Technical report on railway traction technologies

European Investment Bank
The EU bank

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The suitability of different railway traction technologies for different categories of rolling stock, the related trends for each category, constraints of new technologies and their likely availability on the market and resulting impact on their markets in the short and medium term

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Foreword

Fight against climate change has been a priority of the Bank for many years. Railway is, alongside inland waterways, the most energy efficient and least polluting land transport mode, both for passenger and goods transport, and therefore financing railway projects has been a priority for the Bank.

The Paris Agreement requires all countries and sectors to step up efforts to limit the global warming to well below 2°C, preferably to 1.5°C. The European Green Deal proposed under the new Commission has strengthened the ambition and aims to cut green-house gas (GHG) emissions at least by 55% by 2030 and to achieve net zero emissions by 2050. In this context, the EIB Group Climate Bank Roadmap 2021-2025 was adopted in November 2020 as the Bank's response to support the EU to deliver on the long-term goals of the European Green Deal and UN Sustainable Development Goals more broadly.

Alongside power generation, transport is the largest source of GHG emissions in the EU. In contrast to power generation and nearly all other sectors, GHG emissions from the transport sector continue to rise (by 30% since 1990), with most of these emissions coming from the road sector, followed by shipping and aviation. Decarbonising the transport sector requires a combination of efficiency improvements in vehicles, shifting passengers and freight from high-emitting to low-emitting transport modes (such as rail) and using alternative low-carbon fuel sources such as electricity and advanced biofuels. Around 80% of the European railway traffic already takes place on electric trains, which will become cleaner in line with the decarbonisation of the power grid. However, in order to achieve the net zero emissions target it is also important to find alternative solutions for diesel traction technology; new emerging technologies, such as hydrogen and battery powered trains, will play an important role in the decarbonisation of non-electrified lines where the electrification might not be economically sensible.

With this in mind, the Bank commissioned this technical report for having a better insight into suitability of different railway traction technologies for different categories of rolling stock, the related trends for each category, constraints of new technologies and their likely availability on the market in the short and medium term.

Summary

This report summarises the suitability of different railway traction technologies for different categories of rolling stock, the related trends for each category, constraints of new technologies and their likely availability and resulting impact on their markets in the short and medium term.

The introduction of new traction technologies for railway vehicles in most cases follows a two-step approach:

1) the generic development of a new traction drive technology for various purposes such as road vehicles, ships and railway vehicles; followed by

2) integration by a rolling stock manufacturer into, for example, locomotives and/or trainsets. Due to the capacity/power required by the type of vehicle (such as from electric multiple unit to multi-system-locomotive) and the state-of-the-art technology available, a difference in the pace of introduction is natural. In 2020, the focus for hydrogen and battery technology is in the mid-range — up to 2 MW — which is enough for shunters and passenger trainsets.

The experts involved in this project agreed on the following findings:

- Zero emission traction technologies for railways in the range up to 2 MW are ready for large-scale roll out. This includes passenger trainsets and mid-range locomotives such as shunters.
- All technologies include the usage of batteries and intelligent power/trip management systems.
- Fuel cell hydrogen has the potential to replace diesel in remote areas (no need for overhead wires).
- Battery electrical technology enables the reduction of costly overhead wires in urbanised areas (tunnels, last miles, shunting).
- Hydrogen trains are in general more suitable to replace diesel multiple units for large distances between stations, and battery trains to replace diesel multiple units for shorter distances between stations.
- Shunters are to be replaced by new silent zero emission-based hybrids or full battery or fuel cell vehicles.
- The new developments are not mature enough for a rule of thumb or key indicators to be given. Each project will be based on a case-by-case approach.

Conclusions

The railway industry is able to deliver the technology for the new age of zero emission railways up to mid-range power classes. Special care must be taken for those sectors where the market is continuing to shrink — such as the diesel locomotive market. Another issue will be the ability of railway undertakings and vehicle owners to finance the necessary retrofits even where the technology is available.

To be able to evaluate/assess new railway projects introducing fuel cell or battery technology, further research and development of expert methods are needed. This shall be done in parallel with the development of the minimum standards needed to prevent an unmanaged introduction of new non-harmonised technologies.

1. Introduction

1.1 Assignment

In December 2011, the EIB adopted its current Transport Lending Policy[1], which among other things indicates that the fight against climate change is a priority for the Bank.

Rail is overall one of the most efficient modes of transport in terms of greenhouse gas emissions by tonne/km and passenger/km. On the basis of its energy efficiency merits, the sector has traditionally been prioritised from an environmental policy perspective as a "green mode", regardless of the traction type. The type of traction was simply determined by efficiency parameters, with diesel commonly accepted for lines with lower traffic intensity.

However, recent international agreements (Paris Agreement, Green Deal Europe and others) require all countries and sectors to step up efforts to limit global warming to under 1.5°C. The European Green Deal proposed under the new European Commission has strengthened the ambition and aims to achieve reductions of 50-55% by 2030 and net zero emissions by 2050.

This increased ambition means a significant change: energy efficiency is no longer sufficient, as all modes will need to achieve levels of CO_2 reductions of over 80% and ensure that emissions are "firmly on the way to zero by 2050".

In the rail sector, this means the removal of diesel traction in the mid/long term and the operation of zero direct emission trains (together with the decarbonisation of the power grid in parallel). Electrification of rail lines is of course one key solution for some lines, but is not cost efficient in other lines with low traffic, on which other technologies (hydrogen, battery power trains, advanced biofuels) are emerging as more efficient alternatives for decarbonisation in certain traffic types.

To get an actual overview of the existing and emerging technologies, **WHB Rail Management,** who collaborated with **Ricardo,** was contracted for an assignment with the following with the following scope: preparing a technical report summarizing the suitability of different railway traction technologies for different categories of rolling stock, the related trends for each category, constraints of new technologies and their likely availability on the market and resulting impact on their markets in the short and medium term.

To prepare a technical report summarising:

- the suitability of different railway traction technologies for different categories of rolling stock;
- the related trends for each category;
- the constraints of new technologies;
- their likely availability on the market; and
- resulting impact on their markets in the short and medium term.

[1] https://www.eib.org/en/publications/eib-transport-lending-policy.

1.2 Method of working

The main categories of railway rolling stock will be analysed: the existing state-of-the-art railway traction technologies, as well as railway traction technologies under development, in the pilot project phase or in early market entry stages. The report will be based on first-hand experience in the field and information available in the public domain.

The main categories of railway rolling stock selected for the analysis are:

- passenger trainsets: such as electric multiple units (EMUs) and diesel multiple units (DMUs);
- locomotives for freight and passenger services;
- vehicles for shunting and feeding purposes;
- track maintenance vehicles (on-track maintenance machines or OTM).

Please note that the information found and included will not be verified but presented as is.

1.3 Graduate assignment

During the project, Tomas de Wit, a student at the University of Rotterdam, was added to the team with the intention to perform his graduate assignment and to combine the outcome of the assignment with this report.

In the graduate report, the following question was answered: “What adaptations need to be made to current rail infrastructure to enable the introduction of emission-free, market-ready traction technologies and what are the associated costs and benefits?” This question was answered using the railway network in Northern Ireland as a case study. The following three traction technologies were compared to diesel traction:

- Electrical traction by overhead catenary (electric multiple units or EMU)
- Electrical traction by battery (battery electric multiple units or BEMU)
- Hydrogen traction (hydrogen multiple units or HMU)

To determine the performance of each traction technology, a calculation model was made. Based on this, three model designs were created to give an indication of the costs and benefits of each traction technology.

This report presents a summary of his work.

2. Railway traction technologies

2.1 State-of-the-art railway traction technologies

Since the dawn the railway age, three main categories and one high-speed category of traction/propulsion technology have been used, developed and improved:

- steam engines (not considered in this report);
- diesel engines;
- electrical engines (AC/DC);
- maglev propulsion engines (not considered in this report).

Diesel engines

Diesel engines are used in various configurations:

- as an engine connected to a gear box connected to the wheels;
- as an engine connected to a hydraulic pump-motor combination connected to the wheels;
- or as an engine connected to a generator powering an electrical drive which is connected to the wheels.

Electrical engines

Electrical engines fed by an overhead wire are also used in various configurations:

- technology based on the usage of direct current (DC) motors directly or via a gearbox connected to the wheels using one overhead line voltage (such as 1.5 kV DC, 3kV DC, 15 kV AC or 25 kV AC);
- technology based on the usage of alternating current (AC) motors directly or via a gearbox connected to the wheels using one overhead line voltage (such as 1.5 kV DC, 3kV DC, 15 kV AC or 25 kV AC);
- technology based on the usage of AC motors directly or via a gearbox connected to the wheels using multiple overhead line voltages (a combination of 1.5 kV DC, 3kV DC, 15 kV AC or 25 kV AC) enabled by solid state inverter systems. This configuration has become the current standard in modern multiple units for passenger transport and locomotives for the operation of international networks.

Combination of diesel and electrical engines

The industry has designed and built several solutions integrating both diesel and electrical technologies, such as for transport in tunnels and through mountain areas.

2.2 Railway traction technologies ready for full-scale deployment

While electrical engines and inverters have been mature for 40 to 60 years, this was not the case for batteries and fuel cells fit for railway purposes. Both technologies have recently become industrially mature and available in a power range of up to 2 MW, meaning that railway applications have become feasible. This includes passenger trainsets and mid-range locomotives such as shunters, with these technologies entering the full-scale deployment phase by way of, for example, battery multiple electrical units and hydrogen multiple units.

In the diesel category, developments are there but not as radical in the electrical domain. Some examples are:

- the use of compressed natural gas and liquid natural gas;
- the use of advanced biofuels (hydrotreated vegetable oil or HVO);
- electrical locomotives with a small diesel generator for last mile operations.

These developments are still in the pre-phase of full-scale deployment. In some cases, they are engineered in such a way that during a retrofit the diesel engine can be replaced by batteries or fuel cells due to a modular design of the vehicle.

2.3 Classification method of maturity of technology

Several methods are available for estimating development stages (such as Technical Readiness Levels or TRL). During this project, a dedicated method was found that was specifically developed for railway applications[2]: the Rail Industry Readiness Levels (RIRL) method. The definitions of the levels used are:

RIRL 1: Conception
Early awareness of a need and potential outcomes thought worthy of developing.

The industry is aware of the opportunity and may have some ideas about implementation and high-level benefits, but does not have a clear route to market, a defined customer or a good understanding of the manufacturing process.

RIRL 2: Opportunity development
Thinking, supported by research, to develop understanding of need and possible approaches to obtain qualitative benefits.

Opportunity is defined to the state that the industry is able to conceive plans to develop the necessary facilities required for delivery. Cooperation and co-financing amongst several independent entities may be required, but no business case exists as yet and barriers to implementation are not understood.

RIRL 3: Proof of concept
Conceptual design supported by experimentation proves viability and feasibility of the concept.

Initial business and production plans, with associated test, qualification and certification are available. Draft business case is developed and end customer is identified along with analysis of their needs.

[2] https://www.railengineer.co.uk/rail-industry-readiness-levels-rirls-defined-and-explained/.

DEMONSTRATION

RIRL 4: Industry specification
Qualitative plans to deliver the concept are supported by positive market and business analyses.

Technologies required to manufacture/produce or deliver are understood and associated facility capability planning is underway in accordance with the market potential and supported by the business plan. Customers and suppliers have agreement on how realistic demonstration of the research project might be undertaken.

RIRL 5: Prototype
Prototype assets and/or services developed under quality-controlled methodology are available.

The industry is capable of pre-production using bespoke processes and able to deliver pre-production standard goods and services in support of whole system and market development. The conditions for implementation are understood. Agreement between project partners stipulates how the successful project should be exploited.

RIRL 6: Operational transition
Supply of goods and/or services of appropriate and repeatable quality meets market needs.

The industry is capable of repeated standards of production to the required levels, and realistic operational demonstrators are in place. The competitive landscape is understood.

DELIVERY

RIRL 7: Initial deployment
Operational credibility builds as goods and services are employed; feedback used to confirm user expectations.

Low-level production begins to ramp up to full production rates in a controlled and planned manner that matches demand and marketing strategies. No barriers from a legislative or standardisation point of view exist. The technology is incorporated in to the wider system. Manufacturers are established and ready to deliver.

RIRL 8: Roll out
Supply meets demand in a timely manner, product/service deemed mature and deployable with ease.

Steady state production output is sustained with supply able to meet demand, with products and services at a mature and qualified state. The product/service is exportable. Customers start to implement the technology because of a strong business case, customer or legislative compulsion.

MAINTENANCE

RIRL 9: Whole life management (full-scale deployment)
Continued product/service improvement; business as usual; actual whole life cost measured.

Products and/or services are mature with the ability of being supplied off the shelf to meet expanding demand; with the opportunity to undertake a reasonable level of tailoring to meet new markets. The product/service is in worldwide usage.

In this report, this method is used to define the stage of development of the emerging technologies used in the latest product developments.

The author of the method included an interesting graph where a relation between the RIRL levels and the need for financing is given:

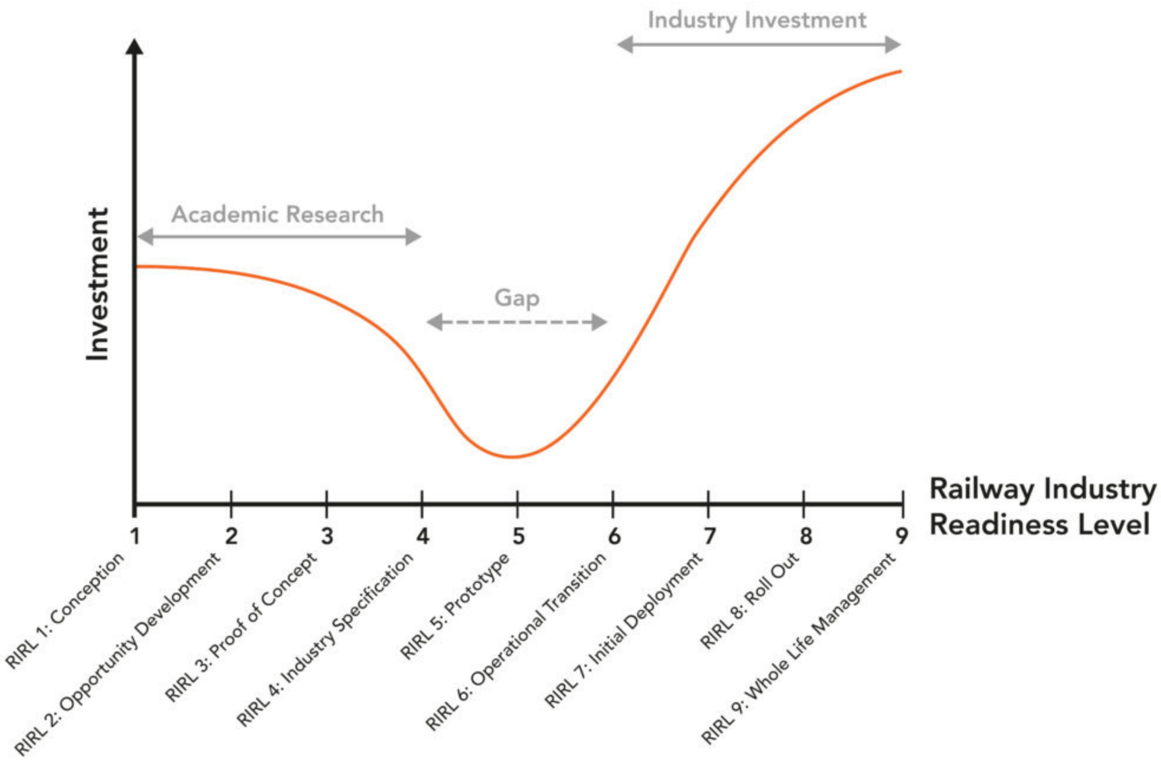

Figure 1: Valley of death (or innovation gap): the struggle to continue funding for development

