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REVIEW

Onboard energy storage in rail transport: Review of real applications and techno-economic assessments

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Abstract

Despite low energy and fuel consumption levels in the rail sector, further improvements are being pursued by manufacturers and operators. Their primary efforts aim to reduce traction energy demand, replace diesel, and limit the impact of electrified overhead infrastructures. From a system-level perspective, the integration of alternative energy sources on board rail vehicles has become a popular solution among rolling stock manufacturers. Surveys are made of many recent realizations of multimodal rail vehicles with onboard electrochemical batteries, supercapacitors, and hydrogen fuel cell systems. The ratings, technical features, and operating data of onboard sources are gathered for each application, and a comparison among different technologies is presented. Traction system architectures and energy-control strategies of actual multimodal units are explored and compared with literature research. Moreover, the maturity and potential of recent technologies and alternative topologies of power converters for multimodal traction systems are discussed. Ultimately, onboard storage systems are compared with other solutions for energy-saving and catenary-free operation, with particular focus on their current techno-economic attractiveness as an alternative to diesel propulsion.

1 | INTRODUCTION

The reduction of carbon emissions is a crucial factor in tackling climate change and improving air quality, with an emphasis on public health, the environment, and the economy. While significant results have been achieved in the energy and waste sectors, the transport sector is still behind. Indeed, transport currently accounts for almost 25% of Europe's greenhouse gas emissions and is the primary cause of air pollution in cities [1].

Europe's answer to emission targets in the transport sector is a growing push towards low-emission mobility. Rail is a very low-carbon form of transport for both passenger and freight service. However, railway electrification requires large investments in infrastructure and an expensive connection to the power grid. Therefore, many medium-traffic branches are still operated by diesel trains, raising concerns about journey time, air pollution, and noise. Such concerns encourage replacing traditional diesel vehicles with batteries, hydrogen fuel cells, and other low-carbon energy sources. Ultimately, all diesel vehicles should be taken off the network by 2050, in compliance with long-term emission targets set by the European Commission [2].

Currently, hybrid-electric trains are generally based on dual-mode diesel/electric powertrains. However, the last decade saw an increasing interest in rail vehicles with onboard energy storage systems (OESSs) for improved energy efficiency and potential catenary-free operation. These vehicles can minimize costs by reducing maintenance and installation requirements of the electrified infrastructure. Furthermore, they benefit from the high efficiency of the electric traction system and the reuse of recovered braking energy [3]. A major limitation to the widespread adoption of OESSs is the current state of the art of electrochemical and chemical energy storage technologies, given the severe operating requirements of rail vehicles. Rail systems with discontinuous electrification can employ storage units of reduced size compared to the case of non-electrified systems. Nevertheless, the OESS sizing problem in electrified networks poses many design challenges. Oversizing might unnecessarily increase the weight and volume of OESSs, while undersizing could be critical for energy efficiency and time-schedule compliance [4]. For the broader use of energy storage systems and reductions in energy consumption and its associated local environmental impacts, the following challenges must be addressed by academic and industrial research: increasing the energy and power density, reliability, cyclability, and cost competitiveness of chemical and electrochemical energy storage devices [5, 6]; integrate onboard and wayside storage systems and develop efficient control strategies for energy sources [7–12]; increase the power density of electronic converters and introduce new concepts and materials for traction motors [13–15].

Since a relevant number of OESSs have been tested and integrated onboard light rail vehicles (LRVs) in recent years, academic research on this topic has grown accordingly. Many studies and surveys about energy storage systems and multimodal propulsion concepts are found in the literature. In [16], the authors review onboard and wayside applications of electrochemical batteries, supercapacitors (SCs), and flywheels in urban rail systems. Particular detail is given to the analysis of standard techniques for the energy control of onboard supercapacitors. A similar contribution can be found in [17], where a non-comprehensive presentation of batteries, SCs, and flywheels for onboard and wayside storage applications is given. Reference [18] presents a complete classification of propulsion architectures for a wide range of rail applications. A brief discussion on OESSs and other techniques for saving energy is included but mainly confined to electrified railways. Furthermore, no design or operating data of actual OESS installations are collected. A broader technological analysis of electrochemical, mechanical, and superconductive storage systems is presented in [19], together with a review of some stationary and onboard storage applications. A detailed discussion of recent rail vehicles equipped with electrochemical and chemical OESSs is given in [20, 21]. A relevant amount of data is collected regarding the type of multimodal vehicles, the energy and power ratings of the OESSs, and autonomy under catenary-free operation. Despite that, there is no information regarding traction system architectures or control strategies. Moreover, these surveys lack a discussion about the techno-economic challenges of electrochemical and hydrogen energy systems.

In light of the above literature review, this paper aims to present a more comprehensive techno-economic survey of onboard electrochemical batteries, supercapacitors, and fuel cell systems for rail vehicles. To this end, the design and operating data of OESSs are collected as installed by manufacturers in real multimodal trains. The system-level energy and power densities of these realizations are compared to highlight to what extent theoretical feature ranges are affected by installation practices. Many multimodal propulsion architectures and energy management strategies are detailed. The analysis also comprises alternative solutions to energy management that are found in the literature. New technologies and non-conventional architectures of rail converters are surveyed to highlight current research trends and prospects. Finally, a discussion is presented about the pros and cons of OESSs, both as energy-saving technology in electrified systems and as an alternative to diesel in non-electrified railways. Specifically, economic assessments are reviewed to discuss the current cost attractiveness of battery and hydrogen trains to replace diesel in suburban and regional rail systems. The structure of this review paper is shown in Figure 1.

2 | CURRENT STATUS OF THE RAIL SECTOR

Rail is already among the lowest-emitting and most efficient transport sectors. Despite a 9% share of total passenger and freight transport activity, railways account for less than 2% of direct and well-to-wheel greenhouse gas (GHG) emissions and about 3% of final overall energy use. The energy consumption and global emissions of different transport sectors are highlighted in Figure 2 [22].

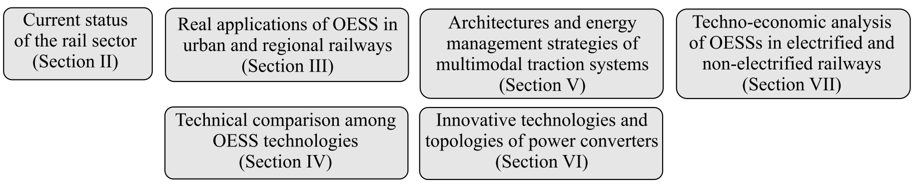


FIGURE 1 Structure and contents of the paper. OESS, onboard energy storage system

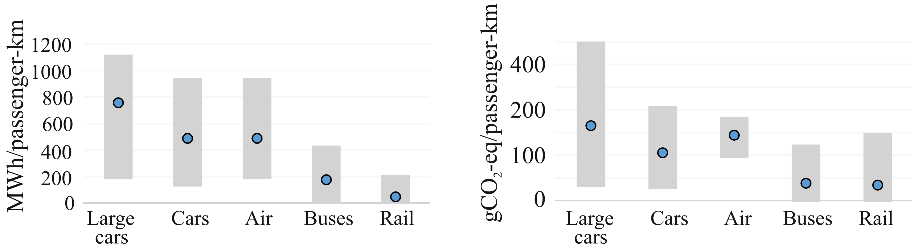


FIGURE 2 Global energy consumption and well-to-wheel CO_2-equivalent emissions per passenger-kilometre for different means of passenger transport [22]. The bars indicate the ranges of variation observed worldwide, while the blue dots indicate world averages. Energy and emission data are from 2017 and 2019, respectively. Passenger transport by rail is more energy-efficient and produces less greenhouse gas emissions than road and air alternatives

The low energy demand per passenger-km is due to lower losses caused by friction and drag, the higher energy efficiency of electrical drives than combustion engines, braking energy recuperation, and higher load capacities. On the other hand, electrification plays a vital role in the low GHG emissions of rail transport. The carbon impact of electrification depends on the generation mix among fuel and renewable sources, and many railway operators already use a significant share of renewable energies. In Europe, almost 40% of the electricity mix is low carbon, with an average of 20% produced directly from renewables [22]. Worldwide, several rail operators are increasingly operating their power plants to meet traction energy demand with a lower carbon imprint. In this context, the share of renewable and nuclear energy in the global railway electricity mix increased more than twofold from 1995 and was at 13.5% in 2015, as shown in Table 1.

Regarding the share of usage between electricity and diesel, electric trains run three quarters of passenger-km and about half of freight tonne-km worldwide. However, large differences exist among countries and between freight and passenger activity: Japan, Russia, and Europe lead the chart while North and South America still rely heavily on diesel [22]. Despite a high share of electric trains in passenger transport and a general trend towards electrification, only one third of the rail tracks worldwide are electrified. Again, big differences among countries exist, from more than 75% track share in Korea, to 50%–60% in Europe, Japan, Russia, and India, and to a modest few percent in North and South America. Figure 3 summarizes fuel utilization and electrified track shares for the global rail sector from 2000 to 2016.

TABLE 1 Railway energy generation mix in 1990 and 2015 [23]

		1990	2015
Oil Products		57.9%	56.0%
Coal Products		24.8%	4.8%
Biofuels		0.0%	0.4%
Electricity	Fossil	11.0%	25.7%
	Nuclear	2.9%	4.1%
	Renewables	3.4%	9.0%

Global rail activity is slowly shifting towards electricity for both passenger and freight transport. Passenger transport is significantly more electrified than freight transport: areas with the highest share of electricity use (i.e. Europe, Japan, and Russia) tend to be those with the highest passenger rail activity. Electrified rail routes have higher utilization rates than non-electric ones: on average, five times more passenger-km per track-km and twice as many tonne-km runs. High throughput of passengers or freight is necessary to shorten the payback period of the needed investments. Virtually all urban networks use electric trains, while conventional passenger transport relies on electricity to meet about 60% of its needs [23].

Suburban and regional services account for about three quarters of total passenger activity. However, these railway systems have generally experienced little change in extension over the past 20 years. In contrast, urban and high-speed rails have experienced rapid growth in passenger activity and track length, primarily due to unprecedented investments made in Asia. Between 2005 and 2016, high-speed rail tracks increased by 187% in Europe, while China has built two thirds of the global high-speed lines after starting with virtually none. In the last decade, metro and light rail lines grew by 3.5% per year. Higher rates were recorded in largely populated cities, where the unparalleled passenger capacity of light rail systems can significantly reduce road congestion and air pollution. Again, China accounts for almost half of the total urban rail activity and stands as the main driver behind this transit mode's growth [24].

3 | REAL APPLICATIONS OF ONBOARD ENERGY STORAGE SYSTEMS

Rail transport has experienced significant improvements in energy efficiency and GHG emissions reductions, equating to more than a 20% change in each over the past 20 years [23]. Manufacturers have increasingly employed multimodal vehicles with onboard storage devices as a feasible solution to accomplish further improvements. Indeed, numerous OESSs

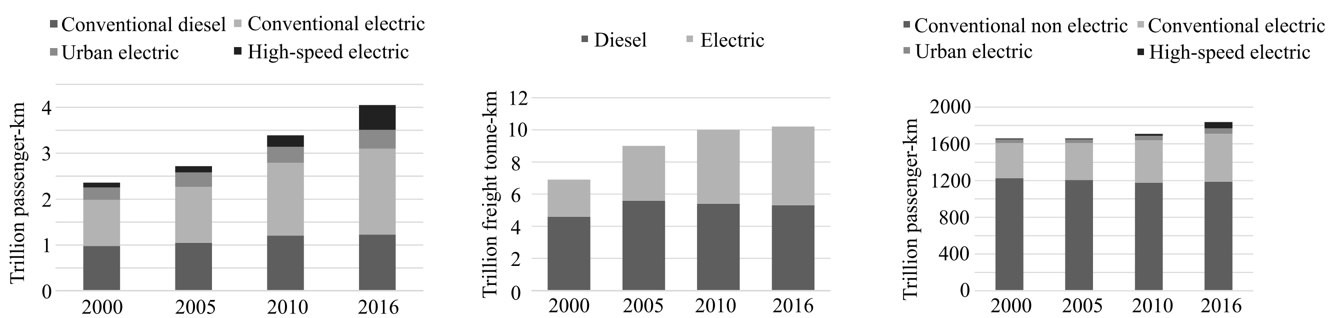


FIGURE 3 Evolution of electricity (left), fuel use (centre), and share of electrified lines (right) in global rail transport from 1995 to 2015 [24]. Conventional rail comprises suburban and regional services, while urban rail aggregates metro and light rail transit. Passenger transport is mainly operated by electric trains, while freight transport still relies more on diesel propulsion. Big differences in the electrification share of rail tracks are observed among geographic regions. The trends show a progressive shift towards electrified trains in both applications; however, most of the tracks worldwide are still lacking electrification

for energy-saving enhancement and catenary-less operation in urban and regional services have been developed and adopted worldwide in the last decade. Many of these applications are reviewed here. Throughout the remainder of this paper, the nomenclature shown in Figure 4 will be adopted for rail vehicles with multiple energy sources.

3.1 | Bimodal vehicles with onboard batteries

A relevant number of urban and regional rail vehicles with onboard batteries are in operation in Europe, America, and Asia at this time. Practical use of such storage devices has shown that energy savings, line voltage stabilization, and catenary-free operation can be effectively achieved [16]. Among many different chemistries, nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion) batteries represent a standard solution for rolling stock manufacturers [17]. Ni-MH batteries are the most common nickel-based batteries on the market, guaranteeing robust reliability and low maintenance. However, they exhibit poor efficiency and a high self-discharge rate. Li-ion batteries represent the leading technology for portable electronics and have gained momentum in electric traction applications due to considerable incentives and cost reductions. These batteries exhibit higher energy and power densities, with high efficiencies and low self-discharge rates. However, they suffer from limited durability and high capital costs [19]. Although Li-ion batteries are often treated as a homogeneous group, different chemistries yield different performance and costs, as shown in Figure 5. While nickel-metal-cobalt (NMC) and lithium-manganese-oxide (LMO) batteries feature a higher energy density, they suffer from lower lifetimes. Conversely, lithium-titanate (LTO) and lithium-iron-.

In April 2003, a remodelled battery/catenary hybrid 120 kW tramcar (the 'Lithey-Tramy') with LMO batteries was put on a test run by the Railway Technical Research Institute (RTRI) in Japan [26]. The distance achieved in wireless operation was 17.4 km, with stops every 250 m and speeds up to 40 km/h. The battery's maximum power, energy, and weight were 300 kW, 33.0 kWh, and 1160 kg, respectively. The energy density of the whole device was 28 Wh/kg, approximately one half the energy density of single LMO cells [27]. In January 2005, this vehicle was equipped with a new contact-wire/battery hybrid current reversible step-down chopper corresponding to a 750 V or 1500 V electrified line.

A prototype LMO Li-ion battery pack for battery tramcar testing was developed at Fukui University in Japan in 2007 [28]. The battery pack consisted of 18 submodules, each one comprising nine parallel-connected strings of 12 cells each. The energy and weight of the battery pack were 45 kWh and 540 kWh, respectively, with an overall energy density of 83 Wh/kg, around 30% less than the energy density of the single cells and three times higher than what achieved by RTRI in 2003. The prototype tram was tested on the Fukubu business line of Fukui railway and ran up to 25 km on one charge with a maximum speed of 65 km/h.

