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Onboard Energy Storage Systems for Railway: Present and Trends

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ABSTRACT Governments have recently been dedicating relevant funds to cope up with the inevitable transition to sustainable mobility aiming for a greener transportation sector. This scenario is backed up by the deteriorating global energy crisis, which is predicted to hasten the transition to sustainable energy. Focus has been given to railway systems being globally considered as a tractor project for promoting the use of green and renewable energy by helping build the required infrastructure. As a result, a high tendency for integrating onboard energy storage systems in trains is being observed worldwide. This article provides a detailed review of onboard railway systems with energy storage devices. In-service trains as well as relevant prototypes are presented, and their characteristics are analyzed. A comprehensive study of the traction system structure of these vehicles is introduced providing an overview of all the converter architectures used, categorized based on the type of onboard energy storage device on the train. The current situation of hydrogen fuel cells in railway systems is presented as well, highlighting consistent tendencies. This article also provides a glimpse into commercial battery and fuel cell products used on operating trains.

INDEX TERMS Hydrogen fuel cell, lithium-ion (Li-ion) battery, onboard energy storage, railway traction.

NOMENCLATURE

OESD	Onboard energy storage device.
EMU	Electric multiple unit.
DMU	Diesel multiple unit.
EDMU	Electro-diesel multiple unit.
BEMU	Battery electric multiple unit.
HEMU	Hydrogen electric multiple unit.
HMU	Hydrogen multiple unit.
Li	Lithium.
Li-ion	Lithium-ion.
LTO	Lithium titanate oxide.
NMC	Nickel manganese cobalt.
EoL	End of life.
SoC	State of charge.
SoH	State of health.
NTP	Normal temperature and pressure.

I. INTRODUCTION

Integration of energy storage devices onboard trains has become a trending topic of the railway transportation sector [1]. This comes to address the massive measures being undertaken worldwide by public and private sectors to cope with road maps toward reducing carbon emissions [2], [3]. One key target is achieving a more sustainable mobility and green transportation sector reaching a net zero emission by 2050 [2]. According to the International Energy Agency (IEA), transportation sector currently accounts for almost 37% of global carbon emissions after an 8% rebound in 2021, as shown in Fig. 1 [4]. It can be seen that railway is one of the sectors with the lowest carbon emissions. However, many trains are still operated using diesel engines, which goes against worldwide road maps and increasing efforts toward reduction of carbon emissions, such as the 2050 European road map implying the

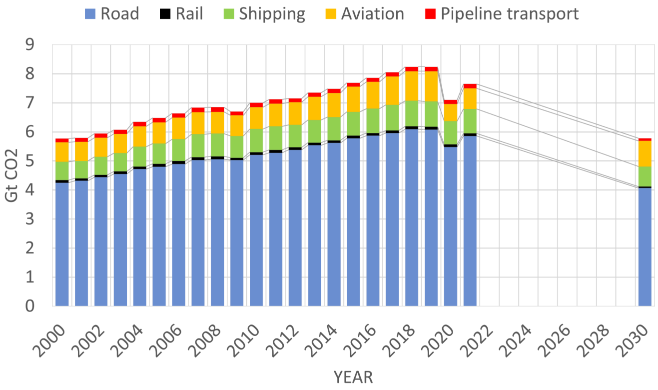

FIGURE 1. **Global CO_2 emissions from transport by subsector [4].**

complete ban of diesel trains by this year [2]. Only one-third of railway tracks worldwide are electrified [5], [6]. The USA has the least share with less than 1% electrified lines where there is still a strong dependence on diesel trains [6]. On the other hand, Europe has more than 60% of electrified tracks, while Asia has almost 50% with a significant increase observed in the last decade, the highest share being in Japan, South Korea, and China [7], [8]. In many scenarios, railway electrification is very difficult due to the requirement to change the infrastructure and, in some situations, it is impossible to achieve due to tunnels and narrow gauges. This has encouraged the integration of energy storage devices onboard trains as the only possible solution to replace diesel engines and operate on catenaryless and nonelectrified routes. Besides, the rail sector is being considered as a tractor project for promoting the use of green hydrogen in the industrial sector by building up the infrastructure [9]. This scenario is backed up by the global energy crisis, which, according to the IEA's recent world energy outlook, would potentially hasten the transition to sustainable energy [10], [11].

The technical feasibility of using OESDs in railways has been proven with many trains already in service for several years. However, the massive integration of OESD in railways seen recently is still facing some major limitations, especially related to the demanding railway operation conditions compared to other applications of energy storage devices. These limitations have urged industry to look for solutions to facilitate the fast transition by actively involucrating multiple stakeholders, including industry, public agencies, and academic research.

Several papers have presented a review of the status of OESD in railways in the past few years. In [12], a broad technoeconomic survey of onboard batteries, supercapacitors, and fuel cell systems for rail vehicles is presented (up to 2021). A technical comparison is performed among different types of OESDs used in railways, and available details of urban and regional trains with OESD are summarized. In [13], a review of the application of energy storage devices in railway systems is presented. The work focuses on increasing the efficiency of regenerative braking systems discussing three types of energy storage systems, i.e., battery, supercapacitor, and flywheel, while fuel cells have not been discussed. A review of the developments in OESD is presented in [14] focusing on the technology and the functionalities in railway where a comparison between the different technologies of OESD is introduced. In [15], a review of rail transport is presented focusing on market demand, consumption, emissions, and costs. The work analyzes the technical, regulatory, and economic problems and identifies necessary policies to cope with the transition to more sustainable rail transportation. In [16], a literature review of the developments and applications of energy storage devices in electrified railways is presented (up to the year 2014) with the main focus being comparing the different types of energy storage practically used in rail transport.

The objective of this article is to review railway systems integrating different types of OESDs in their main drive. The latest advancements and current status of OESD technology used in railways up to this date are highlighted. A relevant amount of data are collected from most railway projects either currently in service or undergoing tests (static and dynamic) or in a prototyping stage. Furthermore, the traction system power converter architectures are analyzed for each type of train with OESD, and their main characteristics are discussed. Using these detailed data, it is possible to identify some consistent trends as well as clear future tendencies and expectations for the next years. Countries with the largest investments in this field and well-positioned manufacturers of rolling stock and OESDs are charted. Finally, the challenges facing the integration of OESD in railway transportation are compiled and discussed.

The rest of this article is organized as follows. An overview of OESDs in railway systems and their function per rail type is addressed in Section II. Traction power converter architecture integrating OESD is described in Section III. Fuel cell trains and battery trains in service as well as undergoing tests are presented in Sections V and IV, respectively. Challenges facing the integration of OESDs in railway are discussed in Section VI. Finally, Section VIII concludes this article.

II. OVERVIEW OF OESD IN THE RAILWAY SYSTEM

The world's first fuel cell locomotive was built by Vehicle Projects Inc., Golden, CO, USA, in 2002 for mining purposes with 17-kW power and was later enhanced in collaboration with BNSF railway as well as the U.S. military to a full-scale traction switcher locomotive fitted with a lead-acid battery demonstrated in 2009 [17], [18]. In the USA, during the last decade, several railway projects with OESD have started. Besides, some U.S. states are seeing a rapidly maturing hydrogen infrastructure, e.g., California with more than 50 hydrogen refueling stations already in operation for other mobility applications [19], [20], which would certainly pave the way for massive use of hydrogen fuel cells in railway vehicles. Nowadays, the technology of OESD in railway is considered most mature in Japan and China with trains already in service since 2016 [21]. In Europe, there has been a recent interest

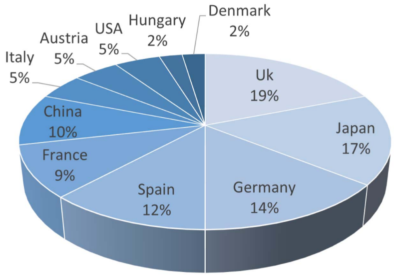

FIGURE 2. Share of countries investing in trains with OESDs. Based on data from [9] and [23].

in battery as well as hydrogen fuel cell trains with projects and orders mostly reported in the U.K., Germany, and Spain. According to [19], most of the fuel cell trains global market developments are currently concentrated in Europe with a potential technology export to North America and Southeast Asia in the short term.

Fig. 2 shows the countries worldwide with the most relevant investments in trains with OESD showing the share of each based on the number of projects undertaken. Germany represents the first country to put into service a hydrogen fuel cell train: the Coradia iLint developed by Alstom [22].

In this section, the functions of OESDs in railway systems are described specifying their use for each rail type. OESD technologies typically used on railway vehicles are presented, and their characteristics are briefly compared.

A. OESD FUNCTION IN RAILWAY

Fig. 3 shows the functions of OESD on railway vehicles; these are described as follows:

1) power assist (also called peak shaving), for example, at weak catenary points and low line voltage [see Fig. 3(a)]. In this case, the traction power peaks during acceleration are supplied by the OESD;
2) regenerative braking recovering the kinetic energy generated during braking [see Fig. 3(b)] [24]. The recovered power is principally used to feed the auxiliary loads. If this power is higher than the auxiliary demand, the rest is stored in the OESD (dotted green arrow). Otherwise, if it is not sufficient, power is drawn from the catenary (dotted red arrow);
3) providing first and last mile (<80 km) [see Fig. 3(c)];
4) traction and auxiliary power supply in nonelectrified or catenaryless sections [see Fig. 3(c)];
5) assisting in emergencies, for example, train traction till nearest station [see Fig. 3(c)];
6) load leveling during periods of light loading by storing power in OESD [25]. This can be especially important for the catenary to suppress load fluctuations and avoid power pulsation. For gensets, it enables operating at the optimum point most of the time, which increases the efficiency.

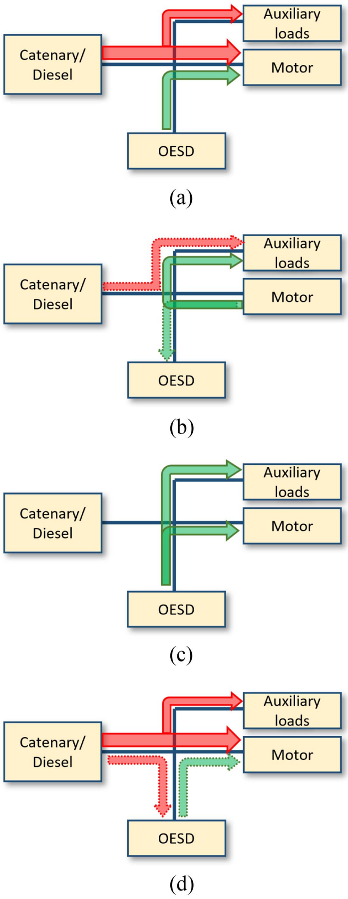

FIGURE 3. OESD function in railway. (a) Power assist. (b) Regenerative braking. (c) Traction. (d) Load leveling.

OESDs have the potential of improving the quality and the efficiency of the overhead line system and the infrastructure since they can provide catenary current peak shaving and voltage stabilization [12].

B. OESD FUNCTION PER RAIL TYPE

The function of OESD on railway vehicles differs based on the type and purpose of each vehicle. Railway vehicles are classified based on service to two main categories: passenger and freight services. Based on this, rail types are typically classified in four main types: urban, regional, high-speed, and cargo. These are described as follows discussing the function of OESD for each.

1) URBAN RAIL

Urban rail includes trams, light rail vehicles (LRVs), street cars, and subway. It is usually supplied using overhead catenary lines, and their service is mainly passenger transport inside urban areas with speeds up to 70 km/h. An OESD is mainly used for emergency running and backup and in some urban areas where there are gaps in overhead lines or these are being removed for aesthetic reasons. Also, OESD has been installed on some urban rail for recovering the braking energy.

TABLE 1. OESD Characteristics [30]

OESD type			Energy density	Power density	Cost	Cell voltage	Cycle life	Safety/clean	Charging time
1	Battery	Li-ion	Highest in batteries <200Wh/kg	High 0.5–0.9 kW/kg	Very High	2.4–3.7 V	10 years (NMC, LFP) 15–20 years (LTO)	Safety issues (highly flammable)	≈10 min (LTO)
		Pb-acid	High <40 Wh/kg	Lowest in batteries <0.05 kW/kg	Low	2.1 V	5–7 years	Hazardous (Toxic)	≈60 mins
		Ni-MH	High <100 Wh/kg	Low 0.1-0.6 kW/kg	High	1.2 V	5 years	Cleaner than other battery types	>60 mins
		Ni-cd	High <100 Wh/kg	Low 0.04-0.2 kW/kg	Low	1.2 V	15 years	Hazardous (Toxic)	≈60 mins
2	Fuel cell		Highest in OESD 100-800 Wh/kg	Very low <0.07 kW/kg	High	0.6–0.8 V	>30,000 h ≈15 years	Clean Safety issues (highly flammable)	≈15–20 mins
3	Supercapacitor		Low <0.1 Wh/kg	Very High 0.8-6 kW/kg	High	2.5–48 V	≈30,000 h 10–15 years	Safer than batteries	1–10 sec
4	Flywheel		High ≈11 Wh/kg	High 0.5-2 kW/kg	High	-	≈20 years	-Clean -Safety issues (mechanical)	<15 min

An example is the Kawasaki's SWIMO LRV in Japan [26], which uses energy recovered from braking to accelerate under a low-voltage line or drive the vehicle in catenaryless segments.

2) COMMUTER, REGIONAL, AND INTERCITY

These trains are used for transporting passengers between near cities in the same region with speeds up to 140–160 km/h. Their main energy source is overhead catenary lines or diesel engines. OESDs are installed to avoid the use of diesel engine and achieve low carbon emissions especially near urban areas. It is also used for recovering the braking energy and assisting in power peaks. For the case of Europe, coping with the 2050 European road map will imply the complete ban of diesel trains [2]; regional train manufacturers are dedicating big investments to replacing diesel engines with OESDs. Examples are discussed in Sections IV and V.

3) HIGH-SPEED

These trains are used for longer distances, transporting passengers between regions or countries with speeds up to 200–400 km/h. The majority of high-speed trains are electrically driven through overhead catenary lines. In this case, OESD is used to assist in power peaks and for backup in the case of emergency. An example is the Japan N700S bullet train, where Toshiba SCiB LTO batteries were added in 2020 [27]. Four of the N700S train's 16 carts carry batteries below their frame. The objective of the battery is to support operation in the case of disruption of the overhead line, for example, due to an earthquake, in which case it will be used to drive the train at a lower speed to the nearest station [28].

