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Future Freight Locomotives in Shift2Rail – Development of Full Electric Last Mile Propulsion System

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Abstract

Present mainline electric locomotives with last mile (LM) feature propulsion system usually rely on small diesel engines with ca. 200-300kW power output. Full electric last mile propulsion systems, based on Li-Ion batteries, with up to 500kWh energy and power in the range of 1 MW, will bring the innovation to a next level. Operators will be able to run trains on short non-electrified lines and restricted areas, with zero exhaust gas and low noise emissions. Furthermore, recuperation of braking energy will lead to increased system efficiency.

This paper addresses the challenges of the integration of such batteries by focusing on system design and homologation. It also highlights the advantages of full electric propulsion over systems relying on diesel engines and provides simulation results of load profiles of various trains, introducing advanced mission management concepts and charging schemes.

Keywords: Spatial Planning / Last Mile; Energy Efficiency; Clean Energy for Transport; Transport on Demand; Air Quality / Noise / Health Issues; Integration of Transport / Energy / IT Systems

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Nomenclature

BMS	Battery Management System
FFL4E	Future Freight Locomotive for Europe
FELM	Full Electric Last Mile
IP	Innovation Program
LM	Last Mile
LMB	Last Mile Battery
LMD	Last Mile Diesel
nNMC	Nano Lithium Nickel Manganese Cobalt Oxide
TCU	Thermal Conditioning Unit

1. Introduction

In Shift2Rail the pillar "Technologies for attractive and sustainable European Freight" (IP5) has a clear target vision: Increase competitiveness by automating and digitalizing the processes along the value chain, and by integrating and offering advanced functionalities. Various projects within IP5 cover these aspects, such as e.g. "Automated Train Operation", which is underway within the "Automated Rail Cargo Consortium" and the project "Long Train Distributed Power System" which is part of the consortium "Future Freight Locomotive for Europe" (FFL4E).

FFL4E also works on the "Hybridization of future locomotives" studying the potential of hybrid propulsion concepts and the integration of onboard energy storage systems (OESS) in freight locomotives. In the context of this topic, the integration of Full Electric Last Mile (FELM) propulsion systems is analysed in detail and described in this paper.

The concept of the Last Mile (LM) propulsion system on a mainline electric locomotive, first proposed by Bombardier Transportation few years ago, was a disruptive and successful innovation giving to customers the independence from shunting operators and full flexibility in daily operation. These electric locomotives are equipped with a small diesel engine with ca. 200-300kW power at the shaft which allows moving a heavy freight train on non-electrified lines with low speed.

In FFL4E, the aim is to go a step further by replacing the diesel engines by powerful OESSs. Full electric last mile propulsion systems, based on Li-Ion batteries, with up to 500kWh energy and higher peak power in the range of 1MW, occupying the same space in the locomotive as the last mile diesel engines, will bring the innovation to a next level. Operators will be able to run long and heavy freight train compositions on short non-electrified lines and to enter restricted areas, with zero exhaust gas and low noise emissions. Furthermore, the battery will allow recuperating large amounts of braking energy, helping to reduce the overall energy consumption.

However, Li-ion batteries are still not common on railway application. There may be multiple reasons for this, such as e.g. high system costs, working temperature requirements, difficulties in homologating due to missing standards and norms, safety aspects and the need of complex and smart mission management systems.

The FFL4E consortium addresses these challenges, focusing especially on the system design and homologation of hybrid propulsion systems with OESS providing last mile functionality. This paper details them. It also describes the possibilities and the flexibility that Li-Ion based last mile propulsion systems give to customers and highlights the advantages over systems relying on diesel engines only (e.g. access restricted areas, energy harvesting, peak power shaving). Furthermore, simulations of load profiles of various freight trains are presented, introducing advanced mission management concepts including charging schemes for charging such powerful batteries in time and as much as possible for free.

Finally, an outlook about the advantages of hybridizing last mile propulsion systems, by combining fuel cells with powerful Li-Ion batteries, is provided.