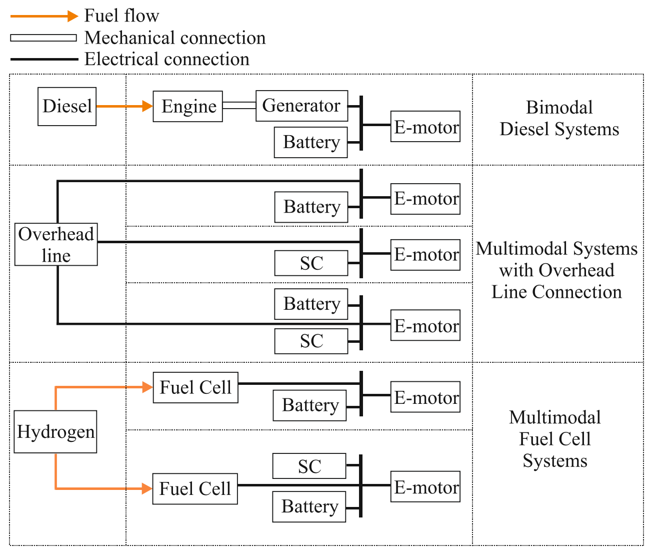


FIGURE 4 Topological classification of rail vehicles with onboard energy sources

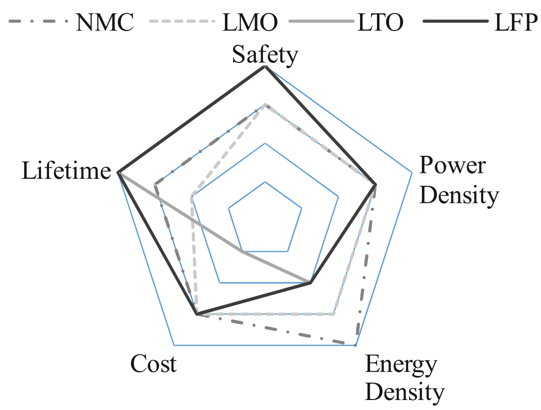


FIGURE 5 Comparison of the primary Li-ion battery chemistries [25]. LFP, lithium-iron-phosphate; LMO, lithium-manganese-oxide; LTO, lithium-titanate; NMC, nickel-metal-cobalt

Since 2001, Hitachi Ltd. has been developing hybrid drive systems to reduce environmental load. In collaboration with East Japan Railway Company (JR East), Hitachi developed the prototype 'NE Train' equipped with a series hybrid powertrain. A diesel generation unit and a Li-ion storage system powered two electric motors for a total traction power of around 400 kW. The experience gathered through the NE Train project eventually led to the realization of the KiHa E200 series hybrid diesel-electric multiple units (DEMUs) [29]. In these single-car vehicles, each of the two roof-mounted battery packs comprises eight submodules for total installed energy and power of 15 kWh and 270 kW [30]. Together with a 230 kW diesel generating unit, the batteries supply two induction motors for a traction power of around 200 kW. Since 2007, these hybrid DMUs are in regular service together with standard diesel multiple units (DMUs) on the Koumi line in Japan. In 2010, the HB-E300 and HB-E210 series railcars with the same hybrid system of the KiHa E200 began operational service on the Ou, Gono, and Senseki Tohoku lines in Japan.

In 2007, JR Hokkaido and Hitachi Nico Transmission Ltd performed tests on a prototype diesel/battery hybrid railcar with a parallel-hybrid powertrain. In this vehicle, a 240 kW diesel engine was assisted by a 120 kW traction motor connected to it through a proper transmission system. The motor was powered by a Li-ion battery with rated energy and power of 7.5 kWh and 190 kW [31]. The running tests aimed to evaluate the reduction in fuel consumption for a baseline diesel configuration. The differences between the considered parallel-hybrid architecture and the more common series hybrid one was also addressed.

Since November 2007, a fleet of 'Citadis' catenary/battery hybrid tram vehicles by Alstom has been in regular passenger service on the T1 tramway line in Nice. The tramcars are equipped with Ni-MH batteries and have estimated energy and weight of 27.7 kWh and 1450 kg, respectively [32]. Catenary-free operation is carried out on a four-stop 900 m segment between Massena and Garibaldi, as installation of overhead wires would severely impact the aesthetics of the historical centre.

In Japan's electrified line of Sapporo Municipal Transport, a prototype catenary/battery hybrid LRV by Kawasaki Heavy Industries named 'SWIMO' was put in operation from December 2007 to March 2008. The vehicle, equipped with proprietary Ni-MH battery technology, could run up to 37.5 km with a maximum speed of 40 km/h on a single charge [26]. The onboard storage system consisted of a series of 16 modules of 7.5 kWh and 200 kg each, for a total energy density of around 37.5 Wh/kg [33]. SWIMO is currently available in the portfolio of low-floor LRVs by Kawasaki.

In November 2007, a 240 kW prototype catenary/battery hybrid tram called 'Hi-tram' with onboard LMO lithium-ion batteries was developed and tested by RTRI. The rated values of maximum power, rated energy, and weight were 600 kW, 72 kWh, and 2000 kg, for an overall installed energy density of 36 Wh/kg [32]. Several tests were conducted on the Hi-tram from November 2007 to November 2009. The maximum catenary-free distance achieved during tests on Sapporo tramway in 2007–2008 was 25.8 km at a maximum speed of 40 km/h, while 4 km or more could be run with a 60 s partial recharge (around 14% of rated capacity) from the catenary at a current of 1000 A. The recorded regenerative ratio, the amount of regenerated energy divided by the energy consumed in operation, was 41%. In November 2009, further testing was carried out at higher speeds on the Yosan railway, resulting in 60 min, 49.1 km catenary-free operation with a regenerative ratio of 23.9% [34].

In March 2013, RTRI completed the conversion of a series 817-100 AC electrical multiple units (EMU) into an AC catenary/hybrid EMU test train [35]. The project's primary purpose was to analyze the capabilities of battery-powered vehicles running on routes with partial AC electrification. The onboard air-cooled battery was based on LMO Li-ion cells and featured rated energy and weight of 83 kWh and 1536 kg, respectively, for an overall energy density of around 54 Wh/kg. Running tests were performed on the electrified Chikuho main line and the non-electrified Hitahikosan line. The longest distances achieved in wireless operation at a maximum speed of 80 km/h ranged from 30.4 km in the summertime to 20 km in wintertime, depending on the amount of energy absorbed by air-conditioning. Quick-charging tests were also conducted—the battery state of charge (SOC) increased by 20% to 95% for a charging time of 8 to 12 minutes, depending on the battery temperature. According to the authors, the experimental results demonstrated sufficient performance of the dual-source EMU on electrified and non-electrified routes.

After the commissioning of the hybrid diesel KiHa E200 railcar in 2007, JR East has continued to work to reduce the environmental impact of railway vehicles. In 2008, development was started on a hybrid powertrain that could operate on non-electrified segments [36]. As a result, in March 2014, the catenary/battery hybrid series EV-E301 trains began commercial service on the electrified Tohoku line and the non-electrified Karasuyama line. The trains are equipped with two Li-ion battery packs of 95 kWh each and four induction motors with a total traction power of 380 kW. On the Karasuyama line, the trains run without catenary for 22.4 km at a maximum speed of 100 km/h and are recharged at the terminal station of Karasuyama through stationary fast-charge facilities [37].

In January 2015, a prototype catenary/battery hybrid EMU was put into passenger service in the United Kingdom. As part of a project founded by Network Rail, Bombardier modified an existing Class 379 Electrostar train by installing a Li-ion battery pack on board [38]. The target was to operate the train on battery power up to 120 km/h for a distance up to 50 km, requiring a battery capacity of around 500 kWh [39]. The vehicle could also be powered and recharged by the 25 kV AC overhead line. Bombardier has since received orders for battery electric units—for example, a contract was signed with Austrian Federal Railway (ÖBB) in July 2018 for the delivery of 25 battery EMUs to be operated in regional transit [20].

In April 2015, Kagoshima Transportation Bureau and Toshiba started running tests on a new catenary/battery hybrid tram [40]. Drawing power only by a 23.4 kWh Li-ion LTO battery pack manufactured by Toshiba, the vehicle ran approximately 10 km in catenary-free mode on the Toso line from Kagoshima eki-mae to Korimoto.

Between mid-2016 and early 2019, Japanese railway operator JR Kyushu put several BEC819 series catenary/battery hybrid trains manufactured by Hitachi into service. These units can run under both catenary and onboard battery power. The rated energy of the onboard battery is about 360 kWh at 1600 V [35]. Battery power is mainly employed on two non-electrified routes: an 11 km section on the Wakamatsu main line and the entire Chikuho regional line. On the latter route, one halfway recharge is needed for the trains to cover the entire distance of 25.4 km.

Since 2014, a fleet of 15 'Flexity 2' catenary/battery hybrid tramcars manufactured by Bombardier and CSR Puzhen is in service in the Chinese city of Nanjing [41]. The vehicles are equipped with proprietary 'PRIMOVE' battery technology based on NMC Li-ion chemistry, which provides 98 kWh of nominal energy for each tram. The vehicles are operated on the 8 km long Hilin line and 9 km long Hexi line and run catenary-free for around 90% of their route, as overhead wires are installed mainly in stations or steep-gradient sections [42]. The battery packs are charged at stops in around 45 s.

Following the example of Nanjing, several city authorities around Europe and America have ordered and put into commercial service battery tramcars from 2014 on [41]. In the United States, the manufacturer Brookville Equipment Co. has provided its Liberty Modern catenary/battery hybrid streetcar to the cities of Dallas (TX), Detroit (MI), and Oklahoma City (OK). The streetcar has an installed traction power of around 280 kW and can run without catenary on non-electrified segments due to an NMC Li-ion battery installed on board. In these cities, the average catenary-free operation is carried out on half of the total length of the tramway lines. In Dallas, battery power is used along the 1.6 km Houston Street viaduct between Union Station and Trinity River, which lacks overhead wires. In Seattle, the First Hill Streetcar line is operated since 2016 with six catenary/battery hybrid Trio 121 streetcars by railway manufacturer Inekon. Each car is equipped with two Li-ion battery packs featuring 30.4 kWh of rated energy and 1500 kg of total weight for an overall energy density of around 20 Wh/kg. The streetcars operate without overhead wire for the entire 3.8 km inbound journey, which is predominantly downhill. In Brazil, a fleet of catenary/battery hybrid 'Tramlink V4' tramcars are in service in the metropolitan area of Santos. The onboard storage enables catenary-free operation on a short section of the route in the city centre [43].

In Europe, a few other LRVs with only batteries as an additional energy source have been put into service since 2007. In Konya, Turkey, 12 'Forcity Classic 28T' catenary/battery tramcars started operation in 2015. The vehicles are equipped with batteries based on LTO Li-ion cells and can run without overhead wire for a distance of approximately 2 km [38]. In 2018, railcar manufacturer CAF proposed a retrofitting of the operating fleet of 'Urbos 100' tramcars on the West Midlands Metro line connecting Wolverhampton with Birmingham [44]. The catenary/battery hybrid vehicles are equipped with 80 kWh LFP Li-ion batteries to operate without overhead wire on a non-electrified extension in Birmingham city centre between Grand Central and Library stops, which has been completed in December 2019 [45]. Catenary-free operation is also considered on the Edgbaston and Wolverhampton extensions currently under construction. In July 2019, the city of Timisoara in Romania signed a contract with Bozonkaya A.S. to deliver 16 battery-powered trams to enter operation in 2021, when the Rumanian city becomes the European Capital of Culture [46].

In 2018, Bombardier's 'Talent 3' catenary/battery train was unveiled to the public. The vehicle is a 3-car battery electrical multiple unit (BEMU) meant for regional transport. It can run under 15 kV AC catenary and battery power with a maximum speed of 140 km/h. The onboard battery packs of a first demonstrator feature NMC technology for overall rated energy of 300 kWh, with a catenary-free range of around 40 km [47]. The project is now in the testing and homologation phase. Delivery orders for fleets of Talent 3 trains have been signed recently by Bombardier with transportation authorities in Austria, Germany, and Italy [47].

In October 2018, Stadler Rail and Welsch railway operator Keolis Amey Operations Ltd. signed a contract to deliver 24 trimodal multiple units in February 2019 [48]. These units can travel under overhead lines at 25 kV AC and on non-electrified routes owing to onboard battery energy. The accumulators are based on Li-ion LTO technology and have rated energy of 180 kWh, enabling the vehicle to range up to 80 km in catenary-free mode. Diesel generation units are also provided for battery charging and improved dependability in case of battery failure. The vehicles are expected to begin operation on the partially electrified South Wales railway network by 2023. In the same year, Vivarail launched a two-car Class 230 demonstrator equipped with two Li-ion battery packs. The batteries have rated energy of around 420 kWh and enable wireless operation up to 64 km [49]. The prototype vehicle ran successfully in trial passenger service on the Bo'ness & Kinneil Railway with the support of Transport Scotland and Scotrail in October 2018. Moreover, trials on a three-car diesel-battery hybrid Class 230 train have been carried out since autumn 2019. This vehicle is based on the two-car battery prototype but includes a third car equipped with four diesel generators. A fleet of five such units was scheduled to begin passenger operation by Transport of Wales rail services in 2020 [20, 50].

Since September 2019, a prototype catenary/battery EMU manufactured by Siemens for ÖBB has entered passenger operation on non-electrified routes in low Austria as part of the 'Update Fleet Strategy 2035' program undertaken by the local operator [51]. The train has a maximum traction power of 2.6 MW and is powered from a 15/25 kV AC overhead line and a 528 kWh LTO Li-ion battery with an expected catenary-free range of around 80 km [52]. The test program will determine the availability of such trains on the ÖBB network. Potential sites for charging stations will be identified to offer an alternative to diesel traction for regional railway transit.

Table 2 summarizes the features of commercial and prototype railway vehicles with onboard batteries, including vehicle size, railway type, battery technology, and energy and power ratings. Figure 6 provides a general picture of the energy capacity and off-wire autonomy of the abovementioned battery vehicles.

3.2 | Bimodal vehicles with onboard supercapacitors

Compared with batteries, supercapacitors exhibit higher power densities and longer lifecycles [19]. The lack of chemical reactions on the electrodes ensures a very low internal resistance and higher efficiencies. At the same time, specific energy and daily self-discharge typically exhibit worse values than battery systems. Due to these features, SCs are considered an excellent choice as a secondary energy source in catenary vehicles when regeneration of braking energy and power assist during heavy load operation is of primary importance.

TABLE 2 Rail vehicles with onboard batteries

#	Place, year	Rail system	Vehicle info	Owner/installer	Battery type	Energy [kWh]	Power [kW]	Off-wire length [km]	Total length [km]	Ref.
1	Japan 2003	Light rail (750-1500 VDC)	Mo3301 car[a] (120 kW)	RTRI	LMO	33	300	17.4	n.a.	[26, 27]
2	Fukui (JP) 2007	Light rail (600 VDC)	Nagoya Railroad 602-type[a]	Fukui Univ.	LMO	45	45	25	n.a.	[28]
3	Japan 2007	Regional rail	'KiHa E200' DMU(400 kW)	Hitachi	LMO	15.2	270	78.9	n.a.	[29, 30, 53]
4	Japan 2007	Light rail	LRV[a] (360 kW)	JR Hokkaido	(Li-ion)	7.5	192	n.a.	n.a.	[31]
5	Nice (FR) 2007	Light rail (750 VDC)	'Citadis 302'tram	Alstom	Ni-MH	27.7	200	0.91	8.7	[31]
6	Sapporo (JP) 2007	Light rail (600 VDC)	LRV(100 kW)	Kawasaki	Ni-MH	120	250	37.5	n.a.	[26, 33]
7	Sapporo (JP) 2007	Light rail (600 VDC)	LRV[a] (240 kW)	RTRI	LMO	72	600	Up to 49	n.a.	[32, 34]
8	Japan 2013	Light rail	'Series 817-1000' EMU[a] (600 kW)	RTRI	LMO	83	560	Up to 30	n.a.	[35]
9	Japan 2014	Regional rail (1500 VDC partial)	'EV-E301' EMU(380 kW)	J-TREC	LMO	190	630	22.4	34.1	[36, 37]
10	Nanjing (CN) 2014	Light rail (750 VDC)	'Flexity 2' tram (480 kW)	Bombardier	NMC	98	244	90% of route	7.6 (16 with future extension)	[20, 42, 54]
11	Essex (UK) 2015	Regional rail (25 kV AC)	Class 379 Electrostar EMU[a]	Bombardier	LFP	500	n.a.	Up to 50	n.a.	[20, 38, 39]
12	Dallas (US) 2015	Light rail (750 VDC)	'Liberty Modern' streetcar (390 kW)	Brookville Equipment	NMC	84.1	340	1.6	3.9	[55–58]
13	Konya (TR) 2015	Light rail (750 VDC)	'Forcity Classic 28T' tram (400 kW)	Skoda	LTO	n.a.	n.a.	1.8	21	[38, 41]
14	Santos (BR) 2015	Light rail (750 VDC)	'Tramlink V4' tram (420 kW)	Stadler rail	LTO	n.a.	n.a.	0.4	11.4	[41, 43]
15	Kagoshima (JP) 2015	Light rail (600 VDC)	'Little Dancer' tram[a]	Kagoshima Transp. Bureau	LTO	24.3	n.a.	Up to 10	n.a.	[40, 41]
16	Japan 2016	Regional rail (20 kV AC)	'BEC-819' EMU (380 kW)	Hitachi	(Li-ion)	360	1080	10.8	66.1	[35]
17	Seattle (US) 2016	Light rail (750 VDC)	'121 Trio' streetcar (260 kW)	Inekon	(Li-ion)	60.7	n.a.	4 (downhill)	n.a.	[55]
18	Detroit (US) 2017	Light rail (750 VDC)	'Liberty Modern' streetcar 260-300 kW)	Brookville Equipment	NMC	n.a.	n.a.	5 approx.	10.6	[55]
19	Oklahoma city (US) 2018	Light rail (750 VDC)	'Liberty Modern' streetcar (260-300 kW)	Brookville Equipment	(Li-ion)	n.a.	n.a.	3 approx.	7.7	[55]
20	Japan 2018	Regional rail	'BEC-819' EMU(380 kW)	Hitachi	(Li-ion)	360	1080	All route	25.4	[35]

(Continues)

TABLE 2 (Continued)

#	Place, year	Rail system	Vehicle info	Owner/installer	Battery type	Energy [kWh]	Power [kW]	Off-wire length [km]	Total length [km]	Ref.
21	Birmingham (UK) 2018	Light rail (750 VDC)	'Urbos 100' tram	CAF	LFP	80	400	0.6 (2.3 km future extension)	21	[44]
22	Wales (UK) 2018	Regional rail	'Class 230' EMU	Vivarail	(Li-ion)	420	n.a.	Up to 64	n.a.	[49]
23	Germany 2018	Regional rail (15 kV AC)	'Talent 3' EMU (~1500 kW)	Bombardier	NMC	300	n.a.	Up to 40	n.a.	[47]
24	Timisoara (RO) 2021	Light rail (600 VDC)	Tram (480 kW)	Bozankaya A.S.	n.a.	n.a.	n.a.	n.a.	n.a.	[46, 59]
25	Wales (UK) 2023	Regional rail (25 kV AC)	'Flirt' hybrid DMU (2.6 MW)	Stadler rail	LTO	180	n.a.	Up to 80	n.a.	[20, 48]
26	Austria 2019	Regional rail (15/25 kV AC)	'Cityjet Eco' EMU (2.6 MW)	Siemens	LTO	528	1300	Up to 80	n.a.	[52]
27	Germany 2023	Regional rail	'Mireo plus B' (1.7 MW)	Siemens	n.a.	700	n.a.	Up to 120	n.a.	[60]

Abbreviations: LFP, lithium-iron-phosphate; Li-ion, lithium-ion; LMO, lithium-manganese-oxide; Ni-MH, nickel-metal hydride; NMC, nickel-metal-cobalt.
[a]Prototype vehicle.