2.4 Functional design traction in vehicles

Old and new traction technologies are combined in many ways due to the functional designs of the traction systems in railway vehicles. See Figure 2 for some examples:

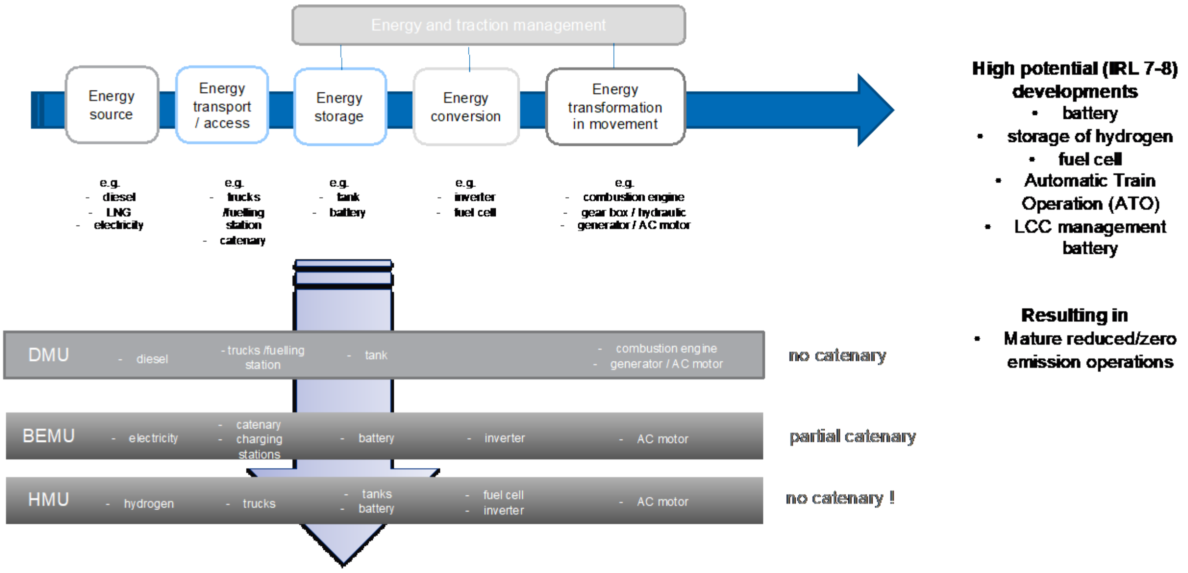

Figure 2: Overview of design combinations of technologies used in railway vehicles

2.5 Standards

Standards for the new developments are also being drafted. The CEN-CENELEC (European Committee for Standardization-European Committee for Electrotechnical Standardization) work programme 2020 (page 77 on Rail) indicates that the organisations are working in close cooperation with the EU Shift2Rail project for the development of new standards for new technologies. Shift2Rail has battery electric multiple units and hydrogen multiple units in their work programme[3]. Topics include the charging of vehicles, retrofitting, economy, and standardisation of interfaces.

2.6 Overview of railway traction technologies

At the start of this project, an extensive survey was carried out to facilitate an overview of the existing and emerging traction technologies used in railway applications. On the basis of expert judgement, an indication of the applicable RIRL levels was made. The experts considered that the latest projects with an RIRL indication of between 6 and 8 are especially interesting for the purposes of the zero emission strategies. These are indicated with the following symbol:

Table 1 projects the results of the survey in a matrix combining the vehicle categories (presented on the horizontal axis) and the technologies (shown on the vertical axis).

In the following chapter, a selection of combinations (such as self-propelled trainsets with the fuel cell hydrogen technology) will be discussed more in detail.

[3] See page 54 of https://shift2rail.org/wp-content/uploads/2020/02/Annual-Work-Plan-and-budget-for-2020-REV.01.pdf.

Table 1: Overview of traction technologies for railway applications

Traction technology for railway vehicles		Categories of railway vehicles			
		Self-propelled passenger trainsets 	**Locomotives** 	**Shunters** 	**On-track machines** 
Internal combustion engines (ICE)	**Diesel**	RIRL 9: Mature and significant deployment	RIRL 9: Mature and significant deployment	RIRL 9: Mature and significant deployment	RIRL 9: Mature and significant deployment
	CNG/LNG	RIRL 6: Operational Transition	RIRL 6: Operational Transition		
	Advanced Biofuels (HVO)	RIRL 6-7: Operational Transition	RIRL 5: Prototype		
Bi-mode and multi-modes based on power cell-based technologies, internal combustion engines (ICE)	**Bi-mode with diesel and electrical under overhead contact line**	Hybrid RIRL 8: Roll out	Hybrid RIRL 8: Roll out	Hybrid RIRL 8: Roll out	
	Bi-mode with electrical traction under overhead line with last-mile diesel		Hybrid RIRL 8: Roll out	Hybrid RIRL 8: Roll out	
	Bi-mode with diesel and on-board battery	Hybrid RIRL 7-8: Start of roll out		Hybrid RIRL 7-8: Start of roll out	Hybrid RIRL 5: Prototype
Zero emission Power cell (hydrogen fuel cell, battery) and electrical traction technologies	**Fuel cell hydrogen**	FCH RIRL 7-8: Start of roll out	FCH RIRL 5: Prototype	FCH RIRL 7-8: Start of roll out	
	Overhead wire combined with battery and/or capacitor	Battery Electric Multiple Unit (BEMU) RIRL 7-8: Start of roll out		AC/DC/MS RIRL 7-8: Start of roll out	
	Electrical traction under overhead contact line	EMU RIRL 9: Mature and significant deployment	AC/DC/MS RIRL 9: Mature and significant deployment		

1: Conception	2: Opportunity development	3: Proof of concept	4: Industry specification	5: Prototype	6: Operational transition	7: Initial deployment	8:Roll out	9: Mature deployment
The industry is aware of an opportunity	The industry is able to conceive plans about its deployment	A conceptual design is made and supported by experiments	Plans are made about the production of the concept	The industry is capable of pre-production using a defined system	Realistic operational demonstrators are in place	Manufacturers are established and ready to deliver	Customers start to implement the technology	Product can be supplied of the shelf

3. Mature traction technologies and new developments

3.1 Introduction

The existing technologies and upcoming developments are summarised in this chapter. Factsheets are added as the annexes of this report, to provide more insights and references to recent projects and/or publications.

For the purposes of readability and consistency, these factsheets are structured as shown in the table below:

Table 2: Structure used to assess existing and new technologies

Definition	**Project cases**
Maturity of technology	Technology-specific characteristics
Constraints for further development	Operations
Opportunities	Financial
Transition strategies	References
Outlook for deployment	
Contribution to zero emission goal	

In this chapter, the following "generic" categories of vehicles will be briefly discussed:

- Diesel multiple units
- Electric multiple units
- Locomotives
- Shunting vehicles
- On-track maintenance vehicles (OTM)
- New: hydrogen multiple units (HMU)
- New: battery electrical multiple units (BEMU)

For more information, the following factsheets are provided in the annexes:

1) Diesel multiple units (DMU)
2) Electric multiple units (EMU)
3) Locomotives
4) Battery electric multiple units (BEMU)
5) Hydrogen multiple units (HMU)
6) Shunters

3.2 Diesel multiple units (DMU)

Definition

Diesel rolling stock (diesel multiple units or DMU) is often used on lines without overhead wires. This type of rolling stock[4] derives the energy it needs for propulsion from diesel fuel. Several types of diesel traction system exist, including diesel-mechanical, diesel-hydraulic and diesel-electric.[5]

[4] https://en.wikipedia.org/wiki/Diesel_multiple_unit.

[5] https://upload.wikimedia.org/wikipedia/commons/4/4f/Gailtalbahn_BR_5022_K%C3%B6tschach-Mauthen.jpg.

Figure 3: A diesel multiple unit operated by ÖBB

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of diesel rolling stock is level 9 (Whole Life Management). This technology is used commercially in multiple units, shunters and locomotives across the world. There is wide-ranging, off-the-shelf supply that is customisable to meet typical rolling stock owner requirements based on the existing technology.

Constraints for further deployment

- Use of fossil fuels.
- Developments in competing emission-free technologies.
- Governments are actively decarbonising the rail sector.
- High noise generation.
- The market for the diesel engines typically required in rolling stock is relatively small. The development of diesel engines that fulfil the increasingly stringent requirements of Euro norms is therefore dependent on the strategies and resources of a limited number of suppliers.[6] [7]

Opportunities

- The infrastructure required is fairly simple.
- The technology is fully developed — many off-the-shelf products exist and developing new rolling stock requires relatively low engineering costs. However, it will likely be more difficult to ensure that the technology itself will comply with the new Euro norms.
- Rolling stock with diesel engines can be made more efficient — reducing emissions significantly — when used in conjunction with stop-start, selective engine shutdown and advanced driver advisory systems.[8]
- The CO_2 emissions of diesel rolling stock can be reduced by using biodiesel.

[6] https://www.mtu-solutions.com/content/dam/mtu/download/applications/rail/16120789_Rail_Flyer_EuStageV.pdf/_jcr_content/renditions/original./16120789_Rail_Flyer_EuStageV.pdf.

[7] https://www.euromot.eu/wp-content/uploads/2018/09/RAIL-STAGE-V-FAQ.pdf.

[8] https://catalogues.rssb.co.uk/Pages/research-catalogue/T1145.aspx.

Outlook for deployment

- Diesel multiple units will in future be replaced by zero emission rolling stock because diesel engines will always have a certain level of emissions.

3.3 Electric multiple units (EMU)

Definition

Electrical traction via an overhead contact line (simply referred to as electrical traction below) is a proven technology that is used all over the world. The overhead contact line is required to provide the rolling stock with the energy required for propulsion. Relatively high infrastructure costs mean that this technology is mainly used on relatively busy lines.

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of electrical traction is level 9 (Whole Life Management). This technology is used commercially in multiple units and locomotives across the world. There is wide-ranging off-the-shelf supply that is customisable to meet typical rolling stock owner requirements. An increasing variety of rolling stock can be used under different line voltages, making it easier to use in cross-border operations.

Figure 4: An electric multiple unit

Constraints for further deployment

- The infrastructure needed for the use of electrical traction rolling stock is relatively expensive.
- The copper used for overhead lines is a finite resource.

Opportunities

- The technology is fully developed — many off-the-shelf products exist and developing new rolling stock requires relatively low engineering costs.
- Lower rolling stock-related operational costs for electrical traction with respect to diesel technology.
- The rolling stock does not require refuelling or charging stops.
- The maximum speed of this type of rolling stock is high, meaning that it can be used on high-speed lines.

Outlook for deployment
Electric multiple unit trains are mainly attractive for high-frequency lines. Capital costs for the construction of overhead contact lines are high, so the usage rate should be high to justify the outlay.

3.4 Locomotives

Definition
Locomotives powered by diesel, electricity on one or multiple voltages in the range of 1 MW to 6 MW are quite common and deployed worldwide. In some countries (such as India), multiple locomotive diesel units are built for remote long-distance haulage. Locomotives are used for both passenger and freight trains.

Figure 5: A multi-system locomotive

Maturity of the technology
The Rail Industry Readiness Level (RIRL) of the locomotives available on the market is level 9 (Whole Life Management). The traction technology is used commercially in locomotives across the world. There is wide-ranging off-the-shelf supply that is customisable to meet typical rolling stock owner requirements. An increasing variety of rolling stock (multi-system locomotives) can be used under different line voltages, making it easier to use in cross-border operations.

Constraints for further deployment

- The infrastructure needed for the use of electrical traction rolling stock is relatively expensive.
- The copper used for overhead lines is a finite resource.
- For diesel locomotives, strict Euro norms can delay further developments.

Opportunities

- The proven technology is fully developed — many off-the-shelf products exist and developing new rolling stock requires relatively low engineering costs.
- Lower rolling stock-related operational costs for electrical traction with respect to diesel technology.
- The maximum speed of this type of rolling stock is high, meaning that it can be used on high-speed lines.

Outlook for deployment

Electrical

- Multi-system locomotives are mainly attractive for electrified international corridor lines.
- The use of locomotives for passenger trains is falling due to replacement with trainsets.
- The limited number of suppliers in Western Europe (where Siemens is the market leader) is concerning.
- The latest developments include the possibility of having an auxiliary diesel generator on board multi-system locomotives for last-mile operation.

Diesel

- Incumbent companies are continuing to overhaul their ageing diesel fleet (over 30 years old) and retrofit it for the European Rail Traffic Management System (ERTMS).
- Overall, the market for new diesel locomotives is relatively small, with a limited number of suppliers. As a consequence, the evolution of diesel locomotives is highly dependent on other transport sectors, such as those for trucks and ships.
- In the absence of technical solutions from their suppliers, locomotive owners are removing diesel vehicles from their portfolios due to increasingly strict emission requirements. Only new Euro norm engines — which are subject to limited availability[9] — can replace old diesel engines during overhauls.

Both diesel and electrical locomotives can benefit from smart technology developments, such as automatic train operation functionality, under Shift2Rail.

3.5 On-track maintenance machines (OTM)

Definition

The on-track maintenance machines category covers a wide range of vehicles, including:

- Tamping machines.
- Ballast distributing and profiling machines.
- Ballast stabilisation and profiling machines.
- Ballast bed cleaning.
- Track renewal and track laying.
- Material logistics.
- Measuring and monitoring vehicles.
- Catenary installation and maintenance vehicles.
- The category includes all dedicated vehicles for the construction, renewal and maintenance of tracks, tunnels, bridges and stations.

[9] https://www.mtu-solutions.com/content/dam/mtu/download/applications/rail/16120789_Rail_Flyer_EuStageV.pdf/_jcr_content/renditions/original./16120789_Rail_Flyer_EuStageV.pdf.

Figure 6: An on-track maintenance machine

Maturity of the technology
Production numbers in this category are typically relatively low and many designs are tailor-made for specific work. They are hardwearing and able to work in remote areas without catenary lines. Due to the absence of catenary lines and the high power levels needed, traction is in most cases based on diesel engines connected to hydraulic drives. Machines can reach a significant age (40-50 years) with ongoing overhauls.

Constraints for further development
The market is relatively small, there only a limited number of suppliers and many machines are tailor-made. Developments are driven by infrastructure managers (such as quality improvements and reduction in the time needed for maintenance).

Opportunities
Some suppliers are introducing new traction (drive line) designs, for example where the hydraulic drive line is replaced by an electrical drive line powered by a diesel generator. From there, it is a small step to replace the diesel generator with a new fuel cell or batteries when appropriate.

Transition strategies
Suppliers are gradually replacing the most-used diesel-hydraulic drive lines with diesel-electric and hybrid machines based on battery/fuel cell/pantograph-electric drive lines.

Outlook for deployment
The replacement of existing machines with new builds will most likely proceed slowly due to the existence of a large number of high-value machines already in service and low demand from infrastructure managers.

Contribution to zero emission goal
Due to fleet seize and utilisation, actual impact is relatively low (for example for diesel multiple units and diesel locomotives) and will be lower in the future when new technologies are introduced.

3.6 Hydrogen multiple units (HMU)

Definition

Fuel cell hydrogen (FCH) trains are able to utilise the energy stored in hydrogen gas to generate the electrical energy required for propulsion. The local emissions of a hydrogen multiple unit (HMU) comprise steam and condensed water. Hydrogen trains include battery cells to store excess energy and to recover energy during braking to improve energy efficiency.

Figure 7: An HMU

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of hydrogen multiple units is estimated to be around level 7-8 (Roll out). The Coradia iLint from Alstom is the first hydrogen rolling stock series to have entered commercial service (in 2018) [39]. Furthermore, in the United Kingdom several projects are currently ongoing to retrofit electric multiple units into hydrogen multiple units. Alstom currently has an order for an additional 27 fuel cell hydrogen trains in Germany [28] and Stadler has received an order for up to five of these trains in the United States [35]. In summary, the initial deployment of hydrogen multiple units is ongoing.