4) CARGO/FREIGHT LOCOMOTIVE

Cargo locomotives typically have speeds up to 140 km/h. OESD is used for providing first- and last-mile capability. An example is the CRRC 5.6-MW cargo locomotive built for Hungary with a 350-kW 200-kWh Li battery providing a range of up to 10 km along a flat line for first- and last-mile operation [29].

C. OESD TECHNOLOGIES FOR RAILWAY

The two relevant differences between OESD technologies when considered for railway application are: 1) the required energy and power densities and 2) the number of cycles to EoL. This is somehow determinant of the application and type of vehicle where each OESD technology is used. Table 1 shows the key characteristics of the most frequently reported OESD in railway applications [30], and Fig. 4 graphically compares their power and energy densities [31]. The considered OESD technologies are briefly discussed as follows.

1) SUPERCAPACITOR

Characterized by their very high power density, high dynamic response, and low energy density, supercapacitors are most often used when high power peaks are required for very short periods.

Supercapacitors are very suitable for applications where high power peaks are frequent [32], [33]. They are usually used in urban rail transit of all types [34], [35], [36]. Thanks to their fast response and their fast charging capability (in the range of tens of seconds), charging can be performed at any station during short stops when in service operation as well as during the braking process. There is a number of trams and metros already in service using supercapacitors. Spain,

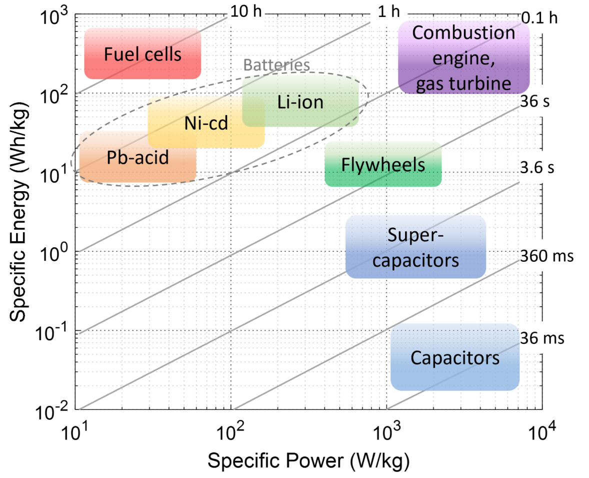

FIGURE 4. **Energy density versus power density of considered OESDs for railway [31].**

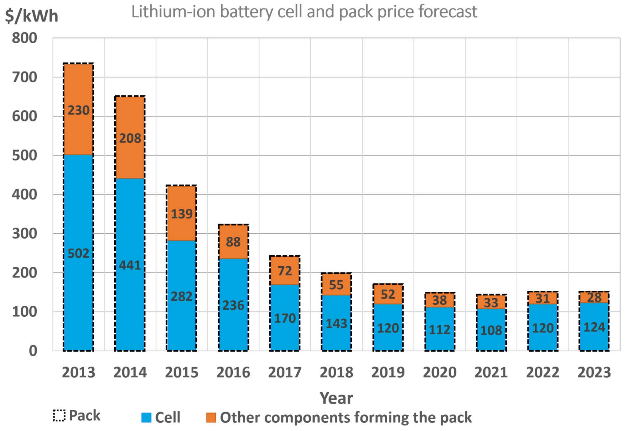

FIGURE 5. **Li-ion battery cell and pack volume-weighted price projection (based on data from electric vehicles, buses, and stationary storage projects) [41], [43].**

Portugal, and China are considered innovators and leading countries in the adoption of this technology.

An example is the CRRC low-floor LRV tram in China, which is fitted with two supercapacitor banks of 45 F, 528 V; each is composed of 11 series 3 parallel assembly of 48-V modules [37]. Another example is the CAF urban tramway in Seville, Spain; it is fitted with supercapacitors on the rooftop providing a range of approximately 3.2 km being charged at stops in around 30 s [38]. Also, another example is the Altsom RATP Citadis tramway in Paris developed within the STEEM project; it uses 54-V 130-F supercapacitor modules assembled in series–parallel with a total of 48 modules where the usable energy is 1.6 kWh [39]. The Brussels tram line (Bombardier Flexity tram T3000) is another example; it is supplied from a 700-V dc catenary and onboard supercapacitors of around 580 V in addition to the Blackpool and the Mannheim tramways in the U.K. Several metro lines are already using supercapacitors, like Madrid and Brussels.

2) BATTERY

Batteries are characterized by their high energy density and lower power density compared to supercapacitors, as shown in Table 1, but noting that significant differences can exist depending on the battery technology. Onboard battery storage systems have been reported for almost all rail types; however, their function differs for each of them, as explained in Section II-B. Examples of trains integrating battery OESD are discussed in Section IV. In some onboard systems, supercapacitors are used to support the battery during power peaks, for example, during acceleration and braking, which leads to a better stabilization of the catenary voltage and a higher battery lifetime [34], [40].

Battery types reported for use in railways are mainly Li-ion and lead-acid (Pb-acid). Nowadays, the majority of applications use Li-ion due to the environmental issues related to Pb-acid since it contains toxic and hazardous materials. Furthermore, Li-ion has higher energy and power densities as well as lower charging duration (see Fig. 4 and Table 1). Li-ion battery has seen significant developments during the last decade with its cost being reduced by more than 80% in specific sectors, as shown in Fig. 5 [41], [42]. It can be observed that the cell price accounts for around 80% of the pack total cost. It is noted that the current costs of Li-ion batteries for railways are significantly larger than those shown in Fig. 5. However, similar trends would be expected for railways if mass production becomes viable.

There are several chemistries of Li-ion batteries reported for railway trains; they use liquid electrolytes and only two anode materials: graphite and LTO. The main three rival Li-ion technologies for railway applications are: 1) NMC having a graphite anode and NMC cathode; 2) LTO having an LTO anode and NMC cathode; and 3) lithium iron phosphate (LFP) having a graphite anode and LFP cathode. LTO has a faster charging rate and a significantly higher number of cycles to EoL than NMC and LFP (i.e., superior cyclic life) [44], [45]. On the other hand, LTO has a relatively lower energy density attributed to the lower cell voltage (2.4 V) compared to NMC (3.7 V) and LFP (3.2 V) [46]. Regarding safety, theoretically, LFP is considered the safest of the three technologies since its cathode material (LFP) has the highest thermal runaway temperature (270° C) compared to NMC and LTO (210° C), which both have NMC cathodes. Recently, the rolling stock sector has been seeing a tendency toward LTO for OESDs due to the need to significantly cut down the battery charging time and increase its lifetime, in this case compromising volume and weight [45], [47], [48]. On the other hand, some manufacturers are still going for NMC batteries to enhance energy density like the case of Alstom for the Coradia iLint [22], [49].

Other types of batteries, such as redox flow batteries, are not reported for railway application; the reason can be contributed to their higher weight and size (i.e., lower energy density) and the lack of commercial solutions, and therefore, they do not provide a competitive alternative.

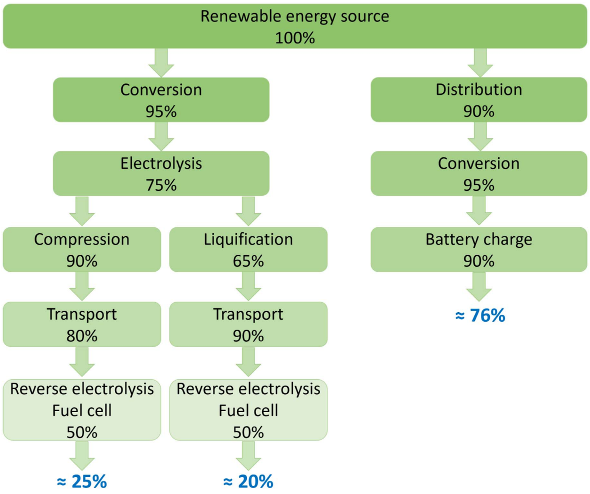

FIGURE 6. **Energy efficiency of battery versus hydrogen fuel cell storage systems. Based on a study by the Administrador de Infraestructuras Ferroviarias [52], [53].**

3) HYDROGEN FUEL CELL

Hydrogen gas has a high gravimetric energy density of 33 kWh/kg, but, at atmospheric pressure and normal ambient temperature, each kg occupies 11.2 Nm^3, having, therefore, a very low volumetric energy density of around 3 kWh/Nm^3 (i.e., at NTP). Consequently, it has to be compressed to be transportable.

There are several aspects to take into consideration when comparing hydrogen fuel cells and batteries: 1) gravimetric/volumetric energy densities and their variation with the required OESD capacity mainly determined based on the target autonomy and the vehicle size; 2) the overall system efficiency; and 3) power density.

The gravimetric (Wh/kg) and volumetric (Wh/m^3) energy densities of batteries are more or less constant (i.e., achieving higher capacity is done by paralleling battery packs), meaning that doubling the kWh doubles the volume and weight. This is not the same for fuel cells where the overall system consisting of the fuel cell and the hydrogen storage tank has an increasing specific energy as the kWh increases [50]. For this reason, batteries are preferred for shorter distances and lighter vehicles, while for higher millage and heavier vehicles where more kWh is required, the fuel cell starts to be competitive since it could provide a better overall volume and weight than batteries [50]. That is the reason why, at the moment, the railway market scope for hydrogen fuel cells is focused on regional trains with more than 80 km of nonelectrified route, relatively lower frequency of trains, and limited inactive time, which does not permit battery charging [9].

Regarding efficiency, a fuel cell has significantly lower efficiency compared to a battery (50% and 85%, respectively). This is due to the electrochemical reaction known as reverse electrolysis used to generate electrical energy by combining hydrogen and oxygen. The reaction by-products are heat and water vapor [51]. Fig. 6 shows a comparison between efficiency of a fuel cell versus battery energy storage systems starting from generation using renewable energy.

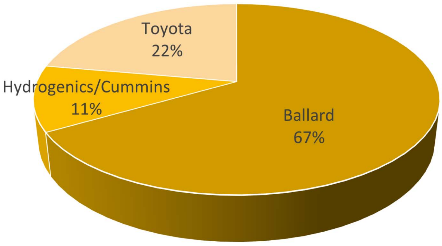

FIGURE 7. **Share of fuel cell manufacturers in railway projects and operating trains with OESDs. Based on reviewed data.**

Finally, the battery has a higher power density than the fuel cell (see Table 1), and for this reason, a fuel cell system for railway usually includes a battery. While the fuel cell provides the average power, the battery absorbs fast power changes (i.e., recovering kinetic energy during braking) and provides peak power during acceleration [54]. The battery is also used to provide the start-up power for auxiliary loads (i.e., air and heating, ventilation, and air conditioning (HVAC) compressors, motor ventilation fans, etc.) [34], [55] .

Regarding the type of fuel cells used in rail applications, the Proton-exchange membrane fuel cell, also known as polymer electrolyte membrane (PEM), represents the most selected type due to its low operating temperature (60–120° C), fast start-up, low corrosion, and maintenance as well as the flexibility to scale up the system [56].

Hydrogen storage tanks typically used in railways are type IV cylinders, which are made of composite material composed of carbon fiber with a polymer liner [57]. Compared to types I–III, which are based on metallic composites (steel and aluminum), the weight is significantly reduced making it very convenient for use in railway [9]. Hydrogen is normally compressed given its very low volumetric energy density where typical pressure levels used in railways are 200, 350, and 700 bars. Hydrogen liquefaction can be used to further reduce the volume; however, this process is less efficient compared to compression resulting in almost 25% lower overall system efficiency [9]. The most commonly reported manufacturers of hydrogen fuel cells for railways are Ballard [58], Cummins [59], and Toyota [60]. Fig. 7 shows the share of each manufacturer in reported railway projects and operating trains using hydrogen fuel cell technology. The most commonly reported manufacturers of hydrogen storage solutions are [57]: NPROXX [61], Hexagon Purus [62], and Luxfer [63].

4) FLYWHEEL

Flywheels were investigated for some railway projects mainly in urban rail LRV and locomotives. An example is the British Parry People Mover railcar powered by a flywheel, which had been in service since 2010 [64]. Also, SNCF France and Alstom in their PLATHEE Project (Energy Efficient and Environmentally Friendly Train Platform) have investigated the use of flywheel on a hybrid diesel locomotive, but it did

TABLE 2. **Train Types Categorized by the Type of Hybridization**

Train type	Hybridization	Example trains
EMU	Catenary	Stadler CITYLINK tram, Siemens Mireo
BEMU	Catenary Battery	Stadler FLIRT Akku [66], Siemens Mireo plus B
HMU	H_2 fuel cell Battery	Alstom Coradia iLint, [54] Siemens Mireo plus H [48]
HEMU	H_2 fuel cell Battery catenary	Alstom Coradia polyvalent
DMU	Diesel engine	Stadler FLIRT DMU
EDMU	Diesel engine Catenary	Bombardier Diesel AGC, Stadler BTR 813 FLIRT
Hybrid DMU	Diesel engine Battery	JR East NewEnergy train, RailPower Green Goat
Hybrid EDMU	Diesel engine Catenary Battery	Hitachi Eversholt intercity battery train for the UK

not enter service [40]. Another example is the Alstom Citadis flywheel tram, which had undergone tests in Rotterdam since 2005 [39]; however, no clear plans for entering commercial service were publicly reported. Research is going on for developing robust flywheel systems for railway traction; however, the technology has not proven sufficient maturity for passenger trains till the moment, one of the reasons being mechanical safety concerns.

D. CLASSIFICATIONS OF RAIL VEHICLES WITH OESD

Existing trains with OESD can be retrofitted or new. Retrofitted trains can either replace a diesel engine with an OESD or add an OESD to a catenary-fed existing series train. An example is the CAF hydrogen retrofit Renfe Civia train for the FCH2Rail European project [65], which is based on adding a hydrogen fuel cell and a battery to the existing Renfe 3-car commuter unit belonging to CIVIA series [9]. New series trains are those newly designed including an OESD as a primary energy source. Actual railway vehicles with OESD are a retrofit of an existing series, and consequently, they are not optimized. Trains with OESD can be classified based on the energy sources used for supplying the traction chain and other onboard systems, in other words, the type of hybridization of the energy sources feeding the train. This is summarized in Table 2 showing a real example of each train type for multiple-unit trains. A multiple-unit train consists of several traction motors incorporated within its cars with no need for a locomotive car. The same types are applicable to locomotives. Both locomotives and multiple units can be fed electrically using catenary overhead lines, a diesel engine/genset, an OESD, or a combination of the previous. The latter is called multimode rail vehicles comprising multiple energy sources, which enable supplying the train auxiliary and propulsion system from different sources [12].

