Battery electric and fuel cell trains

Maturity of technology and market status
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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 diesel tog være batteri- eller brenselcelle drevne tog.


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 hydral, 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)
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 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) for useful comments.

Oslo, December 2019
Institute of Transport Economics

Gunnar Lindberg  Jardar Andersen
Managing Director  Research Director

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\(^1\) Including international aviation
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Summary

Battery electric and fuel cell trains
Maturity of technology and market status

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

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.

Outlook is bright in Norway and in Europe

No fuel cell or battery electric trains have yet been tested in operation in Norway, but the Norwegian Railway Directorate (Jernbanedirektoratet) is working to find zero emission train solutions for stretches of line such as the Nordland line that are difficult to electrify. Key findings from the work so far is that in the 2020s, battery electric technology may be most attractive, but that from the year 2030, hydrail is expected to be the best overall option. Both options are considered to be a better option than diesel and catenary in future since they couple the low energy costs of catenary with the low infrastructure costs of diesel. Nevertheless, research in general indicates that fuel cell and battery electric technologies are complementary to each other. Hydrail may offer a greater range (and interoperability) for long-distance freight trains, whilst battery electric trains may be used for shorter stretches of non-electrified rail.

To conclude, the 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 between 2020 and 2025. With current focus on further implementation both in Norway and 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

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 brenselceller. 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 ansees som en kostnadseffektiv løsning.

Null-utslipps tog for ikke-elektrifiserte jernbanestrekninger

De fleste togene i Europa drives i dag av elektrisitet fra en tredje strømførende jernbaneskinne eller overhengende kabler, 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 gode nullutslippsalternativer til dieselframdrift.

Teknologien og markedet er under utvikling

Batteri og brenselcelle-teknologier har utviklet seg betydelig de siste årene, og har hatt en økende anvendelse 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 (for forsøk og i kommersiell drift).

For øyeblikket er alle nullutslippstogprosjekter relatert til persontog, og (etter forfatterenes kjennskap) er det ingen dedikerte batterielektriske- eller hydrogen-løsninger for godstog som ennå er i drift. 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 nå for lansering. Når det gjelder brenselcelletog (hydral), ble et passasjertog fra Alstom med brenselcelleteknologi lansert i 2018 for kommersiell drift i Tyskland. Det er allerede planer om å implementere brenselcelletog for passasjertrafikk i andre land. Erfaringene fra disse batterielektriske og hydralprosjektene er så langt positive.
Behov for ny infrastruktur


Framtidsutsiktene ser lyse ut i Norge og Europa


For å konkludere, jernbanesektoren har hatt en betydelig utvikling innen batterielektrisk- og hydrail-togteknologi og tilgjengelighet de siste årene, og begge teknologiene har potensial til å være teknologisk modne mellom 2020 og 2025. Med nåværende fokus på videre implementering både i Norge og resten av Europa, er det klart at denne trenden vil 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. This is 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).

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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. 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).

Electrification of EU main rail lines is progressing, not only due to various national programs to reduce environmental impacts, but also due to the associated low maintenance cost, quiet operation and increased passenger comfort (Mwambeleo and Kulworravanichpong 2017). High-density passenger and freight lines have already mostly been electrified since this is the most cost-effective solution with highest carbon savings.

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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.
(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).](image)

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).

<table>
<thead>
<tr>
<th></th>
<th>NCA LiNiCoAlO₂</th>
<th>SLFP LiFePO₄</th>
<th>NMC LiNiMnCoO₂</th>
<th>LTD LiTiO₄₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell voltage, 100%/50% SOC</td>
<td>4.0 V/3.6 V</td>
<td>3.8 V/3.3 V</td>
<td>4.2 V/3.7 V</td>
<td>2.8 V/2.4 V</td>
</tr>
<tr>
<td>Energy</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>–</td>
</tr>
<tr>
<td>Power</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Calendar life</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Cycle life</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Safety</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^5\) Batteries for railway applications are covered by the IEC 62620 international standard.
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.

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

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\(^6\)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).](image)

![Figure 7: Hybrid (energy storage-fuel cell) energy drive. Source: Meegahawattea et al. (2010).](image)
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 variation in summer and winter due to changes in rolling resistance and air resistance.

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).
4 Market development

4.1 Battery electric trains

Despite the early development of the battery electric train (Railway Technology, 2015), 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, 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.

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

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).

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, Siements 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 development9 (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).

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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. 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 addressed (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).