The level of organisational capability and maturity needed to operate and manage the fuel cell hydrogen technology differs from that required for diesel, in that it involves full computer-controlled electrical traction skills and the knowledge and means to handle hydrogen installations. Additional investments in workshops, tooling and engineering are necessary.

Constraints for further deployment

- For future deployment of hydrogen multiple units, it is important that passengers and authorities consider the hydrogen technology to be safe for use in rolling stock.
- Hydrogen takes more space than the energy-equivalent amount of fossil fuels.
- Storage of enough hydrogen in gaseous form requires large pressure.
- Storage of hydrogen in liquid form requires very low temperatures.
- Fuelling speed for large amounts of hydrogen is low compared to diesel.
- The mean time between maintenance intervals is still quite short.
- The infrastructure for hydrogen supply to the railways is not yet developed. Temporary or mobile installations are currently being used.
- Generating hydrogen from green sources requires large installations. The majority of the hydrogen that is now available is derived from fossil fuels. Hydrogen has extensive potential

uses in other sectors also looking for more sustainable energy sources, potentially making it scarcer. However, this may also lead to opportunities, as the transport and production will be more mass produced, and this will potentially result in cost reductions. Dedicated facilities producing green hydrogen will need to be developed alongside fleet deployments to avoid price uncertainty.
- The necessary investments in infrastructure should not be underestimated for less-developed countries (see also chapter 4).

Opportunities
- Costs of fuel cells and batteries are declining.
- Hydrogen infrastructure may advance in step with the general development of hydrogen technology due to use in the automotive and maritime industries.
- Hydrogen safety has significantly improved recently due to the use of advanced materials for hydrogen storage, together with sensors. When the use of hydrogen becomes more common, the perception of hydrogen safety may change.
- Transport using hydrogen can help consume excess loads in renewable networks, lowering the median and possibly peak load, minimising the need for energy infrastructure.

Outlook for deployment
- Hydrogen multiple units are still relatively expensive. As deployment increases, the technology will progress and batteries and fuel cells will become cheaper, and the price of the trainsets will decrease.
- The potential range of hydrogen multiple units (1 000 km in 2020) is much wider than for battery electric multiple units, meaning that their performance is superior to that of battery electric multiple units for longer non-electrified sections.

3.7 Battery electric multiple units (BEMU)

Definition

The development of electric cars has led to battery technology being seen as one of the most promising paths towards phasing out diesel-powered trains. The energy that battery electric multiple units (BEMU) require for propulsion is stored in rechargeable batteries. In practice, most of these trains are hybrids, and an overhead contact line can be used for both propulsion and battery charging, as shown in Figure 8.

Figure 8: A battery electric multiple unit

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of battery electric multiple unit trains is estimated to be around level 7-8 (Roll out). Currently, a limited number of these trains are operational, with most being demonstration trains. In recent years, Siemens, Stadler, Alstom and Bombardier have all received firm orders of between 11 and 300 trains. This indicates that production rates are increasing and that initial roll out is starting.

The level of organisational capability and maturity needed to operate and manage battery electric multiple unit technology differs from that required for diesel, in that it involves full computer-controlled electrical traction skills. Additional investments in workshops, tooling and engineering are necessary. The impact on engineering skills is relatively low.

Constraints for further deployment

- Although developments are still ongoing, battery power density and capacity remains a key factor when designing timetables and range.
- The weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure.
- Charging the batteries takes time. Faster charging is possible by using super capacitors. However, these have a larger mass and volume with respect to batteries.
- The maximum current that can be extracted from the infrastructure while charging.
- The availability of power connections to the energy grid of network operators. A possible solution for this constraint may be by storing energy (for example in batteries) near the charging facility, which will reduce the grid load while charging.
- The necessary investments in infrastructure should not be underestimated for less-developed countries (see also chapter 4).

Opportunities

- Developments in battery technology making it possible to travel longer distances with higher power. This also ensures that batteries degrade more slowly and that they can be produced using less material.
- The battery price per kWh is decreasing rapidly over time.
- Automatic train operation can be useful for this train type. It can create a driving strategy to minimise energy consumption and extend the lifetime of the battery.

Transition strategies. Transition of rolling stock

Battery electric multiple units can be purchased new, or created by retrofitting existing rolling stock. Typical components are batteries, a battery management system and charging facilities.

Outlook for deployment

- Battery electric multiple unit trains have relatively low power, a short range and a maximum speed of 140 km/h.
- This technology is ideal for urban areas with short distances and tracks with tunnels.
- The introduction of fuel cell hydrogen technology will most likely be more successful for longer distances.

- Several of these trains are already in use around the world. As the technology advances, batteries keep getting cheaper while their performance improves. This also means that this type of train will keep getting cheaper as capabilities improve.

3.8 Shunting locomotives

Definition

Shunters are railroad locomotives used for moving other rolling stock at classification yards for assembly, disassembly or maintenance. Shunters are generally used at low speeds to haul variable loads in short runs with large idle times in between runs. The majority of shunters currently in use are based on diesel traction. Three traction technologies with reduced carbon dioxide emissions are currently under development: diesel-battery hybrid, battery and hydrogen. Diesel-battery hybrid shunters use their diesel engines to charge their batteries when they are low.

Figure 9: A shunting locomotive

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of hybrid diesel-battery shunters is estimated to be around level 7-8 (Roll out). Several orders for battery-diesel hybrid shunters have already been made. Alstom has received an order for 12 Prima H3 shunters, Toshiba has received an order for 100 Toshiba HDB 800 shunters and Transmashholding has reached an agreement for delivering up to 131 shunters.

This indicates that production rates are increasing and that initial roll out is starting. The RIRL of battery shunters is estimated to be around level 6-8 (Roll out). Many battery shunters exist; however, these are mostly in the lower power class. High-power battery shunters are much less common, but some examples do exist: Alstom has made a battery version of the H3, Stadler has received an order for seven battery shunters and BEMO rail has a BRE150 battery shunter. The RIRL of high-power battery shunters is therefore estimated to be around level 6-7 while the battery shunters in the lower power class are at level 7-8.

The RIRL of hydrogen shunters is estimated to be around level 5-6 (prototype). Studies have shown the potential of hydrogen powered shunters but few examples currently exist: ÖBB has retrofitted a 1063 038 into a fuel cell hydrogen shunter and BNSF tested one between 2008 and 2009.

The level of organisational capability and maturity needed to operate and manage the battery or fuel cell hydrogen technology differs from that required for diesel, in that it involves full computer-controlled electrical traction skills. The impact on the engineering skills is relatively low when using battery technology. For the fuel cell hydrogen technology, the knowledge and means to handle hydrogen installations is required and additional investments in workshops, tooling and engineering are necessary.

Constraints for further deployment

Diesel-battery hybrid

- Due to developments in battery and hydrogen technology, this technology is most likely a temporary solution that at some point will no longer be required. As the capacity of batteries increases, hybrid shunters will be able to operate for longer without using their diesel engine, with the diesel engine eventually being replaced by other charging mechanisms.
- The weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure.

Battery

- Battery power density and capacity are key factors for the power and range of the shunters.
- The weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure.
- Charging the batteries takes time. Faster charging is possible by using super capacitors. However, these have a larger mass and volume with respect to batteries.
- The maximum current that can be extracted from the infrastructure while charging is limited.
- The availability of power connections to the energy grid of network operators. A possible solution for this constraint may be by storing energy (for example in batteries) near the charging facility, which will reduce the grid load while charging.

Hydrogen

- Hydrogen takes more space than the energy equivalent amount of fossil fuels.
- Storage of enough hydrogen in gaseous form requires large pressure.
- Storage of hydrogen in liquid form requires very low temperatures.
- Fuelling speed for large amounts of hydrogen is low compared to diesel.
- The mean time between maintenance intervals is still quite short.
- The infrastructure for hydrogen supply to the railways is not yet developed. Temporary or mobile installations are currently being used.
- Generating hydrogen from green sources requires large installations. The majority of the hydrogen that is currently available is derived from fossil fuels.

Opportunities

Diesel-battery hybrid

- This technology reduces the emissions of diesel shunters. Because the diesel engine is not running while the shunting locomotive is idle, emissions are reduced by about 50% compared to diesel shunters.
- Combining battery and diesel technology can result in large emission reductions, as the consumption of diesel generators in idling mode is very inefficient for regular diesel shunters.

Battery

- Developments in battery technology make it possible to use a shunter over a longer time, to the extent that the shunter can be used for a whole day without charging. In the case of a 24/7 usage of the shunter, the operations regarding the shunter charging should be designed in a well thought-out way.
- The battery price per kWh is significantly decreasing over time.

Hydrogen

- Costs of fuel cells and batteries are declining.
- Hydrogen infrastructure may advance in step with the general development of hydrogen technology due to use in the automotive and maritime industries.
- The energy consumption of shunter trains is low, so fuelling of hydrogen shunters is required only once a day or less.

Outlook for deployment

- Hybrid diesel-battery shunters are expected to appear only temporarily as an intermediate step between diesel and zero emission shunters.
- Long idle times, short runs and low speeds make battery technology very suitable for shunters.
- Battery shunters are already widely available in the low-power class. As the power density of the batteries increases, more high-power battery shunters are expected in the future.
- Hydrogen technology is currently still relatively expensive. As deployment increases, the technology advances and batteries and fuel cells become cheaper, the price of hydrogen shunters will decrease.

Contribution to zero emission goal

- Hybrid diesel-battery shunters can result in emission reductions of around 50% compared to diesel shunters.
- Battery shunters and fuel cell hydrogen shunters can be charged with energy obtained from sustainable sources, without CO2 emissions.
- According to research by Shift2Rail, a switch from diesel to emission-free shunters can result in a reduction of 3 250-4 500 grams CO2 emissions per shunter per kilometer.

4. Case study: a comparison of diesel multiple units, electric multiple units, battery electric multiple units and hydrogen multiple units in Northern Ireland

4.1 Graduate assignment

In this report, the following question was answered: "What adaptations need to be made to current rail infrastructure to enable the introduction of emission-free, market-ready traction technologies and what are the associated costs and benefits?" This question was answered using Northern Ireland as a case study.

Typical elements:

- Regional passenger transport
- Low frequency
- No electrification
- Relatively simple network
- Not financially attractive for electric multiple units

The following three traction technologies were compared to diesel traction (diesel multiple units):

- Electrical traction by overhead catenary (electric multiple units)
- Electrical traction by battery (battery electric multiple units)
- Hydrogen traction (hydrogen multiple units)

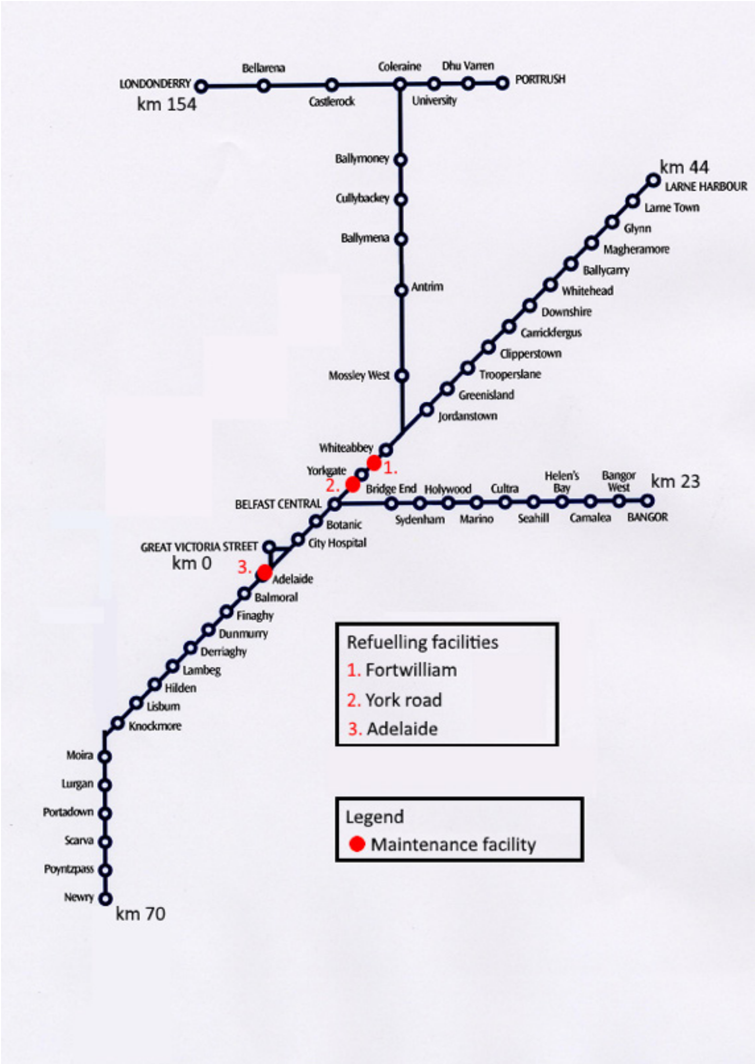

Figure 10: Regional passenger network in Northern Ireland

4.2 Design of model to compare total costs of ownership per variant

To determine the performance of each traction technology, a calculation model was created. Based on this model, three designs were completed to give an indication of the costs and benefits of each traction technology. The calculation model is a simplification of reality. As a result, some numbers might deviate from reality. There are many developments ongoing in the field of batteries and fuel cells: lifespan and power density are increasing, and costs are decreasing.

4.3 Design of model to compare total costs of ownership per variant

The following designs were created with the aid of the model:

- a network design enabling the use of battery electric multiple units using partial catenaries and fast charging points;
- a network design for the usage of hydrogen multiple units with H_2 fuelling stations.