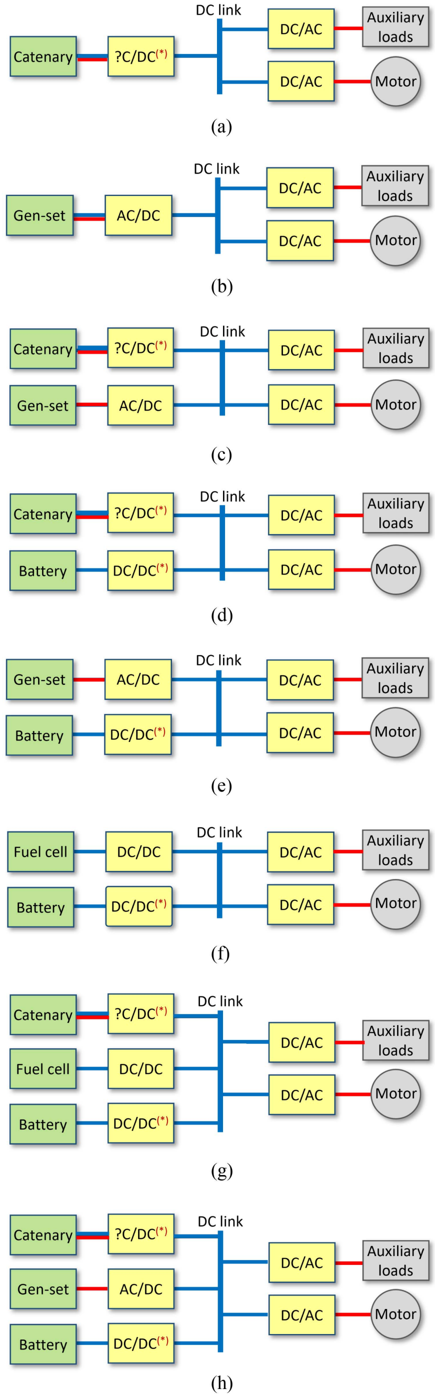

FIGURE 8. **(a)–(h) Train converter structure based on the type of hybridization. Converter marked with * can exist or not depending on topology characteristics (i.e., dc catenary and/or battery can be connected directly to the dc link). The symbol ? indicates ac or dc depending on the catenary type. Blue and red connections stand for dc and ac voltages, respectively.**

III. POWER CONVERTER ARCHITECTURES

The onboard power converter structure differs based on the type of train and hybridization concept. Fig. 8 shows the possible onboard power converter architectures being categorized by the type of hybridization of the train.

TABLE 3. Summary of General Characteristics of Trains With OESD

	Train	**Country (service)**	**Train type**	**Speed (km/h)**	**Hybrid type**	**Converter structure** (Fig. 8)	**OESD Range (km)**	**Year of testing or service**
Hydrogen	Alstom Coradia iLint	Germany	Regional	140	HMU	8f	600–800	Service 2018
	Porterbrook HydroFLEX	UK	Project	80	HMU	8f	120 (Final 1000)	Prototype 2018
	Siemens Mireo plus H	Germany	Regional	160	HMU	8f	800–1000	Service December 2024
	Stadler FLIRT H_2	USA	Passenger	127	HMU	8f	460	Order September 2022
	Talgo TPH2 Vittal-One	Project (Spain)	Regional	140 (fuel cell) 220 (catenary)	HEMU	8g	800	Testing November 2021
	CAF Hydrogen	Project (Spain)	Commuter	–	HEMU	8g	-	Dynamic tests June 2022
	HYBARI	Japan	Project	100	HMU	8g	140	Start test March 2022
	CRRC Low floor tramway	Japan	Light rail	70	HMU	8f	125	Service December 2019
Battery	Siemens Mireo plus B	Germany	Regional	140	BEMU	8d	80–120	Service December 2023
	Siemens Desiro ML cityjet eco	Austria	Regional	120 (battery) 140 (catenary)	BEMU	8d	80	Passenger test end 2019 (behind schedule)
	Stadler FLIRT Akku	Germany	Regional	150	BEMU	8d	150	Service end 2022
	Stadler CITYLINK tram	UK	tram (possible intercity)	100	BEMU	8d	-	Delivery 2024
	Hitachi DENCHA	Japan	Regional	120	BEMU	8d	30	Service 2016
	CAF Civity	Germany	Regional	160	BEMU	8d	-	Order June 2021
	Bombardier/Alstom Talent 3	Germany	Regional	160	BEMU	8d	40–100	Test operation till May 2022
	Alstom AGC retrofit	France	Regional	160	BEMU	8d	80	Dynamic tests End 2022

The main power converters forming the train electrical system are the catenary converter, the auxiliary converter, the traction inverter, and the OESD converter. These are discussed in this section as follows.

Table 3 shows the general characteristics of some of the trains with OESDs either in service or under commissioning indicating the converter architecture for each train (referred to Fig. 8).

A. AUXILIARY CONVERTER

It is used to supply the auxiliary circuits and devices on the train, for example, the lighting system, air conditioning, single-phase plugs in passenger vehicles, as well as air braking compressors and motors ventilation fans. The auxiliary converter has a dc–ac topology where the input is connected to the train dc bus and the output 400 Vac forms the train low-voltage grid. It is typically formed by a dc–ac inverter stage. However, for dc bus voltage above 1 kV, the topology can be formed by a dc–dc converter followed by a dc–ac inverter. It can include an isolation stage depending on the dc-link voltage level and the standards in the country of service. Generally, for voltages below 1 kV, no isolation is required, while for voltages above 1 kV, it is, in the majority of cases, compulsory to integrate an isolation transformer for complying with safety standards. The isolation stage can be either integrated into the dc–dc converter, e.g., using a dual active bridge (DAB), or a low-voltage transformer is added at the ac output.

B. CATENARY CONVERTER

The catenary converter, also called the main converter, is used to supply the train from the catenary overhead line. Its topology is dependent on the type and characteristics of the catenary system. The railway electrification systems can be classified into dc and ac; dc overhead catenaries include 600 Vdc, 750 Vdc, 1.5 kVdc, and 3 kVdc, while ac catenaries include 25 kVac at 50 Hz, 15 kVac at 16.7 Hz, and 20 kVac at 50/60 Hz. The power converters in the traction chain of electrically powered trains depend on the type of catenary system, and the voltage level at which it is intended to operate.

In the case of a dc catenary, a dc–dc converter can be used; however, in the majority of cases, this converter is not used. This is commonly reported for 600- or 750-V catenaries, usually used for urban rail. As for 1.5- and 3-kV dc catenaries, removing this converter would very likely implicate the use of an isolation stage for feeding the train auxiliary circuitry (i.e., in the auxiliary converter) to comply with the railway standards of many countries for dc buses above 1 kV. An additional concern, if the catenary converter is not used, is that the voltage fluctuations allowed in the catenary will be transferred directly to the dc link, consequently affecting to other converters. This is typically solved using an *LC* filter.

In ac catenaries, the converter is compulsory and usually denoted as active front end (AFE). An active four-quadrant converter (4QC) is typically reported in railway applications for providing active and reactive power control, power factor correction, and, in some cases, harmonic current filtering [67], [68], [69]. A transformer is mandatory to step down the high voltage of the catenary (20 kV/50–60 Hz, 25 kV/50–60 Hz, or 15 kV/16.7 Hz) to a lower level typically in the range of 400 Vac up to 2 kVac to be handled by the AFE.

C. DIESEL GENSET CONVERTER

For diesel trains (DMU, EDMU, and hybrid DMU), similar to the case of ac catenary, an ac–dc converter is required to rectify the ac voltage output of the diesel genset to form the dc bus. This ac–dc converter is unidirectional and, therefore, can either be a diode rectifier or a controlled rectifier.

D. BATTERY DC–DC CONVERTER

This converter is used to interface the battery to the train dc bus and to control battery charge and discharge.

Regarding the topology, the most common choice of dc–dc converter for the battery energy storage system in railway is the nonisolated bidirectional two-level (2L) buck–boost converter [70], [71]. A three-level (3L) buck–boost converter has been proposed in literature [72]; however, it has not been reported in any real train project. A review of other dc–dc converter topologies proposed for integrating battery energy storage onboard rail vehicles can be found in [73].

SiC technology provides a promising solution for battery dc–dc converter allowing operation at higher switching frequencies, which helps reduce the size and weight of passive filter components [74]. On the other hand, employing SiC dc–dc converters has several issues impeding commercial use in rail vehicles such as electromagnetic interference (EMI) due to the large dv/dt and di/dt, complicating the design of filters. Also, the lower current rating compared to Si implicates the use of several devices in parallel [74].

The converter includes a differential mode filter normally used in all the dc–dc converters to filter switching ripple. This ripple should be attenuated to levels that would not compromise battery health. Recently, several studies have investigated this issue; and it is becoming one of the important criteria for differential filter design [75]. A common choice is an *L* or an *LC* filter [24], [70], [71], while an *LCL* filter is less often used. Interleaving is repeatedly reported for battery applications to reduce the current ripple achieving a smaller filter design and providing redundancy [74], [76], [77], [78]. In [74], a volume reduction of 30% was reported when redesigning the battery dc–dc converter of a tram to use interleaving as well as full-SiC power devices.

In addition to the differential mode filter, a common-mode filter is very often necessary to protect the battery from common-mode voltage, which could compromise its operation or falsely trigger battery management system (BMS) protections. It is typically implemented using coupled inductors and Y capacitors (i.e., series capacitors with the midpoint connected to ground) [79].

The control of this converter differs according to the state of the battery (i.e., charging/discharging). During battery charge, the control would start by fixing the current, and then, when the battery reaches the required SoC, it would fix the voltage. On the other hand, when the battery is feeding the dc bus (discharging), the converter would be required to regulate either the bus voltage or the delivered power depending on the overall control strategy. If another converter is regulating the dc bus voltage, then the battery dc–dc converter would regulate power, tracking a certain reference provided by the power management strategy (PMS) and energy management strategy (EMS). Droop control can also coordinate different converters connected to the dc bus and contributing to its regulation [80]. This would be applied through the PMS and EMS [37]. In the case of voltage control, a cascaded control can be used with an inner current loop regulating battery current and an outer voltage loop regulating the bus [70].

It is possible to remove this converter with the objective of reducing size, weight, cost, and losses as well as simplifying the overall system. However, this has to be carefully analyzed since it directly affects, not only battery health but also the operation of the other converters connected to the dc bus since the battery would fix the bus voltage. As mentioned previously, Li-ion batteries are the most common selection in railway traction batteries. These are characterized by their low ohmic resistance, in the range of tens of milliohms, so a ripple in dc-link voltage as low as 5 V can cause large current ripples at the battery side. A ripple of 20 V in the dc link could lead to a blown battery fuse. For this reason, battery manufacturers usually tend to recommend the use of a dc–dc converter. An example appears with ac catenaries. The fact that the catenary is single phase implies the generation of a 2F (2 × frequency) superimposed ac component in the dc-link voltage (i.e., low-frequency ripple). This can easily cause a ripple as high as 50 V, which cannot be applied directly to the battery. In this case, a 2F filter should be used; the size of this

TABLE 4. Summary of Typical Power Converters Characteristics for Reviewed Railway Applications

Converter type	Function	Power range	Input voltage	Topology	Power direction
Auxiliary	Supply auxiliary loads	40 – 100 kW	1 – 4 kV	Three-phase 2L inverter	Unidirectional
Catenary	Supply train from catenary	300 – 1000 kW	ac : 400 – 2000 Vac dc: 1– 3 kV (if used)	4QC	Bidirectional
Diesel	Rectify the ac voltage of the Diesel genset	300 – 3000 kW	400 – 1000 V	Diode or controlled rectifier	Unidirectional
Battery	Control battery charge and discharge	100 – 300 kW	500 – 800 V	Non-isolated: 2L or 3L DC/DC (Buck/Boost) Isolated: DAB	Bidirectional
Fuel cell	Regulate power delivered by fuel cell	100 – 200 kW	500 – 800 V	2L DC/DC (Buck/Boost)	Unidirectional
Traction	Drive traction motors	600 – 2000 kW	600 – 3600 V	Three-phase 2L inverter or 3L NPC	Bidirectional

filter is directly proportional to the catenary voltage and the dc bus voltage, leading in the end to a bulky solution. Furthermore, the filter design would be inefficient because it should be made based on the battery minimum voltage (worst case), and therefore, most of the time, it would be operating away from its optimum point resulting in reduced efficiency. This is also the case for all the other components connected to the bus since the battery would fix the bus voltage, and therefore, these must be rated for the minimum battery voltage. This is dependent on the battery SoC, for example, a pack with 850-V nominal voltage can have as low as 700 V at 30% SoC. This would result in overrating of the current for all components (e.g., cables, auxiliary converter, traction inverter, etc.) most probably leading to a higher cost and size.

In conclusion, using a dc–dc converter for the battery is a tradeoff that has to be studied for each train system depending on its specifications.

E. FUEL CELL CONVERTER

A dc–dc converter is necessary at the output of the fuel cell to regulate the power delivered. This converter is unidirectional since power is delivered only from the fuel cell to the system. Isolation is not necessary for this converter since the fuel cell output voltage is usually several tens of volts below the dc bus voltage. Reported fuel cell converters could have an input voltage in the range of 500–800 V and an output voltage in the range of 600–1500 V. Typically, the employed topology in most reported projects is a nonisolated unidirectional boost dc–dc converter [34], [37]. A differential filter is necessary in order to reduce the high-frequency current ripple seen by the fuel cell being induced by the dc–dc converter switching.

F. TRACTION INVERTER

It is used to drive the traction motor having a dc–ac topology being supplied from the train dc bus. The most typically used topologies in railways are 2L three-phase inverters and 3L neutral-point-clamped (NPC) inverters. As seen from the dc link, it is normally modeled as a constant power source.

Table 4 shows a summary of the typical ratings, characteristics, as well as functionality of each of the converters comprising the railway main drive and reviewed in this section.

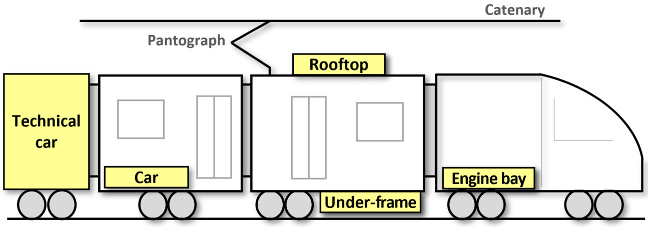

FIGURE 9. Types of OESD installation in railway vehicles.