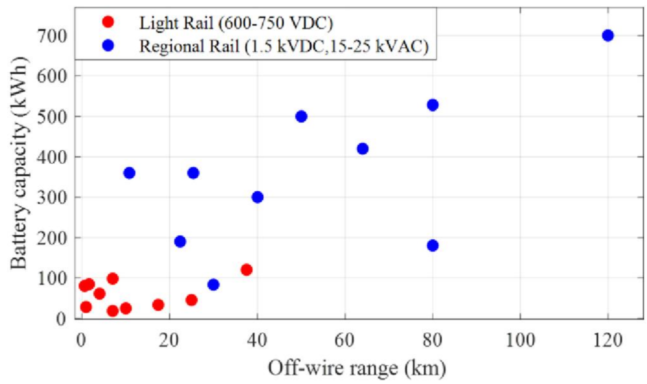


FIGURE 6 Distribution of onboard energy capacity and wireless autonomy for the bimodal battery trains reported in Table 2

The first representative example of an electric double-layer capacitor (EDLC) installed on board is the MITRAC module first developed by Bombardier in 2003 [61]. The storage system was installed and demonstrated on a prototype LRV with a catenary/EDLC hybrid powertrain and a total traction power of around 380 kW. Each EDLC module featured a rated energy and capacitance of 850 Wh and 45 F, respectively, while providing a maximum power of 300 kW with a weight of 477 kg. This resulted in specific energy and power of 1.78 Wh/kg and 629 W/kg for each air-cooled module. The tests carried out showed a considerable reduction in the power and energy demand from the overhead line, with a 50% reduction in the current drawn from the pantograph and consequent stabilization of the line voltage [62]. Furthermore, the vehicle was operated in catenary-free operation for 500 m with speed up to 26 km/h. After the initial testing, the system has become commercially available on Bombardier's 'Flexity 2' LRV. Since 2012, 'Variobahn' rolling stock equipped with MITRAC module is in passenger service on the Mannheim to Heidelberg line in the Rhine-Neckar Land, Germany [41].

In January 2005, the Central Japan Railway Company (JR Central) and Toshiba Co. installed an onboard experimental storage system based on EDLCs on the Series 313 trains operating on the electrified Chuo line in Japan [63]. The storage devices featured 600 Wh and 180 kW of rated energy and power, with a total weight of 430 kg and consequent specific energy and power of 1.4 Wh/kg and 418 W/kg, respectively. Experimental tests on the catenary/EDLC hybrid units showed a modest 1.6% reduction in the peak power demand from the overhead wire during accelerations due to the amount of energy stored in previous braking phases. Moreover, the systematic use of regenerative braking led to a relevant reduction in the pressure and temperature distribution at the brake cylinders and wheel treads, resulting in reduced mechanical wear and improved lifetime.

Several catenary/EDLC hybrid 'Citadis 402' tram vehicles started passenger service on the T3 line Paris in 2009, under the STEEM project undertaken by Alstom, public transport operator RATP, and public research institute INRETS [64]. The main aims of the project were energy-saving and wireless operation capability. Each vehicle was equipped with 48 submodules for an overall energy and power rating of 1.6 kWh and 500 kW. The entire system weight was 1340 kg, resulting in a specific energy and power of 1.2 Wh/kg and 373 W/kg. Measures performed in springtime showed an average daily energy reduction of 13% compared with a baseline vehicle, a good result considering the high receptivity of the chosen tramway line. Moreover, catenary-free operation was successfully achieved on a 300 m long segment between Porte d'Italie and Porte de Choisy.

Spanish manufacturer CAF has been developing onboard storage solutions for railway vehicles since around 2010. One of these, the 'Greentech Evodrive' system, is based only on SCs and has been specially designed for trams to recover kinetic energy during frequent braking phases [65]. Catenary/EDLC hybrid trams equipped with Evodrive systems have been in commercial service in Cuiabà, Brazil, and Tallinn, Estonia since 2015 [66].

During the same period, Siemens entered the market of onboard SCs with the 'Sitras MES' module, which is claimed to be versatile enough to be installed on new vehicles or integrated into existing vehicles for retrofitting. Application of Sitras MES can be found on tramways of Innsbruck, Austria, and Guangzhou, China. According to the first case, a 0.85 kWh, 288 kW and 820 kg system has been employed in the manufacturer [67]. This translates in overall specific energy and power values of approximately 1 Wh/kg and 351 W/kg. The vehicles run without catenary on the entire non-electrified 7.7 km long route on the Guangzhou tramway, with the SCs being the only available energy source [41].

Other tram vehicles equipped with SCs in passenger service can be found in Shenyang, China, and Kaohsiung, Taiwan [41]. In Shenyang, supercapacitors are employed together with an overhead line and a wireless operation only on short sections. On the other hand, the vehicles in Kaohsiung are powered only by SCs for operation on the non-electrified 8.2 km long route in present service and on the future 13.4 km long extension currently under completion [67]. Others have been running in the last decade in Portland, USA, Rostock, Germany, and Wroclaw, Poland.

Table 3 summarizes commercial and trial railway vehicles with onboard storage systems based solely on supercapacitors.

3.3 | Multimodal vehicles with onboard batteries and supercapacitors

Hybrid energy storage systems (HESSs) comprising batteries and SCs can offer unique advantages due to the combination of the advantages of the two technologies: high energy density and power density. For this reason, HESSs have gained momentum for application in light railway systems.

In 2008, LRVs operated on the 'Metro Ligeiro da Margem Sul do Tejo' (MTS) railway in Almada, Portugal, were fitted with a HESS developed by Siemens. This system, named 'Sitras HES', was installed to reduce the power demand from the overhead wire and enable partial catenary-free operation [38]. Since then, the vehicles have been in standard revenue service. Sitras HES is a flexible modular solution whose rated energy and power can be made application specific. In MTS trams, the Ni-MH battery features rated energy and power of 18 kWh and 85 kW, respectively, while the supercapacitors' rated power output is 288 kW. The total weight of the hybrid storage system is 1646 kg, resulting in specific energy and power of 11.45 Wh/kg and 226 W/kg, respectively. The storage solution demonstrates effective energy savings and wireless operation capability up to 2.5 km. Since 2016, tram vehicles running on the tramway line in Doha, Qatar, have been equipped with Sitras HES devices for catenary-free operation on the entire 11.5 km long route, with the storage system being recharged at each of the 25 stops [19].

Spanish rolling stock manufacturer CAF is an established player in the market of onboard HESS. Its 'Freedrive' modules comprise air-cooled supercapacitor and air-cooled battery branches. As of 2014, each SC branch featured rated energy and power of 435 Wh and 50 kW (100 kW peak power), while each battery branch is made up of Ni-MH cells for total energy and power of 12 kWh and 10 kW (48 kW of peak power), respectively [32]. Since 2011, CAF has delivered fleets equipped with Freedrive modules to the cities of Seville, Zaragoza, and Granada in Spain, Kaohsiung in Taiwan, Luxembourg in Luxembourg, Newscastle in Australia [19, 39]. Some of these tramways are completely catenary-free with charging at stops, while others are typically electrified and require onboard energy only along a segment of the route.

Although usually associated with ground power supply technology, Alstom has also developed its own proprietary modular HES solution, named 'Ecopack'. Reported applications of such systems can be found in the 'Citadis' trams operating in Rio de Janeiro, Brazil, and Nice, France, since 2015 and 2018, respectively [32]. In the Brazilian city, onboard storage is used in conjunction with ground power supply since 2015 to avoid catenary installation on the entire line. In Nice, the vehicles equipped with Ecopack modules have Ni-MH batteries with rated energy of 13.5 kWh that can be recharged at stops and ensure catenary-free operation on the entire 11.3 km long T2 tram line [17].

Table 4 reports the documented applications of onboard HESSs in urban and regional rail vehicles.

3.4 | Multimodal vehicles with fuel cell systems

Hydrogen technology has been long suggested as a promising alternative for many road and railway transport applications. Several studies by academia, consulting agencies, and government departments show that hydrogen may be a feasible alternative to fossil fuel transportation. In railway applications, this holds particularly true where long-term technical-economic factors make electrification of non-electrified routes a poor option, as in low-traffic rural railways [71]. Hydrogen storage is a key enabling technology for the significant advancement of hydrogen vehicles. In the last decades, fuel cell developers have made significant steps beyond the proof-of-concept phase, with

TABLE 3 Rail vehicles with onboard supercapacitors

#	Place, year	Rail system	Vehicle info	Owner/installer	Energy rating [kWh]	Power rating [kW]	Off-wire length [km]	Total length [km]	Ref.
1	Mannheim (DE) 2003	Light rail (750 VDC)	LRV[a] (380 kW)	Bombardier	0.85	300	0.5	n.a.	[61]
2	Japan 2005	Regional rail (1500 VDC)	'313 series' EMU[a]	Central JR/Toshiba	0.6	180	n.a.	87.8	[63]
3	Paris (FR) 2009	Light rail (750 VDC)	'Citadis 402' tram	Alstom/RATP/ INRETS	1.6	500	0.35	7.9	[64]
4	Innsbruck (AT) 2011	Light rail (600 VDC)	LRV	Siemens	0.85	288	n.a.	19.5	[67]
5	Rhine-Neckar (DE) 2012	Light rail	'Variobahn' LRV	Stadler	n.a.	n.a.	n.a.	n.a.	[41]
6	Portland (US) 2012	Light rail	'SD660' tram	American Maglev/ Maxwell	0.7	n.a.	None	97	[65]
7	Cuiabà (BR) 2012	Light rail	'Urbos' tram	CAF	0.8	400	n.a.	22	[65]
8	Shenyang (CN) 2013	Light rail (750 VDC)	LRV	CNR Changchun/ Voith	n.a.	n.a.	2.5	69.9	[41]
9	Tallinn (EE) 2013	Light rail (600 VDC)	'Urbos' tram	CAF	0.8	400	n.a.	19.7	[65]
10	Rostock (DE) 2014	Light rail (750 VDC)	'Tramlink 6N2' tram (400 kW)	Vossloh	n.a.	n.a.	None	n.a.	[66]
11	Guangzhou (CN) 2014	Light rail	LRV	Siemens	0.85	288	All route	7.7	[41]
12	Wroclaw (PL) 2015	Light rail	'Twist' tram	Pesa	n.a.	n.a.	None	n.a.	[66]
13	Kaohsiung (TW) 2019	Light rail (750 VDC)	'Citadis 305' tram	Alstom	n.a.	n.a.	All route	8.2 (13.4 with future extension)	[41, 68]

Abbreviation: LRV, light rail vehicles.

[a]Prototype vehicle.

ongoing applications from trams and buses to regional trains in Asia, Europe, and America [72]. Due to their intrinsic characteristics, fuel cell systems are usually employed with secondary storage devices such as batteries or SCs.

In Japan, the first trials involving prototype vehicles equipped with fuel cell systems were started in 2006. Two main projects were carried out by JR East and RTRI [72]. Both prototypes were LRVs intended for regional service, with a traction power of around 190 kW per motored car. Their powertrains were essentially derived from a standard battery/diesel series hybrid configuration, with the fuel cell stack replacing the diesel generator unit. The trial car proposed by JR East was a modification of the 'NE train' and featured 270 L of hydrogen stored at 350 bar and two PEMFC stacks with a total power of 130 kW. A 19.5 kWh, 340 kW Li-ion battery was connected directly to the DC bus for power assist and braking energy recovery [73]. The prototype vehicle developed by RTRI was a little different. It featured a single 120 kW PEMFC stack and Li-ion battery pack with 36 kWh of rated energy, 360 kW of rated power and a total weight of 1200 kg, for an energy and power density of around 30 Wh/kg and 300 W/kg, respectively. The battery was connected to the DC bus through an additional bidirectional DC/DC converter. Hydrogen was stored in four cylinders at a pressure of 350 bar for a total capacity of 720 L [74]. Both projects were mainly aimed at unveiling hydrogen potential and all the technical shortcomings related to its integration onboard a passenger train. In Europe, one of the first reported applications of light rail transport with onboard hydrogen storage dates back to 2011. In that year, a prototype series 3400 railcar was remodelled and tested on the Santander-Oviedo regional line in Spain [41, 75]. The vehicle had a total traction power of around 120 kW and featured a complex hybrid storage system with a fuel cell stack, a lithium-ion battery, and SCs. A total of 600 L of hydrogen were stored at a pressure of 200 bar, while the battery featured a rated energy of around 50 kWh. Renfe Feve and Valladolid University undertook the project as a test bed for multimodal LRV operation.

TABLE 4 Rail vehicles with onboard batteries and supercapacitors

#	Place, year	Rail system	Vehicle info	Owner/installer	Energy rating [kWh]	Power rating [kW]	Off-wire length [km]	Total length [km]	Ref.
1	Almada (PT) 2008	Light rail (750 VDC)	'Combino plus' tram[a] (730 kW)	MTS/Siemens	0.85 (SC)/18 (LiB)	288 (SC)/85 (LiB)	Up to 2.5	7	[69]
2	Seville (SP) 2011	Light rail (750 VDC)	'Urbos 3' tram	CAF	0.8 (SC)/15 (LiB)	400 kW	0.6	2.2	[41, 70]
3	Zaragoza (SP) 2013	Light rail (750 VDC)	'Urbos 3' tram	CAF	0.8 (SC)/15 (LiB)	400 kW	2.2	12.8	[41, 70]
4	Rio de Janeiro (BR) 2015	Light rail	'Citadis' tram	Alstom	n.a.	n.a.	All route (W/GLPS)	22.8	[66]
5	Kaohsiung (TW) 2015	Light rail (750 VDC)	'Urbos 100' tram	CAF	0.8 (SC)/15 (LiB)	400 kW	All route	8.2 (13.4 with future extension)	[41, 70]
6	Doha (QA) 2016	Light rail	'Avenio' tram	Siemens	n.a.	n.a.	All route	11.5	[41]
7	Granada (SP) 2017	Light rail (750 VDC)	'Urbos 3' tram	CAF	0.8 (SC)/15 (LiB)	400 kW	4.9	15.9	[41, 70]
8	Nice (FR) 2018	Light rail	'Citadis 405' tram	Alstom	13.5 (Ni-MH)	n.a.	Around 80%	11.3	[20, 41]
9	Luxembourg(LU) 2018	Light rail (750 VDC)	'Urbos 3' tram	CAF	0.8 (SC)/15 (LiB)	400 kW	3.6	16	[41]
10	Newcastle (AU) 2019	Light rail (750 VDC)	'Urbos 100'5-car tram	CAF	0.8 (SC)/15 (LiB)	400 kW	All route	2.7	[70]

Abbreviations: LiB, lithium-ion battery; Ni-MH, nickel-metal hydride.