2. Future Freight Locomotives: Hybridization of propulsion systems

Modern mainline freight locomotives are interoperable and powerful but still do not offer the required flexibility and competitive LCC. A study regarding the state-of-the-art of nowadays locomotives in the European market shows that there is a high presence of locomotives with BoBo axle configuration to work in light duty conditions and a much smaller share of CoCo configuration for heavy duty. Most of the locomotives are fully electrically propelled although there are also diesel-electric locomotives. Maximum service speed is mostly 140km/h although several platforms can go up to 160-200km/h. Normally, maximum axle weight is below 22,5Tn and power output varies depending on the type of locomotive; electric ones have a high-power output (in the range of 5,0MW-6,5MW) while diesel-electric ones have a middle power output (in the range of 2,0MW-3.6MW).

European Rail freight transportation characteristics show that in case of the fully electrically locomotives, although mostly BoBo ones are likely to work in light duty conditions, as a result of mixed traffic networks, a high average speed is required to them not to interfere with passenger transportation. Hence, higher payloads are likely to result in a high-power requirement for them. In consequence, a shift from BoBo to CoCo axle configuration may be observed.

In the present context, Future Freight locomotives seek enhancing locomotive functionalities. Hybridization is one way. Thanks to the hybridization of propulsion systems with powerful energy storage systems, for example Li-Ion ones, future locomotives will potentially offer maximum flexibility and features to the customers, going beyond today's interoperability:

- Last mile run: running capability in absence of overhead line for a limited distance
- Peak shaving: control of catenary current consumption in order to prevent power peaks applied to the line
- Backup mode: running capability when primary energy source is not available
- Energy Efficiency: energy recovery capability when braking and efficient operation of diesel engine
- Power Boost: increase of available power either for accelerating or for facing steep gradients
- Electric Mode: 100% electric operation in low emission zones (either noise or fumes)

Among all the above potential functionalities, this paper focuses on Last Mile Run functionality which is deeper assessed with real case conditions. For this purpose, a system architecture for the integration of OESS in hybrid electric multi-system locomotives is specified (Fig. 1).

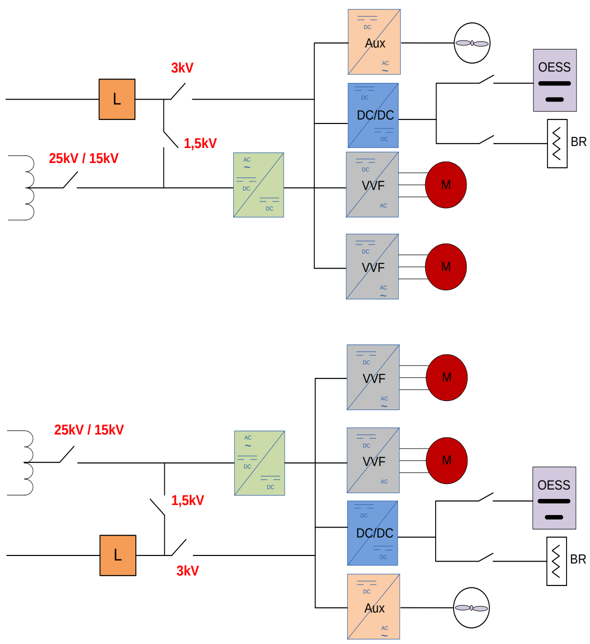

Fig. 1 Simplified one-line diagram of a Hybrid Electric Multi-System locomotive

Using as a base this architecture and the electric locomotive reference model (Table 1), result of the study regarding the state-of-the-art of nowadays locomotives in European market, simulations on CRUISE M (Fig. 2) are launched.

Table 1. Light duty reference electric locomotive.

Characteristics	Value
Axle configuration	BoBo
Power supply	AC – 25 kV / 15 kV
	DC – 1,5 kV / 3 kV
Maximum service speed	160 km/h
Maximum axle weight	21,5 t
Maximum power	6,5 MW
Starting Tractive Effort [STE]	300 kN
Continuous Tractive Effort [CTE]	245 kN @ 90 km/h

These simulations give the opportunity to analyse and identify the requirements for the OESS to provide Last Mile Run functionality at different boundary conditions such as real track profiles or operating modes.

