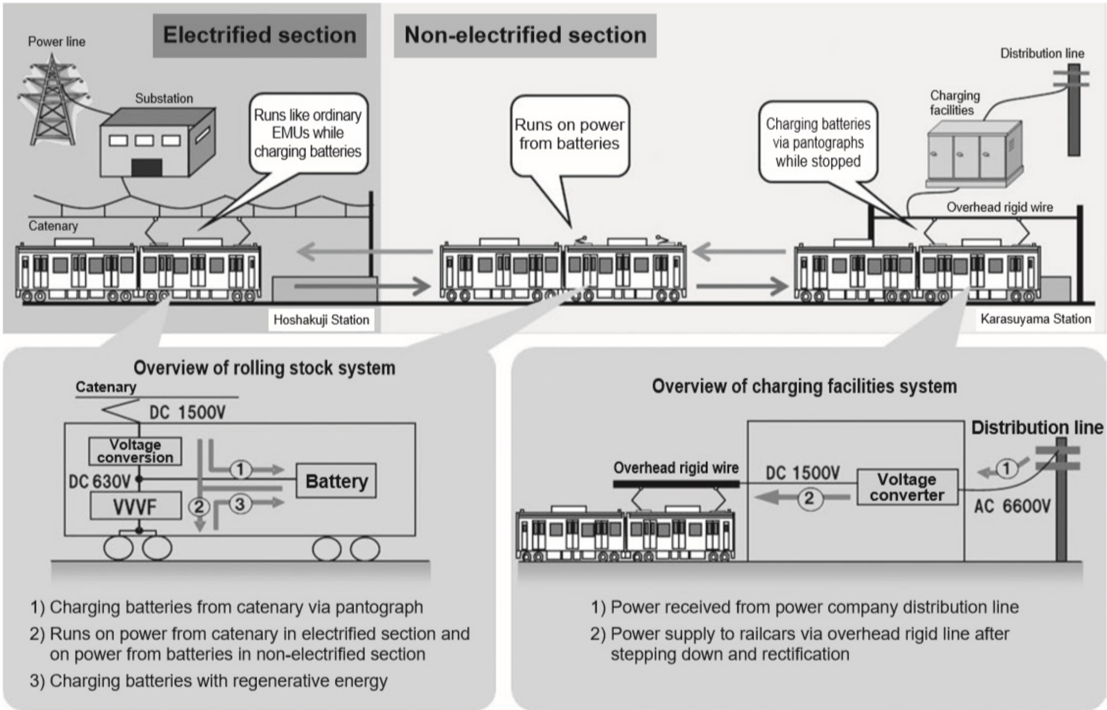


Figure 16: Dynamic and stationary battery charging of the Series EV-E301 railcar. Source: Takiguchi (2015).

5.2 Fuel cell trains

For fuel cell trains, a hydrogen production and distribution network must be in place able to supply large quantities of hydrogen each day. Purchasing hydrogen today is considered to be more expensive than diesel, especially if it is liquid hydrogen (as used for the first few iLints). However, calculations indicate that a with full deployment hydrogen would be significantly cheaper than diesel, reducing to a 2020 price of 36 NOK/kg and 24 NOK/kg from 2030 (Zenith et al. 2019). This potentially requires local hydrogen production; thus, hydrail routes should be connected to a main traffic junction, which has the necessary infrastructure for on-site production of hydrogen (Ruf et al. 2019).

Although costs of hydrogen (and its infrastructure) have the potential to be lower compared to catenary-electric and hybrid diesel-electric trains (Siddiqui and Dincer 2019), a key current challenge is that this infrastructure is not yet in place. In addition, owing to its low volumetric density, hydrogen requires large storage spaces. Although space can technically be reduced by compression, this can convey safety issues (Siddiqui and Dincer 2019), and safety requirements may limit the ability to store large quantities of hydrogen in terminals in city centres. Nonetheless, with the establishment in 2016 of Hydrogen Europe (the European Hydrogen and Fuel Cell Association), there is an international push to expand the supply infrastructure and make hydrogen more readily available.