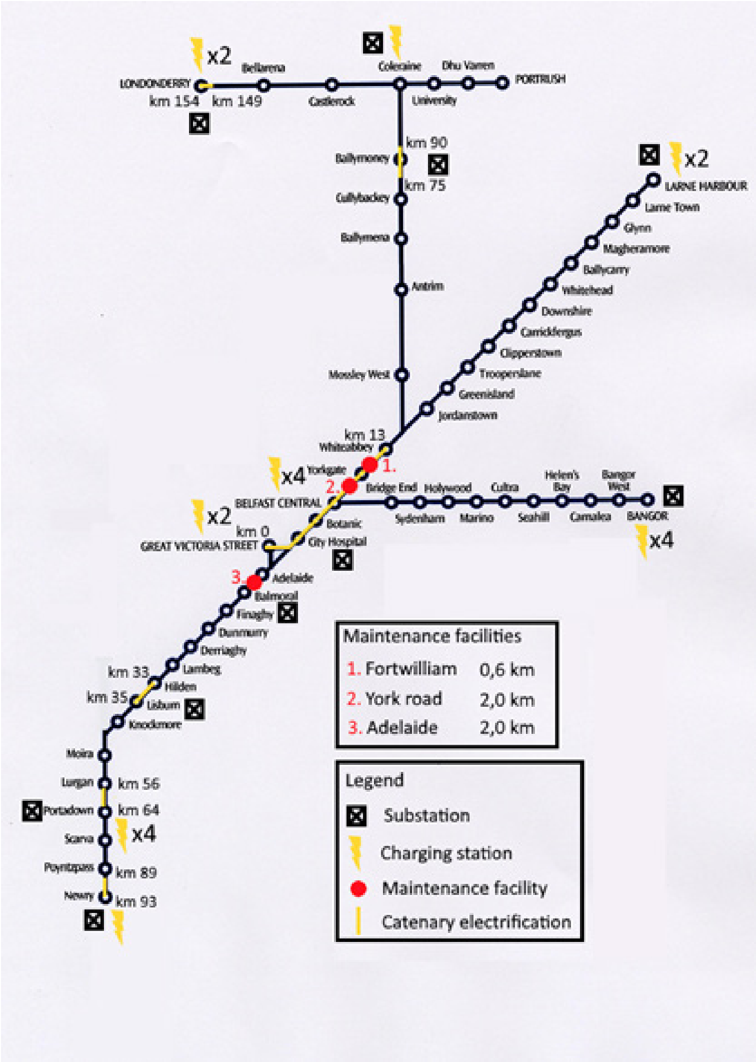

Figure 11: Network design for battery electric multiple units

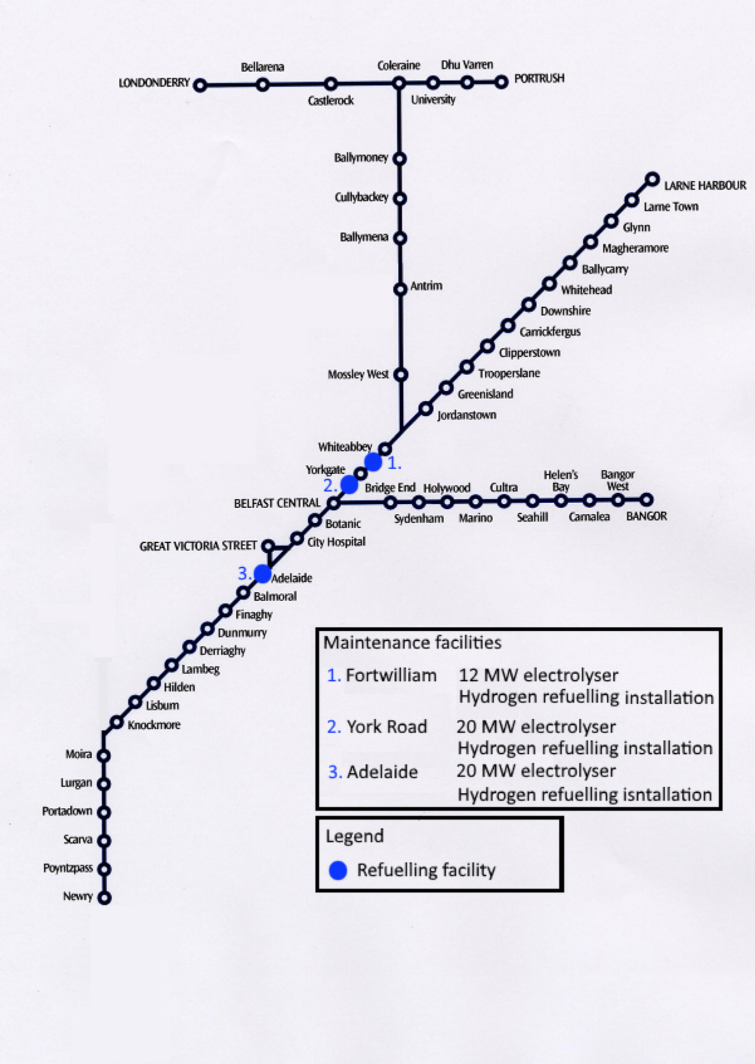

Figure 12: Network design for hydrogen multiple units

Table 3: Results comparison: total costs of ownership for multiple unit types[10]

	Initial cost of infrastructure (€ million)	Operating costs of infrastructure (€ million)[11]	Initial costs of rolling stock (€ million)	Operating costs of rolling stock (€ million)	Average energy usage (kWh/km)	Average CO_2 emissions (gram CO_2/km)[12]
DMU	30	27	219	829	23.77 (2.45 l/km)	6.542
EMU	407	244	198	422	6.12	2.692
BEMU	101	67	237	488	6.45	2.838
HMU	56	84	267	738	18.44 (0.37 kg/km)	8.140
DMU	30	27	219	829	23.77 (2.45 l/km)	6.542

10 Based on full capacity of NIR Class 3000 DMU: 200 seated and 280 standing passengers.
11 For a period of 30 years.
12 Considering emissions of 440 grams CO_2 per kWh (the current situation in Northern Ireland).

If electrical traction by catenary were to be introduced, a catenary system would have to be installed across the entire rail network. The rolling stock (electric multiple units) is lightweight and contains few complex parts. This makes electrical traction by catenary primarily profitable in areas where many trains travel many kilometres a day.

If electrical traction by battery (battery electric multiple units) were to be introduced, only a handful of sections of overhead catenary would have to be installed across the rail network, avoiding the need for civil works. In addition, several charging stations would need to be installed at important stops. To avoid overloading the power grid, buffer batteries should be installed at the location of charging stations. The trains contain heavy batteries that have a lifespan of approximately five to six years. These need to be replaced regularly. Battery trains are primarily profitable in low frequency areas. Because the infrastructure is based on the timetable, it becomes more difficult to make changes.

If hydrogen traction (hydrogen multiple units) were to be introduced, the diesel refuelling installation would need to be replaced by hydrogen refuelling facilities. In addition, electrolysers with sufficient production capacity for the daily operations should be built. Hydrogen trains use a fuel cell that has a lifespan of approximately one year. These need to be replaced regularly. 50 kWh of electrical energy is needed to produce 1 kg of hydrogen. Hydrogen trains should be refuelled daily. Furthermore, legislation would need to be amended to allow hydrogen on the tracks. Hydrogen trains are primarily profitable for areas where long distances are travelled at a very low frequency.

Each of these traction technologies are quieter than diesel trains (diesel multiple units). They also cause fewer vibrations than diesel trains. Public transport often gains in popularity if an emission-free traction technology is introduced.

Moreover, the generation of electrical energy will emit progressively lower levels of CO_2. As a result, zero emission traction technologies will become increasingly attractive in the future.

5. Findings and conclusions

5.1 Findings

The introduction of new traction technologies for railway vehicles follows, in most cases, a two-step approach:

1) the generic development of a new traction drive technology for various purposes such as road vehicles, ships and railway vehicles; followed by
2) the integration by a rolling stock manufacturer into, for example, locomotives and/or trainsets. Due to the capacity/power required by the type of vehicle (such as from electric multiple unit to multi-system locomotive) and the state-of-the-art technology available, a difference in the pace of introduction is natural. In 2020, the focus for hydrogen and battery technology is in the mid-range — up to 2 MW — which is enough for shunters and passenger trainsets.

The experts involved in this project agreed on the following findings:

- Zero emission traction technologies for railways in the range up to 2 MW are ready for large-scale roll out. This includes passenger trainsets and mid-range locomotives such as shunters.
- All technologies include the usage of batteries and intelligent power/trip management systems.
- Fuel cell hydrogen has the potential to replace diesels in remote areas (no need for overhead wires).
- Battery electrical technology enables the reduction of costly overhead wires in urbanised areas (tunnels, last miles, shunting).
- Hydrogen trains are in general more suitable to replace diesel multiple units for large distances between stations, and battery trains to replace diesel multiple units for shorter distances between stations.
- Shunters are to be replaced by new silent zero emission hybrids or full battery or fuel cell vehicles.
- The new developments are not mature enough for a rule of thumb or key indicators to be given. Each project will be based on a case-by-case approach.

5.2 Conclusions

The railway industry is able to deliver the technology for the new age of zero emission railways up to mid-range power classes. Special care must be taken for those sectors where the market is continuing to shrink — such as the diesel locomotive market. Another issue will be the ability of the railway undertakings and vehicle owners to finance the necessary retrofits even where the technology is available.

To be able to evaluate/assess new railway projects introducing fuel cell or battery technology, further research and development of expert methods are needed. This shall be done in parallel with the development of the minimum standards needed to prevent an unmanaged introduction of new non-harmonised technologies.

Annexes

1. Diesel multiple units (DMU)
2. Electric multiple units (EMU)
3. Locomotives
4. Battery electric multiple units (BEMU)
5. Hydrogen multiple units (HMU)
6. Shunters
7. Cost comparison EMU, BEMU, HMU to DMU

Annex 1: Diesel multiple units (DMU)


Figure 1: Example of a DMU train

Definition

Diesel Multiple Units (DMU) rolling stock is often used on lines where full overhead line electrification is not financially feasible. DMU is a type of rolling stock for which the required energy for propulsion comes from diesel fuel. Several types of diesel traction systems exists: diesel-mechanical, diesel-hydraulic and diesel-electric.

Maturity of the technology

The Rail Industry Level (RIRL) of diesel rolling stock is at level 9 (Whole Life Management). This technology is commercially used in multiple units, shunters and locomotives all across the world. There is a large off-the-shelf supply that is customizable to meet the demands of typical rolling stock owner requirements. This is based on the existing technology.

Constraints for further deployment

- Use of fossil fuels;
- Development in competing emission-free technologies;
- Governments are actively decarbonizing the rail sector;
- High noise generation;
- The market of the typical diesel engines required in rolling stock is too small to develop diesel engines that fulfill the increasingly strict Euro-norm requirements.

Opportunities

- The required infrastructure is fairly simple;
- The technology is fully developed – many off-the-shelf products exists and developing new rolling stock requires relatively low engineering costs. Although the technology itself will probably have more difficulties in complying to the new Euro norms;
- Rolling stock with diesel engines can be made more efficient to significantly reduce emissions, when used in conjunction with stop-start, selective engine shutdown and advanced Driver Advisory Systems[13];
- By using biodiesel, the CO_2 emission of diesel rolling stock can be reduced[13].

Transition strategies

- DMU's are a widespread technology that is used in a lot of railway systems. Transition of other types of rolling stock into diesel is currently not ongoing. Instead diesel is being replaced by other traction technologies;
- Diesel engines can be used with minor changes in combination with biofuels.

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13 https://catalogues.rssb.co.uk/Pages/research-catalogue/T1145.aspx

Outlook Deployment

- DMU will in future be replaced by zero-emission rolling stock because diesel engines will always have a certain emission.

Contributions to zero emission goal

- The CO_2 emission reduction of 40% could be achieved if the rolling stock with diesel engines are made more efficient[13].

Background information

Financial

This section gives an indication of the costs of exploitation of electrical traction in comparison to diesel traction. The comparison is done for several cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: “study on the use of fuel cells & hydrogen in the railway environment”[14] . The examples that are used in this study are based on low utilization lines and have the purpose of comparing diesel, electrification, hydrogen and battery rolling stock on the lines. The resulting costs would be much more favourable for electrification when using lines with higher utilization. The infrastructure investments would then be divided over more infrastructure users. As can be seen from Table 1 and Table 2, the infrastructure costs are significant for the total costs when using low utilisation lines.

Table 1 shows the most important properties of the cases which relate EMUs to DMUs and gives the total costs of ownership for both types of rolling stock. Table 2 goes into more detail and shows for each case the subdivision of the costs into several categories. The colours in this table indicate whether the costs of EMUs are lower (green), equal (yellow) or higher (red) compared to the costs of DMUs.

Table 1: Cost estimations for four different cases comparing EMUs with DMUs

Case	Country	Track length (km)	Number of rolling stock	Number of seats	Costs Electrical traction under overhead contact line (€/km)	Costs Diesel (€/km)
1	France	140	3 x 4 car trains	230	27.5	18.5
2	Spain	165	2 x 4 car trains	270	22.6	9.3
3	Romania	149	2 x 2 car trains	150	44.9	8.8
4	Netherlands	300	70 x 3 car trains	230	4.5	4.8

[14] Shift2Rail - Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment Analysis boundary conditions for potential hydrogen rail applications of selected case studies in Europe

Table 2: Distribution of the costs (in €/km) into multiple elements for the four cases mentioned in Table 1.

		Case 1		Case 2		Case 3		Case 4	
		Diesel	**Elec**	**Diesel**	**Elec**	**Diesel**	**Elec**	**Diesel**	**Elec**
Rolling stock	Financing	2.5	2.4	2.5	2.3	2.8	2.7	0.4	0.4
	Maintenance	1.3	0.4	0.8	0.3	0.9	0.4	0.9	0.4
	Depreciation	2.4	2.4	1.3	1.2	1.0	0.9	0.4	0.4
Infrastructure	Financing	0.0	7.4	0.0	11.3	0.0	30.8	0.0	0.5
	Maintenance	0.1	1.0	0.1	0.7	0.1	1.6	0.0	0.1
	Depreciation	0.0	2.9	0.0	2.5	0.0	5.6	0.0	0.2
	Track access	9.0	9.0	2.9	2.9	2.4	2.4	1.9	1.9
Other	Fuel	1.5	0.3	0.8	0.5	1.4	0.3	0.8	0.2
	Salary	1.7	1.7	0.9	0.9	0.2	0.2	0.4	0.4
Total		**18.5**	**27.5**	**9.3**	**22.6**	**8.8**	**44.9**	**4.8**	**4.5**

These tables show that the rolling stock costs and the fuel costs are in general lower for EMUs than for DMUs. The track access costs and salary are in equal for HMUs and DMUs. The costs related to infrastructure are higher for EMUs than for DMUs. This table also shows that for a low number of rolling stock (for cases 1 till 3) the large infrastructure costs will have a huge impact. In case number 4 the amount of rolling stock on this line is higher. Therefore, the infrastructure costs are divided over more EMUs, making the total costs significantly lower.

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Annex 2: Electric multiple units (EMU): Electrical traction with an overhead contact line

Figure 2: Example of an EMU train

Definition

Electrical traction via an overhead contact line (further called electrical traction in this fiche) is a proven technology that is used all over the world. The overhead contact line is required to provide the rolling stock with the required energy for propulsion. Because of the relatively high infrastructure costs, this technology is mainly used on relatively busy lines.

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of electrical traction is at level 9 (Whole Life Management). This technology is commercially used in multiple units and locomotives all across the world. There is a large off-the-shelf supply that is customizable to meet the demands of typical rolling stock owner requirements. Increasingly more rolling stock can be used under different line voltage which makes it easier to use across the borders.

Constraints for further deployment

- The infrastructure needed for the use of electrical traction rolling stock is relatively expensive;
- The copper used for the overhead line is a finite resource.

Opportunities

- The technology is fully developed – many off-the-shelf products exists and developing new rolling stock requires relatively low engineering costs;
- Lower rolling stock related operational costs for electrical traction with respect to the diesel technology;
- The rolling stock does not require refueling or charging stops;
- The maximum velocity of this type of rolling stock is high, such that it can be used on high-speed lines.

Transition Strategies

- Electrical rolling stock can be obtained from retrofitting DMU, preferably with diesel-electrical traction;
- Large adaptations are required for the infrastructure, with the construction of overhead lines.

Outlook deployment

- EMU trains are mainly attractive for high frequency lines. As the capital costs of the construction of an overhead contact line are high, the usage rate should be high to justify the cost.

Contribution to zero emission goal

- EMU trains can be provided with energy obtained from sustainable sources, without CO2 emission;
- According to research by Shift2Rail:
    - a switch from DMUs to emission-free rolling stock like EMU trains can result in a reduction of 750-1500 grams CO_2 emissions per coach per kilometre [2].
    - A switch from diesel to emission-free locomotives results in a reduction of approx. 7-10 grams CO_2 emissions per ton-kilometre.

Background information

Financial

This section gives an indication of the costs of exploitation of electrical traction in comparison to diesel traction. The comparison is done for several cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: “study on the use of fuel cells & hydrogen in the railway environment”[15] . The examples that are used in this study are based on low utilization lines and have the purpose of comparing diesel, electrification, hydrogen and battery rolling stock on the lines. The resulting costs would be much more favourable for electrification when using lines with higher utilization. The infrastructure investments would then be divided over more infrastructure users. As can be seen from Table 1 and Table 2, the infrastructure costs are significant for the total costs when using low utilisation lines.

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15 Shift2Rail - Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment Analysis boundary conditions for potential hydrogen rail applications of selected case studies in Europe.