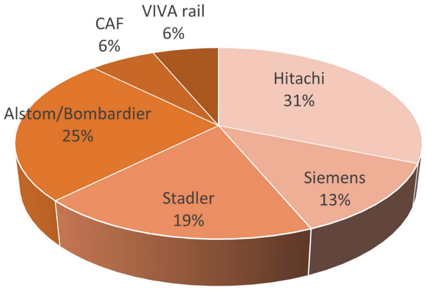

FIGURE 10. Rolling stock manufacturers share of battery train projects. Based on reviewed data.

IV. BATTERY TRAINS

In this section, some of the relevant railway vehicles with an onboard battery system are described. The section is not intended to provide an exhaustive revision, but an overview of the current situation and trends.

Table 5 shows a summary of the characteristics of the considered battery trains. Unlike fuel cells, the Li-ion battery market for railway is much wider with several battery manufacturers supplying modules and packs especially designed for rail providing several mounting possibilities (underframe or underfloor, rooftop, inside the car, and technical car, as illustrated in Fig. 9), as shown in Table 5. Fig. 10 shows the share of relevant rolling stock manufacturers in the recent development of battery railway vehicles based on reported data.

Examples of battery pack suppliers with railway commercial systems already installed on battery trains are Saft, Leclanché, Hoppecke, and ABB [89], [90], [91]. Examples of LTO cell manufacturers are Toshiba, Hitachi, and Saft [21],

TABLE 5. Characteristics of Battery Trains

Train	Battery chemistry	Battery manufacturer	Power Energy	Output voltage	Battery installation	Traction power	DC bus voltage	Catenary	Ref.
DENCHA	Li-ion	Hitachi	360 kWh	1598 V	underframe	380 kW	1.5 kV	20 kVac (60 Hz)	[21]
Stadler FLIRT Akku	Li-ion	ABB	180 kWh	–	–	2x500 kW	–	15 kVac (16.7 Hz)	[66], [81]
Bombardier Talent 3	NMC	Bombardier Primove	300/440 kWh 220 A	532 V	rooftop	–	3 kV	15 kVac (16.7 Hz)	[23], [82]
Alstom Coradia continental	Li-ion	Leclanché	840 kWh	–	–	1450 kW	–	15 kVac (16.7 Hz)	[83]
Siemens Mireo Plus B	LTO	Toshiba and Siemens	700 kWh	–	underframe	1700 kW	–	15 kV (16.7 Hz) 25 kVac (50 Hz)	[84]
Siemens Desiro ML Cityjet eco	LTO	–	528 kWh	–	–	up to 2600 kW	–	15 kVac or 25 kVac	[5]
CRRC cargo locomotive	Li-ion	–	200 kWh 350 kW	–	–	5600 kW	–	15 kVac (16.7 Hz) 25 kVac (50 Hz)	[29], [85]
CAF Civity	LTO	–	–	–	–	up to 4400 kW		1.5 kVdc, 3 kVdc 15 kVac or 25 kVac bi-mode / tri-mode	[86]
Vivarail battery train	Li-ion	Hoppecke	106 kWh	–	–	–	–	750 Vdc	[87]
Seibu 2000 commuter	Li-ion	–	7.6 kWh 240 A	692 V	underframe	–	–	1.5 kVdc	[24]
Kawasaki SWIMO LRV	Ni-MH	Kawasaki GIGACELL	7.6 kWh 240 A	532 V	inside car	–	600 V	600 Vdc	[26], [88]

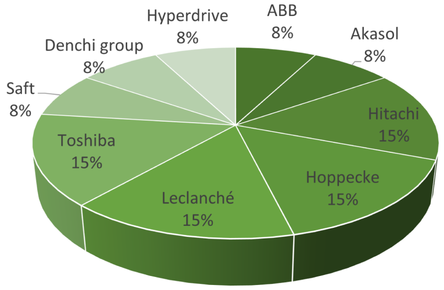

FIGURE 11. Share of traction battery providers in railway projects and operating trains with OESDs. Based on reviewed data.

[27], [92]. Fig. 11 shows the share of each in the reported railway projects.

It is observed that battery packs used in railway vehicles have a wide voltage range with most of the reported systems having a nominal voltage in the range of 500–800 V with a current rating in the range of 200–240 A.

A. HITACHI–JR KYUSHU SERIES BEC819 DENCHA

DENCHA (Dual Energy Charge) BEMU train is the world's first battery-powered train charged from ac overhead lines in Japan [21]. It was developed in a collaboration between Hitachi and Kyushu Railway Company Japan (JR Kyushu). The DENCHA is designed for ac catenary of 20 kV/60 Hz with a traction power of 380 kW.

The train has the structure of a BEMU [see Fig. 8(d)]. The converters architecture and placement are shown in Fig. 12, where a high-voltage battery is used to avoid installing the battery dc–dc converter. The battery structure consists of three battery packs, each containing 72 series modules of Hitachi high-energy-density Li-ion 75-Ah battery module [21]. Each pack has a capacity of about 120 kWh/pack providing a total capacity of 360 kWh and a voltage of 1598 V. The battery system provides an autonomy range of 30 km.

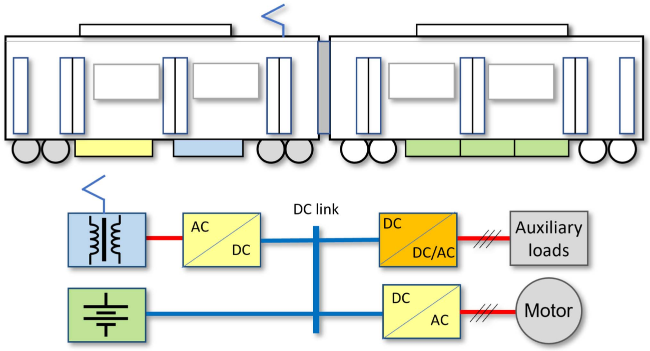

FIGURE 12. DENCHA battery train converter architecture and placement [12], [21].

B. STADLER FLIRT AKKU

FLIRT (Fast Light Intercity and Regional Train) Akku train is Stadler's first battery-powered train. It is equipped with a 180-kWh Li-ion battery and traction converters provided by ABB for a total of 55 BEMUs [90]. The battery system provides an autonomy of 150 km and it was demonstrated in a test a 224 km in battery-only mode breaking the world record for battery-powered train autonomy. The batteries are charged while the trains are operating in electrified sections and at selected locations of the route. The traction converter ensures that the battery energy storage systems can be charged with 400 V or 1 kV in operating and charging modes without the need for additional power electronic equipment than what is required for an ac EMU train [81]. It has a charging time of 15 min under catenary [66].

The converter architecture is that of a BEMU [see Fig. 8(d)] with an ac–dc catenary converter; however, there is no provided information about the usage of a dc–dc converter for the battery.

C. BOMBARDIER TALENT 3 BEMU

Bombardier has designed a three-car BEMU train based on its Talent 3 train platform [82]. The project was funded by the German federal government in the framework of an innovation program for electromobility. Design rights were divested to CAF in 2021 as a condition of the European Commission for the clearance of Alstom acquisition of Bombardier. The train can be fed from 15-kV ac catenary as well as from the onboard Li-ion NMC MITRAC (Modular Integrated TRACtion system) batteries developed by Primove and installed on the rooftop [23]. The battery system consists of two parallel packs each equipped with a BMS and the system has a common thermal conditioning unit. According to [23], each pack contains 12 battery modules with 49 kWh of total energy and a nominal voltage of 532 V. The total battery system weight is 837 kg, and the volume is approximately 0.9 m^3 [23]. The train has a maximum speed of 140 km/h. The converter architecture is that of a BEMU shown in Fig. 8(d). It has a dc link of 3 kV, and consequently, the battery is integrated through an isolated medium-frequency dc–dc converter where a modular DAB topology was considered [93].

D. SIEMENS MIREO PLUS B

This train is developed by Siemens for regional and intercity operation. It is a variant of their Mireo EMU train platform fitted with an onboard battery system. This BEMU can also be fed from overhead ac catenary at 15 kV/16.7 Hz or 25 kV/50 Hz. The battery system has 700 kWh, which provides up to 80-km range at a maximum speed of 140 km/h with a traction power up to 1.7 MW and can be charged via the 25-kV overhead line [84]. It currently uses LTO batteries, but Siemens reports that it would be going for the niobium titanium oxide (i.e., referring to the anode material) [94]. Siemens is codeveloping the batteries with Toshiba using their SciB LTO battery [47]. The battery system is mounted underframe and is installed in two battery containers (see Fig. 9).

The converter architecture of the train is that of a BEMU shown in Fig. 8(d), where Siemens reports the use of SiC devices for the battery dc–dc converter similar to their Mireo plus H hydrogen train.

E. CRRC CARGO LOCOMOTIVE

The 5.6-MW ac four-axle locomotive, built by CRRC for Rail Cargo Hungaria (RCH), has a top speed of 140 km/h and a traction force of 300 kN. It is fitted with a 350-kW 200-kWh Li battery. It can be supplied from ac catenary of 15 kV/16.7 Hz or 25 kV/50 Hz [29]. The locomotive provides first- and last-mile operation capability using the onboard battery system covering a range of up to 10 km along a flat line. CRRC has built two hybrid freight locomotives and two hybrid shunting locomotives for RCH [85].

F. KAWASAKI'S SWIMO LRV

This three-section 15-m-long prototype vehicle is developed by Kawasaki Japan. It can be fed from 600-V catenary overhead lines as well as the onboard nickel-metal-hydride (Ni-MH) Kawasaki GIGACELL battery [26]. The battery has a 240-A 7.6-kWh rating and a nominal voltage of 576 V. It provides an autonomy of 10 km at a maximum speed of 40 km/h on a 5-min charge [88]. The converter architecture is the one shown in Fig. 8(d), where no catenary converter is used since it is fed from dc 600-V catenary. The battery is connected to the dc bus using a nonisolated buck–boost bidirectional dc–dc converter having a voltage range of 576–600 V, 250 kW and uses pulsewidth modulation at a switching frequency of 4 kHz [26].

G. HITACHI BLUES

It is a trimode train developed by Hitachi for Trenitalia. It is a retrofit of Hitachi Caravaggio platform with three- and four-car models. The train can be fed from diesel onboard battery or 3-kV dc overhead catenary. It is scheduled to enter service in 2023 [95]. The Blues converter architecture is based on the one shown in Fig. 8(h).

Other examples of battery trains are the Vivarail British BEMU, the Siemens Desiro ML cityjet eco for ÖBB Austria, which is a retrofit of their Desiro diesel platform, the CAF civity BEMU train, and the Seibu 2000 commuter train in Japan. These are summarized in Table 5.

V. FUEL CELL TRAINS

In this section, some of the relevant railway vehicles with onboard hydrogen fuel cells are described. The section is intended to provide an overview of the current situation and trends rather than an exhaustive revision. The design and operation of the fuel cell system will be strongly conditioned by the onboard battery system. For this reason, the battery system for each case will be discussed to a certain level of detail.

Table 6 shows a summary of the characteristics of the considered hydrogen fuel cell rail vehicles. It is remarked that Ballard™ has the highest share of hydrogen fuel cells in the railway market with competition from Toyota and Cummins (previously Hydrogenics). It is observed that the fuel cell modules used in railway vehicles have a voltage range of 500–800 V and a power range of 100–200 kW where hydrogen is typically stored at 350 bar.

TABLE 6. Characteristics of Hydrogen Fuel Cell Trains

Train	OESD	Chemistry	Manufacturer	Power/Energy	Voltage	H_2 storage kg (bar)	Installation type	Traction power	Ref.
Alstom Coradia iLint	FC	PEM	Cummins	2×200 kW	-	178 kg (350 bar)	Rooftop	628 kW	[22]
	Battery	NMC	AKASOL 2 packs (3×18 AKM 46 POC/pack)	111kWh, 139 Ah 221 kW (per pack)	800 V	N/A	Under-frame (IP67)		
HydroFLEX	FC	PEM	Ballard FCveloCity® -HD	100 kW	500 V	20 kg (4×5kg) (350bar)	Car	1 MW	[96]
	Battery	LFP	Denchi Group SLICE®	125 kW 84 kWh, 138 Ah	625 V	N/A	Car		
CRRC Foshan tram	FC	PEM	Ballard FCvelocity® -XD	2×100 kW	-	12 kg (350bar) 6 cylinders	Rooftop	373 kW	[97]
	Battery	Li-ion	-	2×20 kWh	-	N/A	-		
Stadler FLIRT H_2	FC	PEM	Ballard FCmove®-HD+	100×6 kW	280-560 V	350 bar	Technical car	700 kW	[98], [99]
	Battery	LTO	-	-	-	N/A	Rooftop		
Talgo TPH2	FC	PEM	Ballard FCmove-HD	70×8 kW	250-500 V	350 bar	Car (power pack)	1.3 MW	[100]
	Battery	-	-	-	-	N/A	-		
CAF FCH2rail	FC	PEM	Toyota Motor Europe	-	-	-	Rooftop	-	[101]
	Battery		CAF	-	-	N/A	-		
Siemens Mireo Plus H	FC	PEM	Ballard	-	-	-	Rooftop	1.7 MW	[48], [89]
	Battery	LTO	Saft	1 MW	-	N/A	Under-frame		
HYBARI	FC	PEM	Toyota	60×4 kW	-	700 bar (51L) 5 tanks x 4 units	Under-frame	95x4 kW	[102]
	Battery	Li-ion	Hitachi	120×2 kWh	-	N/A	Under-frame		

A. ALSTOM CORADIA ILINT

The Coradia iLint developed by Alstom is a two-car hydrogen fuel cell HMU train intended for regional service [103]. It was developed within cooperation between Germany, Austria, and Holland and operated on evb German railway company network. The train was announced in 2016 and in September 2018, a Coradia iLint entered service in Germany with daily passenger service according to the regular timetable since then [22]. RMV transport company in Frankfurt ordered 27 iLint to be delivered in December 2022 with more orders in France and the U.K. [9].

The train is developed on a version of Alstom Lint 54 DMU (54 m, 160 seats) replacing the diesel engine by a fuel cell and a battery system [22].