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

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 hydral 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).](image)

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 hydral train 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.
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.
Figure 15: Example a) catenary system, and b) pantograph and catenary system combined. Source: Pappalardo et al. (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 iLint trains). However, calculations indicate that 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).
Battery electric and fuel cell trains

(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 CO2 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 CO2 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\textsuperscript{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, have synchronous-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\textsubscript{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\textsubscript{2} each year (Norwegian Department for Transport 2017). Electrification of all lines is not desirable due to visual pollution and costs, as well as other practical factors. For example, tunnels on old railway lines may not allow for the use of catenary systems without expansion. However, no fuel cell or battery electric trains have yet been tested in operation in Norway.

![Figure 17: Historic and predicted emission from different transport sources in Norway. (in 1000-ton CO\textsubscript{2}) Source: Norwegian Department for Transport (2017).](https://example.com/figure17.png)

The question of which zero emission train technology is better suited for the non-electrified lines is dependent on many parameters. To this end, analysis has been performed for the Norwegian Railway Directorate (Jernbanedirektoratet) using criteria for environmental impacts, technological readiness, regulatory framework, economic viability and flexibility (Møller-Holst 2016, Zenith et al. 2016, Zenith et al. 2018, Zenith et al. 2019). Several lines were considered (Trønder, Nordland, Roros, Raumabanen and Solør), and key findings were that zero emission freight trains can be taken into use on parts of these lines. This may be particularly important due to the expected lack of state electrification budget for parts of these lines (NRK 2019).

\textsuperscript{11} Data from 2017.
Capital and operating cost summaries for the technologies are shown in Figure 18 for the Nordlands line, a 731 km line from Trondheim to Bodø that crosses the polar circle\(^{12}\) (Zenith et al. 2019). Both hydrogen 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 hydral. 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).

Similarly, 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).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure18.png}
\caption{Capital and operational costs of different freight train technologies on the Nordland line. Annual costs (in million \$ per year) for 2020, 2030 and 2050. Source: Zenith et al. (2019).}
\end{figure}

\(^{12}\) In places this line has a gradient of 19 \(^{\circ}\), and represents some of the most challenging rail transport conditions in Europe.
When overall favourability was considered based on multi-criteria (environment, technology readiness, regulatory framework, economy, flexibility and robustness), a slightly different picture emerged (Figure 19) (Zenith et al. 2019). For the year 2020, it was estimated that biodiesel will be the most favourable technology, although battery technology favourability is estimated to increase and is considered to be the best solution for most of the next decade. Fast-charging battery trains scored poorly in 2020, due to a combination of mediocre economy and uncertain availability of multi-MW fast chargers. By 2030 Zenith et al. (2019) estimate that hydrail will be most favourable, although battery solutions and hydrogen hybrid will become increasingly favourable. At this time, it is thought that fossil diesel will no longer be competitive.

Local conditions in Norway (relating to e.g. climate and landscape) must also be accounted for when anticipating technology performance. For example, Norway has mountainous regions and cold winter temperatures which may affect battery performance and lifetime, if battery trains are implemented. Likewise, consistent charging speeds over different seasons will be vital for the overall dependability of a rail-system using battery electric propulsion. However, it is likely that the use-characteristics variation between summer and winter can be low if the battery system is properly designed. 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 (Urban Transport Magazine 2019). Nevertheless, climatization of passenger trains may still lead to large variations in energy use and subsequent range.

Although it is difficult to make assumptions of how hydrail would perform in Norway, modern hydrogen fuel cell light vehicles have been found to have similar performance in a wide range of temperatures. In addition, the fuel cell design can be adapted to the landscape requirements; According to Ruf et al. (2019), a flat route profile combined with large distance between stops requires a train design with high maximum speed and low maximum tractive effort, whereas with a strong elevation profile, a higher average power would be required.
7 Discussion

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 economic, interoperability or visual reasons. Low 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. This report therefore aimed to summarise the global maturity and market status of battery electric and fuel cell technology (for regional passenger and freight rail connections), using publically available literature sources, as a prelude to further case study work in Norway.

Both fuel cell and battery electric trains are available on the market but are (at present) still mostly at the prototype phase in Europe, and are still not tested for freight transport. Both battery and fuel cell technologies have the potential to be technologically mature between 2020 and 2025.

Fuel cell and battery electric technologies are complementary to each other. For example, since hydrogen trains offer a greater range they may be used for long-distance freight trains, whilst battery trains may be used for shorter stretches of non-electrified rail (such as those partially electrified with catenary systems). 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).

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 hydrogen trains 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 to be considered 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.

To conclude, the rail sector has seen significant developments in battery electric and hydrail train technology and availability in recent years. With current focus on further implementation both in Norway and across Europe as a whole, it is clear that this trend is set to continue.
8 References


Bombardier Transportation (2018). World Premier: Bombardier Transportation presents a new battery-operated train and sets standards for sustainable mobility.


Battery electric and fuel cell trains


Battery electric and fuel cell trains


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