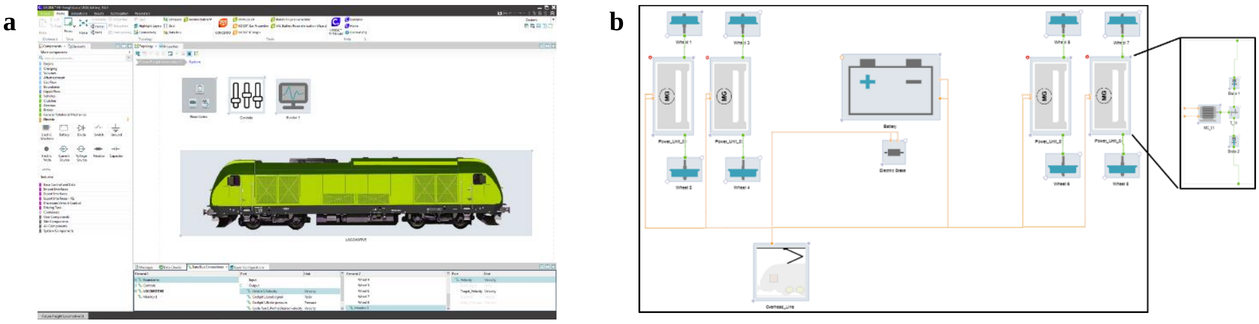

Fig. 2 (a) (b) Simulation model overview of a BoBo Hybrid Electric Multi-System locomotive on CRUISE M.

With the aim at calculating an averaged size of the onboard Li-Ion battery for Last Mile Run application, simulations are carried out on four different real track profiles (TP) that connect specific towns with industry companies in Europe and require this functionality:

- TP1: Bruck an der Mur – Paper Mill in Gratkorn
- TP2: Zeltweg – Pöls
- TP3: Bruck an der Mur – Magna Steyr in Graz
- TP4: Lüneburg – Hamburg

Fig. 3 shows an extract of the simulation results for TP1. It includes part of the track velocity and inclination as well as the locomotive power consumption during overhead line operation (blue) and Last Mile Run mode (black). The maximum effective power during the Last Mile Run mode is limited to 1 MW which is sufficient for the operation of a train under the assumed boundary conditions, listed in Table 2. The battery model used in the simulation enables the sizing of the battery and gives additional information on the battery status such as voltage drop during discharging.

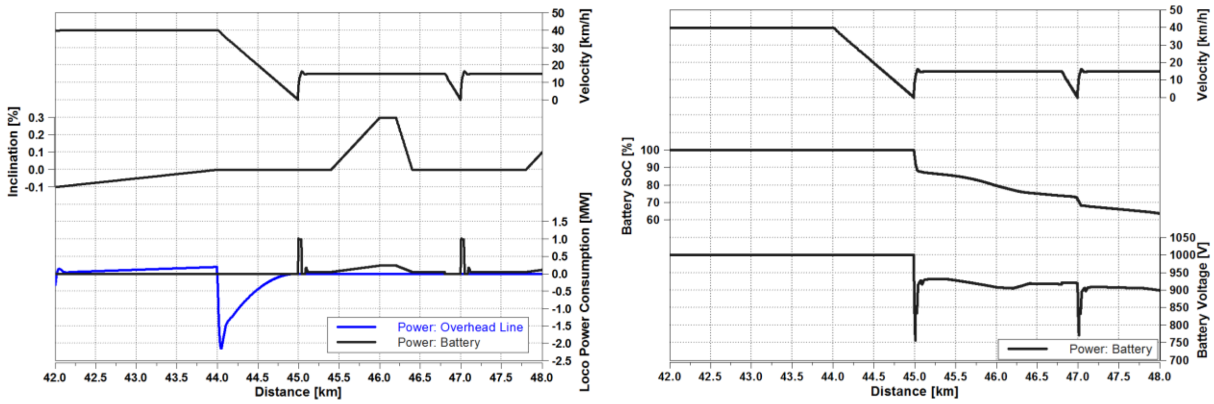

Fig. 3 Simulation results, (a): track profile & power consumption, (b): battery SoC & voltage.