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	Maintenance	0.1	1.0	0.1	0.7	0.1	1.6	0.0	0.1
	Depreciation	0.0	2.9	0.0	2.5	0.0	5.6	0.0	0.2
	Track access	9.0	9.0	2.9	2.9	2.4	2.4	1.9	1.9
Other	Fuel	1.5	0.3	0.8	0.5	1.4	0.3	0.8	0.2
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Annex 3: Locomotives

Definition

Locomotives powered by diesel, electricity on one or multiple voltages in the range of 1 MW to 6 MW are quite common and worldwide deployed. In some continents e.g. India, multiple locomotive diesel units are built for remote long-distance haulage. Locomotives are used for both passenger and freight trains.

Figure 3: Example multiple system locomotive

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of the locomotives available on the market is at level 9 (Whole Life Management). The traction technology is commercially used in locomotives all across the world. There is a large off-the-shelf supply that is customizable to meet the demands of typical rolling stock owner requirements. Increasingly more rolling stock, so called multiple system locomotives, can be used under different line voltage which makes it easier to use across the borders.

Constraints for further deployment

- The infrastructure needed for the use of electrical traction rolling stock is relatively expensive;
- The copper used for the overhead line is a finite resource;
- For diesel locomotives, strict euro norms can delay further developments.

Opportunities

- The proven technology is fully developed – many off-the-shelf products exists and developing new rolling stock requires relatively low engineering costs;
- Lower rolling stock related operational costs for electrical traction with respect to the diesel technology;
- The commercial maximum velocity of this type of rolling stock is high (up to 200km[16]), such that it can also be used on high-speed lines.

Transition Strategies

- Large adaptations are required for the transition from diesel to an electrical infrastructure due to the construction of overhead lines. Diesel locomotives still can be used in mixed traffic with electrical locomotives.
- Recent build diesel locomotives, which are designed with a modular structure, can be retrofitted with fuel cell and/or battery systems.

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16 https://en.wikipedia.org/wiki/Railway_speed_record

Outlook deployment

Electrical

- Multiple System -locomotives are mainly attractive for electrified international corridor lines;
- The usage of locomotives for passenger trains is decreased due to the replacement by trainsets;
- Latest developments are the possibility for the last mile to have an auxiliary diesel generator on board of MS locomotives;
- A concern for the owners is the limited number of suppliers in Western Europe whereby Siemens is market leader.

Diesel

- Incumbents keep on overhauling aged diesel fleet (>30 years old) and retrofitting with ERTMS;
- Overall, the market for new diesel locomotives is relatively small with limited suppliers. As a consequence, the evolution of diesel locomotives is highly dependent on other transport sectors e.g. trucks and ships;
- Locomotive owners eliminate diesel vehicles from their portfolio due to increasing emission demands without having technical solution from their suppliers. Replacing diesel engines at overhaul can only be done with new Euro norm engines which are not available.

Both diesel and electrical locomotives are subject for smart technology developments, e.g. ATO functionality, in Shift2Rail.

Contribution to zero emission goal

- Electrical locomotives can be provided with energy obtained from sustainable sources, without CO_2 emission;
- In Eastern Europe and other continents references are found for conventional diesel engine design with filter packages and/or usage of LNG [17], dual fuel mode[18] or biofuels;
- Initial developments are found in Poland where hydrogen and batteries are used in a locomotive designed and build by Pesa[19];
- According to research by Shift2Rail[20]: a switch from diesel to emission-free locomotives results in a reduction of approx. 7-10 grams CO_2 emissions per ton kilometre.

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17 Estonia develops its first LNG-powered locomotive published on 21-10-2019 by RailTech.com.

18 http://digasgroup.com/our-solution/.

19 Poland on the way to own hydrogen locomotive published on 17-12-2019 by RailTech.com.

20 Shift2Rail - Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment Analysis boundary conditions for potential hydrogen rail applications of selected case studies in Europe.

Background information

Financial

This section gives an indication of the costs of exploitation of electrical traction in comparison to diesel traction. The comparison is done for several cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: "study on the use of fuel cells & hydrogen in the railway environment" [1].

Table 1 shows the most important properties of the cases which relate electrical traction locomotives to diesel traction locomotives and gives the total costs of ownership for both types of rolling stock. Table 2 goes into more detail and shows for each case the subdivision of the costs into several categories. The colors in this table indicate whether the costs of electrical traction locomotives are lower (green), equal (yellow) or higher (red) compared to the costs of diesel traction locomotives.

Table 1: Cost estimation for diesel versus electrical locomotives

Case	**Country**	**Track length (km)**	**Number of rolling stock**	**Costs Electrical traction under overhead contact line (€/km)**	**Costs Diesel (€/km)**
1	Estonia	210	2 locomotives	24.4	22.6
2	Sweden	230	5 locomotives	22.0	5.7
3	Germany	720	5 locomotives	6.4	9.2

Table 2: Distribution of costs (in €/km) for diesel versus electrical locomotives.

		Case 1		**Case 2**		**Case 3**	
		Diesel	**Elec**	**Diesel**	**Elec**	**Diesel**	**Elec**
Rolling stock	Financing	0.7	1.0	0.8	1.0	0.2	0.3
	Maintenance	2.0	0.7	2.0	1.1	2.0	1.0
	Depreciation	0.5	0.6	0.4	0.5	0.3	0.4
Infrastructure	Financing	0.0	4.5	0.0	13.2	0.0	0.7
	Maintenance	0.2	0.4	0.1	1.4	0.2	0.1
	Depreciation	0.0	1.5	0.0	3.9	0.0	0.4
	Track access	15.4	15.4	0.4	0.4	2.9	2.9
Other	Fuel	3.7	0.2	1.7	0.2	3.4	0.4
	Salary	0.1	0.1	0.3	0.3	0.2	0.2
Total		**22.6**	**24.4**	**5.7**	**22.0**	**9.2**	**6.4**

These tables show that electrical traction locomotives have in general lower maintenance and fuel costs. The track access and salary costs are in general equal for electrical traction and diesel locomotives. All other costs are in general higher for electrical traction locomotives as for diesel locomotives.

References

[1] Shift2Rail - Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment Analysis boundary conditions for potential hydrogen rail applications of selected case studies in Europe.

Annex 4: Battery electric multiple units (BEMU)

Definition

Due to the development of electric cars, the battery technology is seen as one of the most promising technologies to get rid of diesel-powered trains. A Battery Electric Multiple Unit (BEMU) train is a type of rolling stock for which the required energy for propulsion is stored in rechargeable batteries. In practice, most BEMU trains are hybrids where an overhead contact line can be used for both propulsion and battery charging, as shown in Figure 2.

Figure 4: Example of a BEMU train. [1]

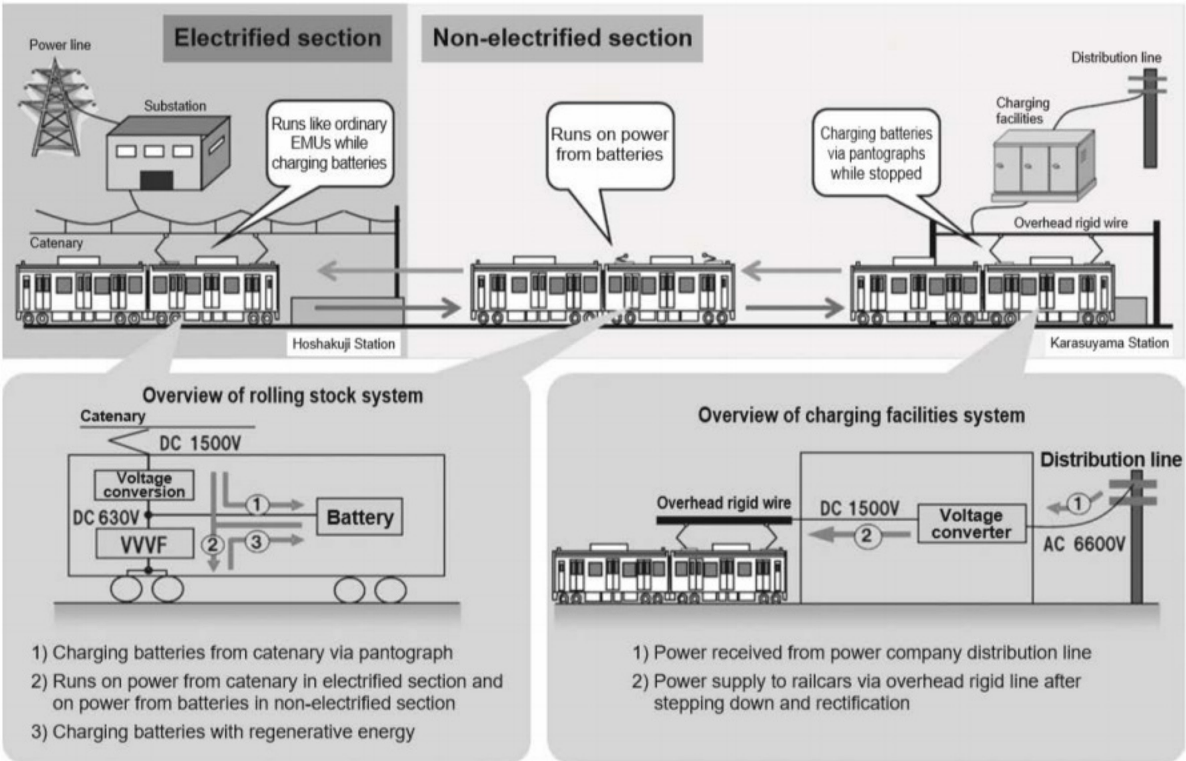

Figure 2: Working principle of BEMU trains. [2]

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of BEMU trains is estimated to be around level 7-8 (Roll out). Currently, limited amount of BEMU trains are operational, of which most are demonstrator trains. In recent years, Siemens, Stadler, Alstom and Bombardier have all received serious orders, where they will produce between 11 and 300 BEMU trains per order [7], [30], [31], [32]. This indicates that production rates are increasing and that initial roll out is starting.

The level of capability and maturity of the organization needed to exploit and manage the BEMU technology will change from diesel skills to full computer controlled electrical traction skills. Additional investments in workshops, tooling and engineering are necessary. The impact on the engineering skills is relatively low.

Constraints for further deployment

- Although developments are still ongoing, the battery power density and capacity remains a key factor when designing the time table and range;
- Weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure;
- Charging the batteries takes time. Faster charging is possible by using super capacitors. However, these have a larger mass and volume with respect to batteries [23];
- The maximum current which can be extracted from the infrastructure while charging;
- The availability of power connections to the energy grid of network operators. A possible solution for this constraint can be by storing energy, in e.g. batteries, near the charging facility, which will reduce the grid load while charging;
- The necessary investments in the infrastructure should not be underestimated for less developed countries.

Opportunities

- Development in the battery technology which makes it possible to travel longer distances with higher power. This also ensure that batteries degrade more slowly and that they can be produced by less material;
- The battery price per kWh is decreasing rapidly over time, see Figure 3;
- ATO can be useful for BEMUs. ATO can create a driving strategy to minimise the energy consumption and expands the lifetime of the battery.

Transition strategies

Transition of rolling stock

BEMUs can be obtained by acquisition of new rolling stock or by retrofitting currently existing rolling stock. Typical components of BEMUs are batteries, a battery management system and charging facilities.

Retrofit of Diesel Multiple Unit (DMU)

When retrofitting a diesel train, the space of the generator, engine and fuel tank can be used to store the typical components of BEMUs. DMUs can be classified into multiple transmission types: electric, hydraulic and mechanical. DMUs with electrical transmission are in general most suitable for conversion into BEMUs, as then the least number of components have to be replaced. DB RegioNetz Verkehrs GmbH has developed an EcoTrain eMode BEMU, which is obtained by retrofit of DMUs [35] Furthermore, there is currently a project ongoing to retrofit a DMU with hydraulic traction into a battery powered train [15].

Retrofit of Electrical Multiple Units (EMU)

As the components used in BEMU trains are very similar to the components of EMU trains, retrofitting of EMU trains into BEMU trains is relatively simple. Several EMU trains have already been converted into BEMU, see Table 1, which proves that retrofitting of EMU trains into BEMU trains is possible. Retrofitting EMU trains into BEMU is currently mainly done for the prove of concept.

Transition of infrastructure

Charging stations and partial overhead lines will need to be built in order to charge the batteries. Where the charging stations should be built, depends largely on the timetable of the service. Charging stations should be built in the marshalling yards and on stations with long stopping times. At positions where trains are charged while being stationary, a reserve battery may be used to avoid overloading the power grid.

Besides charging stations, partial overhead lines can also be implemented to charge the BEMU batteries. Most cost-effective is to implement these on tracks that are regularly used by a large part of the fleet. Due to the increased costs, overhead lines should preferably not be built in areas with bridges and tunnels.

Outlook Deployment

- BEMU trains have a relative low power, a short range and a maximum velocity of 140km/h;
- This technology is ideal for urban areas with short distances and tracks with tunnels while the introduction of FCH technology will most likely be more successful on longer distances;
- Several BEMU trains are already in use around the world. As the technology advances, batteries keep getting cheaper while their performance improves. This means that also BEMU trains will keep getting cheaper while their capabilities improve.

Contribution to zero emission goal

- BEMU Trains can be charged with energy obtained from sustainable sources, without CO_2 emission.
- According to research by Shift2Rail, a switch from DMUs to emission-free traction rolling stock like BEMU trains can result in a reduction of 750-1500 grams CO_2 emissions per coach per kilometre [33].

Background information

Project cases

Several cases of self-propelled passenger trainsets using battery technology already exist, either as a demonstrator train or in commercial use. In Table 1, the main examples of currently existing BEMU trains are shown.

Technology specific characteristics

Rolling stock

The following components are typical for a BMU train:

- Battery;
- Power electronics for charging and motor-control;
- Traction motors;
- Pantograph for charging capabilities.

Some important notes regarding these components are given in the following subsections.

Rolling stock battery

- Most batteries for BEMU trains are NMC Lithium-ion with an energy density of around 140Wh/kg [13].
- Because of weight and volume, the amount of batteries to be stored in a single BEMU is limited.
- The battery price and weight per kWh is decreasing over time, as shown in Figure 3 and Figure 4.

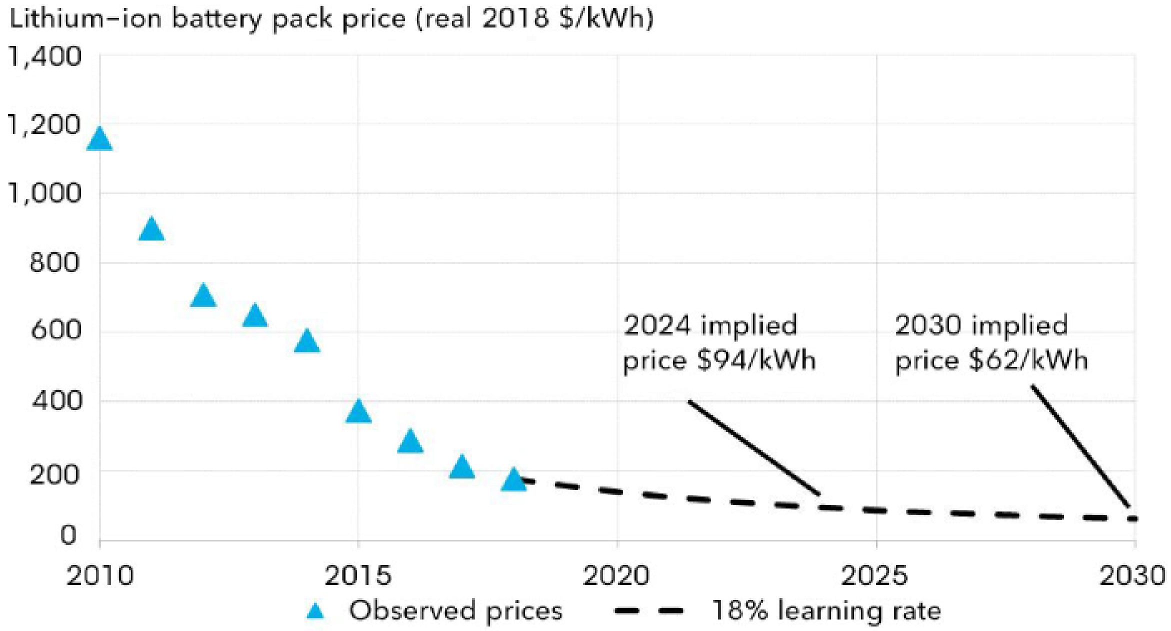

Figure 3: Bloomberg study of the Lithium-ion battery costs [14] [24].