The hydrogen fuel cell is provided by Cummins having a power of 200 kW. It takes 15 min to refuel the iLint, which holds 178 kg of hydrogen stored in 32 Type IV cylinders at 350 bar (consumed at an approximate rate of 0.25–0.3 kg/km) sufficient for a total autonomy of up to 1000 km. The battery system is composed of two packs (one per car), and each pack is composed of three modules of 18 AKM 46 POC Li-ion batteries from AKASOL, Germany [49]. The pack is liquid-cooled providing 111 kWh, 800 V, an average power of 221 kW, and peak power of 450 kW (40 s). The battery systems are designed for railway operation and comply with regulations IEC 61508 and EN 12663, and the modular subsystems are tested in accordance with EN 61373, EN 50121, EN 60529, and UN 38.3 [22]. The iLint is currently used for a nonelectrified rail line of 125 km, where it is able to reach 140 km/h and travel 600–800 km on a full tank of hydrogen. Details of the battery and fuel cell systems installed onboard the train are summarized in Table 6.

The power converter structure of the Coradia iLint has the architecture of an HMU [see Fig. 8(f)], where the battery is directly connected to the dc bus without a dc–dc converter [22]. The architecture and placement of converters are shown in Fig. 13.

B. HYDROFLEX

The prototype was developed within a collaboration between the University of Birmingham and the British Rolling stock company Porterbrook [17], [105]. The current prototype vehicle does not have the installation to be fed from the overhead catenary. However, it is reported that the production version of the train would be bi-mode [96]. The hydroFLEX uses an 84-kWh battery system from Denchi group [106] and a 100-kW fuel cell module from Ballard [58] (see Table 6).

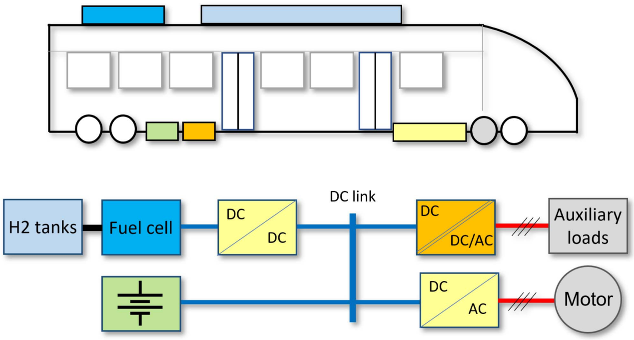

FIGURE 13. Alstom Coradia iLint Hydrogen train converter architecture and placement for one car [12], [104].

According to the university of Birmingham, the most challenging task for the fuel cell is to design the cooling system since it has low efficiency and produces lots of heat [96]. On the other hand, the battery system was regarded to be much more complicated than the fuel cell due to the increased number of components and protections to handle, mainly due to railway environment conditions (noise, EMI, etc.)

The power converter structure of the HydroFLEX has the same architecture as the Coradia iLint without a battery converter and using a nonisolated dc–dc boost converter for the fuel cell. The dc–dc converter output voltage range is 580–650 V, while the battery nominal voltage is 625 V [96].

C. STADLER FLIRT H_2

It is the first hydrogen-powered passenger train intended for service in the USA [107]. Stadler has an agreement to deliver 25 trains for California following its project for San Bernardo county [108]. It is designed for intercity and long-distance travel with a range of 460 km, a maximum speed of 127 km/h, and a maximum power of 700 kW [99]. This train is a retrofit of Stadler's FLIRT DMU which is being deployed by San Bernardo county transport (SBCTA) in California, USA. The hydrogen retrofit is the outcome of the SBCTA need to convert the DMUs to a zero-emission technology [98], [108].

The FLIRT H_2 vehicle consists of two cars and a middle section referred to as the "powerpack" or "technical car," which holds the fuel cells and the hydrogen tanks. The fuel cell system is based on Ballard FCmove-HD+ 100-kW module [109]. Stadler provides the option of fitting the train with pantographs for its use under overhead catenary lines [107].

D. SIEMENS MIREO PLUS H

It is a two-car hydrogen fuel cell HMU developed based on Siemens Mireo EMU train platform with a range of up to 800 km. The three-car variant of the train would have a range of 1000 km [110]. It features a traction power of 1.7 MW and a maximum speed of up to 160 km/h. Siemens has developed the fuel cell system in collaboration with Ballard where two fuel cell systems are mounted on the rooftop. The train is also fitted with a high-power battery system (more than 1 MW) provided by Saft and placed in a compartment under the floor [89]. The battery dc–dc converter uses SiC technology to achieve a compact design, lightweight, and low losses [47], [89]. The train is being developed within the project H2goesrail, which is a collaboration between Siemens mobility and Deutsche Bahn and is expected to enter regular passenger service as of 2024 [110].

The power converter structure of the Mireo plus H has the architecture of an HMU where the battery is connected to the dc bus through a dc–dc converter [47].

E. TALGO TPH2 LOCOMOTIVE

The TPH2 is a test prototype locomotive for the Talgo Vittal-One hydrogen train. The train is composed of a Talgo Travca MS locomotive, which can change gauges and run under different electrification systems, and five Talgo hauled cars. The train includes a fuel cell system from Ballard complemented by a battery system to boost the power required at start-up and store the energy from regenerative braking [100].

This bi-mode or dual train can also be powered from overhead catenary lines having the architecture shown in Fig. 8(g). In hydrogen mode, the traction power would be 1.3 MW having a maximum velocity of 140 km/h and an autonomy of 800 km, while, in catenary mode, it could reach 3.2 MW and 220-km/h maximum velocity [9].

The dynamic tests started in May 2022 with the objective of testing the correct functionality of the main traction system components.

F. CRRC LIGHT RAIL FOSHAN TRAMWAY

This is a three-section low-floor hydrogen fuel cell powered tram for the 17-km Gaoming line in Foshan, China [97]. The tram has two Ballard FCveloCityÂ-XD fuel cell modules of 200 kW mounted on the rooftop [58]. Six onboard hydrogen cylinders provide a range of 125 km with a maximum speed of 70 km/h. The tram line began service in December 2019 and has operated for more than 7400 hours and 73 000 km since August 2020 [97]. Currently, there are no published details about the converter architecture on the CRRC hydrogen tram nor about the employed battery system.

VI. ASSESSMENT AND MAIN CHALLENGES FOR OESD INTEGRATION IN RAILWAY

Studies have shown that OESD is the best alternative when compared to off-board energy storage and reversible substations in terms of energy recovery, vehicle performance, catenary-free operation, and safety. On the other hand, OESD adds weight and cost to rail vehicles [111]. Table 7 summarizes some of the relevant advantages and disadvantages of OESD integration in rail vehicles.

Railway applications can be really demanding from the point of view of operational conditions, regulations, and constraints. Adding OESD or replacing gensets by OESD is relatively new to many manufacturers and, therefore, raises a lot of challenges and concerns.

The first decision is the sizing of OESD especially for vehicles operating on electrified routes [112]. Typically, this

TABLE 7. Advantages and Disadvantages of OESD Integration in Rail Vehicles [111]

Advantages	Disadvantages
No infrastructure cost	Higher total cost
Higher efficiency (recovering braking energy)	Higher weight and reduced space
Back-up in emergency situation	Safety compromise
Catenary stabilization	Complicated system testing (less mature technology)
Catenary-free operation (autonomy)	Reduced vehicle life cycle
Reduced emissions	Higher frequency of preventive maintenance

is a multiobjective task where the main targets are minimizing cost, weight, and volume and maximizing lifetime while complying with the required safety, autonomy, reliability, and compatibility with railway standards [34], [113]. An example of multiobjective optimization problems is shown in [113], in which the use of genetic algorithms for sizing of an OESD system consisting of battery and supercapacitor on a light tram vehicle is proposed. Technical factors to take into consideration include the following [83], [113]:

1) vehicle characteristics, including the number of cars, maximum admitted load, maximum power at wheel, and auxiliary power consumption;
2) train route characteristics including slopes, maximum velocities, available energy sources (e.g., overhead lines, third rail, etc.), and country of service;
3) mission or service profile including schedule, number and duration of stops, service duration, feeding/charging duration, required autonomy, and reliability;
4) infrastructure and mechanisms available for charging;
5) energy management system including control strategies and technical capabilities of OESDs control units like communications, and thermal and power management units.

Once objectives and constraints are defined and vehicle models are built, simulation can be used for power and energy analysis. PMS and EMS can be this way defined [113]. The availability of several energy sources implicates precise coordination between available sources and load demands while ensuring the instantaneous power balance [83]. Investigation, development, and implementation of real-time EMSs represent an important challenge and are being extensively handled in literature [114].

At this point, preliminary sizing is possible by evaluating the resulting overall system efficiency and performance. The goodness of the solution is then assessed, and the process is repeated till an optimal solution is determined.

It is worth noting that sizing of OESD is a function of vehicle and route characteristics such as speed as indicated in the above list. However, a key point is the function intended for the OESD, which differs for each vehicle, as described in Section II-B. For example, if an OESD is required to provide traction and auxiliary power supply in catenaryless sections, then, if higher speeds are required (even in catenaryless section), the size of the OESD would likely be increased to support the higher acceleration peaks. On the other hand, if the function of the OESD is to provide first- and last-mile operation or for emergency backup, then this may be done at a reduced speed meaning the OESD size may not be significantly affected. However, each vehicle has its specific characteristics, and a detailed simulation would be necessary to achieve accurate sizing of each OESD.

It is also interesting to remark that the power handled by the battery (variable power and peaks) would increase significantly as a function of train mass when compared to the power handled by fuel cell (average fixed power). This can be attributed to the increase of inertia and the consequent increase in power peaks during acceleration [83]. This explains the reason why OESD is not currently targeted for main drive traction in large trains, especially for high scheduled train frequency, which would make route electrification more viable.

In the following sections, the challenges specific to fuel cell and battery OESDs are overviewed separately since the operation, as well as requirements of both systems, is quite different in railway applications.

A. FUEL CELL CHALLENGES

System validation and certification and lack of infrastructure are two of the main challenges according to rolling stock companies (i.e., manufacturers, operators, and infrastructure managers).

Till now, there is no published standard with requirements for certification of rail vehicles using hydrogen fuel cells for traction [83]. Work is being done to develop standards such as the IEC 63341-1 [115] and IEC 63341-2 [116] planned to be published in 2024/2025. However, for the moment, rolling stock companies are considering other standards as a reference. Some of these are described in Table 8 [9], [22], [83].

Infrastructure for green hydrogen generation, distribution, and refueling is one of the reasons for its high price. Construction of large-scale facilities is, therefore, required [9]. According to Alstom, a float of 14 Coradia iLint trains with an average consumption of 0.25–0.3 kg/km (around 10 kWh/km [23]) would require approximately 12 recharges and 1600 kg of hydrogen per day [83]. According to [117], this amount of hydrogen, resulting in approximately 4 MW of traction power, can be produced by electrolysis using 11 MW of wind power (i.e., taking into consideration losses due to conversion, compression, and transportation, as shown in Fig. 6). For other mobility applications, this is already being seen worldwide where as of 2022, China had around 250 open stations compared to 160 in Japan, 90 in Germany, and

TABLE 8. Reference Standards for Hydrogen Fuel Cell System in Railway [9], [22]

Standard	Certification description
EC 79/2009	Type approval of hydrogen-powered motor vehicles
ISO 4126-1	Safety devices for protection against excessive pressure
EN 61373	Validation of structural safety chock and vibration test
EN 62282-3-100	Fuel cell (stationary use)
EN 45545-2	Fire safety – railway conditions
EN 50125/IEC 60077	Environment – railway conditions
EN 50121-3-2	EMC – railway conditions

more than 50 in California (i.e., approximate numbers based on [118]).

Finally, cooling of the fuel cell has been reported to be a challenge due to its low efficiency, as discussed in Section II-C [96].

B. LI-ION BATTERY INTEGRATION CHALLENGES

Railway systems have very demanding operating conditions including vibrations, conducted and radiated noise, as well as extreme temperature conditions. These make designing the battery system and its protections a challenging task. Specific challenges related to the integration of battery onboard railway vehicles include [12], [112], [119]: 1) safety issues, protections, and the consequent high number of electronic components and 2) recharging infrastructure and scheduling.

Li-ion batteries can be dangerous if they undergo a thermal runway also called thermal avalanche, which is an irreversible process that eventually causes the battery cells to catch fire or even explode depending on the battery type [120]. Thermal runaway is triggered if Li-ion cell safety is compromised when any of its internal components are misused or undergo instability due to extreme operation. The latter situation would eventually lead to the release of stored energy in an uncontrolled manner increasing rapidly the cell temperature and leading to the thermal runaway phenomena, most probably propagating nearby cells and jeopardizing the complete battery system. Some of the conditions that could lead to thermal runaway include overvoltage between battery terminals, overtemperature, overcurrent, isolation failure (i.e., overvoltage between any terminal and ground), etc.

In order to survive the harsh railway conditions without compromising cell safety, the battery system needs to be very carefully designed and monitored [120], [121]. For this reason, battery packs are necessarily equipped with a BMS and a battery thermal management system [122]; these have direct control over the precharge circuit and the power box containing the main circuit breakers/contactors and fuses.

The presence of these electronic units often adds complexity to the system and increases the number of components as well as making the system more susceptible to noise interference. Consequently, filters are needed. Differential- and common-mode filters are typically included to attenuate differential- and common-mode noise. Common-mode filter still represents an open issue for battery system design [79]. It requires battery manufacturers to have very precise knowledge of their battery pack immunity limits regarding tolerable dv/dt, common-mode voltage, EMI, etc., and define acceptable noise levels imposed by other system components especially switching converters.

VII. TENDENCIES AND FUTURE EXPECTATIONS

Tendencies observed for the railway system across the world are going toward zero emissions, higher efficiency, sustainability, and reduced cost and time to entering service [19], [123], [124], which will push toward more electrified trains equipped with onboard energy storage. The following is a summary of expected future trends and some insights on their effect to OESD integration in railway vehicles.

A. DIESEL TRAINS PHASE OUT

The tendency to replace diesel engine with alternatives to comply with regulations regarding decreasing emissions and noise inside and near to urban areas is clear. This has led to retrofit of existing trains as the fastest solution to replace the diesel engine with OESD. However, this does not usually result in an optimized solution. Alstom has reported a 45% reduction of carbon emissions achieved by its hydrogen train, the Coradia iLint, compared to a Diesel Lint unit. This reduction is claimed to be possible when hydrogen is produced from natural gas, while up to 95% reduction could be achieved if hydrogen is produced from renewable energy [117]. In Japan, only 1% of trains are expected to run on diesel by 2040, and in Europe a complete phase out of diesel trains would take place in several countries starting as early as 2030 [125]. Similarly, in the USA, restrictions on diesel trains would be applied starting 2030 specifically in California [126].