From the simulation results (Table 2) it is concluded that the characteristics of the OESS for TP1 and TP3 show comparable requirements from energy point of view, 180-190 kWh. Nevertheless, required battery capacity becomes higher, ≈240 kWh, if a battery-power limit of 5 C-rate is imposed and ≈480 kWh, if a battery-power limit is reduced to 2.5 C-rate in order to enhance lifetime. The same amount of energy is required by TP4 if this power restriction from batteries is kept. TP2 seems to be too challenging for the given boundary conditions (1095 kWh required). So a significant reduction of the load would be necessary for this application.

Table 2. OESS characteristics of a hybrid electric freight locomotive for Last Mile application in four different track profiles.

	Track profile and OESS characteristics				
Track profile	Track profile	TP1	TP2	TP3	TP4
	Distance with battery [km]	10	14.5	11.8	7
	Altitude [m]	2	114	1	0
	# of stops [-]	3	-	1	3
	Train load and locomotive weight [t]	1500	←	←	←
OESS charac.	Battery power max. (incl. aux. & losses) [MW]	1.2	1.2	1.2	1.2
	Battery traction power max. [MW]	1	1	1	1
	Battery size – Energy point [kWh]	190 (6.3 C-rate)	1095 (1.1 C-rate)	180 (6.7 C-rate)	145 (8.3 C-rate)
	Battery size – Final [kWh] at 5.0 -Crate	240	1095 (1.1 C-rate)	240	240
	Battery size – Final [kWh] at 2.5 C-rate	480	1095 (1.1 C-rate)	480	480

It is concluded with this first assessment that Li-Ion batteries up to 500 kWh and 1 MW power are enough to answer most of the nowadays Last Mile Run demand. The implementation of such OESS in hybrid electric freight locomotives may provide, furthermore, different features all-in-one: Last Mile Run, Peak shaving, Backup mode and Energy Efficiency, as relevant similarities are observed in OESS design along the different locomotive applications.

3. Use cases for Full Electric Last Mile propulsion systems

A detailed Bombardier internal market analysis prior to the development of the Bombardier TRAXX AC3 locomotive (first electric locomotive with last mile functionality based on a 230kW diesel engine supported by a small lead acid battery [L.Altmann et al. 2011]), showed that customers wish to perform shunting operations in catenary free areas without the need of specific locomotives for this purpose. Electric locomotives integrating last mile feature propulsion systems are a potential solution for it. The market of these systems, nevertheless, is still young and as the available power is still very limited, potential customers do not have a clear picture how they can take commercial advantage of this new functionality yet. Next two sets of values describe them: (1) Last mile functionality per se, and (2) last mile functionality enhanced with a powerful Li-ion battery system replacing diesel engine.

Value added of last mile functionality:

- Rental of shunting locomotive services at harbours and other freight terminals will no longer be necessary. Rental rates vary significantly, depending on their monopolistic positioning and applicable shunting tariff regulations. However, port authorities may either forbid entry with (large) locomotives or do shunting with reasons expressed such as safety concerns. Alternatively, the authorities may charge entry fees to compensate for losses for not providing their shunting services.
- Accessing branch lines to industrial sites for pickup and deliveries.
- New methods of transporting goods. Similar to passenger trains, the freight trains could pass through multiple stations with side tracks where mobile cranes transfer selected containers between trains, trucks and probably a temporary storage site. This allows for relatively short stops at the stations and therefore enables rapid and efficient transportation services.

Value added of last mile functionality based on powerful Li-Ion battery systems:

- Last Mile System provides an important increase in tractive power. This makes the performance level comparable to a typical shunting locomotive.
- The proposed last mile battery system allows improved heavy haul operation as well as operations on tracks with steeper gradients.
- Over a certain distance, emission free operation is possible, driving with battery only. This means zero CO2 and NOx-emissions as well as low noise.
- Energy recuperation into battery possible when braking.
- Recharging of the battery from the catenary can be declared as "emission reduction".