Hydrogen is dispensed through refuelling stations (HFS), which typically should be designed to have enough capacity to supply a fleet at peak consumption whilst avoiding over-capacity (Ruf et al. 2019). There are already 200 HFS in use in Japan, Europe and the U.S., mostly for other mobility operations (Ruf et al. 2019). For the Coradia iLint train, the two trains currently in operation are fuelled at a mobile HFS from a 40 ft steel container situated next to the tracks at Bremervörde station (Railway Technology 2018). This is sufficient to power the train throughout the network for the whole day, i.e. a total autonomy of 1,000 km (Hydrogen Fuel News, 2018). It takes 15 minutes to refuel the iLint, which holds 178 kg of hydrogen supplied at 350 bar (consumed at 0.3 kg/km)

(RailEngineer 2018). Alstom also plans to have the world's first stationary hydrogen train refuelling facility at a modified Bremervorde depot, to be built and operated by the Linde Group (RailEngineer 2018). This is scheduled to go into operation in 2021, and will cost around 10 million euro (Hydrogen Fuel News 2018). Similarly, in Japan, Toyota Motor Corporation and JR-East announced in September 2018 that they will build a HFS on JR-East's property.

Currently, the bulk of hydrogen produced derives from reforming of natural gas, conveying relatively high lifecycle emissions (Mehmeti et al. 2018). Clean methods for hydrogen production thus need to be developed to maturity that convey low lifecycle emissions (Siddiqui and Dincer 2019). Examples can be electrolysis using various types of fuel cell and electricity derived from renewables, or by utilizing CO_2 capture and storage (CCS) (Voldsund et al. 2016, Mehmeti et al. 2018). Although 'green' hydrogen currently has a higher cost than diesel, for sustainability reasons Alstom plans at a later stage to produce green hydrogen on-site by electrolysis powered by a wind turbine, which is expected to save 700 t of CO_2 emissions per year for each iLint (RailEngineer 2018). If all hydrogen for the planned fleet of 14 iLint trains was produced by electrolysis, a wind farm of 10 MW generating capacity would be required to power the required electrolysis plant with suitable back up, along with sufficient hydrogen storage (RailEngineer 2018). Similarly, the Zillertal Railway plans to produce hydrogen using energy supplied by local hydroelectric power stations (Reidinger 2018).

Alternatively, according to Ruf et al. (2019), hydrogen can be sourced directly from industry (such as from oil and gas refining), which is otherwise burnt as heat or discarded. This may provide optimization in terms of cost, and to some degree, emissions. Alternative sustainable fuel cell fuels may additionally be used (Siddiqui and Dincer 2019).

6 Status in Norway

In Norway, of the 4,208 km national railway network[11], 58 % (2,459 km) is electrified (Store norske leksikon 2018), and approximately 80 % of all trains (in train-kilometre) in Norway are powered electric (Norwegian Department for Transport 2017). NSBs newest electric trains, the El.18, has synchronic-motors that makes it possible to vary the voltage. The train has a power of 5,880 kW and a maximum speed of up to 200 km/h (Store norske leksikon 2018).

By 2030 Norway is obliged to reduce greenhouse gas (GHG) emissions by at least 40 % compared to the level in 1990 (Norwegian Department for Transport 2017). Although the Norwegian rail sector is a minor contributor to total CO_2 emissions (Figure 17), the Norwegian transport plan for the period 2018-2029 nonetheless includes measures to reduce the emissions from railway by about 88,000 t CO_2 each year (Norwegian Department for Transport 2017). As of 2019, there are seven non-electrified stretches of railway line in Norway that utilize diesel trains (Jernbanedirektoratet 2019b), but full electrification with overhead contact line is not desirable for all lines due to costs and practical feasibility.

