



D1.2

Energy Management & Pre-Standardisation for Alternative drive trains and related railway system Intermediate Report N° 2

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1	25/07/2025	First issue

Document update between D1.1 and D1.2		
2	Abbreviations and acronyms	New abbreviations and acronyms added according to the inputs in the main text of the document
5.2.2	Input from WP7 for Hydrogen Propulsion	Section updated based on the inputs from RAIL4EARTH WP7
5.2.3	Input from WP9 for Hydrogen Refuelling	List of standards identified has been updated for hydrogen refuelling station. More specificities for railway sector compared to road vehicles standards for hydrogen refuelling have been added
5.3.1	BEMU Charging	Section updated with references to last TS 50729 standards (description of charging infrastructure types), new sub-parts on DC power charging plug and underfloor charging system
5.3.2	Shore Energy Supply for parking of BEMUs and FCMUs	Section updated with a new structure (sub-parts) on requirements for shore energy supply, potential solutions to apply, results and future works to do
5.3.3	Hydrogen Refuelling	Section updated with a new structure (sub-sections). A sub-section dedicated to the common working group between WP1, 7 and 9 on hydrogen refuelling has been added. More detailed information on the requirements and State of the art on interfaces (mechanical, refuelling and communication) and next steps
5.4	Pre-Standardisation of Operational Interfaces	Section updated with a new structure (sub-sections). A sub-section on required data for energy functions related to operation has been created. Part on “additional functions to improve operation of alternative drive trains” updated with reference to battery vehicle fleet management in mobility sector.
5.5.1	Battery ESS	Section updated with a parts on the benefits of the standardisation related to battery, and with a detailed description of ESS structure and battery interfaces, based on the state-of-the-art from industry and future interfaces

		preferred solution.
6.1.2	Energy Management Functions in ERJU RAIL4EARTH WP5 (on-board)	<p>List of energy management table updated according to:</p> <ul style="list-style-type: none"> - The update made by WP5.3 - The combination of some functions for the pre-standardisation purpose - New functions suggested by the members of WP1 with interested to develop pre-standardisation <p>New frame for each energy management function part, with a description of the function, a block-diagram, requirements and impacts on standardization / regulations</p>
6.1.3	Energy Management Functions in Infrastructure (on-ground)	Section removed due to low maturity and experience on infrastructure side. 6.2 Optimization of Charging Process for Battery Trains
6.2	Optimization of Charging Process for Battery Trains	Section updated with renewable energy part
6.2.1	Optimization of the Battery Train Charging on Current Battery Trains	Section updated with new figure for high SoC/SoE charging strategy, and more details description on the effect of this strategy (ageing of battery, higher cooling, etc.)
6.2.2	Optimization of the Battery Train Charging from Infrastructure Side	Section updated with new figure for reduced charging strategy at low speed, and more details description on the effect of this strategy (limitation of infrastructure constraints, impact of lower SoC/SoE)
6.2.3	Optimization of the Battery Train Charging With Respect to Battery's Lifetime	Section updated with new figures for reduced charging strategy, and more details description on the effect of this strategy (limitation of charging power, reduced auxiliary consumption for cooling), and additional requirements for "BEMU charging" energy management functions
6.2.4	Optimization of the Battery Train Charging With Respect to Energy Costs	No major changed
6.2.5	Optimization of the Battery Train	New section added

	Charging With Respect to grid production (Rail2Grid)	
6.3	Preconditioning of Vehicle and ESS	New structure of the section, with more detailed description of the preconditioning of vehicle and of ESS on rolling stock
6.4	Auto Adaptive Train Energy Consumption Functions	Section updated with more detailed description (definition, example in other application, comparison with energy management functions)
7	Optimization of energy management at railway system level	Previously chapter 6.5 in D1.1. New structure of the chapter, with methodology approach changed, new criteria and sub-criteria for comparison. Apply on the same use case described in D1.1, with additional scenario, especially for long range BEMU evaluation. New use case added for Sweden, with analysis of several case of study
8	Exchange With Other Flagship Projects	New chapter, dedicated to resume the link between FP4 WP1 and other FPs and SP
9	KPIs	Previously chapter 7 in D1.1. Updated of KPIs impacts
10	Conclusion	Previously chapter 8 in D1.1. Updated of conclusion based on D1.2 progress
11	References	Previously chapter 9 in D1.1. Updated of references
12	Appendices	Previously chapter 10 in D1.1.

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1. Executive Summary

The present document constitutes the Deliverable D1.2 “Energy Management & Pre-Standardisation for Alternative drive trains and related railway system intermediate report n°2” in the framework of the Flagship Project FP4 – Rail4EARTH.