The attempt to quantify the customer value of the last mile function in a particular use case leads to annual savings of 150 k€. In this case, an operator with an own terminal and an own shunter locomotive commutes between a port and its own terminal (Table 3).

Table 3. Specific use case for customer value calculation.

Characteristics	Value
Shunting services / port visit	500€
Port access fee for last mile locomotives	300€
Savings per visit	200€
# Days / Year	300
# Port Visits / day	1
Savings per year	60 k€ (200€ * 300)
Costs own shunter per activity	300€
Saving for not using an own shunter	90k€ (300€ * 300)

Cumulated savings for the customer until battery replacement, that depending on the use case may be between 7 and 10 years, can be as high as 1 Mio €. The calculation takes into account the saving of shunting service, savings in form of shorter cargo delivery time and additional track access cost. However, the savings both in upward and downward directions depend on the respective use cases. Furthermore, there is value opportunity for the customer when using last mile functionality to offer a more rapid transportation service than the competing operators.

4. Integration of Li-Ion batteries in Full Electric Last Mile propulsion systems

According to Chapter 2 conclusions, 500kWh battery systems (sized to work at 2.5 C-rate to prolong lifetime) cover most of the potential last mile applications. The integration of such batteries in the application can be done in two different architectures:

- A unique battery system of 500kWh with its own Battery Management System (BMS) and thermal conditioning unit (TCU) connected to a single DC/DC converter that integrates it in the application.
- A given number of battery building blocks, thus, smaller systems of e.g. 50kWh arranged in parallel and or in series, each with the own BMS and thermal conditioning unit and connected to the own DC/DC converter to be integrated in the application.

In general terms, while the first approach promises a lower number of components and simplified interfaces, FFL4E considers that the second approach allows a better usage of the battery systems, regarding better balancing, higher safety, lower maintenance effort and more efficient adaptation to the various needs of the customers. FFL4E also considers that this architecture will facilitate the retrofit with last generation battery technologies.

In this context, FFL4E specified a battery building block of 49kWh based on (1) the latest generation of water-cooled Bombardier Primove nNMC battery units with 49kWh installed energy, (2) a dedicated TCU and (3) an advanced BMS, all to be integrated into one sealed cubicle to be placed in the machine room.

Table 4 provides the overview of the most important technical parameters of the battery building block.

Table 4. The battery building block

Type	Bombardier Primove nNMC
Installed Energy	49kWh
Nominal Voltage	532V
Continuous Charging / Discharging power	127kW
Max. Charging power	200kW (20s)
Max. Discharging power	400kW (20s)
Weight	670 Kg

nNMC (Nano Lithium Nickel Manganese Cobalt Oxide) has been selected by Bombardier for railways applications due to its well-balanced characteristics compared to other chemistries: very high discharge power, high charging power, high energy content and good safety features. For a detailed description, please refer to Figure 4 and the [Battery University].

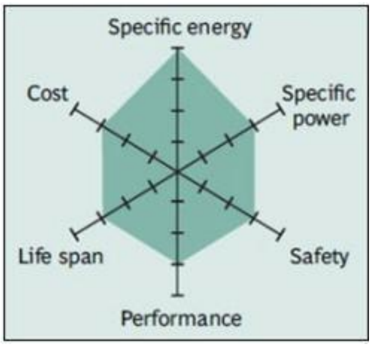

Figure 4: nNMC characteristics, Courtesy of Cadex

The battery building block is electrically connected to a DC/DC converter which supplies the DC-link of the locomotive traction converter.

It has a dedicated BMS electronics that supervises and controls the battery system. It receives input data from the Local Monitoring Units on module level and calculates the state of charge, state of health, voltage and current values and limits of the single modules and cells. It is responsible for making sure that all working parameters are kept within the allowed range. It coordinates the cell balancing and maintains a safe operation by monitoring the temperature and supervising each single cell. It is connected directly to the central processing unit of the traction converter which controls the chopper and is responsible for safe isolation of the battery (by opening the switches that are located in the connection box of the battery unit case and if necessary its own switches to protect both) when required. Furthermore, the BMS provides to the vehicle control unit actual environmental data, such as state of charge, state of health, max possible power (supply or for charging), etc. and takes request information like for instance power request. In case of a critical situation, every sub-system (battery/converter/vehicle processing unit) communicates with the other sub-systems involved, informing about the incidence.