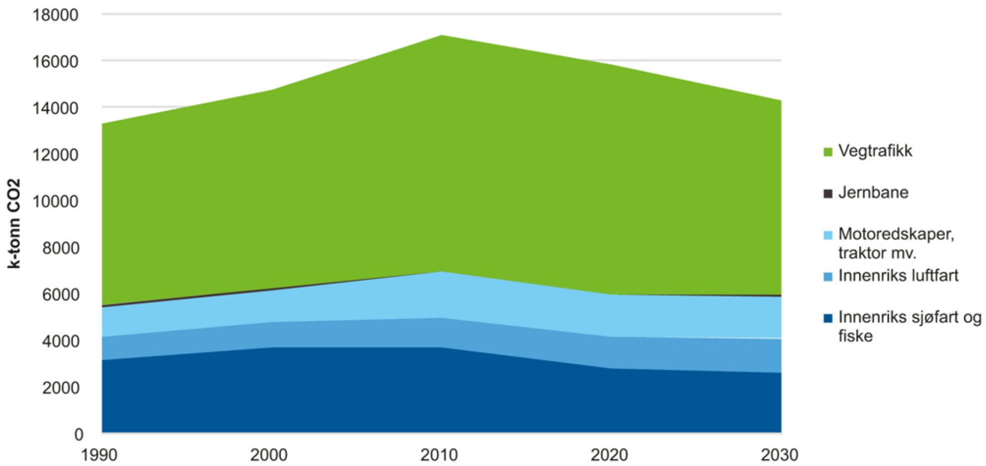


Figure 17: Historic and predicted emission from different transport sources in Norway. (in 1000-ton CO_2) Source: Norwegian Department for Transport (2017).

The question of which zero emission train technology is better suited for the non-electrified lines is dependent on many parameters and is not clear cut. To investigate this, Jernbanedirektoratert carried out a project, NULLFIB, between January to December 2019, which aimed to update underlying knowledge for a possible transition to forms of operation other than fossil-based diesel for non-electrified stretches of railway line in Norway (Jernbanedirektoratet 2019b). The Nordland Line was chosen for a case study since it is the most challenging railway stretch, and criteria for feasibility, investment and operation and climate and environment were utilized. For input to NULLFIB, work from SINTEF and Norconsult was commissioned; Norconsult investigated partial electrification

[11] Data from 2017.

for Nordlandsbanen (Norconsult 2019) and SINTEF performed analysis investigating different technological solutions using criteria for environmental impacts, technology readiness, regulatory framework, economic viability and flexibility for Trønder, Nordland, Røros, Raumabanen and Solør lines (Møller-Holst 2016, Zenith et al. 2016, Zenith et al. 2018, Zenith et al. 2019). The following sections outline the cost and overall favourability results from these analyses.

6.1 Costs of zero emission solutions

In NULLFIB, costs were investigated by considering the sum of resulting changes when switching from diesel operation to a new technology, due to railway infrastructure investment, vehicle investment, and operating costs of both railway infrastructure and vehicles (Jernbanedirektoratet 2019a). Results are shown in Figure 18, which shows that full battery solutions were calculated to be the most cost effective for society (savings of 283 million NOK), with battery operation with partial electrification and biodiesel second (savings of 4 million NOK[12]). According to Jernbanedirektoratet, this is because these technologies have lower operating costs than for hydrogen, biogas and biodiesel, and because large investments on railway infrastructure are not needed. Infrastructure costs for partial electrification were explored by Norconsult in their work as part of NULLFIB, with summary results shown in Figure 19.

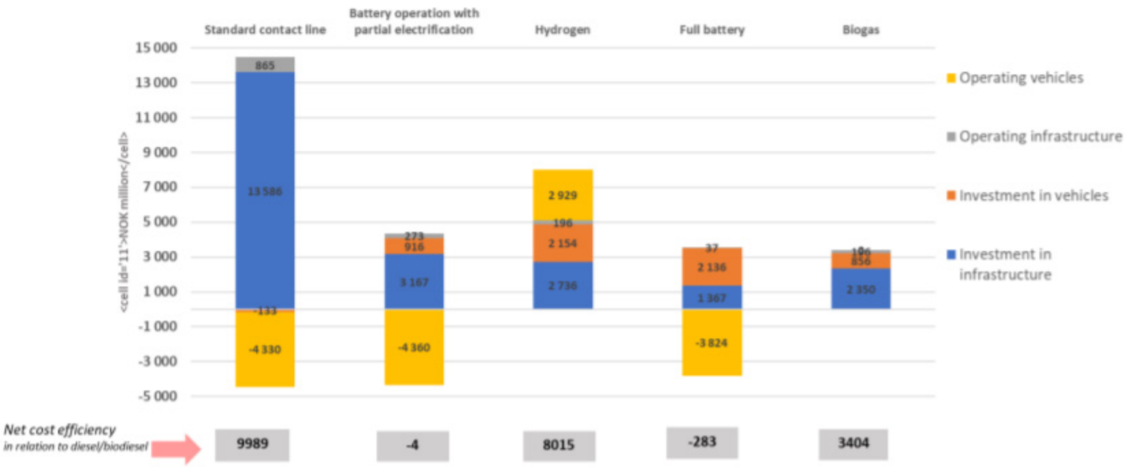


Figure 18: The cost difference (million NOK) of a change from diesel to zero emission technology on the Nordland line[13]. Net values are indicated above/below the columns. Source: Jernbanedirektoratet (2019b).