The activities carried out up to now within the FP4 WP1 led to the drafting of this second version of the document which reports the status of the SP3-WP1 of Rail4EARTH after 32 months of work on

the different subtasks:

- Pre-standardisation of battery interfaces: ongoing, battery interfaces are identified and discussed between partners to propose standardised ones,
- Pre-standardisation of interfaces between train and operation: preliminary, state of the art of range operation calculation and first description of needs for operators to supervise alternative drives trains,
- Pre-standardisation of interfaces between train and infrastructure: ongoing, identification of standards impacts and requirements for battery train charging, parking energy supply, and hydrogen train refuelling,
- Pre-standardisation of energy management functions: ongoing, state of the art build commonly with RAIL4EARTH WP5 for energy management functions + definition of different strategies for charging of battery trains,
- Optimization of energy management at railway system level: ongoing, description of a methodology to compare use cases and scenarios from railway system view. Definition of a first use case in France and scenario with a 1st generation battery train, with the application of the methodology and the analysis of the results,
- Identification of standards to be adopted for the interfaces and components of trains with alternative drives and related infrastructure,
- Integration of the standards identified into the “Standardisation and TSI input plan” STIP of FP4-Rail4EARTH WP28.

As this Report is the second intermediate WP1 progress report, some works are still pending and will be finalized until end 2026. The progress is according to the plan, no major deviations to be reported.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
AC	Alternative Current
ADIF	Administrador de infraestructuras ferroviarias, infrastructure manager
ANFIS	Adaptive Neuro Fuzzy Inference System
ATEX	ATmosphères EXplosibles
ATO	Automatic Train Operation
ATO-OB	Automatic Train Operation - On-board
ATO-TS	Automatic Train Operation - Trackside
ATSA	ALSTOM SA, train manufacturer
BEMU	Battery Electrical Multiple Unit
BMS	Battery Management System
BoL	Beginning of Life
BTMS	Battery Thermal Management System
CAF	Construcciones y Auxiliar de Ferrocarriles, train manufacturer
CAN	Controller Area Network
CAPEX	Capital EXpenditure
CBO	Common Business Objective
CCS	Command / Control System
CEIT	Centro de Estudios e Investigaciones Técnicas, research centre
CFO	Catenary Free Operation
CHSS	Compressed Hydrogen Storage System
CO2	Carbon dioxide
CPF	Conventional Power Follower
CSM	Common Safety Methods
C-DAS	Connected-Driver Advisory System
DAS	Driver Advisory System
DB	Deutsche Bahn, train operator
DC	Direct Current
DCP	Distributed Co-Simulation Protocol
DEMU	Diesel Electric Multiple Unit (Diesel engine + Generator)
DEBMU	Diesel Electric and Battery Multiple Unit
DLR	Deutsches Zentrum für Luft- und Raumfahrt, research centre
DMU	Diesel Multiple Unit (Diesel mechanic / hydraulic traction drive)
DP	Dynamic Programming
DOD	Depth of Discharge
D-AD	Demand ADaptive
ECM	Entity in Charge of Maintenance
EMC	Electromagnetic Compatibility
EMU	Electrical Multiple Unit
EoL	End of Life
ESS	Energy Storage System
ESU	Energy Storage Unit
ETCS	European Train Control System

FCE	Full Cycle Equivalent
FCMU	Fuel Cell Multiple Unit
FCH2Rail	Within the Clean Hydrogen Partnership funded "Fuel Cell Hybrid PowerPack for Rail Applications" Grant Agreement No. 101006633
FINE1, FINE2	European project funded within Shift2Rail. Furthering Improvements in Integrated Mobility Management (I2M), Noise and Vibration, and Energy in Shift2Rail
FMI	Functional Mock-up Interface
FSI	Ferrovie dello Stato Italiane, infrastructure manager
FP1	Flagship Project 1 - Mobility management multimodal environment and digital enablers "MOTIONAL"
FP2	Flagship Project 2 - Rail to Digital automated up to autonomous train operation "R2DATO"
FP4	Flagship Project 4 - Sustainable and green rail systems "RAIL4EARTH"
FP6	Flagship Project 6 – Delivering innovative rail services to revitalise capillary lines and regional rail services "FutuRe"
GA-SOC-AD	Genetic Algorithm for SoC Adaptive
GA-D-AD	Genetic Algorithm for Demand Adaptive
HEMU	Hydrogen Electrical Multiple Unit (hydrogen + catenary)
HMU	Hydrogen Multiple Unit (no pantograph)
HRS	Hydrogen Refuelling Station
HSS	Hydrogen Storage System
HV	High Voltage
HVAC	Heating Ventilation Air Conditioning
H2GoesRail	German funded project to develop a fully integrated H2 rail system consisting of a hydrogen EMU and hydrogen infrastructure with fast refuelling capabilities, and to integrate this system in regular operation.
IKOP	In-kind contribution for operational activities
KPI	Key Performance Indicator
LCC	Life Cycle Cost
LV	Low Voltage
MCS	Megawatt Charging System
MCS-H2	Monitoring and Control System for hydrogen
OHS	Occupational Health and Safety
OPEX	OPERating Expenditure
PPS	Primary Power Source
PINTA3	European project funded within Shift2Rail. PINTA3 addresses demonstrators for the next generation of traction systems, smart maintenance, virtual validation and eco-friendly Heating, Ventilation Air conditioning and Cooling (HVAC) and Technical research on battery and hydrogen powered regional trains (BEMU/ HMU).
PKP	Polskie Koleje Państwowe, train operator
railML	Railway Markup Language
Rail4EARTH	Europe's Rail Flagship Project 4 - Sustainable and green rail systems