B. ENERGY EFFICIENCY TREND

Energy efficiency has become one of the main trends in rail sector [124]. This would implicate targeting higher efficiencies for all onboard components. Usage of OESD along with SiC technologies for power converters could provide significant improvement in overall efficiency as well as weight. Almost 30% of reduction in total energy consumption and 65% reduction in size have been reported by Mitsubishi Electric Corporation when employing their all-SiC traction inverters on Japan-Tokyo metro rail vehicle [111].

Recovered energy from regenerative braking can contribute significantly to efficiency, especially for the case of high-speed operation [127]. Studies have shown that the use of energy recovery stored in OESD in high-speed railway vehicles can provide almost 30% of energy savings allowing a relevant increase in efficiency as well as safety [127], [128], [129]. In [130], a case study on Trenitalia 9.8-MW high-speed train developed by Bombardier shows a possible reduction of energy consumption by almost 800 MWh/year when employing one energy storage system of 728-kWh nominal energy.

C. DIGITAL TWIN

A clear trend toward the use of digital twin in rail sector is being observed. Among other uses, it has been recently gaining much interest in system validation, fault diagnosis, and certification. It is reported that the use of digital twin could facilitate the faster testing and deployment of more environmentally friendly rail vehicles [123]. Recently, digital twin has been approved for virtual certification as shown in some new standards where certain situations allow using digital twin models instead of costly and complex physical tests on track [131]. OESD integration represents a challenge for train manufacturers since the technology is relatively new and still faces lots of challenges and safety concerns. Proper design and implementation of digital twin models can ease the path and speed up time to entering service of trains integrating new onboard battery and hydrogen energy storage system.

Digital twin can also make use of artificial intelligence (AI) for enhancing the modeling and parameter estimation of the system as well as accurate prediction of system behavior. This can allow increasing the lifetime of the overall rail vehicle including the integrated OESD. Finally, a main challenge facing digital twin would be the data and model sharing between operators, manufacturers, and infrastructure managers [131].

D. FREIGHT SHIFT TO RAIL

In Europe, freight rail is expected to transport 75% of the inland freight by 2050 where projections show a traffic increase of freight rail by 50% in 2030 and doubling by 2050 [132]. Globally, it is expected to see a tendency for shifting of a substantial part of freight/cargo carried by road toward transport by rail [132]. However, more than 60% of rail tracks worldwide are not electrified [5], [6], and electrification is in many cases not viable due to economic or technical issues. Shift to rail achieving zero emissions and sustainability targets will require promoting alternative onboard energy sources instead of diesel engines.

For example, the U.S. freight rail sector is fully dependent on diesel and is currently transporting approximately 40% of intercity freight with projections of achieving 80% by 2050 [133]. At this scale, it is expected that the USA will account for 50% of the global diesel consumption by 2050. This scenario has urged national and global environmental organizations to search for electric alternatives like hydrogen fuel cell and battery locomotives.

E. OESD ECONOMICAL TREND

One important future trend is achieving a more economically competitive rail transport compared to other means of transport to promote increased usage [123], [132]. Consequently, rail must deliver more cost-efficient solutions, which would implicate lowering the cost of system components. Currently, the main challenge is the cost of OESD especially Li-ion battery packs. Average battery pack industrial prices have reduced by more than 80% between 2013 (US\$732 kWh^{-1}) and 2023 (US\$151 kWh^{-1}) [42] and is predicted to reach US\$58 kWh^{-1} by 2030 [133]. This significant reduction would support the transition toward a more economic rail transport sector. Some studies show that even at a near future price of US\$100 kWh^{-1}, battery trains can be comparable to diesel trains if environmental costs are considered like carbon capture and storage (CCS) [133], [134]. CCS is believed to be necessary starting 2030 for abating carbon emissions in sectors where net zero emission is not achievable [134].

Furthermore, AI solutions can be employed to optimize energy storage operation, therefore extending its life and achieving a fast return on investment [135]. AI is expected to play a significant role in battery research; some of their applications are battery cell diagnosis and fault detection, cell manufacturing, electrode architecture, and material characterization [136].

F. HIGH-SPEED NETWORK EXPANSION

A global trend of expanding/promoting high-speed rail networks has been observed. The most relevant case likely being China, where high-speed rail network is expected to grow by 30% between 2018 and 2025 and currently accounting for more than 66% of the global high-speed rail network [137]. An increase of 60% in the consumed traction power on China "H" high-speed rail network has been reported between 2013 and 2016 [137]. Also, in Europe, one of the objectives is to double the traffic on high-speed rail by 2030 and triple it by 2050 [132]. In May 2023, France has banned domestic short-haul flights where train alternatives exist, in a bid to cut carbon emissions [138]. Other European countries are considering similar regulations.

G. CROSS-BORDER FUNCTIONALITY TREND

A trend to expand rail network linking different countries is observed; an example can be seen in Europe where one of the objectives of the TEN-T program (Trans-EU transport) is putting into action a relevant industrial project called ERTMS standing for "European Railway Traffic Management System" with the objective of creating an interoperable railway system both for passenger and freight [139]. This would promote for hydrogen fuel cell trains since they can easily provide cross-border operation and interoperability regardless of the different catenary voltage levels [19].

H. ACADEMIC RESEARCH

In addition to industry and market trends, some clear tendencies are observed in academic research:

1) optimization of train operation (i.e., optimal speed trajectory) considering embedded OESD to achieve higher energy-saving rate [140], [141], [142];
2) optimal sizing of OESD to minimize the system operating cost and OESD investment cost. Recent studies consider not only economic aspects but also weight and volume [34], [113], [143];

3) optimal PMS and EMS based on available energy sources (i.e., fuel cell, battery, catenary, diesel, etc.) [113], [144], [145];
4) battery modeling and online parameter identification algorithms [146]. SoC and SoH estimation have been extensively investigated [121], [147];
5) energy saving making use of OESD [148];
6) digital twin and AI solutions for testing, validation, operation optimization, and fault diagnosis [123], [131].

According to [149], the academic research in railway has seen a significant growth of almost 126% in the last two decades. Most of the published research comes from China, followed by the USA and then the U.K., but the majority of international research interaction was observed in other countries, the highest being Canada. Although an increase of around 30% has been observed in topics related to energy efficiency, sustainability, and environmental impact in railways, it is still significantly low compared to other topics (below 3%). These are potential subject for future work and more studies are needed.

One challenge that could hinder research advancement is limited data shared by manufacturers and operators. Although recently more detailed characteristics of railway vehicles integrating OESD have been published, there is limited information about the test results and problems or drawback faced.

VIII. CONCLUSION

This article has presented an overview of OESDs in railways. OESD functions per rail type are analyzed, and the most reported OESD technologies used in railway applications are discussed. It is observed that supercapacitors are mostly reported for LRVs, while batteries and fuel cells are reported for regional locomotives and multiple units. Power converter architectures are reviewed for all types of rail vehicle hybridization, where it is observed that the existing hydrogen train architecture does not typically support catenary overhead lines in contrast to battery trains, which are more commonly fed through catenary. Looking into some of the recent rail vehicles, it is noticed that OESD integration in railways is becoming a priority for the rolling stock sector. Detailed characteristics of several trains with OESD have been summarized highlighting the trends.

Among the major challenges of OESD integration observed in railway applications are optimal sizing, EMSs, lack of regulations in the case of hydrogen fuel cells, and safety issues leading to an increased number of electronic components in the case of Li-ion batteries. It can be concluded from the analyzed trends that battery trains will see faster deployment in the near future. However, hydrogen trains would start to gain advantage for long distances with more than 80 km of nonelectrified sections and for heavier vehicles requiring high energy as well as when interoperability is required.

Furthermore, it can be concluded from the analyzed trends that the future innovative technologies, such as AI, digital twin, and machine learning, would have an important incentive on OESD fast and reliable integration in railways. Digital twin would allow a faster validation and certification processes as well as precise diagnosis during train operation. This comes to address the tendency to hasten deployment of rail vehicles. However, the challenge remains to be the data disclosure and sharing between the different rail sectors.

REFERENCES

[1] E. B. Muruaga, I. Villar, F. Legay, P. Prenleloup, and J.-F. Reynaud, "Onboard ESU sizing and dynamic IPT charging scenarios for a tramway application," in *Proc. 24th Eur. Conf. Power Electron. Appl.*, 2022, pp. 1–7.

[2] European Commission: Long-term Strategy 2050—European Green Deal. Accessed: Oct. 17, 2022. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en

[3] Net Zero by 2050, Int. Energy Agency, Paris, France, 2021. Accessed: Oct. 17, 2022. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050

[4] Global CO_2 Emissions From Transport by Sub-Sector in the Net Zero Scenario, 2000-2030, IEA, Paris, Int. Energy Agency, Paris, France. Licence: CC BY 4.0. Accessed: Oct. 17, 2022.

[5] "Battery Trains Workshop—The UIC Energy Efficiency and CO_2 Emissions Sector. Accessed: Dec. 19, 2022. [Online]. Available: https://uic.org/events/IMG/pdf/battery_trains-slides-v1_compressed.pdf

[6] The Future of Rail—Opportunities for Energy and the Environment. Accessed: Feb. 12, 2023. [Online]. Available: https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf

[7] Worldwide Rail Electrification Remains at High Volume. Accessed: Feb. 12, 2023. [Online]. Available: https://www.railwaypro.com/wp/worldwide-rail-electrification-remains-at-high-volume/

[8] *List of Countries by Rail Transport Network Size*. Accessed: Feb. 12, 2023. [Online]. Available: https://en.wikipedia.org/wiki/List_of_countries_by_rail_transport_network_size

[9] Course on Application of Hydrogen in the Railway Level 1, Organized by the Spanish Railways Foundation (Fundación de Ferrocarriles Españoles) and presented by rolling stock manufacturers and railway operators: RENFE and Adif, Alstom, CAF, Talgo, Calvera, Sep./Oct. 2021.

[10] World Energy Outlook 2022 shows the global energy crisis can be a historic turning point towards a cleaner and more secure future, 2022. Accessed: Dec. 11, 2022. [Online]. Available: https://www.iea.org/news/world-energy-outlook-2022-shows-the-global-energy-crisis-can-be-a-historic-turning-point-towards-a-cleaner-and-more-secure-future/

[11] World Energy Outlook 2022—IEA, 2022. Accessed: Dec. 11, 2022. [Online]. Available: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

[12] E. Fedele, D. Iannuzzi, and A. Del Pizzo, "Onboard energy storage in rail transport: Review of real applications and techno-economic assessments," *IET Elect. Syst. Transp.*, vol. 11, no. 4, pp. 279–309, 2021.

[13] N. Ghaviha, J. Campillo, M. Bohlin, and E. Dahlquist, "Review of application of energy storage devices in railway transportation," *Energy Procedia*, vol. 105, pp. 4561–4568, 2017.

[14] X. Liu and K. Li, "Energy storage devices in electrified railway systems: A review," *Transp. Saf. Environ.*, vol. 2, pp. 183–201, 2020.

[15] A. Ruvio, N. Mortelliti, and S. Orchi, "A review on rail transport in Europe and Italy," in *Proc. IEEE Int. Conf. Environ. Elect. Eng./IEEE Ind. Commercial Power Syst. Eur.*, 2022, pp. 1–6.

[16] T. Ratniyomchai, S. Hillmansen, and P. Tricoli, "Recent developments and applications of energy storage devices in electrified railways," *IET Elect. Syst. Transp.*, vol. 4, no. 1, pp. 9–20, 2014.

[17] A. Hoffrichter, "Hydrogen as an energy carrier for railway traction," Ph.D. dissertation, Birmingham Centre Railway Res. Educ. Electron., Elect. Comput. Eng., Univ. Birmingham, Birmingham, U.K., 2013.

[18] A. R. Miller, K. S. Hess, T. L. Erickson, and J. L. Dippo, "Fuelcell-hybrid shunt locomotive: Largest fuelcell land vehicle," in *Proc. IET Conf. Railway Traction Syst.*, 2010, pp. 1–5.

[19] Y. Ruf et al., "Study on the use of fuel cells and hydrogen in railway environment," *Roland Berger, Munich, Germany, Tech. Rep.*, 2019.

[20] Hydrogen Refueling Stations in California, California Energy Commission, Sacramento, CA, USA, 2022. Accessed: Jan. 31, 2023. [Online]. Available: https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/hydrogen-refueling

[21] Y. Nagaura, R. Oishi, M. Shimada, and T. Kaneko, “Battery-powered drive systems: Latest technologies and outlook,” *Hitachi Rev.*, vol. 66, no. 2, pp. 138–144, 2017.

[22] J. Varney, “Alstom Presentation APTA Rail Conference: Coradia iLint—Hydrogen fuel cell train.,” Accessed: Nov. 25, 2022. [Online]. Available: https://www.apta.com/wp-content/uploadsCoradia-ILint-%E2%80%93-Hydrogen-Fuel-Cell-Train_James_Varney-1.pdf

[23] W. Klebsch, P. Heininger, J. Geder, and A. Hauser, “Battery systems for multiple units—Emission-free drives powered by lithium-ion cells,” VDE, Offenbach am Main, Germany, Tech. Rep., 2018.

[24] M. Ayata et al., “Traction inverter system with lithium-ion batteries for EMUs,” in *Proc. 17th Eur. Conf. Power Electron. Appl.*, 2015, pp. 1–9.

[25] S. Suzuki, J. Baba, K. Shutoh, and E. Masada, “Effective application of superconducting magnetic energy storage (SMES) to load leveling for high speed transportation system,” *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 713–716, Jun. 2004.

[26] K. Ogura, K. Nishimura, and Y. Oku, “A bidirectional DC-DC converter for battery electric light rail vehicle and its test run results,” in *Proc. IEEE 13th Int. Conf. Power Electron. Drive Syst.*, 2019, pp. 1–6.

[27] Toshiba SCiB LTO Cells. Accessed: Jan. 16, 2023. [Online]. Available: https://www.global.toshiba/ww/products-solutions/battery/scib/product/cell.html

[28] EGEB: Japan’s new bullet train has first Li-ion battery self-propulsion system, 2020. Accessed: Jan. 16, 2023. [Online]. Available: https://electrek.co/2020/07/03/egeb-japan-bullet-train-li-ion-battery-self-propulsion-system-chargeup-europe

[29] Mainline Locomotives for RCH, Hungary. Accessed: Dec. 11, 2022. [Online]. Available: https://crrczelc-europe.com/mainline-locomotive-rch-hungary/

[30] R. Thorne, A. H. Amundsen, and I. Sundvor, *Battery Electric and Fuel Cell Trains: Maturity of Technology and Market Status*. Inst. Transport Econ. (T∅I), Nov. 2019. Accessed: Jan. 24, 2022. [Online]. Available: https://www.toi.no/publications/category29.html

[31] Supercapacitors vs. Batteries. Accessed: Jan. 15, 2023. [Online]. Available: https://www.kemet.com/en/us/technical-resources/supercapacitors-vs-batteries.html

[32] R. Barrero, J. V. Mierlo, and X. Tackoen, “Energy savings in public transport,” *IEEE Veh. Technol. Mag.*, vol. 3, no. 3, pp. 26–36, Sep. 2008.