[12] Whether battery operation with partial electrification would be more cost-efficient than diesel is sensitive to assumptions concerning growth in train traffic; in the basis alternative, it was assumed that there will be a 5% increase in the train kilometres driven for passenger traffic every year up to 2030 and no growth subsequently. For freight traffic, the growth follows the forecasts concerning transportation work that the preparation of NTP 2022-33 was predicated upon.

[13] The Stjørdal-Trondheim stretch was excluded from analysis, and results were calculated assuming a lifetime of 75 years.

Lade-strekning	Kostnad kontaktledning fra Tabell 17 (MNOK)	Kostnad konstruksjoner hentet fra Tabell 16 (MNOK)	Kostnad nettilknytning hentet fra kap 7.1 (MNOK)	Kostnad samlet (MNOK)
3 Lade	219	113		332
5 Lade	326	24		350
8 Lade	240	163		403
10 Lade	141	19	100	260 *)
12 Lade	276	59		335
16 Lade	90		18	108 **)
18 Lade	50			50
20 Lade	155	14		169
22 Lade	126	138		264
Totalkostnad inkl. omformerstasjoner (1 020 MNOK)				**3 291**

*) felles kostnad for nettilknytning for 10 og 12 Lade. Kostnad summert opp med 10 Lade
**) felles kostnad for nettilknytning for 16, 18 og 20 Lade. Kostnad summert opp med 18 Lade

Figure 19: Total infrastructure costs (million NOK) of part-electrification. Source: Norconsult (2019).

Capital and operating cost summary results from SINTEF, for implementing various zero and low emission technologies on the Nordland line now and in the future, are presented in Figure 20 (Zenith et al. 2019). According to these results, both hydrail and batteries were found to be a lower cost option for freight trains than diesel and catenary since they couple the low energy costs of catenary with the low infrastructure costs of diesel. Batteries have relatively high investment costs for the year 2020, which are mainly due to the batteries themselves, but these will be reduced in the near future leading to a slight reduced cost to hydrail. Fast charging (a one-hour stop) does not seem economically advantageous since it leads to a shorter battery life. In the biodiesel option the fuel costs (and high locomotive maintenance costs) dominate (Zenith et al. 2019).