[a]Prototype vehicle.

In Oranjestad, Aruba, the first hydrogen trams began passenger operation in February 2013 [75]. The vehicles operate on the non-electrified 2.7 km line connecting the cruise port to the city. The storage system is based on a 14 kW fuel cell stack and Li-ion batteries with rated energy of 160 kWh, powering four traction motors for a total of around 190 kW. Each vehicle can store up to 4 kg of hydrogen, which is enough for a 1-day operation. Hydrogen is produced by electrolysis of water, and refuelling/recharging of the fleet is carried out at night-time. It is claimed that the fuel cells generate more than half of the daily required energy, while the braking energy recovery enabled by batteries is around 12%.

In recent years, many fuel cell-based tram systems have been put into service in China thanks to a partnership between Chinese rolling stock manufacturer CRRC and fuel cell supplier Ballard. In Qingdao, a fleet of catenary/FC hybrid Skoda 'Forcity 15T' trams equipped with PEMFCs is in service since 2016 [75]. Part of the route has a 750 VDC overhead electrification, while in other segments, the vehicles rely entirely on hydrogen power [76]. In Tangshan, a fuel cell light-rail commercial trial with a traction power of around 370 kW was launched in October 2017 [77]. The tram has a hybrid storage system comprising two 150 kW fuel cell stacks, two battery packs of 20 kWh each, and two SC modules with a rated capacitance of 45 F each. A total amount of around 12 kg of hydrogen at 350 bar is stored onboard each vehicle, yielding an average range of approx. 40 km with speeds up to 70 km/h [72]. In December 2019, running tests on a fleet of Forcity 15T hydrogen trams began in Foshan [78]. The vehicles are equipped with Ballard's fuel cell stacks and are claimed to have a range of about 100 km with a maximum speed of 70 km/h. The fleet is expected to operate on the 17.4 km Gaoming line by the end of 2020 [79]. Testing of trial hydrogen trams has started recently in the cities of Saint Petersburg, Russia, and San Bernardino, California [80].

An important application of hydrogen power in railway traction is represented by Alstom's 'Coradia iLint', a hydrogen-electric multiple unit (HEMU) regularly operated on the RB33 regional line in Lower Saxony, Germany, together with standard DMUs, since September 2018 [72]. The trains are equipped with a hybridized powertrain that combines a hydrogen fuel cell as the primary energy source with batteries mainly used for acceleration and energy recovery during braking phases. Hydrogen storage capacity and pressure for each train are 260 kg and 350 bar, respectively, allowing a maximum range of 1000 km, which is enough for a full day of operation without refuelling [60].

The fuel cell stack can output a total power of 400 kW, with extra power being provided by two 110 kWh Li-ion NMC battery units for a total rated traction power of around 570 kW [82]. The local government has planned to increase the fleet with 14 additional units in service by 2021. A similar order has been signed between Alstom and Frankfurt-am-main transport authority to deliver 27 iLint trains by 2022 [41]. In May 2018, the Austrian operator of Zillertalbahn regional railway awarded Stadler a contract to supply five hydrogen trains to replace diesel units for regular passenger service by the end of 2022

TABLE 5 Rail vehicles with fuel cell systems

#	Place, year	Rail system	Vehicle info	Owner/installer	Energy sources	H_2 storage	Aux. storage energy [kWh]	Power rating [kW]	Total length [km]	Ref.
1	Japan 2007	Regional rail	R291 series[a] (190 kW)	RTRI	FC/LiB	720 L @ 350 bar	36	120 (FC) 360 (LiB)	n.a.	[74]
2	Japan 2009	Regional rail	LRV[a] (190 kW)	JR East	PEMFC/LiB	270 L @ 350 bar	19.5	130 (FC) 340 (LiB)	n.a.	[30, 73]
3	Valencia (SP) 2011	Regional rail	LRV[a] (120 kW)	Renfe Feve and Univ. Valladolid	FC/LiB/SC	600 L @ 200 bar	50 (LiB) 0.43 (SC)	24 (FC) 120 (LiB) 89 (SC)	5	[41, 75]
4	Oranjestad (NL) 2013	Light rail	Streetcar (194 kW)	TIG/m	FC/LiB	4 kg	160 (LiB)	14 (FC) ~180(LiB)	2.7	[75]
5	Qingdao (CN) 2016	Light rail (750 VDC)	'ForCity 15T' tram (745 kW)	CRRC and Ballard	Catenary/ PEMFC	n.a.	n.a.	n.a.	8.8	[75]
6	Tangshan (CN) 2017	Light rail	LRV[a] (370 kW)	CRRC and Ballard	FC/LiB/SC	12 kg @ 350 bar	40 (LiB) 3.5 (SC)	300 (FC) 600 (SC)	14	[75]
7	China 2017	Light rail	LRV[a] (200 kW)	Southwest Jiaotong Univ.	FC/SC	n.a.	1.75 (SC)	150 (FC) ~370 (SC)	n.a.	[81]
8	Lower Saxony (DE) 2018	Regional rail	'Coradia iLint' EMU (540 kW)	Alstom	FC/LiB	178 kg @ 350 bar	220 (LiB)	400 (FC) 450 (LiB)	Up to 1000	[72, 82]
9	Foshan (CN) 2019	Light rail	'ForCity 15T' tram	CRRC and Ballard	PEMFC	n.a.	n.a.	200 (FC)	17.4	[79]
10	UK 2019	Regional rail (25 kV AC)	'Class 319' EMU	Porterbrook, UoB and Ballard	PEMFC/LiB	20 kg	n.a.	100 (FC) 200 (LiB)	n.a.	[83]
11	Germany 2021	Regional rail	'Mireo plus H' EMU (1.7 MW)	Siemens and Ballard	PEMFC/LiB	250 kg	350 (LiB)	400 (FC)	Up to 900 km	[60]

Abbreviations: FC, fuel cell; LiB, lithium-ion battery; LRV, light rail vehicles; PEMFC, proton-exchange-membrane fuel cell.
[a]Prototype vehicle.

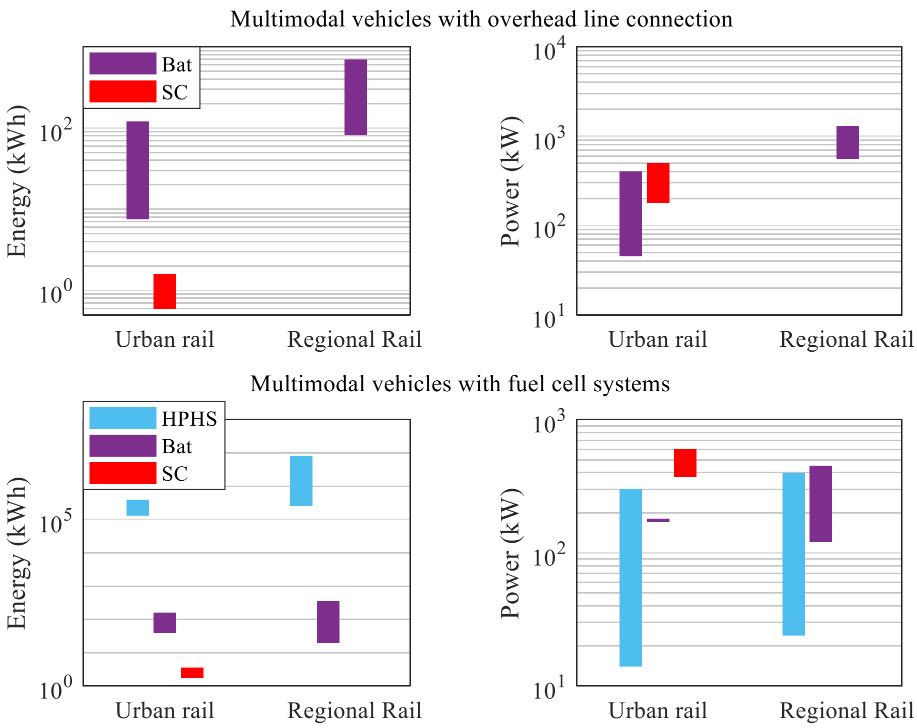


FIGURE 7 Energy and power ratings of onboard energy storage systems in real multimodal vehicles for urban (600–750 VDC) and regional (1.5 kV DC, 15–25 kV AC) service

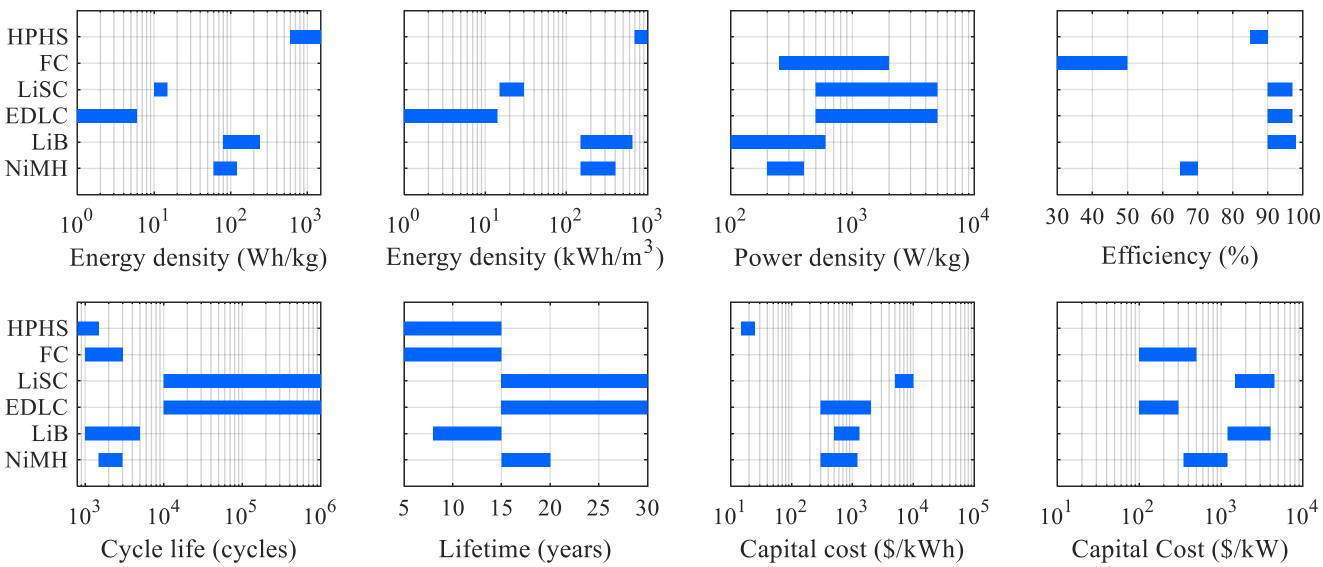


FIGURE 8 Main features of onboard energy storage system technologies for rail applications [5, 19, 67, 88–91]. EDLC, electric double- layer capacitor; FC, fuel cell; HPHS, high-pressure hydrogen storage; LiB, lithium-ion battery; LiSC, lithium-ion supercapacitor

[84]. In March 2020, Alstom performed further testing of the iLint on the 65 km line between Groningen and Leeuwarden in the north of the Netherlands for a pilot project agreement among Alstom and other public and private Dutch parties. The Dutch railway network has around 1000 km of non-electrified lines currently covered by diesel trains. The Netherlands thus became the second country in Europe to test hydrogen-powered railway solutions [85].

In 2017, Siemens and Ballard Power Systems announced an agreement to develop an FC/battery hybrid version of 'Mireo' EMU, with initial deployment planned for 2021. The power system comprises two 200 kW fuel cells and a 350-kWh LTO Li-ion battery [86]. The vehicle is designed for a range of up to 1000 km in the three-car configuration, allowing one refuelling per day. For this project, the manufacturers claim impressive improvements in fuel cell performance: 50% higher power

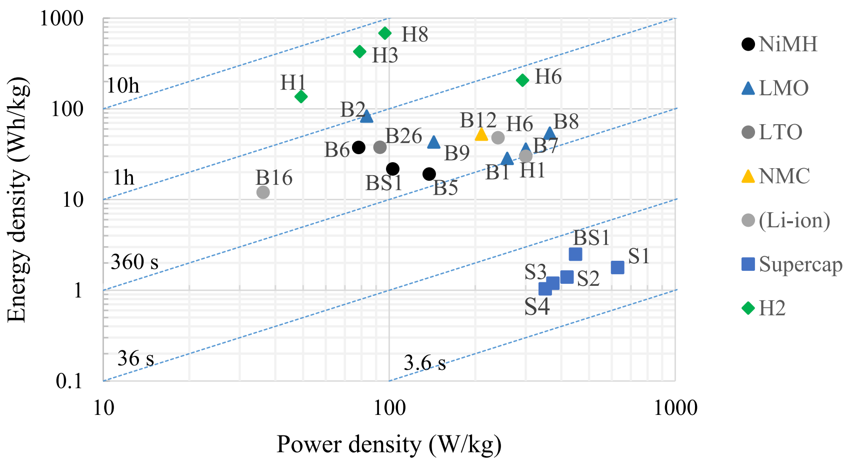


FIGURE 9 Ragone plot of implemented energy storage solutions onboard railway vehicles. The blue dotted lines are constant energy-to-power contours: each line is a locus characterized by the discharge time displayed above it. Supercapacitors have short charging and discharging times, comparable to braking times of urban light rail vehicles. Hydrogen systems can be designed to operate several hours with a single refuelling of the storage tanks, as for conventional diesel units. Batteries exhibit intermediate levels of energy and power density and are employed for short and medium-length off-wire operations. In general, energy and power densities at the system level are significantly reduced compared with cell-level ratings, and important improvements can be still achieved by optimized assembly of the storage units. LMO, lithium-manganese-oxide; LTO, lithium-titanate; NMC, nickel-metal-cobalt; Ni-MH, nickel-metal hydride; Li-ion: lithium-ion

density and three times longer service life than market standards. Other trial projects are currently being developed in Europe. In 2019, a collaboration among Porterbrook, Ballard, the University of Birmingham, and several other collaborators led to the realization and testing of the United Kingdom's first hydrogen train 'HydroFLEX'. The train is a single-car prototype derived from a Class 319 EMU and equipped with a PEM FC stack of 100 kW working as a range extender, a 200 kW Li-ion battery pack, and 20 kg of hydrogen stored in high-pressure tanks. The train can also run under 25 kV AC overhead catenary, thus making it a trimodal vehicle. The prototype was successfully demonstrated in summer 2019 and will be further tested on the mainline railway for passenger service [83]. Vivarail and Siemens also have ongoing projects to integrate hydrogen power plants on board EMUs [20].

Table 5 summarizes the reported installations of fuel cell systems on board prototypes and commercial vehicles in passenger service. A final comparison is presented in Figure 7, which displays the OESS energy and power ratings of the multimodal units reported throughout this section.

4 | COMPARISON OF ONBOARD ENERGY STORAGE SYSTEM TECHNOLOGIES AND INSTALLATIONS

Energy and power densities of different storage technologies for transport are well established and acknowledged at the single cell level. Indeed, battery cells exhibit high energy densities and low to medium power densities. Supercapacitor units exhibit low energy densities but a wide power density range. The energy and power densities of the overall hydrogen power plant depend mainly on the H_2 storage technology. For compressed gaseous hydrogen, which is the most adopted solution, the 2020 target value set by the US Department of Energy is 1.5 kWh-H_2/kg [87]. Figure 8 provides a comparison of different storage technologies.

Despite the characteristics of storage technologies at a single cell level, energy and power densities are affected when the analysis is carried out at a system level. In other words, one may question to which extent the whole assembly of a storage unit penalizes the ratings of a single cell. For instance, in Li-ion battery packs, control electronics, cooling, and housing can account for more than 40% of total weight [38]. Figure 9 presents a Ragone plot with data from some of the onboard storage devices discussed in Section 3. Every point in the plot refers to one of the vehicles listed in the previous tables: the letters refer to the storage technology (B: battery; S: supercapacitor; BS: battery/SC hybrid system; H: hydrogen), while the number indicates the row of the table of a particular technology. The plot allows visualization of the distribution of energy and the power density of batteries, SCs, hybrid storage devices, and hydrogen power units at a system level as deployed in practical railway applications. For hydrogen power plants, some hand calculation is required. In particular, the total weight is here calculated by summing the weight of the fuel cells and hydrogen tanks; when not available, the weight of the tanks is calculated taking into account a gravimetric efficiency–that is, the ratio of H_2 weight to tank weight of 4.5%. Indeed, this can be considered a good benchmark value for 350 and 700 bar high-pressure storage technologies [92, 93]. The amount of available stored energy is evaluated considering the mass of stored hydrogen and its low heating value while assuming a 50% efficiency for the fuel cells. The power rating is evaluated by dividing the rated FC output over the entire system weight (and not over the sole weight of the fuel cells). In this way, H_2 energy storage and conversion subsystems are considered in whole and can be meaningfully compared with electrochemical storage devices.