[33] J. Dixon and M. Ortuzar, “Ultracapacitors + dc-dc converters in regenerative braking system,” *IEEE Aerosp. Electron. Syst. Mag.*, vol. 17, no. 8, pp. 16–21, Aug. 2002.

[34] C. Wu, S. Lu, F. Xue, L. Jiang, and M. Chen, “Optimal sizing of onboard energy storage devices for electrified railway systems,” *IEEE Trans. Transp. Electrific.*, vol. 6, no. 3, pp. 1301–1311, Sep. 2020.

[35] J.-P. Moskowitz, “Onboard energy storage: The experience of a tramway manufacturer,” in *Proc. IET Conf. Railway Traction Syst.*, 2010, pp. 1–45.

[36] B. Destraz, P. Barrade, A. Rufer, and M. Klohr, “Study and simulation of the energy balance of an urban transportation network,” in *Proc. Eur. Conf. Power Electron. Appl.*, 2007, pp. 1–10.

[37] Q. Li, T. Wang, C. Dai, W. Chen, and L. Ma, “Power management strategy based on adaptive droop control for a fuel cell-battery-supercapacitor hybrid tramway,” *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 5658–5670, Jul. 2018.

[38] ACR: Fast-Charging Battery. Accessed: Nov. 5, 2022. [Online]. Available: https://en.wikipedia.org/wiki/Acumulador_de_Carga_Rapida

[39] J.-P. Moskowitz and J.-L. Cohuau, “STEEM: ALSTOM and RATP experience of supercapacitors in tramway operation,” in *Proc. IEEE Veh. Power Propulsion Conf.*, 2010, pp. 1–5.

[40] A. Jaafar, C. R. Akli, B. Sareni, X. Roboam, and A. Jeunesse, “Sizing and energy management of a hybrid locomotive based on flywheel and accumulators,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3947–3958, Oct. 2009.

[41] Top 10 Energy Storage Trends in 2023—Bloomberg NEF, 2023. Accessed: Jan. 15, 2023. [Online]. Available: https://about.bnef.com/blog/top-10-energy-storage-trends-in/

[42] L. Mauler, F. Duffner, W. G. Zeier, and J. Leker, “Battery cost forecasting: A review of methods and results with an outlook to 2050,” *Energy Environ. Sci.*, vol. 14, pp. 4712–4739, 2021.

[43] Lithium-ion Battery Pack Prices Rise for First Time to an Average of 151/kWh—Bloomberg NEF. Accessed: Feb. 24, 2023. [Online]. Available: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/

[44] M. Brady, “Assessment of battery technology for rail propulsion application,” U.S. Dept. Transp. Federal Railroad Admin., Washington, DC, USA, Tech. Rep. DOT/FRA/ORD-17/12, 2017.

[45] T. Huggenberger, “Green railway traction systems industrial session: Design of fuel cell powered traction chains for railway—ABB traction,” in *Proc. Eur. Conf. Power Electron. Appl.*, 2021.

[46] M. Houache, C.-H. Yim, Z. Karkar, and Y. Abu-Lebdeh, “On the current and future outlook of battery chemistries for electric vehicles—Mini review,” *Batteries*, vol. 8, 2022, Art. no. 70.

[47] M. Böhm, “Green railway traction systems industrial session: Traction technology for battery and hydrogen trains—A contribution to green mobility—Siemens Mobility GmbH,” in *Proc. Eur. Conf. Power Electron. Appl.*, 2021.

[48] Siemens Mireo Plus H Accessed: Nov. 14, 2022. [Online]. Available: https://www.mobility.siemens.com/global/en/portfolio/rail/rolling-stock/commuter-and-regional-trains/hybrid-drive-systems/mireo-plus-h.html

[49] Akasol Battery Systems. Accessed: Nov. 7, 2022. [Online]. Available: https://www.akasol.com/en/battery-systems

[50] F. T. Wagner, B. Lakshmanan, and M. F. Mathias, “Electrochemistry and the future of the automobile,” *J. Phys. Chem. Lett.*, vol. 1, no. 14, pp. 2204–2219, 2010.

[51] G. Fontes, C. Turpin, S. Astier, and T. A. Meynard, “Interactions between fuel cells and power converters: Influence of current harmonics on a fuel cell stack,” *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 670–678, Mar. 2007.

[52] A. B. Villalba, “Use of Hydrogen in railway infrastructure,” in *Online Course on Application of Hydrogen in the Railway Level 1*. Spanish Railways Foundation (Fundación de Ferrocarriles Españoles), FFE, Sep. 2021. [Online]. Available: https://www.formacion-ffe.es/OnLine/catalogo.asp

[53] (ADIF Administrador de Infraestructuras Ferroviarias) Spanish Company for Construction and Management of Rail Infrastructure. Accessed: Jun. 13, 2023. [Online]. Available: https://www.adif.es/inicio

[54] Workshop: Fuel Cells and Hydrogen In the Railway Environment, Shift2Rail. Accessed: Nov. 14, 2022. [Online]. Available: https://rail-research.europa.eu/wp-content/uploads/2019/05/FCH-HydrogenTrain-Study-Workshop.pdf

[55] W. Chen, F. Peng, Z. Liu, Q. Li, and C. Dai, “System integration of China’s first PEMFC locomotive,” *J. Modern Transp.*, vol. 21, pp. 163–168, 2013.

[56] Hydrogen National Center Spain: Hydrogen and Fuel Cells Technologies—Fuel Cells. Accessed: Nov. 3, 2022. [Online]. Available: https://www.cnh2.es/en/pilas-de-combustible

[57] M. Böhm, A. Fernández Del Rey, J. Pagenkopf, M. Varela, S. Herwartz-Polster, and B. Nieto Calderón, “Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies,” *Int. J. Hydrogen Energy*, vol. 47, no. 89, pp. 38003–38017, 2022.

[58] Ballard$^{\text{TM}}$: Fuel Cell Power Products. Accessed: Nov. 7, 2022. [Online]. Available: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products

[59] Cummins Hydrogen Fuel Cells. Accessed: Nov. 7, 2022. [Online]. Available: https://www.cummins.com/new-power/applications/trains

[60] TOYOTA Hydrogen Fuel Cell System module. Accessed: Nov. 7, 2022. [Online]. Available: https://global.toyota/en/newsroom/corporate/34799439.html

[61] NPROXX Hydrogen Solutions. Accessed: Jun. 12, 2022. [Online]. Available: https://www.nproxx.com/

[62] Hexagon Purus. Accessed: Jun. 12, 2022. [Online]. Available: https://hexagonpurus.com/

[63] Luxfer Gas Cylinders. Accessed: Jun. 12, 2022. [Online]. Available: https://www.luxfercylinders.com/

[64] The Parry Mover Flywheel Railcar. Accessed: Dec. 4, 2022. [Online]. Available: https://www.modernrailways.com/article/little-and-large

[65] Fuel Cell Hybrid PowerPack for Rail Applications, FCH2RAIL, Horizon 2020. Accessed: Nov. 14, 2022. [Online]. Available: https://cordis.europa.eu/project/id/

[66] STADLER FLIRT: Akku Battery Train. Accessed: Dec. 4, 2022. [Online]. Available: https://www.stadlerrail.com/en/flirt-akku/details/

[67] Desiro ML, ÖBB Cityjet Eco, for ÖBB Personenverkehr AG. Accessed: Dec. 19, 2022. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:bc63830a4b5884d58958e7c49917f0b68331df21/datasheet-desiro-ml-oebb-cityjet-eco.pdf

[68] F.-G. Paul et al., “Power-hardware-in-the-Loop emulation of the low-frequency oscillation phenomenon in AC railway networks,” *IEEE Access*, vol. 10, pp. 87374–87386, 2022.

[69] A. F. Abouzeid, F. F. Trimpe, S. Lück, M. Traupe, J. M. Guerrero, and F. Briz, “Co-simulation-based verification of torsional vibration protection of electric-driven railway vehicle wheelsets,” *Vibration*, vol. 5, pp. 613–627, 2022.

[70] S.-B. Yin, L.-J. Diao, W.-J. Li, R.-J. He, and H.-C. Lv, “On board energy storage and control for inter-city hybrid EMU,” in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, 2017, pp. 3889–3894.

[71] L. Shen, J. Chen, Z. Jin, Z. Liu, D. Zhou, and C. Wu, “Resonating power decoupling using multifunctional bidirectional DC/DC converter in hybrid railway traction application,” *IEEE Trans. Power Electron.*, vol. 37, no. 1, pp. 404–415, Jan. 2022.

[72] X. Ruan, B. Li, Q. Chen, S.-C. Tan, and C. K. Tse, “Fundamental considerations of three-level DC–DC converters: Topologies, analyses, and control,” *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 55, no. 11, pp. 3733–3743, Nov. 2008.

[73] I. Z¨upan, A. Lasić, D. Krušelj, V. Šunde, and Z¨. Ban, “Power converter circuits for recuperation of the regenerative braking energy in rail vehicles,” in *Proc. 42nd Int. Conv. Inf. Commun. Technol. Electron. Microelectron.*, 2019, pp. 174–179.

[74] A. Rujas, V. M. López, A. García-Bediaga, A. Berasategi, and T. Nieva, “Influence of SiC technology in a railway traction DC-DC converter design evolution,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2017, pp. 931–938.

[75] K. Uddin, A. D. Moore, A. Barai, and J. Marco, “The effects of high frequency current ripple on electric vehicle battery performance,” *Appl. Energy*, vol. 178, pp. 142–154, 2016.

[76] A. Rujas, I. Villar, I. Etxeberria-Otadui, U. Larrañaga, and T. Nieva, “Design and experimental validation of a silicon carbide 100 kW battery charger operating at 60 kHz,” in *Proc. IEEE 15th Workshop Control Model. Power Electron.*, 2014, pp. 1–7.

[77] M. Ogasa and Y. Taguchi, “Power electronics technologies for a lithium ion battery tram,” in *Proc. Power Convers. Conf.*, 2007, pp. 1369–1375.

[78] M. Ogasa and Y. Taguchi, “Development of contact-wire/battery hybrid LRV,” in *Proc. IEEE Veh. Power Propulsion Conf.*, 2010, pp. 1–6.

[79] Y. Zhang et al., “Leakage current mitigation of non-isolated integrated chargers for electric vehicles,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2019, pp. 1195–1201.

[80] T. Dragičević, J. M. Guerrero, J. C. Vasquez, and D. Škrlec, “Supervisory control of an adaptive-droop regulated DC microgrid with battery management capability,” *IEEE Trans. Power Electron.*, vol. 29, no. 2, pp. 695–706, Feb. 2014.

[81] ABB Batteries to Power German Trains in Smart Mobility Move. Accessed: Dec. 4, 2022. [Online]. Available: https://www.smart-energy.com/storage/abb-batteries-to-power-german-trains-in-smart-mobility-move/

[82] Y. Laperrière, “Realize your vision with bombardier TALENT 3 BEMU—The battery electric multiple unit train,” in *Proc. APTA Rail Conf.*, 2019.

[83] J. B. Botella and M. C. Sola, “Hydrogen technologies applied to rolling stock,” in *Online Course on Application of Hydrogen in the Railway Level 1*. Spanish Railways Foundation (Fundación de Ferrocarriles Españoles), FFE, Sep. 2021. [Online]. Available: https://www.formacion-ffe.es/OnLine/catalogo.asp

[84] Siemens Mobility to Supply First Battery Powered Mireo Plus B Trains to Denmark. Accessed: Jan. 25, 2022. [Online]. Available: https://press.siemens.com/global/en/pressrelease/siemens-mobility-supply-first-battery-powered-mireo-plus-b-trains-denmark

[85] CRRC Delivers Hybrid Locomotive for Rail Cargo Hungary. Accessed: Jan. 30, 2022. [Online]. Available: https://www.railjournal.com/locomotives/crrc-delivers-hybrid-locomotive-for-rail-cargo-hungary/

[86] CAF Civity, 2022. Accessed: Jan. 6, 2022. [Online]. Available: https://www.caf.net/en/soluciones/familia/civity/index.php

[87] “Vivarail Shows off Battery Train at COP26,” 2022. Accessed: Jun. 6, 2023. [Online]. Available: https://www.railjournal.com/technology/vivarail-shows-off-battery-train-at-cop26/

[88] J. Pringle, “OCS-free light rail vehicle technology,” Accessed: Jan. 25, 2023. [Online]. Available: https://www.miamidade.gov/citt/library/summit/jcpringle.pdf

[89] Siemens Mobility Introduced the First Mireo Plus H Hydrogen train. Accessed: Jan. 24, 2023. [Online]. Available: https://rollingstockworld.com/passenger-cars/siemens-mobility-introduced-the-first-mireo-plus-h-hydrogen-train/

[90] ABB Traction and Battery Technologies to Drive Stadler’s Trains of Tomorrow. Accessed: Dec. 4, 2022. [Online]. Available: https://new.abb.com/news/detail/61814/abb-traction-and-battery-technologies-to-drive-stadlers-trains-of-tomorrow

[91] Leclanché e-Rail Solutions. Accessed: Feb. 2, 2023. [Online]. Available: https://www.leclanche.com/solutions/e-transport-solutions/e-rail/

[92] Saft Rail Batteries, “Saft rail batteries—Innovative solutions for a fast-changing world.” Dec. 2021. Accessed: Feb. 1, 2023. [Online]. Available: https://www.saft.com/download_file/6X7JMGAnv3Fm6HdmtEv%252B2gtlbZ1bRRVHkjS11M6md92GD2EF7vU%252F3Oybbz3WOlG%252BxR8srpA5iCdJ%252FV3IQzTVHQyiTucngZKEg9KkYCLkowAvgaG1hurmAZwcXFM79OcO%252BnejG%252BITbH9CpYenWXWIyr%252BHGY4zUCkPuTIjMEmCseYmLctd%252FA%253D%253D/Rail_Market%2BBrochure_Protected_EN_1221.pdf