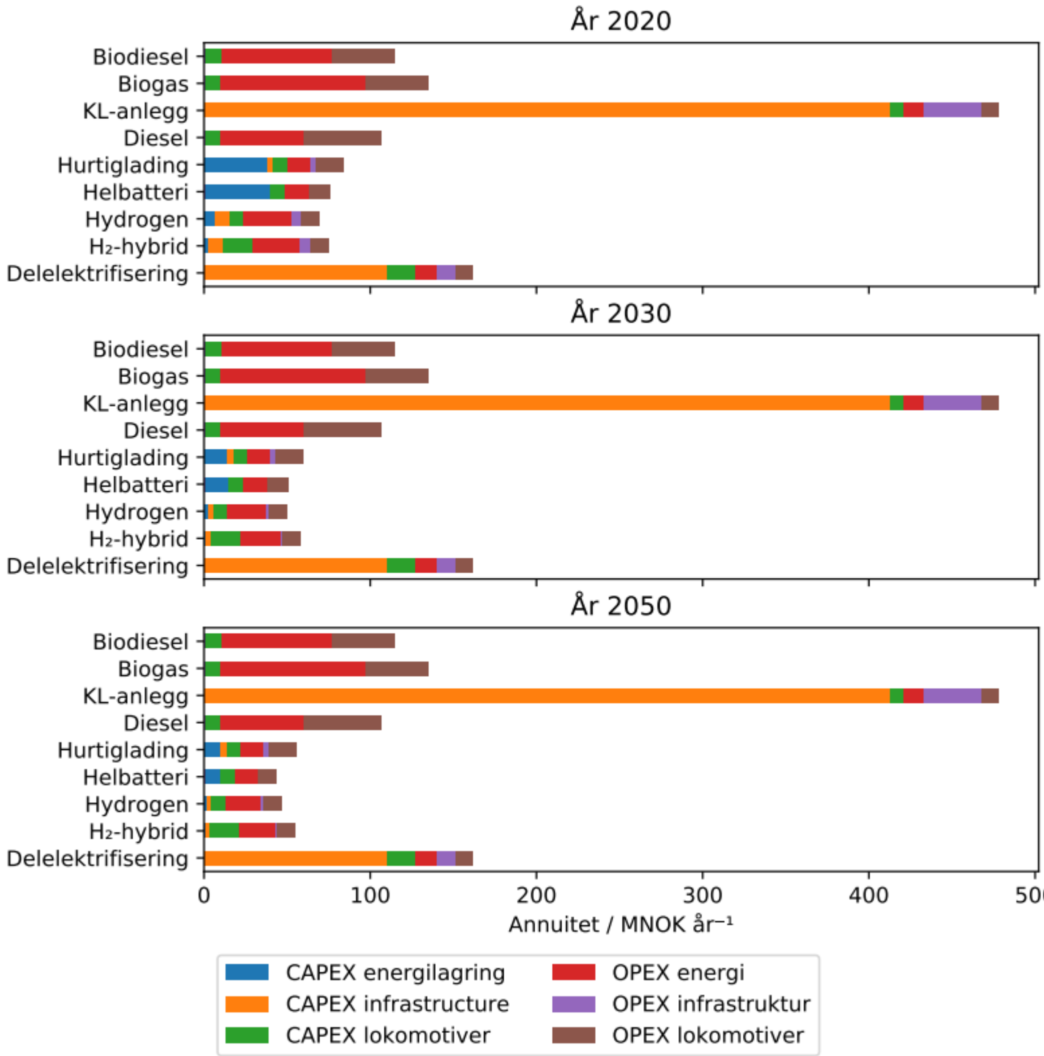


Figure 20: Capital and operational costs of different freight train technologies on the Nordland line; Annual costs (in million NOK per year) for 2020. 2030 and 2050. Source: Zenith et al. (2019).

Differences between these findings are large, reflecting both the inherent uncertainties involved in technology cost assessments and differences in scope, methodology (e.g. annual annuity vs present value) and assumptions in the studies. Other more general studies at a European level, such as Ruf et al. (2019), conclude that both battery electric and hydrogen trains can be cost competitive to other options with specifics depending on the route (location and characteristics) in question. Fuel cell trains were found to make most economic sense when used on longer non-electrified routes over 100 km, for last mile delivery routes, and for main routes that have low utilisation (e.g. up to 10 trains a day).

6.2 Overall favourability of zero emission solutions

In addition to costs alone, both studies from Jernbanedirektoratet and SINTEF considered overall technology favourability based on multi-criteria; criteria in NULLFIB involved feasibility, investment and operation and climate and environment (Jernbanedirektoratet 2019b), whilst criteria considered by SINTEF were environment, technology readiness, regulatory framework, economy, flexibility and robustness (Zenith et al. 2019). Thereafter, a slightly different picture emerged in both studies (results discussed here focus on hydrogen and battery solutions).

Jernbanedirektoratet identified significant differences between the characteristics and suitability of the technologies evaluated for the present day, based on feasibility, investment/operation and climate and environment categories (Figure 21), leading to an overall recommendation for partial electrification (Jernbanedirektoratet 2019b). Other technologies that scored well overall were biodiesel and full battery use, whilst hydrogen scored poorly.

Explanations for this picture can be gained by reviewing the results for the individual markers. For the feasibility marker, their assessments concluded that hydrogen (and to a lesser degree, full battery solutions) are unable to be selected at the current point in time, due to foreseen issues with technological maturity (both for full battery solutions and hydrogen), compatibility with current technology (hydrogen) and safety (hydrogen, due in particular to issues with tunnels). For the investment and operation marker, their assessment concluded that again, neither hydrogen nor full battery solutions are ideal for selection primarily due to issues with vehicle investments (battery and hydrogen) and operation and maintenance expenses (hydrogen). Both technologies performed better on average in the climate and environment category, although hydrogen received a low score for the energy efficiency of its supply chain. Partial electrification with battery operation came out well in all categories, with a lower score for greenhouse emission investment.