- The battery capacity reduces over time. The end of lifetime capacity is about 80%. The lifetime of the battery is determined by the number of charge cycles [8].
- The charging speed of batteries is limited; shorter charging will lead to a reduced battery lifetime.
- The lifetime of the batteries will be shorter than the lifetime of the rolling stock. Therefore, the batteries must be replaced.
- Super-capacitors can be used instead of batteries for faster charging, they however have a lower energy density and higher costs.

Table 1: Self-propelled passenger trainsets using battery technology.

Rolling stock	*Country*	*Manufacturer*	*Operator*	*Retrofit or new rolling Stock*	*Status*	*Maximum speed with battery*	*Mono-mode or Bi-mode*	*Max route length*	*Sources*
Class ETA 150	Germany	Deutsche Bahn (DB)	DB		Commercial service (1955-1995)	100km/h		300-500km	[3]
CityJet Eco	Austria	Siemens	ÖBB	Retrofit from Desiro ML EMU	Demonstrator train (since 2019)	120km/h	Bimode with catenary	80km (120km envisioned)	[4], [5]
Talent 3 BEMU	Germany	Bombardier	DB		Demonstrator train (since 2019)	140km/h	Bimode with catenary	100km	[6], [7], [10]
EV-E301	Japan	J.TREC	JR EAST		Commercial service (since 2014)	65km/h	Bimode with catenary	20km	[2], [8]
BEC 819	Japan	Hitachi	JR Kyushu		Commercial service (since 2016)		Bimode with catenary	25km	[8]
EV-E801	Japan	Hitachi	JR East		Commercial service (since 2017)	85km/h	Bimode with catenary	25km	[8]
Electrostar	U.K.	Bombardier		Retrofit from Class 379 EMU	Demonstrator train (since 2015)	120km/h	Bimode with catenary	50km	[9]
Flirt Akku	Germany	Stadler			Introduced (in 2018)	140km/h	Bimode with catenary	150km	[11], [12]
Mireo plus B	Germany	Siemens			20 multiple units are planned to be delivered in 2023		Bimode with catenary	80km	[34]
Ecotrain eMode	Germany		DB	Retrofit of DMUs			Bimode with catenary		[35]

- Besides the traction energy, the battery should also supply the train with energy needed for heating, cooling, light and different other users.

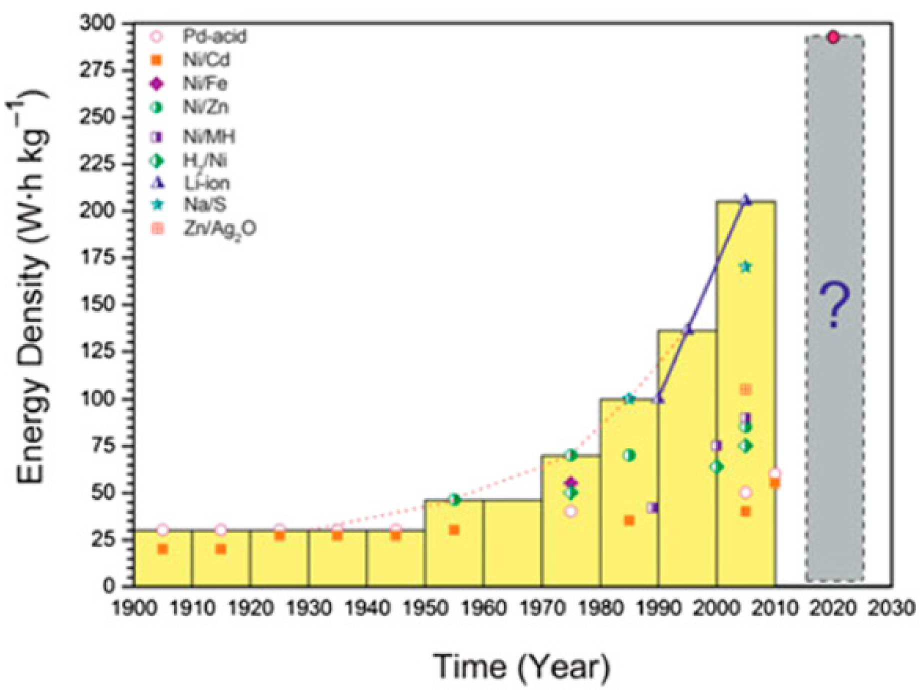

Figure 4: Energy density of batteries over time [25].

Power electronics for charging and motor control

- For traction inverter, the standard components of EMUs and DEMUs can be used. As for each train, the motor and the inverter are unique because of the available space, there are no standard components.
- For controlling the charging power of the battery, extra power electronics is necessary. The technology is comparable with the inverter of the traction installation for feeding the motors. A battery management system is required for safe and optimal performance of the battery. This system will manage the energy of the system by controlling the charging and discharging rates of the battery [13].

Power electronics for charging and motor control

- Standard traction motors of EMUs and DEMUs can be used in BEMUs.

Charging facilities

- A standard pantograph can be used for rolling stock to charge the BEMU train using an overhead contact line. When using low voltages (e.g. 1500V), charging at standstill can lead to overheating of the catenary. The charging power is therefore limited.
- A power plug can be used for charging while standing-still at a station, depot or stabling yard. This however is not very common.
- A 'reversed' pantograph can be used for charging while stand-still. Here the pantograph is fixed to the infrastructure, to reduce costs.

Infrastructure

To use BEMUs, facilities in the infrastructure is necessary to charge the batteries. The most practical and cost-effective solution for charging the batteries should be looked for.

If the trains are operating on tracks with an overhead line or third rail, it is the most cost effective to use these facilities. If this is not enough or does not exist, other charging facilities are necessary. Charging can be done via three different methods [8]:

- during long downtimes (Full charging),
- during driving (In-motion charging) or
- at stations, and end stations (Opportunity charging).

The capacity of the batteries in rolling stock is limited because of the weight and volume. In practice, a combination of charging methods is therefore used.

Full charging

When full charging is used trains charge during long downtime periods. Such as during the night or at end stations. Using this method, the batteries will be fully charged before continuing with the shift. This can be done with a charging station, partial catenary or a power plug. An advantage of this method is that charging facilities are only needed at stabling areas [2] [8].

- Charging facilities required at the stabling areas;
- Overhead line, third rail and power plugs can be used. Power plugs are not common;
- Long charging time with low power.

In-motion charging

In-motion charging is done while the train is driving under a catenary line or 3rd rail. The energy that is not used for traction is stored in the batteries for later use. The construction of a partial catenary network that is long enough for the batteries to charge will be required [2].

- Charging via overhead line or third rail;
- Requires construction of expensive catenary;
- No overheating risk because of movement.

Opportunity charging

With opportunity charging the train tops up its battery charge when it stops at stations. This requires charging stations or partial catenary with a high capacity to be built at stations [8].

- Charging systems required at stations;
- Short charging times;
- At low voltages, the charging power is limited because of the risk of overheating the catenary. Special (reverse) pantograph or special high-power charging facility can solve this.

Considerations

When using opportunity charging the timetable of the train shifts needs to be taken into consideration. Enough charging stations should be added with enough stopping time to give the train enough charge to run a full shift.

When using in-motion charging the partial catenary line should be long enough to give the train enough charge to run its shift [8].

All above methods can be combined. The optimal design of the infrastructure depends on several factors.

The EV-E301 that has been active in Japan since 2014, uses in-motion charging with a catenary line for 11.7 km and uses opportunity charging with an overhead rigid wire at the end station. The train runs on its batteries for 22.4 km [2].

Technical specification

Figure 5: Examples of BEMU trains showing from left to right the EV-E301, the FLIRT AKKU, the OBB Cityjet eco and the bombardier Talent 3 [26] [27] [28] [29].

Typical performance of recent BEMU trains are shown in the following table:

Performance	Unit		References
Power	MW	1.0	[10]
Maximum velocity	km/h	65-140	[5], [6], [8]
Acceleration	m/s^2	0.77-1.1	[5], [6], [7]
Range	Km	20-150	[7], [8], [9], [12]
Number of seats		96-244	[2], [5], [7]
Battery Type	-	e.g. NMC Lithium-ion	[2], [8]
Energy consumption	kWh/km	≈3.7	[8]
Battery capacity	kWh	190-528	[2], [8], [9]
Charging capacity	kW	120 – 1000	
Charging time	Min	7-10	[6]
Battery lifetime	Years	5-8	[10]

Safety with Risk Control Measures (RCMs)

- With low overhead line voltage overheating of catenary line when charging at standstill:
    - Usage of charging rail with higher current capacities or special (reverse) pantograph.
- Power peaks might be too high for the local net:
    - Usage of an energy storage system that draws continuous power from the net. This power will be used when charging the train.
- Battery can lead to fire hazards:
    - The battery management system will provide safe functioning of the battery and protect against fire hazards. For the battery management system, the technology of the automotive industry can be used [17].

- Low battery temperature:
    - Batteries cannot withstand operating at low temperature. In areas where low temperatures are possible, precautions should be taken to warm the batteries before charging and discharging.

Operations

The use of BEMU trains will have the following consequences on operations:

- The timetable is important.
    - When using opportunity charging, the charging time needs to be taken into consideration.
    - When using in-motion charging to charge the battery, the route needs to have enough segments with an overhead contact line.
- When batteries are not charged enough, stranded trains will have to be moved to a charging point.

Advantages of battery trains compared to diesel trains are:

- BEMU trains are quieter than DMU trains.
- Zero emission (see also below).
- No fine dust from diesel engine.
- No vibrations from diesel engine.

Financial

This section gives an indication of the costs of exploitation of BEMUs in comparison to DMUs. The comparison is done for four different cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: "study on the use of fuel cells & hydrogen in the railway environment". [33]

Table 2 shows the most important properties of each case and gives the total costs of ownership both when using diesel and battery based rolling stock. Table 3 goes into more detail and shows for each case the subdivision of the costs into several categories. The colours in this table indicate whether the costs of BEMU are lower (green), equal (yellow) or higher (red) compared to the costs of DMUs.

Table 2: Cost estimations for four different cases comparing BEMUs with DMUs.

Case	**Country**	**Track length (km)**	**Energy consumption (kWh/km)**	**Number of rolling stock**	**Number of seats**	**Costs Battery (€/km)**	**Costs Diesel (€/km)**
1	France	140	-	3 x 4 car trains	230	19.9	18.5
2	Spain	165	-	2 x 4 car trains	270	13.7	9.3
3	Romania	149	-	2 x 2 car trains	150	14.8	8.8
4	Netherlands	300	3.7 [8]	70 x 3 car trains	230	5.3	4.8

Table 3: Distribution of the costs (in €/km) over multiple elements for the four cases mentioned in Table 2.

		Case 1		Case 2		Case 3		Case 4	
		Diesel	**Battery**	**Diesel**	**Battery**	**Diesel**	**Battery**	**Diesel**	**Battery**
Rolling stock	Financing	2.5	3.4	2.5	3.3	2.8	4.3	0.4	0.6
	Maintenance	1.3	1.0	0.8	0.8	0.9	0.8	0.9	0.8
	Depreciation	2.4	3.3	1.3	1.8	1.0	2.0	0.4	0.6
Infrastructure	Financing	0.0	0.3	0.0	1.7	0.0	2.1	0.0	0.2
	Maintenance	0.1	0.3	0.1	0.9	0.1	1.4	0.0	0.2
	Depreciation	0.0	0.3	0.0	0.9	0.0	1.0	0.0	0.2
	Track access	9.0	9.0	2.9	2.9	2.4	2.4	1.9	1.9
Other	Fuel	1.5	0.6	0.8	0.5	1.4	0.6	0.8	0.4
	Salary	1.7	1.7	0.9	0.9	0.2	0.2	0.4	0.4
Total		**18.5**	**19.9**	**9.3**	**13.7**	**8.8**	**14.8**	**4.8**	**5.3**

These tables show that DMUs are in general cheaper compared to BEMUs. Only the maintenance costs and the fuel cost of the rolling stock are in general lower for battery based rolling stock. The track access costs and salary are in equal for both HMUs and DMUs. All other categories mentioned in Table 4 are in general higher for BEMUs than for DMUs.

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Annex 5: Hydrogen multiple units (HMU)

Definition

A fuel cell hydrogen (FCH) train is able to utilize the energy stored in hydrogen gas to generate the electrical energy required for propulsion of the train. The local emission from a Hydrogen Multiple Unit (HMU) is steam and condensed water. Hydrogen trains include battery cells to store excess energy and to recover energy during braking to improve the energy efficiency. The typical components of a hydrogen train are shown in Figure 2.

Figure 1: Example of a hydrogen train. [9]

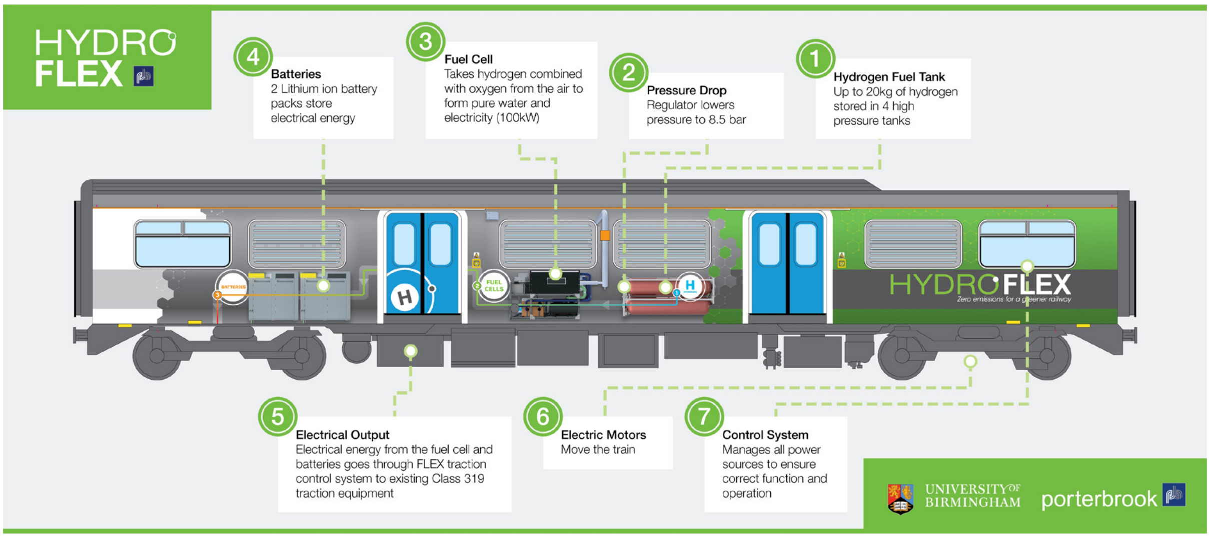

Figure 2: Working principle of hydrogen trains [8].