For batteries, the average energy density achieved at a system level is around 35 Wh/kg, with the highest value of 83 Wh/kg achieved by a prototype unit. Charge and discharge times range from five minutes to one hour, depending on the maximum charge and discharge currents. Therefore they generally do not represent the first choice for urban railway applications, with some exceptions. Supercapacitors exhibit the highest power densities at the system level, too; however, their value is considerably reduced (up to 10 times) for single-cell levels and approaches an upper limit of around 650 Wh/kg. Their discharge time is in the range of seconds and comparable to the typical braking times of metro and light rail systems, representing a good solution for energy saving. At a system level, hydrogen power plants exhibit power densities below 100 W/kg but a high density of usable energy in the range of 200–600 Wh/kg.

These values yield discharging times from 45 min to several hours, depending on the planned number of refuelling per day.

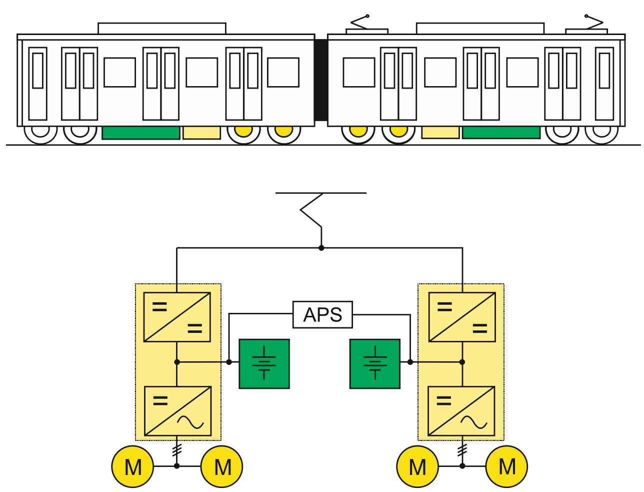


FIGURE 10 Traction system architecture of JR East 'EV-E301' battery hybrid regional train [36]. This unit can operate under catenary power on electrified sections and on battery power on non-electrified segments up to 22 km long. Batteries can be recharged at stops, while the train is running under an overhead line or during braking. APS, auxiliary power supply

The very high energy density of pressurized hydrogen makes it a feasible solution for medium-range regional service.

5 | TRACTION SYSTEM ARCHITECTURES AND ENERGY MANAGEMENT STRATEGIES

In multimodal rail vehicles, multiple energy sources enable several different architectures of the propulsion system. On the other hand, many possibilities arise for the energy management strategy (EMS), which controls the power flows among OESSs during vehicle operation. The EMS is of great importance for safe, reliable, and energy-efficient operation of the multimodal traction system. The following section reviews the architectures and energy management strategies of real multimodal trains.

5.1 | Bimodal systems with batteries

For battery hybrid trains, the onboard energy can be stored in several submodules. According to the system voltage level, the modules are connected to a common DC bus directly or through a dedicated DC/DC power converter.

The hybrid EV-E301 rail vehicle belongs to this category. It is a regional vehicle operated by JR East on partially electrified routes, whose configuration and power system are shown in Figure 10. It comprises two cars: a trailer bogie at the outer end and a motored bogie powered by two induction motors at the inner end. All power components for traction and auxiliaries are accommodated in the underfloor space. The battery modules have a rated voltage of 630 V and are connected directly to DC side of the traction inverters. Two separate DC/DC converters interface each bus with the overhead line, whose rated voltage is of 1500 VDC and thus needs to be reduced at the accumulator voltage level. The power unit feeding the auxiliary loads is supplied from both the DC buses for increased reliability.

The EMS for this vehicle is deployed on four different modes of operations, namely: powering control and standard charging (I); powering control in non-electrified section (II); regenerative brake charging control (III); high power charging

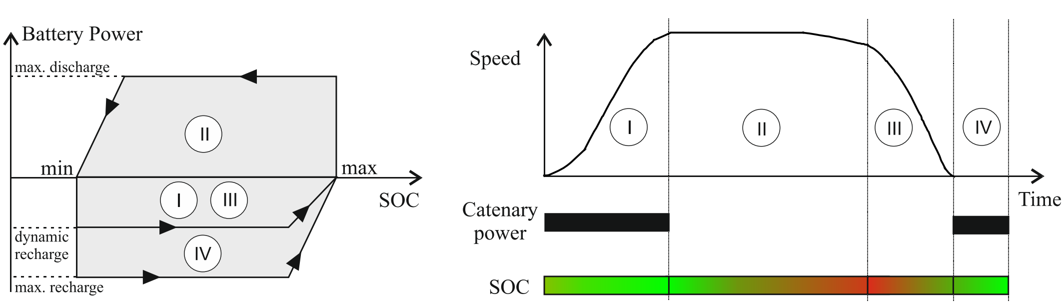


FIGURE 11 Control strategy of onboard battery in JR East 'EV-E301' train: (I) rolling and battery charging under catenary; (II) rolling in non-electrified sections; (III) battery charging through regenerative braking; (IV) fast-charging at stations with a pantograph. SOC, state of charge

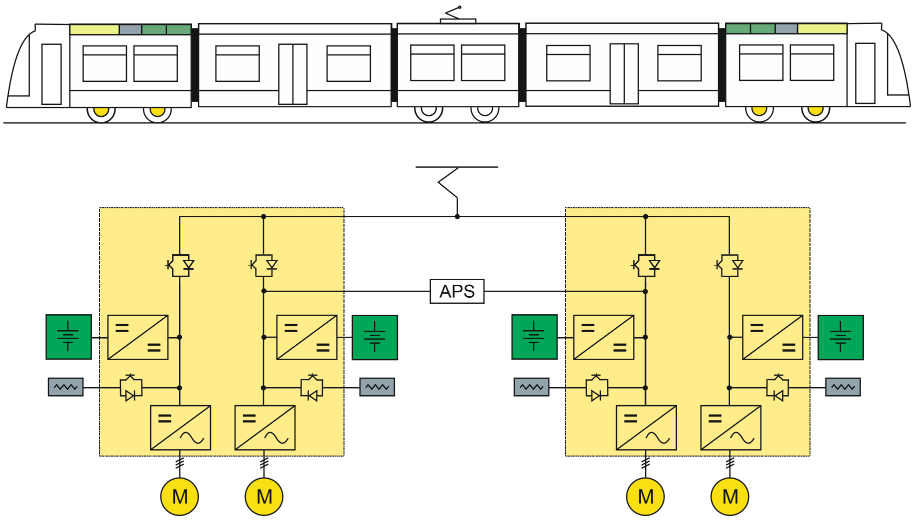


FIGURE 12 Traction system architecture of Bombardier 'Flexity 2' battery hybrid trams in Nanjing, China [54]. Batteries are recharged only in the proximity of stations, where overhead power is available. On the remaining 90% of the route, batteries are employed as the only energy source and enable effective energy recuperation during braking

control (IV). The transitions between different modes depend on the availability of the catenary and the SOC of the battery system. The SOC control scheme and the energy management during each mode of operation are shown in Figure 11 concerning a simplified driving cycle. According to the classification given in [60], this can be classified as a maximum SOC control strategy. In powering control and standard charging (mode I), the catenary is available. The front-end DC/DC converter controls the energy flow required for traction, auxiliary power supply, and battery charging. When the SOC reaches its upper threshold, charging is stopped, and only traction and auxiliary power are fed to the system. In non-electrified sections, the battery must provide the full tractive and auxiliary power (mode II). During braking (mode III), energy is sent back to the DC bus and is used to supply the auxiliary power unit and partially recharge the battery. In rare cases when the battery SOC is at its maximum and the vehicle is braking, the DC/DC converter returns regenerative power to the catenary if the sum of the braking power (negative) and auxiliary power (positive) is negative. When the vehicle is stopping at stations, high power charging mode is entered (mode IV). The DC/DC converters draw a high current from the catenary to fasten the battery charging process. The thermal limits of the pantograph act as the main limitation to the charging current set point.

A higher degree of distribution and redundancy characterizes Bombardier's hybrid trams' power system in Nanjing, as shown in Figure 12. The DC bus is derived directly between the overhead wire and the ground since the catenary has a rated voltage of 750 VDC and requires no additional step-down conversion. Four of the six axles are powered by induction motors, each fed by a dedicated inverter on a parallel branch of the DC bus.

The total amount of energy stored onboard is divided into two units comprising two submodules each. They are connected to the DC bus through a bidirectional DC/DC converter which steps up their rated voltage of around 530 V to the rated system voltage. The converter supplying the auxiliary loads has a double connection to the DC bus, with connection points before and after the input contactors and filter inductors. This enables the auxiliary loads to be supplied in both the catenary and the catenary-free mode with minimum losses.

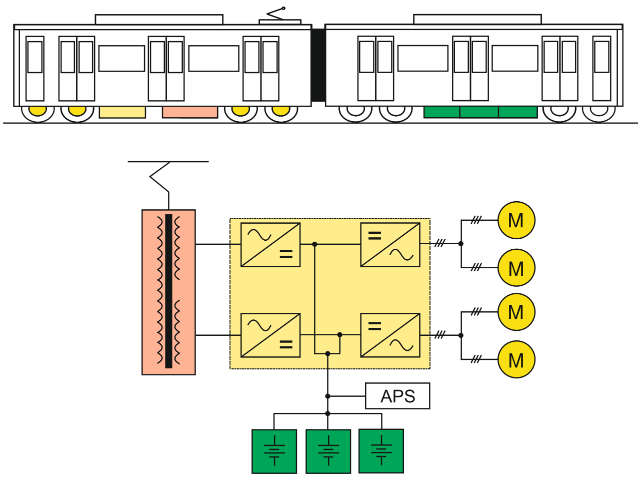


FIGURE 13 Traction system architecture of Hitachi 'BEC-819' battery hybrid train in-service operation in Japan [34]. In the case of AC power available from the catenary, front-end pulse-width-modulated rectifiers are integrated to control the energy split between catenary and batteries. Because of the bulky line-frequency transformer, no additional DC/DC converters for the interface of battery packs are considered

The energy management for this vehicle is similar to what is depicted in Figure 11. On this route, catenary power is available only in the proximity of each station and is used to charge the batteries and provide the required traction effort for accelerations. In this context, traction has the priority on battery charging. The catenary is implemented as overhead bus bars integrated into the station roof to enable higher charging currents. When the vehicle exits the station area, the pantograph is lowered, and cruising is accomplished only by battery power. In contrast, when the tram enters a station, the pantograph is raised to connect the DC bus to the overhead system. The transitions between catenary and catenary-free modes are done dynamically. Thus, particular care is taken to avoid current arcs when lowering the pantograph or feedback currents from the battery when raising it. This is accomplished by adequate control of the DC bus voltage and the IGBTs conduction states.

The catenary/battery trams manufactured by CAF for Birmingham share a similar configuration, with a DC bus connected directly to the pantograph and two battery units interfaced via dedicated DC/DC converters [44]. The same generally applies to LRVs equipped with supercapacitors since the DC converters enable exploitation of the entire SC voltage range and add a degree of freedom for their sizing.

The BEC-819 train is an AC catenary/battery hybrid train manufactured by Hitachi. Its system architecture is shown in Figure 13. This vehicle can be supplied both by the AC catenary and by onboard batteries. The 20 kV, 60 Hz catenary voltage is reduced by a low-frequency transformer and rectified to a value of around 1600 VDC by two front-end active rectifiers. The converters supply power to the DC buses and control the charge and discharge of three battery units. The adoption of high-voltage batteries was found necessary to avoid an additional power converter. All four axles of the powered bogie are motored by four induction motors split into groups of two and fed by two traction inverters. The integrated traction converter and transformer are in the motor car, while the battery modules are accommodated in the trail car. All power components are placed in the underfloor space. The EMS is similar to what has been previously described for other battery vehicles: maximum SOC control. When the catenary is available, the active front-end rectifier controls the amount of power to be drawn from the line. During traction mode, line power is sent to the motors and auxiliary loads while the batteries are not used, meaning no line voltage or current control is implemented. During coasting, the traction inverters require no power, and batteries are recharged. With the pantograph lowered, traction and auxiliary power demand are met by batteries alone. Regenerative braking is managed irrespective of the presence of overhead wire: braking power is entirely utilized to charge the battery, and none of it is sent back to the catenary through the active rectifier. In this context, onboard storage is employed as an alternative to diesel when electrification is missing.

When the battery is added onboard a diesel-electric multiple unit, the resulting configuration is usually a series hybrid type. The onboard storage system supplies additional power to the electric traction motors and enables fuel-free operation when required. This is the case of Hitachi's hybrid DMUs in operation in Japan. The powertrain configuration of the motored car of these units is depicted in Figure 14 [29]. In this application, the DC system voltage is chosen around 700 VDC and is connected directly to the central battery system, composed of two submodules. An emergency battery module is also present for extra redundancy, and its primary function is to crank the diesel engine if the main batteries fail. In such a case, the diesel unit alone has to provide sufficient power for traction and auxiliary loads and charge the emergency battery. The EMS implemented for this powertrain is as follows. The

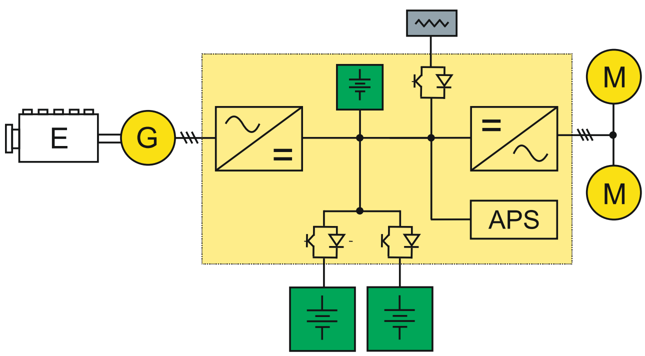


FIGURE 14 Traction system architecture of a motored car of Hitachi diesel/battery hybrid trains [29]. The powertrain is of series hybrid type and results from the hybridization of a diesel-electric multiple unit. Batteries are connected directly to the common DC bus due to its low rated voltage. Emergency batteries are also included in starting the engine in the case of main battery failure. APS, auxiliary power supply

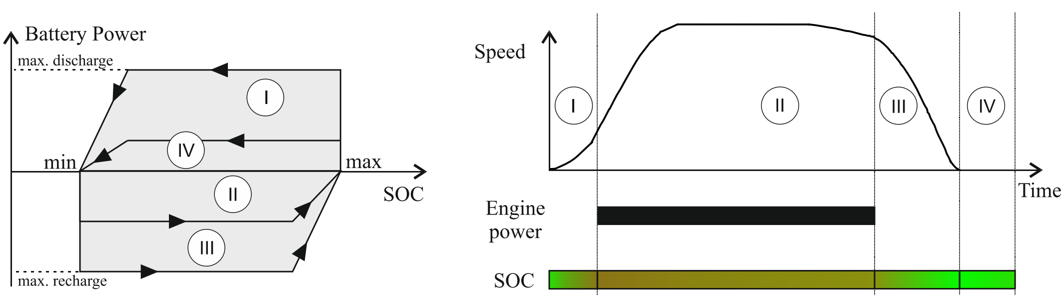


FIGURE 15 Control strategy of the onboard battery and diesel engine in Hitachi hybrid vehicles: (I) early acceleration is powered by batteries only; (II) engine supports late acceleration and cruising; (III) batteries are recharged through regenerative braking; (IV) batteries supply auxiliary systems at stops. Batteries are operated as the only energy source at stops and early accelerations to reduce air pollution in stations. They also allow recuperation of braking energy that would otherwise be wasted in a conventional diesel-electric unit. SOC, state of charge