Indeed, Li-Ion batteries need to be kept in a defined temperature range for save operation and ensure lifetime. This applies during operation as well as during inactivity (including the locomotive standing on a siding). The nominal working temperature is 23°C and charging and discharging limits are strongly affected by the internal temperature. It is commonly known that charging below 0°C may lead to unrepairable damages.

Therefore, the Primove battery building block is water cooled respectively heated. A dedicated TCU tempers the water that flows through the units ensuring at any time an ideal temperature. The TCU is controlled by the battery management system, which sends the relevant information via a CAN Interface

Mechanically, both the battery and the TCU are installed in a dedicated sealed cabinet to be located in the machine room of the locomotive (Figure 5). The TCU takes the air from the external environment and blows the hot air out of the locomotive through a dedicated opening in the roof. A venting opening in the roof also enables the exhaust of poisonous gases in the very unlike event of a failure.

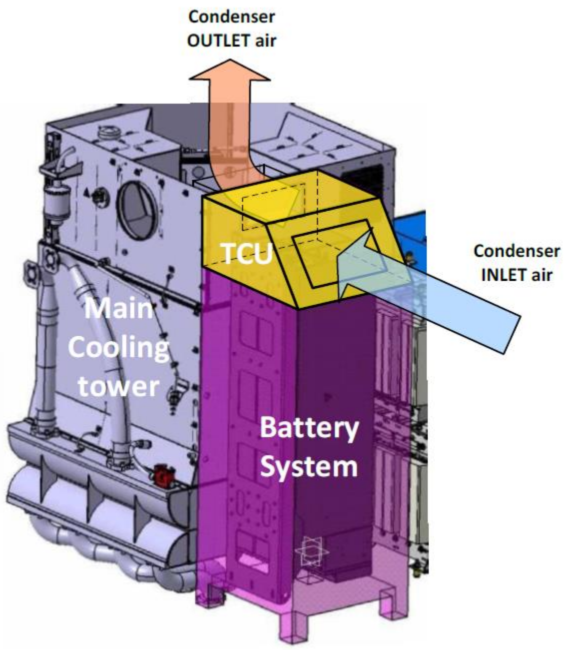

Figure 5: Battery cubicle with air flow of the TCU

5. Safety assessment of Li-Ion batteries in Full Electric Last Mile propulsion systems

Besides the technical issues described in *Section* 4, main focus is put on the safety assessment of the integration, on standardizing, certifying and homologating Li-Ion batteries based storage systems for main line railways.

In this regard, “Safety Directive Rolling Stock” (SIRF), EN 50128, IEC 61508, IEC 62928 (in development) and IEC 62864-1 standards relative to the integration of OESS in railway application are being applied.

The European standard EN 50128 "Railway applications - Communication, signalling and processing systems - Software for railway control and protection systems" specifies procedures and technical requirements for the development of programmable electronic systems which are used in railway control and protection applications. It is a particularization of IEC61508 “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems (E/E/PE, or E/E/PES)”, basic functional safety standard applicable to all kinds of industry, and describes the functional safety in the railway industry intended to cover the development of software for railway control and protection including communications, signalling and processing systems.

IEC 62928 “Onboard Lithium Ion traction batteries” intends to specify the design, operation parameters, safety recommendations, data exchange, routine and type tests, as well as marking designation of onboard lithium-ion traction batteries for railway applications.

It provides references regarding the operational conditions that batteries could support: mechanical conditions (vibration and shock), environmental conditions (ambient temperature, temperature in battery enclosure, temperature for lifetime), electrical conditions (voltage range of the battery connected to traction circuits, control voltage and insulation coordination), electromagnetic compatibility (EMC) and software architecture and validation characteristics.