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of HMUs is estimated to be around level 7-8 (Roll-out). The Coradia iLint of Alstom is the first hydrogen operated rolling stock to have entered commercial services in 2018 [39]. Furthermore, in the United Kingdom currently several projects are ongoing to retrofit EMUs into HMUs. Alstom currently has an order for an additional 27 FCH trains in Germany [28] and Stadler has received an order for up to five FHC trains in the USA [35]. This indicated that initial deployment of the HMUs is ongoing.

The level of capability and maturity of the organization needed to exploit and manage the FCH technology will change from diesel skills to full computer controlled electrical traction skills and the knowledge and means to handle hydrogen installations. Additional investments in workshops, tooling and engineering are necessary.

Constraints for further deployment

- For future deployment of HMUs it is important that passengers and authorities consider the hydrogen technology to be safe for usage in rolling stock;
- Hydrogen takes more space than the energy equivalent amount of fossil fuels [2];
    - Storage of enough hydrogen in gaseous form requires large pressure [18];
    - Storage of hydrogen in liquid form requires very low temperatures [19];
- Fuelling speed for large amounts of hydrogen is low compared to diesel [27];
- The mean time between maintenance intervals is still quite short [27];
- The infrastructure for hydrogen supply to the railways is not yet developed [1] [15]. At this moment temporarily or mobile installations are used;
- Generating hydrogen from green sources requires large installations. The majority of the hydrogen that is now available has its origin from fossil fuels [14] [15];
- Hydrogen has extensive potential uses in other sectors also looking for more sustainable energy sources, making it potentially scarcer. This may also lead to opportunities, as the transport and production will be more mass produced, this will potentially result in cost reduction. Dedicated facilities producing 'green hydrogen' will need to be developed alongside fleet deployments, also to avoid price uncertainty;
- The necessary investments in the infrastructure should not be underestimated for less developed countries.

Opportunities

- Costs of fuel cells and batteries are declining [1];
- The hydrogen infrastructure can advance from the general development in hydrogen technology due to the use in the automotive [6] and the maritime industry;
- Hydrogen safety has recently significantly improved due to the use of advanced materials for hydrogen storage and sensors. When the use of hydrogen becomes more common, the perception of hydrogen safety may change [16] [17];
- Transport using hydrogen can help consume excess loads in renewable networks, lowering the median and possibly peak load, minimising the need for energy infrastructure.

Transition strategies

Transition of rolling stock

HMUs can be obtained by acquisition of new rolling stock or by retrofitting currently existing EMUs. Typical components of HMUs are fuel cells, fuel tanks, batteries, a battery management system and hydrogen fuelling facilities. Several examples show that is it possible to retrofit both diesel as electric material into hydrogen multiple units.

Retrofit of diesel Multiple Unit (DMU)

When retrofitting a diesel train, the space of the generator, engine and fuel tank can be used to store the typical components of HMUs. DMUs can be classified into multiple transmission types: electric, hydraulic and mechanical. DMUs with electrical transmission are in general most suitable for conversion into HMUs, as then the least number of components have to be replaced.

- The Alstom Coradia iLint is developed based on the DMU Coradia Lint 54. The train dimension, architecture and main components from the DMU where used in the development of the iLint; [3]
- A study by the university of Birmingham, Fuel Cell Systems Limited and Hitachi Rail showed that it was feasible to retrofit a class 156 mid-life diesel multiple unit into a hydrogen powered train, while the performance of the rolling stock increases [4].

Retrofit of Electrical Multiple Unit (EMU)

- The HydroFLEX is a prototype train being developed by Porterbrook and BCRRE, which is retrofitted from a Class 319 EMU; [2]
- The Breeze train is a prototype train developed by Alstom and Eversholt, which is retrofitted from a class 321 EMU. [5] As part of the train is used for the storage of hydrogen, the four-carriage 321 EMU is reduced to a three carriage HMU.

Transition of Infrastructure

A hydrogen refuelling station consists of a high-pressure storage unit, compressors, one or more dispensers and a precooling unit. The hydrogen can be produced on-site or off-site. If the hydrogen is produced on-site an electrolyser should also be built at the refuelling station. Adequate energy should be available at the site. If the hydrogen is produced off-site it can be transported by trucks or by pipes. When building a hydrogen refuelling station, a multi-modal approach should be considered to higher the utilisation rate of the electrolyser. Larger quantities of hydrogen can be stored if the hydrogen is in liquid form. To do this it has to be cooled to -252.9^{o}C.

Outlook Deployment

- Currently HMUs are still relatively expensive. As the deployment will increase, the technology advances and batteries and fuel cells will become cheaper, the price of HMUs will decrease;
- The potential action radius of HMUs (1.000 km in 2020) is much larger than for BEMUs, for longer unelectrified sections the performance of HMUs is therefore superior compared to BEMUs.

Contribution to zero emission goal

- The hydrogen can be produced by electrolyzing with energy obtained from sustainable sources, without CO_2 emission. Currently, most hydrogen is produced by natural gas, where carbon dioxide is emitted. The emission of carbon dioxide is in this case only reduced with 24% compared to diesel [7].
- According to research by Shift2Rail, a switch from DMUs to emission-free rolling stock like HMU trains can result in a reduction of 750-1500 grams CO_2 emissions per coach per kilometre [38].

Background information

Project cases

Several cases of self-propelled passenger trainsets using hydrogen technology already exist, either as a demonstrator train or in commercial use. In Table 1, the main examples of currently existing HMU trains are shown.

Technology specific characteristics

Rolling stock

Components typical for a HMU are as follows:

- Hydrogen tanks - For storage of hydrogen;
- Fuel cell - For conversion of hydrogen into electricity;
- Batteries - for storage of energy from either the fuel cell or from regenerative braking;
- Pressure regulator - to regulate the pressure inside the hydrogen tanks;
- Traction drivers - the standard components of EMUs and DEMUs can be used;
- Traction motors - the standard components of EMUs and DEMUs can be used;
- Fuelling facilities - to enable safe fuelling of hydrogen into the hydrogen tanks.

Infrastructure

The components of a hydrogen refuelling station are the following:

- A high-pressure storage system;
- One or more dispensers;
- Compressors;
- Optional: hydrogen production unit;
- Optional: precooling system.

The hydrogen needed for refuelling can be produced in several ways. It can be produced via the process of electrolysis or steam methane reforming. This can either be done on-site or be brought in from an external site.

- On-site production requires more space to be available at the refuelling site. However, transport costs will be reduced.
- Off-site production can either be done close to the site or further away. If production happens close enough to the refuelling site the hydrogen can be transported via pipelines. If the hydrogen is produced further away, it will need to be transported via trucks.

Table 1: Self-Propelled passenger trainset using hydrogen technology.

Rolling stock	*Country*	*Manufacturer*	*Operator*	*Retrofit or new rolling Stock*	*Status*	*Maximum speed*	*Mono-mode or Bi-mode*	*Max route length*	*Sources*
Coradia iLint	Germany	Alstom	EVB	New	Commercial service (2018, -)	140km/h		1000km	[11]
Breeze	United Kingdom	Alstom & Eversholt		Retrofit from 321 EMU	Planned to enter service in 2022	145km/h*		1000km*	[5]
Hydroflex	United Kingdom	Porterbrook		Retrofit from 319 EMU			Bimode with catenary (25kV AC & 750 DC)		
Coradia Polyvalent	France	Alstom			Planned to enter service in 2022	160km/h*	Bimode with catenary	400-600km	[12] [13]
Mireo plus H		Siemens & Ballard			Initial deployment planned in 2021	160km/h*		800-1000km*	[22]
		Hyundai Motor & Hyundai Rotem			Prototype launch is planned in 2020.	70km/h*		200km*	[29][31]
	South Korea	KRRI & Woojin Industrial Systems			Prototype launch is planned in 2020.	110km/h*		600km*	[29][30]
FV-991	Japan	JR EAST	JR EAST		Planned to commercialize in 2024	100km/h*		140km*	[32] [33]
Flirt H2	USA	Stadler	SBCTA		Planned to enter service in 2024	127km/h			[35]

** indicates this is an expected property*

- Due to the low density of hydrogen a large storage is needed to store sufficient amounts to refuel the trains. High pressures are used to reduce the needed space (up to 875 bar). [18]
- The energy content of hydrogen stored at 500 bar and 25°C is 3.7GJ/m^3. Compared to gasoline, which has an energy content of 33.0 GJ/m^3 [36] this is a difference of about a factor 9.

Mass of hydrogen and energy per m³

Pressure level	Mass contained in 1m³	Energy contained in 1m³
1 bar (0.1 MPa), 25°C	0.081 kg H_2	10 MJ (2.7 kWh)
100 bar, 25°C	7.67 kg H_2	922 MJ (256 kWh)
300 bar, 25°C	20.54 kg H_2	2,469 MJ (686 kWh)
500 bar, 25°C	30.81 kg H_2	3,704 MJ (1,029 kWh)
Liquid hydrogen (at boiling point)	70.8 kg H_2	8,501 MJ (2,361 kWh)

Figure 3: Pressure, mass and energy of hydrogen storage [18].

- Ideally the hydrogen is stored in liquid form. Hydrogen is liquid at a temperature of -252.9°C. This would require perfect isolation to maintain. Currently, this is only done in very specific situations, like space travel. [19]

Technical specification

Some examples of HMU trains is shown in Figure 4.

Figure 4: Examples of HMUs with from left to right: Alstom Coradia iLint, Breeze train, Hydroflex [25] [26] [2].

Typical performance of recent HMU trains are shown in the Table 2.

Table 2: Technical properties of HMU trains.

Performance	Unit	Value	References
Max power	MW	0.8-1.45	[38]
Maximum velocity	km/h	70-160*	[11] [5] [12] [29] [32]
Acceleration	m/s^2		
Range	Km	140-1100	[21] [29] [32]
Number of seats		108-270	[20] [35] [38]
Hydrogen capacity	Ltr	1020	[33]
Hydrogen consumption	Kg/km	0.22-0.36	[38]
Hydrogen storage pressure	bar	350-700	[22] [33]
Refuelling time	Min	15	[21]
Battery Type	-	Lithium-ion	[21] [33]
Battery capacity	kWh	50-270	[33] [38]
Charging capacity	kW		
Battery lifetime	Years		

** indicates this is an expected property*

Operations

The use of HMU trains will have the following consequences on operations:

- Depending on the amount of fuelling stations available, the time table should take into account regular passage of these fuelling stations when determining the route.

Advantages of FCH trains in operations compared to diesel trains are:

- HMU trains are quieter than DMU trains;
- Zero emission is possible;
- No fine dust from diesel engine;
- No vibrations from diesel engine.

Financial

This section gives an indication of the costs of exploitation of HMUs in comparison to DMUs. The comparison is done for four different cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: "study on the use of fuel cells & hydrogen in the railway environment". [38]

Table 3 shows the most important properties of each case and gives the total costs of ownership both when using diesel and FCH rolling stock. Table 4 goes into more detail and shows for each case the subdivision of the costs into several categories. The colours in this table indicate whether the costs of HMUs are lower (green), equal (yellow) or higher (red) compared to the costs of DMUs.

Table 3: Cost estimations for four different cases comparing HMUs with DMUs.

Case	Country	Track length (km)	Hydrogen consumption (kg/km)	Number of rolling stock	Number of seats	Costs FCH (€/km)	Costs Diesel (€/km)
1	France	140	0.36	3 x 4 car trains	230	21.2	18.5
2	Spain	165	0.31	2 x 4 car trains	270	12.4	9.3
3	Romania	149	0.36	2 x 2 car trains	150	12.0	8.8
4	Netherlands	300	0.22	70 x 3 car trains	230	5.0	4.8

Table 4: Distribution of the costs (in €/km) over multiple elements for the four cases mentioned in Table 3.

		Case 1		Case 2		Case 3		Case 4	
		Diesel	**Battery**	**Diesel**	**Battery**	**Diesel**	**Battery**	**Diesel**	**Battery**
Rolling stock	Financing	2.5	3.5	2.5	3.6	2.8	3.5	0.4	0.4
	Maintenance	1.3	1.1	0.8	0.7	0.9	1.2	0.9	0.8
	Depreciation	2.4	3.3	1.3	1.8	1.0	1.2	0.4	0.4
Infrastructure	Financing	0.0	0.3	0.0	0.5	0.0	0.9	0.0	0.1
	Maintenance	0.1	0.4	0.1	0.3	0.1	0.3	0.0	0.1
	Depreciation	0.0	0.3	0.0	0.2	0.0	0.4	0.0	0.1
	Track access	9.0	9.0	2.9	2.9	2.4	2.4	1.9	1.9
Other	Fuel	1.5	1.6	0.8	1.5	1.4	1.9	0.8	0.8
	Salary	1.7	1.7	0.9	0.9	0.2	0.2	0.4	0.4
Total		**18.5**	**21.2**	**9.3**	**12.4**	**8.8**	**12.0**	**4.8**	**5.0**

These tables show that DMUs are in general cheaper compared to HMUs. Only the maintenance costs of the rolling stock are in general lower for FCH based rolling stock. The track access costs and salary are in equal for HMUs and DMUs. All other categories mentioned in Table 4 are in general higher for HMUs than for DMUs.

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Annex 6: Shunters

Definition

Shunters are railroad locomotives used for movement of other rolling stock at classification yards for assembly, disassembly or maintenance of the railroad vehicles. Shunters are generally used at low speeds to haul variable loads in short runs with large idle times in-between runs [22]. The majority of shunters currently in use is based on diesel traction. Three traction technologies with a reduced carbon dioxide emission are currently under development: diesel-battery hybrid-, battery- and hydrogen shunters. Diesel-battery hybrid shunters use the diesel engine to charge the batteries. When the state of charge of the batteries is too low, the diesel is switched on to charge these batteries.

Figure 1: Example of a hybrid diesel-battery shunter. [1]

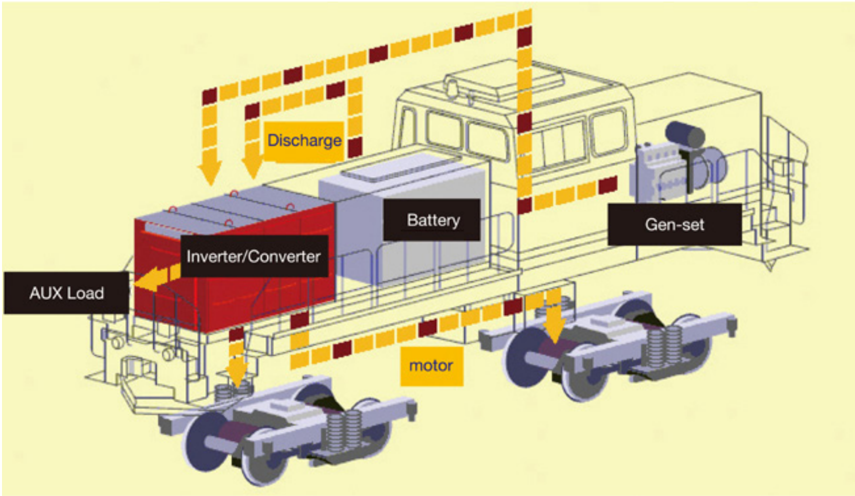

Figure 2: Working principle of a diesel-battery hybrid shunter. [2]

Maturity of the technology

The Rail Industry Readiness Level (RIRL) of hybrid diesel-battery shunters is estimated to be around level 7-8 (Roll out). Several orders for battery-diesel hybrid shunters are already made. Alstom has received an order for 12 Prima H3 shunters [6], Toshiba has received an order for 100 Toshiba HDB 800 shunters [5] and Transmashholding has reached an agreement in delivering up to 131 shunters [4]. This indicates that production rates are increasing and that initial roll out is starting.

The RIRL of battery shunters is estimated to be around level 6-8 (Roll out). Many battery shunters exists, however, these are mostly in the lower power class [26] [27] [28]. High power battery shunters are much less common, However there are some examples: Alstom has made a battery version of the H3, Stadler has received an order for 7 battery shunters and BEMO rail has an BRE150 battery shunter

[29]. The RIRL of high power battery shunters is therefore estimated to be around level 6-7 while the battery shunters in lower power class are at level 7-8.