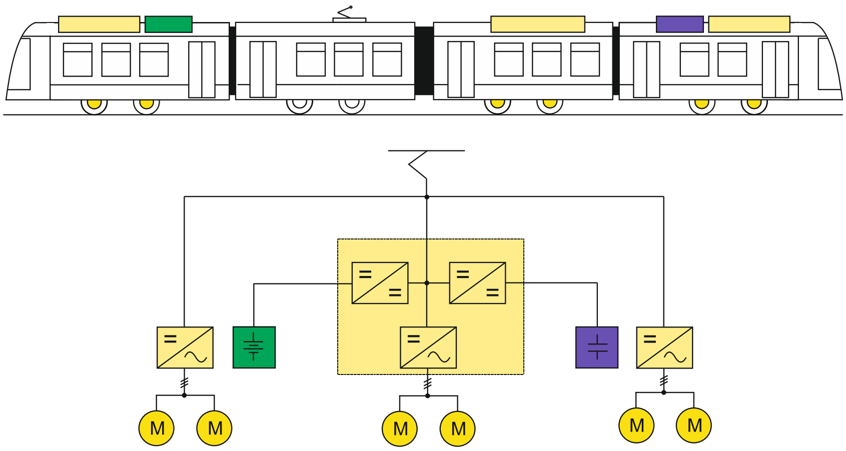


FIGURE 16 Traction system architecture of Siemens 'Combino Plus' multimodal tram in Almada, Portugal [69]. The vehicle can draw energy from catenary, supercapacitors, and batteries. The adoption of dedicated DC/DC converters for each storage unit allows for maximum versatility in the design and energy management of the devices

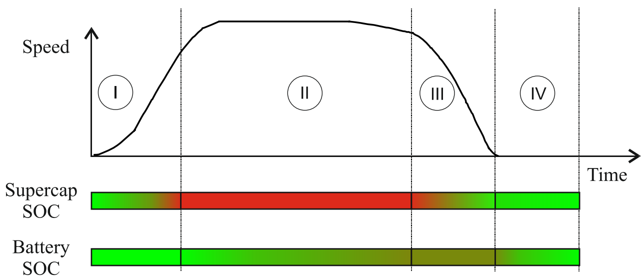


FIGURE 17 Energy management in Siemens 'Combino Plus' multimodal tram vehicles when rolling on non-electrified sections: (I) acceleration power is supplied by supercapacitors; (II) cruising/coasting power is supplied by batteries; (III) regenerative braking recharges supercapacitors; (IV) both storage systems are recharged by the overhead wire at stops [77]. As implicated by their technological characteristics, supercapacitors provide a major share of traction power during acceleration and are recharged during braking, while batteries are more involved in cruising and get recharged more slowly at stops. SOC, state of chargeCAF has implemented the same concept in its Freedrive hybrid storage solution. Each Freedrive module comprises a variable number of supercapacitor branches and a battery, with two independent DC/DC converters to connect to the common DC bus of the vehicle [66]

batteries operate as only energy sources at stops (mode IV) and during early acceleration up to a speed of 30 km/h (mode I).

The diesel generator is then activated for further acceleration and supports batteries during cruising/coasting to avoid excessive discharge and keep their SOC at a medium level (mode II). During regenerative braking, the generator output is shut down, and as much braking energy as allowed by the SOC level is sent to the batteries (mode III). The different operating modes and energy flows are schematically represented in Figure 15.

5.2 | Multimodal systems with overhead line connection

In hybrid power systems comprising batteries, supercapacitors, and catenary supply, selecting a proper interconnection between the sources and the DC bus is non-trivial. The choice of a proper topology must consider many factors, such as system rated voltage, power, and energy sizes of the devices, available space, cost, and complexity.

The Combino Plus MST by Siemens is a trimodal light rail vehicle with the power system architecture shown in Figure 16. Three traction inverters supply six induction motors fed by a common DC bus powered directly by the overhead line at 750 VDC. The roof-mounted battery and SC units, here installed as single units and not split in multiple submodules, are connected to the DC bus through two independent DC/DC converters. The adoption of a dedicated converter for each storage device entails the highest degree of freedom in terms of both design and control of the sources, at the price of higher system cost and lower reliability.

The presence of two different storage devices, together with a stationary supply, allows for a more versatile EMS. On electrified sections, the storage devices contribute to accelerations and high load conditions so that pantograph current is reduced, and line voltage fluctuations are minimized. During braking, the hybrid storage system can be employed for more efficient regeneration of kinetic energy. On non-electrified routes, batteries and SCs can still manage acceleration, cruising, and braking phases. Power demands are split between the two subsystems shown in Figure 17 [94]. Supercapacitors are more involved during early acceleration and braking, i.e. when high power transients occur. The power and energy ratings of the capacitors are indeed designed to meet the requirements of the acceleration phase. Cruising requires more energy but less power and is thus accomplished at the expense of the energy stored in the battery. When braking starts, the regenerative power is absorbed mainly by the SCs, due to their higher power rating. When the vehicle is at standstill, both storage devices are recharged by the stationary charging infrastructure according to their respective states of charge and thermal constraints.

5.3 | Multimodal fuel cell systems

Regarding hydrogen-powered railway vehicles in operation, littler information about their power system architecture is generally available. In [8, 95], a detailed explanation of the power system architecture of FC/battery/SC tram vehicles

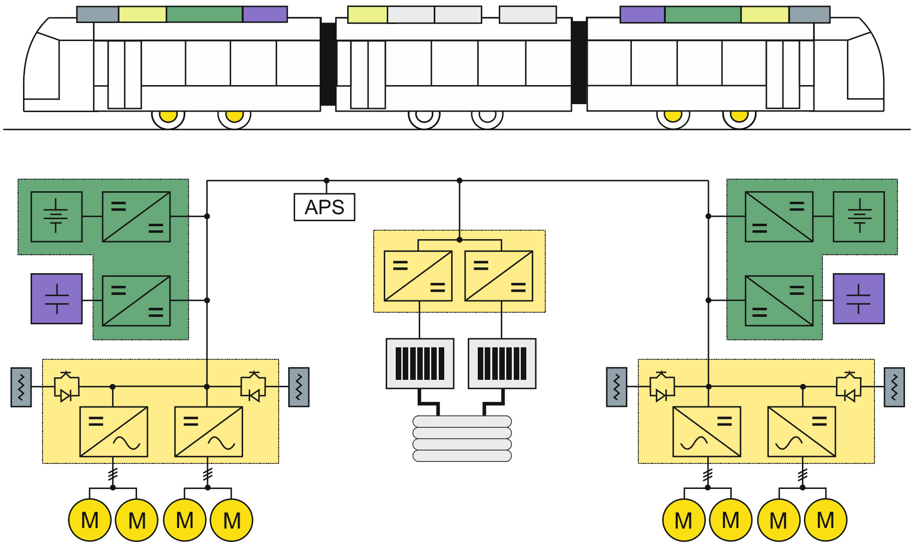


FIGURE 18 Traction system architecture of CRRC multimodal trams in Tangshan, China [95]. Pressurized hydrogen is the primary energy source of the vehicle and supplies two fuel cell stacks, each one connected to the common DC bus through dedicated converters. Additionally, SCs and batteries are integrated to assist fuel cells during high load transient, enable regenerative braking, and provide backup power in case of failure or unavailability of the hydrogen power plant. High operational versatility is achieved at the cost of increased system complexity

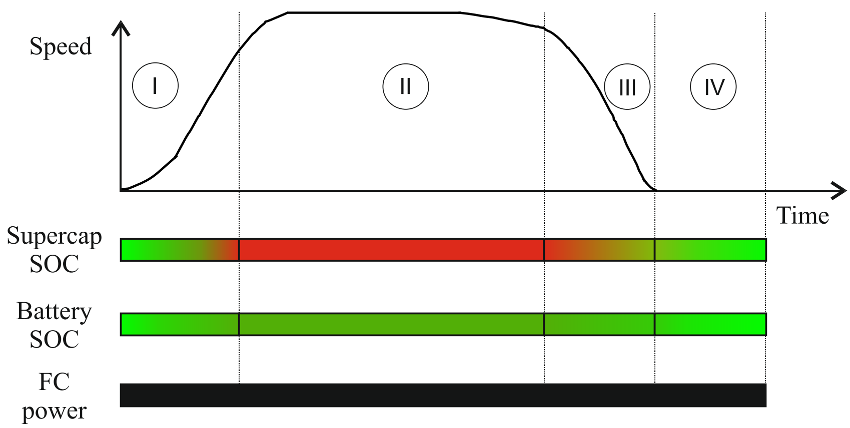


FIGURE 19 Energy management during acceleration and cruising for CRRC multimodal trams in Tangshan, China [80]. Fuel cells provide the necessary traction power up to their upper limit. SCs are then activated to output the demanded additional power, while batteries output a minimum amount of constant power. During cruising, hydrogen is the only energy source. At stops, batteries are recharged by the fuel cells to reduce standby operation. APS, auxiliary power supply; SOC, state of charge

manufactured by CRRC Tangshan can be found. The power system and the distribution of its components are reported in Figure 18. The tram is composed of two motored cars and one central trailer car, with eight PM synchronous motors. On the roof of the trailer car, the whole hydrogen plant is accommodated. It comprises the pressurized hydrogen storage tanks, two PEMFCs with their dedicated boost converters, and the radiator. A battery pack, an SC bank, the traction inverters, the bidirectional DC/DC converters, and brake resistors are mounted on the roof of each motored car. The storage units are connected by two separate bidirectional DC/DC converters to the common DC bus, which operates at a rated voltage of 750 VDC.

The EMS is not known in detail, but the general concept is explained in [95]. The fuel cells are used as the primary energy source to meet the average traction power demand and are controlled in a small power range of around 250 kW. SC modules are employed to supply the additional power needed during accelerations when the total power demand can be higher than 900 kW. They are also the prime utilizers of the energy recovered by the motors during braking. The contribution of batteries to traction is lower with respect to the other sources. They are mainly employed as backup energy sources in the failure or unavailability of the fuel cells, allowing the vehicle to complete its route and return to the depot. In Figure 19, the power split among energy sources is represented. The fuel cells operate at constant power, and SCs compensate for the extra power demand. In this phase, batteries are controlled to output a minimum amount of constant power. When the target

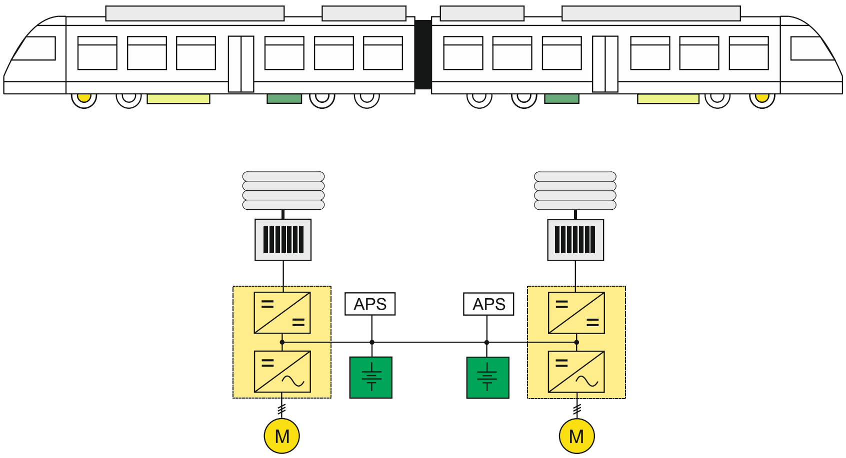


FIGURE 20 Propulsion system architecture of Alstom 'Coradia iLint' hydrogen regional train [82]. Hydrogen fuel cells are separately interfaced to the DC bus through dedicated converters, while batteries are directly connected to the common bus. Hydrogen acts as the primary energy source for traction and auxiliary systems, while batteries are involved as power assist during acceleration and to store the energy regenerated during braking. APS, auxiliary power supply

cruising speed is reached and the input power of the inverters falls under the threshold of 200 kW, batteries and SCs are disconnected, and the fuel cells operate as the only source of power. At stops, fuel cells are kept in operation to recharge the batteries and SCs.

By doing so, the standby operation of cells is minimized to extend their lifetime.

The power system architecture of a hydrogen-based EMU could be derived from a diesel multiple unit whose design is taken as the basis for the hydrogen conversion. This process mainly requires the substitution of diesel generators with fuel cells and preserves other components, especially the traction drives. In the case of Alstom's Coradia iLint, the conversion process is more radical. This train is derived from the Coradia Lint, in which diesel engines directly move the motored axles besides supplying electrical power to the auxiliary loads through a generator. The power system architecture of the iLint is depicted in Figure 20. All diesel-related components are removed to accommodate a modular power system comprising batteries, fuel cells and hydrogen tanks, and traction inverters and motors. The hydrogen generation plant is divided into two units installed on the roof of the two cars. Each unit comprises a hydrogen storage tank and a fuel cell stack, the latter connected to the common DC bus through a unidirectional boost converter. The DC converter and the traction drive powering each motored bogie are integrated into a single converter box accommodated underfloor with the traction motor. The battery storage system consists of two submodules as well, each one mounted in the underfloor space next to the auxiliary converter on the trailer bogies. The accumulators are directly connected to the DC bus, without additional power electronics. The two energy sources are controlled so that hydrogen represents the primary energy supply to the train and is the only one that remains active when the train is coasting. The batteries are mainly employed during accelerations to compensate for fuel cell power limitations and braking to recover kinetic energy.

During cruising, the batteries are controlled to perform load balancing so that, irrespective of the instantaneous traction effort, fuel cells can be operated in a small power range for maximum operating efficiency, reduced stress, and extended lifetime.

5.4 | Alternative approaches to EMS

The abovementioned energy management strategies can be classified as rule-based strategies (RB-EMSs). They use a predefined set of rules to split the load power demand among onboard sources. These rules generally consider the train power demand and the SOC of storage units as main decision boundaries. In [96], two simple RB-EMSs are proposed and tested on a hybrid battery/SC powertrain. The first simple strategy consists of switching between battery and SCs based on a hysteresis control. The controller operates the SCs alone as long as their SOC is above the minimum threshold. In case of excessive discharge, the battery is turned on to provide traction power and recharge SCs. The second rule-based technique decomposes the traction current in low and high-frequency components. The low-frequency component is supplied by the battery, while the high-frequency one by the SCs. In [97], the authors propose a hybrid approach to the energy management of a battery/SC hybrid system. The control strategies integrate a set of rules with a meta-heuristic optimization routine. In particular, a rule-based control layer restricts the search space based on SOC threshold and traction power demand. Within the restricted search space, a heuristic optimization routine calculates the reference values of battery and SC power. A set of equality and inequality constraints is included to account for the dynamics of the energy sources and their operating limits (i.e. SOC and power limits).

Despite their simplicity, these strategies can already exploit the potential of HESS and improve system performance. RB-EMSs are easy to define and implement and guarantee stable operation of the powertrain and proper control of the DC bus voltage [98]. However, rules are set according to qualitative reasoning; that is, no mathematical formulation is employed for their derivation. Therefore, the resulting energy management is likely to be non-optimal for system losses and overall energy consumption [12]. To overcome such limitations, a different class of energy control has been primarily proposed in the literature. These controls address the power-split problem through optimal control theory [99]. In [100], a comparison between rule-based and optimal control strategies is presented. In detail, RB-EMS are evaluated against a more sophisticated model-predictive control (MPC). The MPC algorithm aims at calculating the power targets of batteries and SCs by minimizing a loss function over a future time window of short length. The objective function is expressed as a weighted sum of multiple objects that include battery losses, battery current transients, and SC voltage. MPC is shown to provide low battery degradation and reduced lifecycle costs. Nevertheless, RB-EMSs work comparably well in the considered scenario, with the advantage of lower computational requirements. A slightly modified MPC is proposed in [12] to optimize battery/SC hybrid LRVs. The idea is that, differently from road electric vehicles, the power demand profile of a rail vehicle is known in advance with a good degree of precision. Therefore, the authors propose a predictive control in which, at each instant, the cost function spans over the whole remaining part of the LRV traction cycle. Since the loss function is expressed in terms of OESSs power losses and SOC deviations from targets, the control is shown to achieve lower power losses during the driving cycle and thus a higher energy efficiency. A similar control, but with a more complex cost function comprising also a limitation on the battery, is developed in [101] and achieves comparable reductions in system losses. A different approach is proposed in [102], where the authors suggest the adoption of genetic algorithms (GA) to derive the optimal EMS for a catenary/battery/SC hybrid tram vehicle. In particular, GA optimization is used to derive the OESS power targets that minimize a multiobjective cost function. This function accounts for the capital, maintenance, and replacement costs of battery and SCs and the cost of energy drawn by the overhead line, expressed in EUR/day. The resulting control strategies achieve a simulated average reduction of 17% in the system's total costs. Again, an off-line optimization procedure can be justified by the fact that the load profile of an LRV is largely known in advance and well predictable.