	Feasibility		Investment and operation		Climate and environment		Result
	Average	Lowest score	Average	Lowest score	Average	Lowest score	Total score
Full battery	6	3	6.3	3	8.4	8	5.8
Standard CL	8.5	3	7	1	8.6	3	5.2
Partial elec.	7.2	6	6.3	5	8.4	5	6.3
H2	1.7	1	3.7	3	7	4	3.4
Biogas	2.5	2	6.3	5	4.2	1	3.5
Biodiesel	8.7	8	8.3	6	4.2	1	6
Diesel (ref)	9.7	8	8.7	7	3.4	1	6.3

Figure 21: Overall suitability of technologies at the current time. Source: Jernbanedirektoratet (2019b).

Similarly, SINTEF (Zenith et al. 2019) concluded that biodiesel (and second, full battery solutions) are estimated to be the most favourable technologies at the current time, with hydrogen scoring poorly (Figure 22). However, when looking to the future, full battery favourability was estimated to increase and was therefore considered to be the best solution for most of the next decade[14]. In addition, although hydrail appears unfavourable in the present day by 2030 Zenith et al. (2019) estimate that it will be most favourable. The study differs most to Jernbanedirektorat's in terms of its findings for partial electrification, which came out relatively mediocre for both the present day and overall for all years. A reason for the poor favourability of this technology, according to SINTEF, is that although partial electrification manages to significantly reduce infrastructure (catenary) costs, it does not manage to reduce costs to the degree that it can be competitive with diesel or with other electrification options without these lines. It does, however, increase in favourability through the first half of the 2020s, due to better access to technology as well as a somewhat increased sustainability in battery production until 2025.

[14] Fast charging battery trains did not result so well in the analysis, due to a combination of mediocre economy and uncertain availability of multi-MW fast chargers.

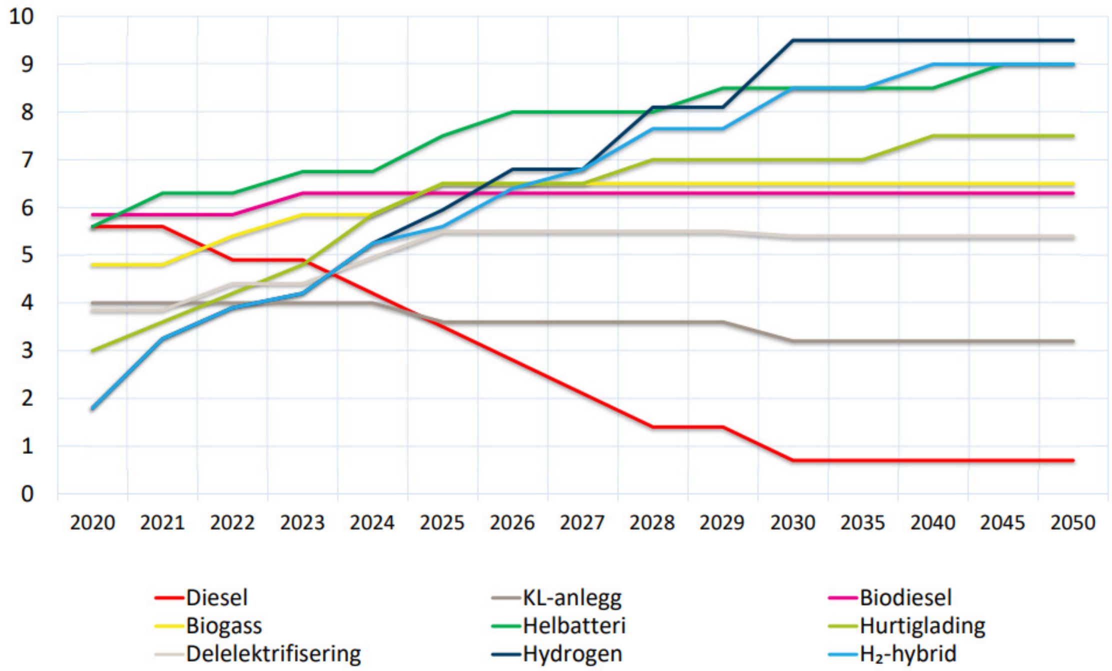


Figure 22: Technology actuality towards 2050. Source: Zenith et al. (2019). The y-axis of this figure gives a total score for each technology solution, based on all evaluation criteria in the study.