It also provides general safety requirements (isolation for maintenance or service and fire protection), electrical requirements (operating voltage range, ripple current, charge and discharge control of the battery system, communications, insulation status and battery management system), mechanical requirements (mechanical integration, shock and vibration and degree of protection), performance requirements (sizing, cooling/heating and end of life performance) and storage and transportation conditions.

In order to prove that the battery systems meet all these requirements the standard defines the following type and routine tests:

- Electrical tests: Electrical characteristics tests (discharge performance at 25ºC, discharge performance at low temperature, high rate permissible current, charge retention and recovery, internal AC resistance, internal DC resistance, endurance in cycles), BMS tests, performance tests, endurance in cycles (general and high power), dielectric test, self-discharge test and operational balancing test.
- Mechanical tests: Physical appearance, mass measurement, shock and vibration test, test of the degree of protection.
- Safety tests: Safety tests according to IEC 62619: product safety tests (external short circuit test, impact test, drop test, thermal abuse test, overcharge test, forced discharge test, consideration for internal short circuit (internal short circuit test, propagation test)) and functional safety tests (overcharge control of voltage, overcharge control of current, overheating control).

Special tests for rolling stocks: safety signs, external short circuit test (combined test, component test), isolation system, fire protection and test of electromagnetic compatibility.

Finally, IEC 62864-1 “Power Supply with Onboard Energy Storage Systems, Series hybrid systems” specifies the basic requirements, characteristics, functions and test methods for hybrid railway systems on: a) energy management to control the power flow among primary source, energy storage system and power converters, b) energy consumption, energy efficiency and regenerated energy, c) vehicle characteristics achieved by energy storage system, d) test methods of combined test and, e) test methods of completed vehicles based on factory (stationary) and field (running) tests.

At present, FFL4E is working on the development and certification of the battery system by hazard and risk analysis and safety evaluation process according to the cited standards.
Every safety relevant component is designed and will be tested and evaluated for fulfilling the defined requirements and safety goals for chemical, mechanical, electronic/electrical, functional and occupational safety, ensuring the final functionality of the system.

6. Outlook

Intensive cost analyses of automotive PEM fuel cell propulsion systems indicate for a time frame up to 2030 that the hybridization of fuel cells and batteries provides a significant cost advantage over pure battery or pure fuel cell (with a very small battery) approaches. Last-mile propulsion systems of electrified locomotives could as well benefit from such a hybridization strategy in order to reduce system cost. This is especially expected after full industrialization (2030+) of fuel cell technology to large scale production volumes. Beside cost reduction, fuel cell technology possesses a considerable higher energy density than Li-ion batteries and thus enables smaller packages and reduced weight compared to respective battery systems. Due to the independent scalability of fuel cell power and energy (i.e. hydrogen) storage the fuel cell/battery hybrid can be designed to specific transportation purposes and ranges, making fuel cell technology an even more attractive alternative for zero-emission last-mile propulsion systems.

7. Conclusions

According to most studies on the topic [e.g. Wootae Jeong et al, Y.Yang, H.Flerlage et al., J.Blassmann] hybrid propulsion systems are of high relevance as they increase operational flexibility and reduce the operational costs as it was evidenced in the present paper. Locomotives equipped with such systems enable operators to run on partly electrified lines without having the need to change locomotive at the transition point. The consequence is an increase in competitiveness which is a target vision of the Shift2Rail pillar “Technologies for attractive and sustainable European Freight” (IP5).

In this context, the consortium FFL4E is analysing and proposing innovative hybridization approaches integrating powerful onboard energy storage systems. Moreover, a full electric last mile propulsion system, relying on powerful Li-ion batteries as the energy source only, is being specified and developed and will be demonstrated at the end of the project.

This paper introduces the analytical approach for the sizing of the battery for hybrid propulsion systems and provides the added values for last mile propulsion systems, based on diesel engine as well as sole battery power. Furthermore, it explains why the approach of using a building block for the battery is advantageous and details the development approach and how the safety assessment is being followed based on specific standards.

The authors firmly believe that an innovative approach for the hybridization of the propulsion system will lead to an important increase of competitiveness of the freight railway sector.

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