Literature studies show that optimal controls can effectively improve the energy efficiency or reliability of a multimodal traction system but at the expense of increased complexity and computational burden. Therefore, a trade-off between these conflicting factors must be considered to choose the alternative that best fits practical real-time applications. The implementation of optimal EMSs for multimode traction systems in commercial operation is unknown due to confidentiality reasons.

6 | EMERGING TECHNOLOGIES AND TOPOLOGIES OF POWER CONVERTERS FOR OESS INTEGRATION

6.1 | Silicon carbide power devices

Power electronic converters play a fundamental role in rolling stock traction systems. Hence, improvements in power semiconductor technology can directly enhance their performance, efficiency, miniaturization, and reliability. Silicon carbide (SiC) power devices have gained momentum as promising wide bandgap (WBG) semi-conductor technology for rail traction systems. Compared with standard silicon IGBTs, these devices exhibit higher operating temperatures, lower switching and conduction losses, higher blocking voltage per unit thickness of the wafer, higher current densities, and higher thermal conductivity [14].

Nowadays, the benefits of hybrid modules (SiC diode with Si-IGBT) and all-SiC MOSFETs have been proved in many research studies and real applications. In [103], a hybrid SiC inverter was developed for a 600 VDC railcar traction system and tested against a standard IGBT inverter. The ratings of the power components were the same for the two inverters and equal to 1.7 kV/1.2 kA. The SiC power components enabled space savings of around 30%, increasing the converter power density by around 43%. A hybrid SiC traction inverter with 3.3 kV/1200 A modules by Fuji Electric has been recently integrated onboard the series-5000 railcars running on the 1500 VDC Sanyo regional line in Japan [104]. The total volume and mass of the converter were reduced by 65% and 45%, respectively, compared with its Si-IGBT counterpart. On the other hand, all-SiC modules for traction and auxiliary inverters have been developed by Hitachi (3.3 kV/800 A) and Mitsubishi (3.3 kV/1500 A) in the last few years [15, 105]. Specifically, all-SiC traction inverters with SiC MOSFETs are installed onboard the EMUs operated by Odakyu Electric Railways in Japan. These converters exhibit around 55% less switching loss than standard 2-level IGBT inverters. Furthermore, size and weight can be reduced by 65% compared with standard silicon technology and 30% compared with Si-SiC hybrid technology [106].

Thanks to their higher switching frequency and lower losses, SiC power converters can facilitate energy storage systems onboard rail vehicles. As seen throughout Section 4, OESSs generally require additional DC/DC converters for their interface with the system DC bus. The passive filtering elements of such converters are bulky and reduce the volume available for the storage units. Since SiC-based DC/DC converters can operate at much higher frequencies, more compact and lightweight inductors can be designed to accomplish volume savings up to 30% [107].

Despite the high expectations towards SiC converters for railway traction, several issues have to be still overcome. Their higher switching frequency demands faster protections from short-circuit faults, optimized packaging and gate circuit design to avoid parasitic ringings, and proper cabling to avoid excessive voltage surges at motor terminals [108]. Moreover, reliability issues concern the lifetime of the MOS gate of the devices, as they tend to suffer from early deterioration at high voltage. Electromagnetic compatibility issues also represent a major design challenge [109]. Overall, SiC devices suffer from design and manufacturing challenges that deserve further research by industry and academia.

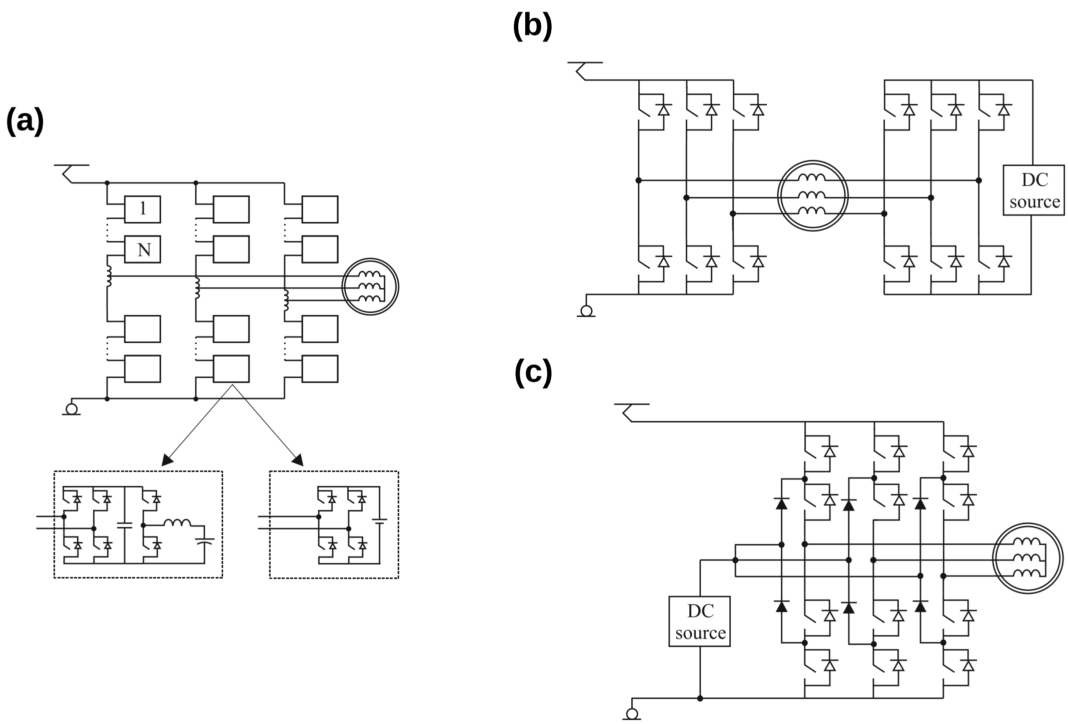


FIGURE 21 Alternative topologies for the integration of onboard energy storage systems in traction systems: (a) modular multilevel converter with embedded energy storage units (left: SC cells, right: battery cells); (b) cascaded two-level inverter with open-end winding traction motor; (c) NPC-type multisource inverter

6.2 | Non-conventional topologies

New power converter topologies have been proposed to interconnect multiple energy sources at reduced size and weight in the last few years. One popular emerging solution is represented by the modular multilevel converter (MMC). The MMC offers many attractive features such as modularity, scalability to high power and voltage levels, and fault tolerance [110]. Its basic architecture was first proposed in [111] as a single-stage interface between the low-frequency line voltage and the medium-frequency transformer. It has been developed and tested by Siemens at power ratings of 2 and 5 MW [108]. The MMC was then introduced in many other fields, including medium voltage traction drives [112]. More recently, the converter has been investigated as a highly integrated solution for electric powertrains with OESSs. Figure 21(a) shows two possible architectures of MMC traction drives with battery or SC cells embedded within each submodule. The performance of an MMC with distributed SC cells for DC rail traction systems was simulated and discussed in [113, 114]. The results showed that this configuration can effectively control the energy flows among the motor, overhead, and onboard SCs. However, complex multilayer control schemes are needed to control the SOC levels of the SC cells and attenuate the low-frequency component of the circulating current. Moreover, the SOC unbalance among SC cells directly affects the distortion of the output voltage. Similar studies have addressed the battery-based architecture but regarding automotive applications [115]. The MMC-based integration of OESSs is thus a recent and open research field with much study and on-field experimentation still to be done, particularly in the field of multimodal rail traction.

A cascaded two-level inverter can be employed to supply traction power from two different DC sources without additional DC/DC converters [116]. The system, shown in Figure 21(b), can supply the motor with multilevel phase voltages and control the power ratio of the two sources, also in the case of different DC voltage levels. Further analysis of this configuration is found in [117] for an FC/SC hybrid system, focusing on the recharging of the SC back during motor operation and at stops. These studies show that the cascaded-inverter topology can effectively manage energy flows between sources while supplying the traction motor to track the reference torque and speed. It has several advantages over a standard configuration with a common DC link, such as redundancy, fast response during transients, multilevel output voltage, and reduced voltage on the switches. Nevertheless, the modulation technique needs non-trivial adjustments for the converter to achieve all operating modes. Moreover, the motor windings have to be accessible at both ends, which is not a typical configuration for the traction motors.

A different architecture, a recently named multisource inverter (MSI), has been discussed in [118, 119]. The converter shares the same topology of a three-level neutral-point-clamped inverter. However, two different DC sources supply the system from its three terminals, as in Figure 21(c). As with the other non-conventional topologies, the MSI aims to manage the energy flows between two

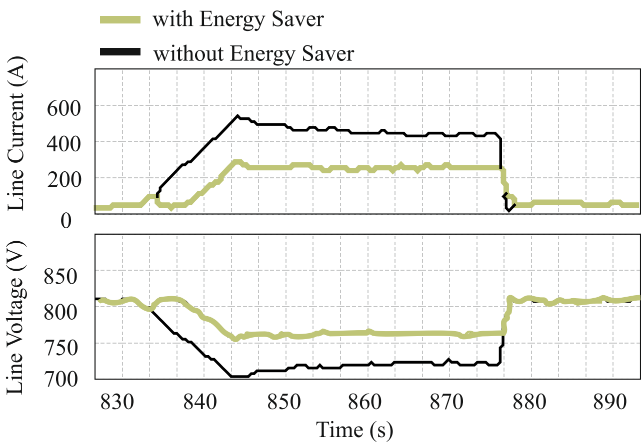


FIGURE 22 Line current shaving and voltage stabilization achieved by Bombardier onboard storage solution [123]

separate sources without additional magnetic elements. Its intrinsic reconfigurability allows connecting one source at a time, recharging one source from the other, or employing both to supply the traction motor. In [120], a current-sharing strategy was proposed to actively control the ratio of average currents supplied by the sources. Despite experimental results showing its technical viability, this converter is at an early research stage. Specifically, further study is needed to assess many open topics, such as the feasibility of recharging operation with motor at standstill; the impact of source voltage variations on motor operation; and economic attractiveness for a standard architecture in terms of capital and operating costs.

7 | ADVANTAGES, CHALLENGES, AND COST ISSUES

7.1 | Onboard energy storage in electrified rail systems

The experience gained through tests and commercial operation indicates that multimodal vehicles with OESSs can indeed provide several technical advantages to electrified rail systems [121, 122]:

- power peaks shaving during accelerations, leading to higher efficiency and reduced energy demand per driving cycle;
- voltage stabilization of overhead line due to reduced current demand, possibly leading to higher traffic densities without modifications in the infrastructure;
- partial catenary-free operation, with reduced load on infrastructures and partial autonomy in cases of power supply failure.

When used in combination with overhead supply, batteries and SCs allow for a considerable improvement in braking energy recovery. Indeed, braking energy is not wasted on rheostats or sent back to the line if feasible but stored onboard the vehicle and reused for subsequent acceleration. Energy savings are more effective for urban transit vehicles, characterized by low commercial speed and frequent accelerations and braking. For this particular goal, SCs usually represent the best choice thanks to high power density, cyclability, and lifetime. Available data from some of the installations presented have shown reductions in energy drawn by the catenary from 10% to more than 30%. As detailed in Section 3, major companies like Siemens, CAF, and Bombardier offer storage solutions for onboard installation and claim their products have maximum energy savings of 20%–30%. Line current shaving and voltage stabilization are important secondary effects of onboard storage and improve the efficiency and service quality of the electrified infrastructure. Figure 22 displays the reduction in line current demand and voltage fluctuation achieved by Bombardier's solution on a standard light rail driving cycle, as claimed by the company. Moreover, OESSs can be used for partial catenary-free operation on urban and regional lines, from a few hundred metres to several kilometres. For such applications, batteries can entail lower investments than electrification and are compliant with aesthetics, noise, and pollution requirements typical of urban environments. For instance, Siemens asserts a reduction of up to 80 tons/year of CO_2 per vehicle from adopting their 'Sitras MES' onboard storage solution [124].

These advantages generally come at the expense of increased weight of the system and high modification costs. For this reason, alternative onboard sources are generally preferred when designing new vehicles rather than when retrofitting existing units [18]. More stringent safety requirements have to be applied due to the presence of passengers on board. On the other hand, maintenance of the storage units necessarily entails vehicle downtime. Moreover, the sizing of OESSs for vehicles operating on electrified networks represents a non-trivial problem. An optimal combination between electrified infrastructure and onboard energy should minimize the total operational costs while meeting system lifetime and reliability constraints [125]. To this end, multiobjective optimization can be employed to allocate sufficient onboard energy capacity, define electrified and catenary-less sections and locate charging points. In [4], mixed-integer linear programming (MILP) is employed to determine the optimal size of three different types of OESSs (batteries, SCs, or flywheels) on the Changping line in Beijing. The loss function is expressed in terms of consumed energy, while weight and capital cost upper limits are included as inequality constraints and spanned in a particular range to see how the optimal OESS technology selected the MILP changes accordingly. Since minimum energy consumption and costs are complex functions of OESS size and energy management, these two factors can be considered in the optimization routine. This is done in [126], where the optimal sizing and power-split targets of OESSs (batteries and SCs) are obtained by solving a multiobjective optimization problem through GA. The problem is formulated in terms of total costs (capital and operational) of the multimode traction system and applied on the tram line in Seville, which comprehends

TABLE 6 Comparison among different approaches for energy demand reduction in railway systems [18, 19]

Solution	Pros	Cons
Reversible substation	- Implementation and maintenance does not interrupt operation - Lower safety constraints compared to onboard solutions - No vehicle modification costs	- Very high infrastructure costs - No possibility of off-wire operation - Lower efficiency compared to local storage - No voltage stabilization or line load reduction
Wayside ESS	- Medium efficiency - Line voltage stabilization - No weight or space constraints - Implementation and maintenance does not interrupt operation - Lower safety constraints compared to onboard solutions - No vehicle modification costs	- Fine-tuned traffic analysis for sizing and location - Medium infrastructure costs - No load reduction at pantograph level - No possibility of off-wire operation
Onboard ESS	- High efficiency - Catenary-free operation - Line voltage stabilization and load levelling - No infrastructure costs	- Space and weight constraints - Increased vehicle costs - Vehicle standstill for maintenance - Increased safety constraints

electrified and catenary-less segments. The optimal solution is shown to bring a significant reduction in the total costs of the system. However, the overall procedure has a relevant computational burden and relies on many assumptions and cost indexes that need to be finely tuned.

Operators can implement other strategies to enhance the energy efficiency of electrified rail systems. The main alternatives to multimodal rolling stocks are represented by reversible substations and wayside storage units [19]. Reversible substations allow bidirectional energy flows between the AC and DC grids. Therefore, they can improve the receptivity of the DC overhead line since the excess braking energy can be fed back to the AC distribution network. The substations must be designed to fulfil several requirements: prioritize the exchange of energy among vehicles, ensure power quality at the AC side, and control the DC-side voltage during all operation modes. If a complete upgrade of the unidirectional substations is not feasible, IGBT inverters can be added in parallel to manage the reverse energy flow that occurs during braking [127]. If a complete replacement is expected, an IGBT converter performing as a controlled rectifier and inverter can represent a compact solution. The installation of reversible substations requires little or no modification of the rolling stock but entails significant infrastructure costs. Moreover, the effectiveness of energy recuperation can be negatively affected by the excessive distance between the braking vehicle and substation and the conversion chain's overall efficiency. A comprehensive review of this topic is given in [18].

Wayside energy storage installation can be a more efficient and cost-effective solution for off-board braking energy recuperation. They can reduce the energy provided by the AC grid and stabilize the DC grid voltage through proper peak-shaving action. Moreover, their design is not affected by space and weight restrictions. Their installation and maintenance do not directly affect rail system operation if a certain overall degree of system redundancy is assured. However, attention must be paid to the displacement of the storage units along the route to minimize transmission losses while containing capital costs.

Variability in traffic conditions must be carefully considered to avoid oversizing. Moreover, wayside storage systems cannot reduce the burden of the overhead supply line nor enable catenary-free operation [19]. A general comparison of different energy-saving solutions in electrified rail systems is given in Table 6.

7.2 | Potential for diesel replacement in non-electrified rail systems

On short to medium ranges, charging times are not an issue and can be effectively accomplished under catenary on electrified sections and at stops through dedicated fast-charging facilities. For instance, Bombardier cites a full charge time of 7 to 10 minutes for their 'Talent 3' to run 40 km without overhead wire [47]. Other manufacturers claim similar charging-time-to-range ratios. In general, the experience with batteries in LRVs has so far been positive. This is indeed proved by the high number of vehicles operating in urban and suburban areas in Asia, America, and to a lesser degree in Europe.