[93] T. Nabais, M. Stojadinović, and J. Biela, “Isolated MF DC-DC converter for traction battery application.” Accessed: Feb. 12, 2023. [Online]. Available: https://pdfs.semanticscholar.org/d91e/8b620634d9a4d1cda3e2c29ff9960c27d7a8.pdf

[94] Totally Fit for the Future–Mireo Plus B. Accessed: Jan. 25, 2023. [Online]. Available: https://www.mobility.siemens.com/global/en/portfolio/rail/stories/totally-fit-for-the-future-mireo-plus-b.html

[95] L. Olga and S. Alexey, “Tri-mode Hitachi trains to enter service in Italy in 2023,” 2022. Accessed: Mar. 8, 2023. [Online]. Available: https://rollingstockworld.com/passenger-cars/tri-mode-hitachi-trains-to-enter-service-in-italy-in-2023/

[96] The Hydroflex Hydrogen Powered Train Project—Webinar. Accessed: Nov. 26, 2022. [Online]. Available: https://youtu.be/bRUz2GRgaD8

[97] CASE STUDY—World’s First Fuel Cell Tram for Foshan, China, 2021. Accessed: Jan. 24, 2023. [Online]. Available: https://www.ballard.com/docs/default-source/motive-modules-documents/case-study-foshan-gaming-tram-final-web.pdf?sfvrsn=935ddd80_4,2021

[98] FLIRT H2: SBCTA and Stadler Strengthen Sustainable Rail Transport in the USA, 2022. Accessed: Jan. 24, 2023. [Online]. Available: https://www.stadlerrail.com/media/pdf/2022_0919_media%20release_innotrans_flirt%20h2_en.pdf

[99] FLIRT H_2—SBCTA, San Bernardino County Transportation Authority. Accessed: Feb. 12, 2023. [Online]. Available: https://www.stadlerrail.com/media/pdf/fh2sbcta0922e.pdf

[100] Talgo Initiates Dynamic Testing of Spain’s First Dual Hydrogen Train, 2022. Accessed: Jan. 24, 2023. [Online]. Available: https://www.talgo.com/-/talgo-comienza-las-pruebas-din%C3%A1micas-del-primer-tren-dual-de-hidr%C3%B3geno-de-espa%C3%B1a

[101] CAF FCH2RAIL Hydrogen Train Starts Test Runs, 2022. Accessed: Jun. 7, 2023. [Online]. Available: https://www.urban-transport-magazine.com/en/caf-fch2rail-hydrogen-train-starts-test-runs/

[102] JR East: Hitachi and Toyota to Develop Hybrid (Fuel Cell) Railway Vehicles Powered by Hydrogen, 2020. Accessed: Jun. 7, 2023. [Online]. Available: https://global.toyota/en/newsroom/corporate/33954855.html

[103] Alstom Coradia iLint–the World’s 1st Hydrogen Powered Train. Accessed: Nov. 25, 2022. [Online]. Available: https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-train

[104] D. Shirres, “Is hydrogen the answer?.” Accessed: Feb. 23, 2023. [Online]. Available: https://www.icheme.org/media/9621/david-shirres-is-hydrogen-the-answer-070319-v2.pdf

[105] Rail Decarbonisation: HydroFLEX Project—University of Birmingham. Accessed: Dec. 6, 2022. [Online]. Available: https://www.birmingham.ac.uk/research/spotlights/rail-decarbonisation.aspx

[106] Denchi Group SLICE Battery Storage System. Accessed: Dec. 6, 2023. [Online]. Available: https://www.cenex-lcv.co.uk/storage/seminar-programme/sessions/presentations/andrew_cowie_1568720454.pdf

[107] STADLER FLIRT H_2 Hydrogen Train. Accessed: Dec. 6, 2022. [Online]. Available: https://www.stadlerrail.com/en/flirt-h2/details/

[108] STADLER FLIRT H_2 Hydrogen Train for California, USA. Accessed: Dec. 6, 2022. [Online]. Available: https://www.electricandhybridrail.com/content/news/stadler-signs-mou-for-25-hydrogen-trains-for-california

[109] Ballard to Equip First Hydrogen Train in US With Fuel Cell Engines, 2022. Accessed: Jan. 24, 2023. [Online]. Available: https://www.railway-technology.com/news/ballard-fuel-cell-engines-hydrogen-train/

[110] Premiere ride: Siemens and Deutsche Bahn Test Hydrogen Train and Mobile Fueling Station for First Time. Accessed: Jan. 24, 2023. [Online]. Available: https://press.siemens.com/global/en/pressrelease/maiden-trip-deutsche-bahn-and-siemens-test-hydrogen-train-and-mobile-hydrogen

[111] D. Ronanki, S. A. Singh, and S. S. Williamson, "Comprehensive topological overview of rolling stock architectures and recent trends in electric railway traction systems," *IEEE Trans. Transp. Electrific.*, vol. 3, no. 3, pp. 724–738, Sep. 2017.

[112] J. F. Reynaud, M. Garmendia, and T. Nieva, "Comprehensive integration of onboard energy storage systems in tramways: Birmingham tram case study," in *Proc. IEEE Int. Conf. Elect. Syst. Aircr., Railway, Ship Propulsion, Road Veh. Int. Transp. Electrif. Conf.*, 2018, pp. 1–6.

[113] V. I. Herrera, H. Gaztañaga, A. Milo, A. Saez-de Ibarra, I. Etxeberria-Otadui, and T. Nieva, "Optimal energy management and sizing of a battery–supercapacitor-based light rail vehicle with a multiobjective approach," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 3367–3377, Jul./Aug. 2016.

[114] F. Vivas, F. Segura, J. Andújar, A. Calderón, and F. Isorna, "Battery-based storage systems in high voltage-DC bus microgrids. A real-time charging algorithm to improve the microgrid performance," *J. Energy Storage*, vol. 48, 2022, Art. no. 103935.

[115] *TC 9—Electrical Equipment and Systems for Railways—Railway Applications—Rolling Stock—Fuel Cell Systems for Propulsion—Part 1: Fuel Cell Power System*, Standard IEC 63341-1. Accessed: Dec. 4, 2022. [Online]. Available: https://www.iec.ch/technical-committees-and-subcommittees

[116] *TC 9—Electrical Equipment and Systems for Railways—ED1 Railway Applications—Rolling Stock—Fuel Cell Systems for Propulsion—Part 2: Hydrogen Storage System*, Standard IEC 63341-2. Accessed: Dec. 4, 2022. [Online]. Available: https://www.iec.ch/technical-committees-and-subcommittees

[117] Utilization of Fuel Cells for Trains—Coradia iLINT. Accessed: Feb. 1, 2023. [Online]. Available: https://www.jttri.or.jp/docs/180221_presentation-03.pdf

[118] Number of Hydrogen Fueling Stations for Road Vehicles Worldwide as of 2022, by Country. Accessed: Feb. 8, 2023. [Online]. Available: https://www.statista.com/statistics/1026719/number-of-hydrogen-fuel-stations-by-country/

[119] C. Streuling, J. Pagenkopf, M. Schenker, and K. Lakeit, "Techno-economic assessment of battery electric trains and recharging infrastructure alternatives integrating adjacent renewable energy sources," *Sustainability*, vol. 13, 2021, Art. no. 8234.

[120] N. Lyu, Y. Jin, R. Xiong, S. Miao, and J. Gao, "Real-time overcharge warning and early thermal runaway prediction of li-ion battery by online impedance measurement," *IEEE Trans. Ind. Electron.*, vol. 69, no. 2, pp. 1929–1936, Feb. 2022.

[121] Z. Wei, G. Dong, X. Zhang, J. Pou, Z. Quan, and H. He, "Noise-immune model identification and state-of-charge estimation for lithium-ion battery using bilinear parameterization," *IEEE Trans. Ind. Electron.*, vol. 68, no. 1, pp. 312–323, Jan. 2021.

[122] G. Yoshikawa, Y. Taguchi, K. Hatakeda, and T. Kaneko, "Development of a parameter identification method for the thermal circuit model of a lithium-ion battery installed on a battery-powered EMU," in *Proc. IEEE Veh. Power Propulsion Conf.*, 2017, pp. 1–5.

[123] Europe's Rail Joint Undertaking Master Plan, 2022. Accessed: Jun. 2, 2023. [Online]. Available: https://rail-research.europa.eu/wp-content/uploads/2022/03/EURAIL_Master-Plan.pdf

[124] Electrification of the Transport System: Studies and Reports, 2022. Accessed: Jun. 2, 2023. [Online]. Available: https://ec.europa.eu/newsroom/horizon2020/document.cfm?doc_id=46372

[125] K. G. Logan, J. D. Nelson, B. C. McLellan, and A. Hastings, "Japan and the U.K.: Emission predictions of electric and hydrogen trains to 2050," *Transp. Res. Interdiscipl. Perspectives*, vol. 10, 2021, Art. no. 100344.

[126] J. Marsh, "California could phase out diesel locomotives," 2023. Accessed: Jun. 4, 2023. [Online]. Available: https://www.freightwaves.com/news/california-could-phase-out-diesel-locomotives

[127] M. Steiner and J. Scholten, "Energy storage on board of railway vehicles," in *Proc. Eur. Conf. Power Electron. Appl.*, 2005, p. 10.

[128] V. Singh, "Efficient utilisation of regenerative braking in railway operations," *Int. Res. J. Eng. Technol.*, vol. 4, no. 12, pp. 1421–1428, 2017.

[129] A. Frilli, E. Meli, D. Nocciolini, L. Pugi, and A. Rindi, "Energetic optimization of regenerative braking for high speed railway systems," *Energy Convers. Manage.*, vol. 129, pp. 200–215, 2016.

[130] M. Ceraolo, G. Lutzemberger, A. Frilli, and L. Pugi, "Regenerative braking in high speed railway applications: Analysis by different simulation tools," in *Proc. IEEE 16th Int. Conf. Environ. Elect. Eng.*, 2016, pp. 1–5.

[131] I. Vermeij, "Opportunities and challenges in sharing digital twins," 2022. Accessed: Jun. 4, 2023. [Online]. Available: https://www.ricardo.com/en/news-and-insights/insights/opportunities-and-challenges-in-sharing-railway-digital-twins

[132] Europe's Rail WORK PROGRAMME 2023-2024 Adopted by the EU-Rail Governing Board on 30, 2022. Accessed: Jun. 2, 2023. [Online]. Available: https://rail-research.europa.eu/wp-content/uploads/2022/12/GB-Decision_14_2022_Annex_AWP_2023-2024-1.pdf

[133] N. D. Popovich, D. Rajagopal, E. Tasar, and A. Phadke, "Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric," *Nature Energy*, vol. 6, pp. 1017–1025, 2021.

[134] D. Hostert et al., "New energy outlook 2022—Bloomberg NEF," 2020. Accessed: Jun. 7, 2023. [Online]. Available: https://about.bnef.com/new-energy-outlook/

[135] A. Goodson, "How is artificial intelligence advancing battery energy storage for renewable plants?—Energy storage solutions—ABB electrification—Whitepaper," 2022. Accessed: Jun. 6, 2023. [Online]. Available: https://library.e.abb.com/public/01837325237641d093b9c237d0ef42a3/AI%20towards%20BESS%20whitepaper%20-2022-0722_DIGITAL_REV1_22-07-2022.pdf

[136] T. Lombardo et al., "Artificial intelligence applied to battery research: Hype or reality?," *Chem. Rev.*, vol. 122, no. 12, pp. 10899–10969, 2022.

[137] Z. Cui, J. Chen, C. Li, Y. Yin, and M. Hao, "The calculation and analysis of carbon emission in traction power supply system of high-speed rail," *Tehnički Vjesnik*, vol. 30, no. 1, pp. 226–234, 2023.

[138] France Bans Short-Haul Flights to Cut Carbon Emissions. Accessed: Jun. 12, 2023. [Online]. Available: https://www.bbc.com/news/world-europe-65687665

[139] ERTMS (European Rail Traffic Management System). Accessed: Jun. 5, 2023. [Online]. Available: https://transport.ec.europa.eu/transport-modes/rail/ertms_en

[140] Y. Cao, Z. Zhang, F. Cheng, and S. Su, "Trajectory optimization for high-speed trains via a mixed integer linear programming approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 10, pp. 17666–17676, Oct. 2022.

[141] M. Schenker and F. Kühlkamp, "Optimization model for operation of battery multiple units on partly electrified railway lines," in *Proc. 16th Int. Conf. Ecol. Veh. Renewable Energies*, 2021, pp. 1–8.

[142] C. Wu, W. Zhang, S. Lu, Z. Tan, F. Xue, and J. Yang, "Train speed trajectory optimization with on-board energy storage device," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 11, pp. 4092–4102, Nov. 2019.

[143] B. Zhang, C. Wu, G. Meng, F. Xue, and S. Lu, "Optimal sizing of onboard hybrid energy storage devices considering the long-term train operation," *IEEE Access*, vol. 10, pp. 58360–58374, 2022.

[144] T. Mizobuchi, K. Kondo, Y. Dairaku, T. Shinomiya, and K. Ishikawa, "Energy-management method to reduce the capacity of lithium-ion batteries in hybrid-voltage-source three-level inverter for DC-electrified railway vehicles," *IEEE Open J. Ind. Appl.*, vol. 3, pp. 41–55, 2022.

[145] J. P. Torreglosa, P. García, L. M. Fernández, and F. Jurado, "Predictive control for the energy management of a fuel-cell–battery–supercapacitor tramway," *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 276–285, Jan. 2014.

[146] W. Zhang, L. Wang, L. Wang, C. Liao, and Y. Zhang, "Joint state-of-charge and state-of-available-power estimation based on the online parameter identification of lithium-ion battery model," *IEEE Trans. Ind. Electron.*, vol. 69, no. 4, pp. 3677–3688, Apr. 2022.

[147] H. Lin, L. Kang, D. Xie, J. Linghu, and J. Li, "Online state-of-health estimation of lithium-ion battery based on incremental capacity curve and BP neural network," *Batteries*, vol. 8, 2022, Art. no. 29.

[148] B. Zhang et al., "Impact of on-board hybrid energy storage devices on energy-saving operation for electric trains in DC railway systems," *Batteries*, vol. 8, 2022, Art. no. 167.

[149] D. Da Fonseca-Soares, J. D. Galvinicio, S. A. Eliziário, and A. F. Ramos-Ridao, "A bibliometric analysis of the trends and characteristics of railway research," *Sustainability*, vol. 14, 2022, Art. no. 13956.

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