As before, differences between assessments seem large, reflecting the uncertainty and differences between e.g. methodologies used and the timeframes considered. For example, aside from being carried out for the present day (in contrast to SINTEF who estimate favourability towards 2050 giving some variation in scope and findings), overall favourability assessments by Jernbanedirektoratet are made by retaining (and weighting) the lowest score in each category.

6.3 Testing status in Norway

Although no fuel cell or battery electric trains has yet been tested in operation in Norway, Jernbanedirektoratet has now decided to test out the solution recommended through their NULLFIB project, which was partial electrification with battery operation. It has been decided to not proceed with any hydrail project. These decisions have now been validated by the Ministry of Transport.

7 Discussion

This report aimed to summarise the global maturity and market status of battery electric and fuel cell technology (for regional passenger and freight rail connections), using publicly available literature sources, as a prelude to planned further case study work in Norway inside the MoZEES project in 2020.

The rail network in Europe is key to decarbonising the transport sector, with requirements laid out by the EU for a higher share of long distance overland freight and medium-distance passenger travel by rail. The European network is already mostly electrified, with further expansion planned. However, electrification of all lines is not always desirable, for e.g. economic and other practical reasons. Zero emission technologies that can run on non-electrified lines such as battery electric and fuel cell trains allow improvements to be made to air quality and noise without expensive investments in electrification infrastructure, as well as avoiding disruption caused by overhead wire installation.

Both fuel cell and battery electric trains are available on the market but are (as of 2019) still mostly at the prototype phase in Europe, and are not tested for freight transport. Both battery and fuel cell technologies have the potential to be technologically mature in the next decade, and there may be a degree of inherent complementarity between them as in other transport segments. In any case, no major change in transport will be possible without the support of an adequate network, which must be planned in a way that maximises positive impact on economic growth and minimises negative impact on the environment (European Commission 2011). Infrastructure for hydrail is currently not developed, compared to the maturity of infrastructure for electric trains. Hydrogen filling stations at main terminals with access for international traffic must therefore be installed. Important questions include considerations of a critical mass, and possibilities for sharing infrastructure with other types of vehicle for cost effectiveness. Sustainability is also a key issue for both battery electric and hydrogen trains, since the energy source (and technology) used to produce the electricity and hydrogen will heavily influence the overall GHG reduction potential. Renewable energy sources, possibly in combination with CCS, are therefore required.

Within Norway, it has been decided to test the solution recommended through Jernbanedirektorat's NULLFIB project, which was partial electrification with battery operation. To date, no battery or hydrail solution has yet been tested in Norway, and although assumptions can be made about how technologies will perform, local Norwegian conditions may influence performance. For example, Norway has mountainous regions and cold winter temperatures which may affect battery performance and lifetime. Although use-characteristic variation between summer and winter can be low if the battery system is properly designed[15] (Urban Transport Magazine 2019), climatization of passenger trains may still lead to variation in energy use and subsequent available battery range throughout the year. This has been shown to be the case with the battery electric buses adopted, for example, in Oslo and other major Norwegian cities, where energy used for heating and ventilation represents around 50 % of the total energy use per km driven (Hovi et al. 2019).

[15] For example, the Desiro ML cityjet has a special thermal concept for the battery containers, meaning it is expected that external weather conditions will have minimal influence on battery life and charge status

The heating requirement for trains may however be less demanding as the doors are opened less frequently than on buses. Following up on user experience in the Norwegian rail sector, as partial electrification is implemented, will be key to successful implementation.

To conclude, the European rail sector has seen significant developments in battery electric and hydrail train technology and availability in recent years. With current focus on implementation of partial electrification in Norway, and zero emission solutions across Europe as a whole, it is clear that this trend is set to continue.

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