For longer distances and higher amounts of stored energy, hydrogen represents a competitor of batteries as a clean alternative to diesel. Alstom claims CO_2 savings of 700 tons/year per vehicle for their hydrogen train [128]. This translates to a 45% reduction compared with the emissions of a standard Lint unit when hydrogen is produced from natural gas. Indeed, several academic research activities on the decarbonization potential of hydrogen endorse the claims of Alstom. In [129], the performances of a 600 kW, 72-ton diesel train were compared with those of fuel cell and FC/battery hybrid trains derived from the same baseline design. Performances were evaluated on an 80 km regional route in

TABLE 7 Challenges of onboard batteries and fuel cell systems as alternatives to diesel

Batteries	Hydrogen FCs
Charging times forlong-range operation	H_2 production, distribution and stocking
Low operational flexibility	Regulatory barriers for rolling stock and facilities O&M
Life cycles and lifetime	
Thermal stress and temperature management	

Abbreviation: FC, fuel cell.

proximity to Birmingham. Under the requirements of equal journey time and passenger capacity and one-day operation without refuelling, a reduction of 34% in fuel consumption for the FC vehicle and 55% for the FC/battery vehicle was observed for the baseline diesel unit. The global CO_2 emissions, assuming steam reforming to produce hydrogen, were found to be lower for both hydrogen-powered trains: 55% for the hydrogen-powered and 72% for the hydrogen-hybrid, assuming that hydrogen is produced from natural gas. In 2016, a collaboration among the University of Birmingham, Hitachi Ltd., and Fuel Cell System Ltd. resulted in a preliminary study on the potential of converting existing DMUs and new regional multiple units to hydrogen power [130]. The proposed powertrain was of FC/battery hybrid kind. Given the same timetable requirements of the baseline diesel units, a 50% reduction in fuel energy demand was evaluated for the hydrogen-powered fleet.

Despite a common set of advantages, battery and FC trains pose technical and non-technical challenges to their adoption as widespread alternatives to diesel power units. A non-comprehensive list is given in Table 7. Large-size batteries require much longer charging times with respect to standard refuelling of diesel trains. For a 200 km range, a battery pack currently could require approximately 50 minutes for a full charge [128]. On the contrary, the relationship between operating range and refuelling time is much more attractive for hydrogen trains and comparable to standard diesel units: 15 minutes of refuelling enable up to 1000 km of range.

Furthermore, hydrogen trains allow for a higher operational and network flexibility like diesel units, while battery vehicles must strictly follow the mission profile to which their accumulators have been tailored. Hydrogen fuel tanks are separated from the power conversion elements, the fuel cells, leading to a higher versatility in the system design. Battery power and energy are correlated and limited by the electrochemical characteristics of the device. A fine tuning of the battery size must be carried out in the design phase according to the specific mission profile to avoid oversizing. Battery charging can be done at stations or depots using pre-existing electrified infrastructures. However, when long-range operation is required, dedicated fast-charging islands along the route become necessary to avoid oversizing of the batteries. To overcome the challenges of fast battery charging, an original solution called 'Fast-Swap Charging' is proposed in [131]. It consists of a fast replacement of depleted storage units with precharged ones at the terminal stations of the route. Empty batteries can be recharged during low electricity-demand periods and at the optimal rate, thereby reducing costs and excessive stress on the storage unit and power supply system. However, this solution is presented for LRVs, and to the authors' knowledge, no similar analysis has been carried out for larger battery trains.

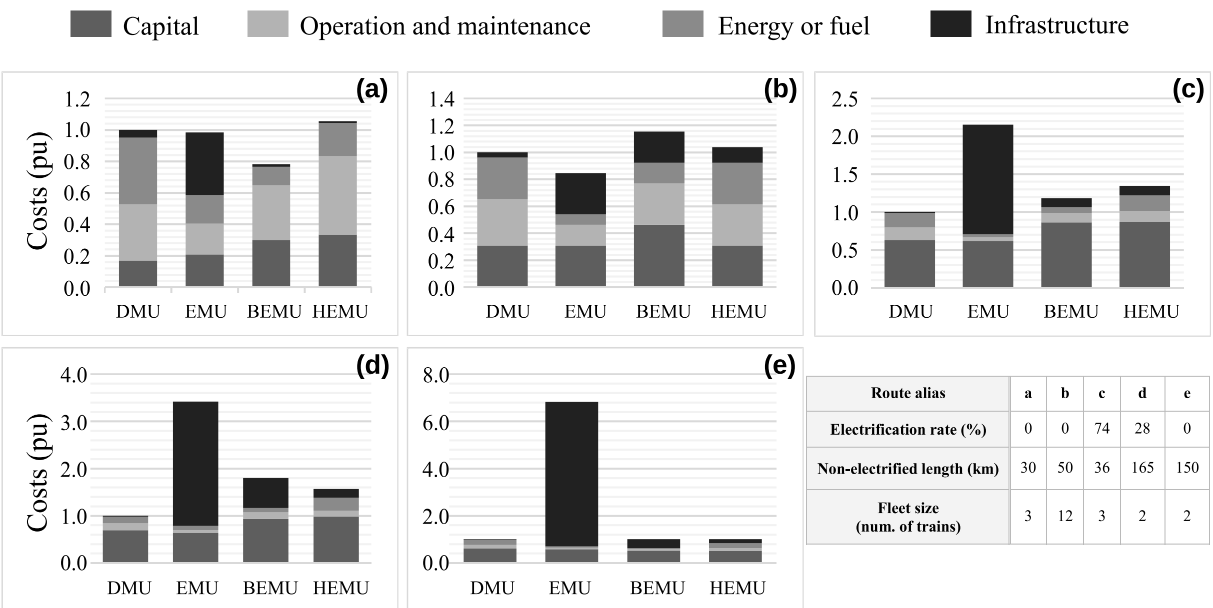
Dedicated facilities are even more necessary for FC trains, since large quantities of hydrogen should be produced, distributed, and stocked every day. For instance, a fleet of 20 iLint would require approximately 3750 kg-H_2 to cover a daily range of 750 km, considering an average hydrogen consumption of 250 g/km [132]. Today's standard solution to H_2 storage is to stock it in high-pressure cylinders. Compressed hydrogen is a highly efficient methodology for storage but entails high costs for the vessels and is intensively energy-consuming [133]. Innovative solutions such as material-based storage through hydrogen absorption have been recently considered to tackle these limitations and represent a research frontier of much interest [134]. Due to less on-field experience, challenges in mechanical and thermal stresses are common to both technologies and must be addressed carefully to ensure the rated operation and adequate lifetime. Thermal ambient conditions typical of rail may need specific heating and cooling units for storage devices thermal management. The health management of batteries and FCs should be addressed carefully given the long mission requirements of trains, as low reliability would result in high operational costs for the rolling stock. Indeed, an incorrect evaluation of OESSs lifetime and health state during train operation can lead to wrong sizing and energy management strategies, leading to an increase in the overall costs [135]. Reliability-oriented energy management strategies can be implemented to tackle these issues and adequately account for OESS degradation. This is, for instance, presented in [136], where degradation metrics are included in the energy control of an FC-based hybrid traction system. The ageing of the FC is coded by three non-interacting degradation indexes that account for three stress factors: too low or high-power operation, transient loading, and start-stop cycles. The resulting optimal control strategy is shown to reduce the estimated FC degradation compared with a baseline control. However, significant computational effort is required to solve the stochastic optimization problem and derive the control look-up table.

On the other hand, legal barriers represent a major disincentive to hydrogen adoption. Indeed, the existing regulatory framework for hydrogen, fuel cells, and related infrastructure is not specific to rail applications, entailing a time-consuming

TABLE 8 Operating and maintenance costs of rolling stock and infrastructure for conventional and alternative rail systems [24, 60, 72]

	DMU	EMU	BEMU	HEMU
Energy consumption	15 ÷ 20 kWh/km-train	6 ÷ 8 kWh/km-train	5 ÷ 6 kWh/km-train	7.5 ÷ 9 kWh/km-train
Fuel consumption	1.5 ÷ 2 L/km	-	-	230 ÷ 360 g/km
Energy/fuel price	1.2 €/l	12 ÷ 15 c€/kWh	12 ÷ 15 c€/kWh	4.5 ÷ 5.8 €/kg-H_2
Vehicle maintenance costs	0.9 ÷ 1.2 €/km-train	0.65 ÷ 0.8 €/km-train	0.85 €/km-train + 600 ÷ 1300 €/kWh/8 years (accumulator)	0.7 ÷ 1.0 €/km-train + 1000 ÷ 2000 €/kW-5 years(fuel cells)
Infrastructure costs	350 k€/station	0.9 ÷ 1.1 M€/km line	5 M€/E-station	1 M€/H_2-station

Abbreviations: BEMU, battery electric multiple unit; DMU, diesel multiple unit; EMU, electric multiple unit; HEMU, ydrogen-electric multiple unit.



Route alias	a	b	c	d	e
Electrification rate (%)	0	0	74	28	0
Non-electrified length (km)	30	50	36	165	150
Fleet size (num. of trains)	3	12	3	2	2

FIGURE 23 Comparison of technology-related costs for rolling stock and infrastructure on five European regional lines for diesel multiple units (DMU), electrical multiple units (EMU), battery electric multiple units (BEMU), and hydrogen-electric multiple units (HEMUs) [60, 72] The costs are normalized to the total cost of diesel fleets, calculated in EUR per km of train operation, and correspond to (a) regional rail network around Düren, Germany (DMU cost: 5.2 EUR/km); (b) regional rail network in the provinces of Groningen and Friesland, Netherlands (DMU cost: 2.6 EUR/km); (c) regional route from Toulouse to Luchon, France (DMU cost: 7.8 EUR/km); (d) regional route from Zaragoza to Canfranc, Spain (DMU cost: 5.5 EUR/km); (e) regional route from Sibiu to Brasov, Romania (DMU cost: 6.2 EUR/km). For each route, the table provides information on the electrification rate (i.e. electrified track length over total track length), the extension of non-electrified sections, and the number of trains in service as a measure of the traffic volume

permitting and approval process for manufacturers and railway operators [72]. This is particularly true for hydrogen distribution and storage facilities. Large amounts of pressurized gas in the tanks can lead to hazards and require dedicated safety procedures, which have not been standardized yet. Similar arguments can be made for defuelling and maintenance procedures of hydrogen refuelling stations. Intensive research and development efforts by rolling stock manufacturers and technology providers, together with supporting activities by local authorities and regulators, are necessary to overcome these barriers in the next future.

In assessing the economic attractiveness of conventional and multimodal train technologies, different cost items must be considered and quantified. In general, technology-dependent and technology-independent costs can be identified. Within the first group, it is possible to list

- capital costs of rolling stock;
- capital costs of infrastructures for electrification/charging/refuelling;
- energy and fuel consumption per km;
- cost of energy per kWh, cost of fuels per liter or kilogram;
- costs per unit energy or power of additional components such as fuel cells, storage tanks, and accumulators;
- maintenance costs of rolling stock and infrastructure;
- replacement costs of the main power components, such as diesel power units, batteries, and fuel cells.

Possible ranges of technology-dependent costs are given in Table 8 for diesel, electric, and multimodal units for suburban and regional service.

In broad terms, DMUs and EMUs exhibit lower provisioning costs for rolling stock, regardless of the characteristics of the route. This is due to the high capital costs per unit energy/power of batteries and fuel cells. Infrastructure costs are almost null for DMUs and usually the highest for EMUs, for whom the extension of the network and its traffic volume are key factors. Costs of operation are comparable for the four different technologies, while regular maintenance is regarded more expensive for DMUs because of the higher operating temperatures and vibrations experienced by diesel power units.

However, power components must be replaced more frequently for HEMUs and BEMUs, given the shorter expected lifetime of batteries and fuel cells compared with diesel engines. Standard EMUs and BEMUs exhibit the lowest costs for traction energy due to the poor efficiency of diesel engines and the high price of hydrogen either when purchased or produced on-site via electrolysis.

In [60, 72], an accurate calculation is made for the total cost of ownership of electric, battery, and hydrogen trains as alternatives to diesel propulsion. The study considers five European regional networks that are currently operated with DMUs. The resulting technology-related costs are reported in Figure 23, together with the main characteristics of each route in terms of electrification rate, length of off-wire sections, and traffic volume.

For each route, the costs of the competitor technologies are normalized to the total cost of the diesel units. Non-technological cost items, like track and station fees, are excluded for better comparison. The results of these analyses help to draw some general remarks. On high-traffic networks with short lines (route b), electrification stands as the most competitive solution. Energy and operating costs are the lowest, while the short extension of the infrastructure and the high traffic volume justifies the corresponding investments. Battery trains represent a feasible alternative to diesel for off-wire operation on short non-electrified routes (route a) or in networks characterized by a high electrification rate (route c), where batteries can be recharged under catenary and do not require dedicated infrastructure.

In these short-range applications, the benefits of hydrogen energy do not outweigh the cost penalties of fuel and infrastructure. On the other hand, HEMUs gain competitiveness and outperform BEMUs on low-traffic lines of over 100 km (routes d and e). On these lines, electrification makes no economic sense, and diesel is currently the dominant technology. Battery trains would require bulky and expensive accumulators, with extra costs in fast recharging facilities along the route. In contrast, HEMUs can fully benefit from the high energy density and flexibility of hydrogen. These vehicles allow for long off-wire operation with a reduced amount of refuelling and corresponding infrastructures. In most cases, DMUs still represent the most cost-attractive solution today. However, the economic disadvantage of battery and hydrogen trains may already low depending on some key route characteristics. Small gaps in technology costs, together with low or zero local emissions, are strong enablers of the transition towards alternative energy sources.

8 | CONCLUSIONS

This paper has presented the current status, challenges, and perspectives of OESSs for urban and regional rail transport. Rail is already an efficient and low-polluting transportation sector. To further reduce energy demand and greenhouse gas emissions, onboard storage devices are being integrated into the propulsion system of light and conventional rail vehicles at an increasing pace. On high-density urban tracks that are mostly or entirely electrified, SCs and small-size batteries enable full exploitation of regenerative braking. Together with a reduction of up to 30% in energy demand from the catenary, current shaving and line voltage levelling are also achieved. Moreover, wireless operation on short non-electrified segments avoids installing electrified wires in demanding environments, such as historical city centres. The adoption of onboard storage devices for light rail applications presents no technological barriers and is likely to continue its positive trend following the ever-increasing passenger activity of urban mass transit worldwide.

For regional rail services, electrification is generally progressing as a reliable and clean alternative to diesel propulsion. Electric trains exhibit lower energy and maintenance costs compared to diesel trains and operate with zero local emissions. However, electrification entails very high investment costs and does not pay off on low-traffic routes with modest passenger or freight activity. Alternative propulsion systems with medium and high-size batteries and hydrogen fuel cells can already be cost-attractive and replace fuel combustion on these routes. Several business analyses endorse this finding, and increasing efforts are being made by manufacturers and operators, with many fuel cell and battery vehicles in commercial or trial passenger service in Asia, Europe, and America. Despite cost feasibility and energetic and environmental advantages, some technological and non-technological barriers have to be overcome. Among the main challenges, it is possible to list slow recharging of high-size batteries, lack of infrastructures for hydrogen production and distribution, low operational versatility of battery trains, low energy and power densities of storage devices at the system level, little on-field experience in lifetime management of batteries and fuel cells, and gaps in the regulatory framework for hydrogen adoption in rail applications. These energy storage technologies have the potential to become technologically mature in the upcoming decade. On their side, emerging semi-conductor technologies and novel converter topologies can play a vital role in this process thanks to the reductions in mass and volume that they can achieve.

Today's integration of storage devices on board rail vehicles represents an attractive field in academic research and common practice in the rolling stock industry. Indeed, it is part of a more comprehensive process of renovation that the rail sector is currently experiencing. Wayside storage systems have established themselves as a reliable solution for energy efficiency and line load levelling and will be increasingly adopted by operators on electrified networks. At the same time, the integration of renewable energy sources such as photovoltaic and wind is gaining increasing attention. Renewables can represent a sustainable means for energy generation, reducing losses on the primary grid and facilitating a flexible exchange of electrical energy at local scales. The management of complex power systems comprising variable train loads, station loads, renewable generation units, and distributed energy storage devices requires a broader application of the smart grid concept to electrified railways. Smart energy management strategies will thus be required for reliable and energy-efficient operation of the railway system. On the other hand, innovative paradigms for the supply system, such as inductive power transfer technology, will unfold alternative solutions to on-board energy storage for long-range wireless operation of rail vehicles. Magnetic resonant power transmission has already been tested on scales of hundreds of metres with promising results. The technology is not yet mature, and many design and control issues remain to be tackled. Major improvements in these fields are possible with adequate supportive policies by institutions and long-term investments by technology providers, rolling stock manufacturers, and rail operators.

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