The RIRL of hydrogen shunters is estimated to be around level 5-6 (prototype). Studies have shown the potential of hydrogen powered shunters [8] but few examples are currently existing: OBB has retrofitted a 1063 038 into an FCH shunter [7] and BNSF has tested one between 2008-2009 [11].

The level of capability and maturity of the organization needed to exploit and manage the battery or FCH technology will change from diesel skills to full computer controlled electrical traction skills. The impact on the engineering skills is relatively low when using battery technology. For the FCH technology knowledge and means to handle hydrogen installations is required and additional investments in workshops, tooling and engineering are necessary.

Constraints for further deployment

Diesel-battery hybrid

Due to developments in battery and hydrogen technology this technology is most likely an temporary solution which at some point will be no longer required. As the capacity of batteries increase, hybrid shunters will be able to drive longer without using the diesel engine, till at some point the diesel engine is replaced by other charging mechanisms;

- Weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure.

Battery

- The battery power density and capacity play a key factor for power and range of the shunters;
- Weight of the batteries should be taken into account in the rolling stock design with respect to maximum axle load as defined by the infrastructure;
- Charging the batteries takes time. Faster charging is possible by using super capacitors. However, these have a larger mass and volume with respect to batteries [21];
- The maximum current which can be extracted from the infrastructure while charging is limited;
- The availability of power connections to the energy grid of network operators. A possible solution for this constraint can be by storing energy, in e.g. batteries, near the charging facility, which will reduce the grid load while charging.

Hydrogen

- Hydrogen takes more space than the energy equivalent amount of fossil fuels [14];
    - Storage of enough hydrogen in gaseous form requires large pressure [15];
    - Storage of hydrogen in liquid form requires very low temperatures [16];
- Fuelling speed for large amounts of hydrogen is low compared to diesel [17];
- The mean time between maintenance intervals is still quite short [17];
- The infrastructure for hydrogen supply to the railways is not yet developed [18] [19]. At this moment temporarily or mobile installations are used;
- Generating hydrogen from green sources requires large installations. The majority of the hydrogen that is now available has its origin from fossil fuels [19] [20].

Opportunities

Diesel-battery hybrid

- This technology reduces the emission by diesel shunters. Because the diesel engine is not running while the shunting locomotive is idle, the emission is reduced with about 50% compared to diesel shunters;
- Combining the battery and diesel technology can already result in large emission reduction, as consumption of diesel generators in idling mode is very inefficient for regular diesel shunters.

Battery

- Development in the battery technology makes it possible to use a shunter over a longer time such that the shunter can be used for a whole day without charging. In case of a 24/7 usage of the shunter, the operations regarding the shunter charging should be designed in a well thought way;
- The battery price per kWh is significantly decreasing over time [25].

Hydrogen

- Costs of fuel cells and batteries are declining [23];
- The hydrogen infrastructure can advance from the general development in hydrogen technology due to the use in the automotive [24] and the maritime industry;
- The energy consumption of shunter trains is low so that fuelling of the hydrogen shunter is required only once a day or even less.

Transition strategies

Transition of rolling stock

To get a smooth transition of diesel shunters into full battery shunters, hybrid diesel-battery shunters are a perfect intermediate step. Building a diesel shunter with an extra battery is a relatively small step, while this can already result in large emission reductions. Batteries keep on improving and therefore the diesel engine is required increasingly less until the point that other options to charge the batteries become favorable.

Similarly, hybrid diesel-battery shunters can also be used as intermediate step for FCH shunters. FCH shunters require both batteries and a fuel cell with respect to diesel shunters and since hybrid diesel-battery shunters already have a battery, the step in obtaining FCH shunters will be reduced. FCH shunters can then be obtained by replacing the diesel generator and diesel engine with a hydrogen storage unit and fuel cell.

Transition of infrastructure

If diesel-battery hybrid shunters are used instead of diesel shunters, a diesel consumption reduction of up to 50% could be reached [32]. This would mean the capacity of the diesel fuel stored on site could be up to 50% smaller. Furthermore, very little changes will have to be made as the diesel infrastructure is still used.

The introduction of battery powered shunters would require shunters to be charged with enough power to operate a full day [29]. The charging will be done overnight. This would require standstill charging stations. This can either be done by a charging station with a conduction rail or a power plug. Regular catenary is not recommended because of overheating.

To successfully transition to the usage of hydrogen shunters a hydrogen filling station needs to be build. Shunters often return to the same place at the end of the day. A singular filling station at a central location should be enough to refuel the entire fleet. [8] An adequately sized and powered hydrogen production unit should be placed at the site. The capacity of the hydrogen storage should be adequately sized and kept under a pressure of at least 350 bar.

Outlook Deployment

- Hybrid diesel-battery shunters are expected to appear only temporary as an intermediate step between diesel and zero emission shunters;
- Long idle times, short runs and low speeds make the battery technology very suitable for shunters;
- Battery shunters are already widely available in low power class. As the power density of the batteries will increase, increasingly more high power battery shunters are expected in the future;
- Currently, the hydrogen technology are still relatively expensive. As the deployment will increase, the technology advances and batteries and fuel cells will become cheaper, the price of hydrogen shunters will decrease.

Contribution to zero emission goal

- Hybrid diesel-battery shunters can result approximately in 50% emission reduction compared to diesel shunters[2];
- Battery Shunters an FCH shunters can be charged with energy obtained from sustainable sources, without CO_2 emission;
- According to research by Shift2Rail, a switch from diesel to emission-free shunters can result in a reduction of 3250-4500 grams CO_2 emissions per shunter per kilometre [33].

Background information

Project cases

Several cases of shunters using either the hybrid diesel-battery technology, the battery technology or the FCH technology exist. In Table 1, the main examples of currently existing BEMU trains are shown.

Technology specific characteristics

Rolling stock

The following components are typical for a hybrid diesel-battery shunter:

- Battery;
- Power electronics for charging and motor-control;
- Traction drivers;
- Traction motors.

The following components are typical for a battery shunter:

- Battery;
- Power electronics for charging and motor-control;
- Traction drivers;
- Traction motors;
- Pantograph or other charging capabilities.

The following components are typical for a FCH shunter:

- Hydrogen tanks - For storage of hydrogen;
- Fuel cell - For conversion of hydrogen into electricity;
- Batteries - for storage of energy from either the fuel cell or from regenerative braking;
- Pressure regulator - to regulate the pressure inside the hydrogen tanks;
- Traction drivers;
- Traction motor;
- Fuelling facilities - to enable safe fuelling of hydrogen into the hydrogen tanks.

Infrastructure

For charging of diesel-battery hybrid shunters, very little changes have to be made to the infrastructure. The shunters still work on diesel so the same infrastructure will be used. The reduction in diesel consumption could however be reduced by up to 50% [32]. This means less diesel will have to be stored on site.

For charging of battery shunters, the following adaptations to the infrastructure are required: Because shunters are required to be in use as much as possible during the day battery shunters should be charged with enough energy to serve a full day. This means the shunters will be charged overnight. Using this method, the batteries will be fully charged before continuing with the shift. This can be done with a charging station, partial catenary or a power plug. As shunters return to the same site at the end of the day charging facilities will only be needed at the stabling area.

Table 1: Shunters using hybrid diesel-battery, battery or FCH technology.

Rolling stock	*Country*	*Manufacturer*	*Operator*	*Retrofit or new rolling Stock*	*Status*	*Maximum speed with battery*	*Mono-mode or Bi-mode*	*Engine power*	*Sources*
H3 battery shunting locomotive	Germany	Alstom	DB		Testing trains	100km/h	Mono-mode with battery	600kW Li-ion	[3]
	Switzerland	Stadler Bussnang	Rhaetian Railway		Order for 7 shunters which are planned to operate in 2020	40km/h (battery) 80km/h (catenary)	Bi-mode with battery and catenary	200kW Li-ion 500kW Catenary	[30] [31]
BRE 150	Netherlands	BEMO rail							[29]
H3 hybrid shunting locomotive	Germany	Alstom	DB		Delivery of first 12 in 2020	100km/h	Bi-mode with battery and diesel	350kW Diesel and 350kW Battery	[3] [6]
TEM5X	Russia	Transmashholding			Concept train		Bi-mode with battery and diesel	200kW Diesel and 240kW Li-ion	[4]
Toshiba HDB 800	Germany	Toshiba	DB cargo		Assembly of 100 shunters starts in 2021.		Bi-mode with battery and diesel		[5]
CBD80/CBD90	UK	Clayton Equipment	Nuclear Decommissioning Authority (NDA) – TATA STEEL				Bi-mode with battery and diesel		[9] [10]
1063 038	Austria	HET verkehrstechnik	ÖBB	Retrofit of 15kV AC locomotive	Prototype	40km/h	Bi mode with hydrogen fuel cell and catenary	800kW	[7]
			BNSF		Test-runs between 2008-2009		hydrogen fuel cell		[11] [12]

For charging of hydrogen shunters, several adaptations to the infrastructure are required. As shunters return to the same site at the end of the day only a singular fuelling station will be required at the stabling area. A FCH shunter hydrogen refuelling stations requires the following components:

- A high-pressure storage system;
- One or more dispensers;
- Compressors;
- Optional: hydrogen production unit;
- Optional: precooling system.

The hydrogen needed for refuelling can be produced in several ways. It can be produced via the process of electrolysis or steam methane reforming. This can either be done on-site or be brought in from an external site.

- On-site production requires more space to be available at the refuelling site. However, transport costs will be reduced.
- Off-site production can either be done close to the site or further away. If production happens close enough to the refuelling site the hydrogen can be transported via pipelines. If the hydrogen is produced further away, it will need to be transported via trucks.

Financial

This section gives an indication of the costs of exploitation of diesel shunters in comparison to battery shunters and FCH shunters. The comparison is done for three different cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: “study on the use of fuel cells & hydrogen in the railway environment”. [33]

Table 2 shows the most important properties of each case and gives the total costs of ownership both when using diesel, battery and hydrogen based rolling stock. Table 3 goes into more detail and shows for each case the subdivision of the costs into several categories. The colours in this table indicate whether the costs of BEMU are lower (green), equal (yellow) or higher (red) compared to the costs of DMUs.

Table 2: Cost estimations for three different cases comparing shunters [8].

Case	Country	Track length (km)	Number of rolling stock	Costs Diesel (€/km)	Costs Battery (€/km)	Costs hydrogen (€/km)
1	Germany	140	15 shunters	10.1	11.7	12.9
2	Latvia	100	15 shunters	20.9	21.8	20.4
3	Poland	35	10 shunters	32.1	36.9	36.7

Table 3: Distribution of the costs over multiple elements for the three cases mentioned in Table 3 [8].

		Case 1			Case 2			Case 3		
		Diesel	**Battery**	**FCH**	**Diesel**	**Battery**	**FCH**	**Diesel**	**Battery**	**FCH**
Rolling stock	Financing	1.0	1.4	1.5	2.6	3.2	3.5	9.5	13.1	12.6
	Maintenance	1.8	1.7	1.6	4.0	1.2	1.3	10.4	5.2	8.8
	Depreciation	1.3	2.4	1.9	1.5	1.8	1.9	5.7	8.0	7.6
Infrastructure	Financing	0.0	0.1	0.2	0.0	2.1	0.9	0.0	2.5	0.5
	Maintenance	0.0	0.1	0.4	0.0	1.0	0.6	0.0	0.9	0.1
	Depreciation	0.0	0.2	0.3	0.0	1.1	0.5	0.0	1.5	0.3
	Track access	2.9	2.9	2.9	9.6	9.6	9.6	3.2	3.2	3.2
Other	Fuel	1.6	1.4	2.6	2.8	1.3	1.7	1.8	1.0	2.1
	Salary	1.5	1.5	1.5	0.4	0.5	0.4	1.5	1.5	1.5
Total		**10.1**	**11.7**	**12.9**	**20.9**	**21.8**	**20.4**	**32.1**	**36.9**	**36.7**

These tables show that diesel shunters are in general the cheapest. Only the maintenance costs and the fuel cost of the battery or FCH shunters are sometimes lower compared to diesel shunters. The track access costs and salary costs are in general equal for all categories. In all other categories mentioned in Table 3, the costs for battery and FCH shunters are higher compared to diesel shunters. This table also shows that it depends on the scenario whether Battery or FCH shunters is financially more favourable.

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Annex 7: Cost comparison EMU, BEMU, HMU to DMU

This section gives an indication of the costs of exploitation of EMU, BEMUs and HMU in comparison to DMUs. The comparison is done for four different cases, each from a different country. The information in this section is based on a study by Shift2Rail JU, FCH JU and the European Union in: “study on the use of fuel cells & hydrogen in the railway environment”. [1]

Table 1 shows the most important properties of each case and gives the total costs of ownership both when using diesel and battery based rolling stock. Table 2 goes into more detail and shows for each case the subdivision of the costs into several categories. The colours in this table indicate whether the costs are lower (green), equal (yellow) or higher (red) compared to the costs of DMUs.

Table 1: Cost estimations for four different cases comparing EMU, BEMUs and HMUs with DMUs

Case	Country	Track length (km)	Number of rolling stock	Number of seats	Costs Diesel (€/km)	Costs Electrical (€/km)	Costs Battery (€/km)	Costs FCH (€/km)
1	France	140	3 x 4 car trains	230	18.5	27.5	19.9	21.2
2	Spain	165	2 x 4 car trains	270	9.3	22.6	13.7	12.4
3	Romania	149	2 x 2 car trains	150	8.8	44.9	14.8	12.0
4	Netherlands	300	70 x 3 car trains	230	4.8	4.5	5.3	5.0

Table 2: Distribution of the costs (in €/km) over multiple elements for the four cases mentioned in Table 1

		Case 1				Case 2				Case 3				Case 4			
		Diesel	**Elec**	**Battery**	**FCH**	**Diesel**	**Elec**	**Battery**	**FCH**	**Diesel**	**Elec**	**Battery**	**FCH**	**Diesel**	**Elec**	**Battery**	**FCH**
Rolling stock	Financing	2.5	2.4	3.4	3.5	2.5	2.3	3.3	3.6	2.8	2.7	4.3	3.5	0.4	0.4	0.6	0.4
	Maintenance	1.3	0.4	1	1.1	0.8	0.3	0.8	0.7	0.9	0.4	0.8	1.2	0.9	0.4	0.8	0.8
	Depreciation	2.4	2.4	3.3	3.3	1.3	1.2	1.8	1.8	1	0.9	2	1.2	0.4	0.4	0.6	0.4
Infrastructure	Financing	0	7.4	0.3	0.3	0	11.3	1.7	0.5	0	30.8	2.1	0.9	0	0.5	0.2	0.1
	Maintenance	0.1	1	0.3	0.4	0.1	0.7	0.9	0.3	0.1	1.6	1.4	0.3	0	0.1	0.2	0.1
	Depreciation	0	2.9	0.3	0.3	0	2.5	0.9	0.2	0	5.6	1	0.4	0	0.2	0.2	0.1
	Track access	9	9	9	9	2.9	2.9	2.9	2.9	2.4	2.4	2.4	2.4	1.9	1.9	1.9	1.9
Other	Fuel	1.5	0.3	0.6	1.6	0.8	0.5	0.5	1.5	1.4	0.3	0.6	1.9	0.8	0.2	0.4	0.8
	Salary	1.7	1.7	1.7	1.7	0.9	0.9	0.9	0.9	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4
Total		**18.5**	**27.5**	**19.9**	**21.2**	**9.3**	**22.6**	**13.7**	**12.4**	**8.8**	**44.9**	**14.8**	**12**	**4.8**	**4.5**	**5.3**	**5**

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