RCS	Regulations Codes & Standards
RFID	Radio-Frequency IDentification
R2G	Railway to Grid
SFERA	UIC Project for Smart communications for efficient rail activities. Project code: 2017/ENV/528
SIM3PO	SNCF-V's simulation tool "Simulation d'Infrastructure et de Matériel roulant au sein d'une Plateforme Polyvalente pour des calculs de Performance et d'Optimisation "
SMO	Siemens Mobility, train manufacturer
SNCF	Société Nationale des Chemins de Fer, railway group
SNCF-V	SNCF Voyageurs, train operator
SNCF-R	SNCF Réseau, infrastructure manager
SoC	State of Charge
SOC-AD	SOC ADaptive
SoE	State of Energy
SoH	State of Health
SoP	State of Power
SoX	Group of data related to the battery (includes SoC, SoE, SoH, SoP)
SP	System Pillar
STIP	Standardisation and TSI Input Plan
STS	Hitachi Rail STS, train manufacturer
TCN	Train Communication Network
TCMS	Train Control & Management System
TLG	TALGO (Tren Articulado Ligero Goicoechea Oriol), train manufacturer
TRV	Trafikverket, infrastructure manager
TMS	Traffic Management System
TSI	Technical Specification for Interoperability
UNISIG	Union industry of signalling
UIC	Union Internationale des Chemins de Fer
VEMS	Vehicle Energy Management System
VOLTAP	Fast charging station developed by Furrer+Frey in partnership with Stadtwerke Tübingen
V2G	Vehicle to Grid
WP1	Work Package 1 " Energy Management & Pre-Standardisation for Alternative drive trains and related railway system"
WP5	Work Package 5 " Development of alternative propulsion based on ESS"
WP6	Work Package 6 " Train demonstrators of alternative propulsion based on ESS"
WP7	Work Package 7 " Development of alternative propulsion based on hydrogen"
WP8	Work Package 8 " Hybrid battery/H2 vehicle demonstrators"
WP9	Work Package 9 " Interoperable Hydrogen Refuelling Station"

3. Background

The works of WP1 are related to previous studies from Shift2Rail PINTA3 WP3 with a first road map for carbon free mobility in railway. PINTA3's WP3 was separated in 5 tasks, working on Uses cases (task 3.1), Infrastructure (3.2), Operation (3.3), Rolling stock (3.4) and Homologation (3.5). Each task was led by a company, with other companies' contributions, to create a collaborative work and approach and for being able to merge the vision on the decarbonization. All these works have been inputs for ERJU "RAIL4EARTH" objectives to close the gaps for supporting alternative drive trains expansion in Europe. Furthermore, another Shift2Rail projects, "FINE1 and FINE2", a cross-cutting activities projects, supports the development of energy efficiency for rolling stock and key inputs for WP1 studies on energy optimization.

4. Objective/Aim

This document has been prepared to provide intermediate results and report the status and progress of WP1 activities until months 32.

WP1 is focused on Energy Management & Pre-Standardisation for Alternative drive trains and related railway system. The work covers various technological aspects, including the definition of requirements for the pre-standardisation of battery interfaces, interfaces between train and operation and between train and infrastructure, and finally on energy functions to improve energy savings. Furthermore, studies on energy management will be produced to optimize energy consumption at system level.

WP1 has a duration of 48 months.

No physical and virtual demonstrator will be developed in WP1.

WP1 will provide information to System Pillar, via the FP4-Rail4EARTH WP28, regarding the collection of expected creation or modification of standards or regulations.

In terms of KPIs, WP1 is linked either directly or indirectly to 4 main KPIs of FP4 project:

- Physical energy consumption (train, infrastructure, station),
- Physical CO2 equivalent emissions,
- Life Cycle Costs reduction,
- BEMU autonomy target 200 km.

5. Pre-standardisation for Trains with Alternative Drives

The definition of common European requirements and interfaces of trains with alternative propulsion system is essential for the improvement of more standardized and cost-efficient solutions in the railway sector. The collaboration of all the railway stakeholders (infrastructure manager, railway operators, rolling stock manufacturers, and research institutions) is one of the keys to have a holistic view and to enhance economic and technical solutions.

The first step to be taken is the identification of the challenges to be faced in terms of requirements for both BEMUs and HMUs. Then, based on this starting point and in a collaborative environment, this pre-standardization task will give the opportunity to achieve agreements about standardized initiatives.

5.1. Introduction, Objective, and Methodology

In Rail4EARTH WP5 – WP9 components of battery and hydrogen trains and supporting infrastructure are developed by industry in collaboration with railway undertakings, infrastructure manager, and research institutions. This opens the chance to standardise interfaces between train and infrastructure as well as operation:

- To allow a flexible vehicle operation,
- To use the infrastructure for charging and refuelling for all vehicle classes,
- To avoid the adaptation of vehicles for application in different areas,
- To avoid different infrastructure for different trains.

This will reduce the costs of vehicles and infrastructure, and moreover, it will support the decarbonization of the railway system. An overview of the interfaces and components of trains with alternative drives and related infrastructure is shown in Figure 1.

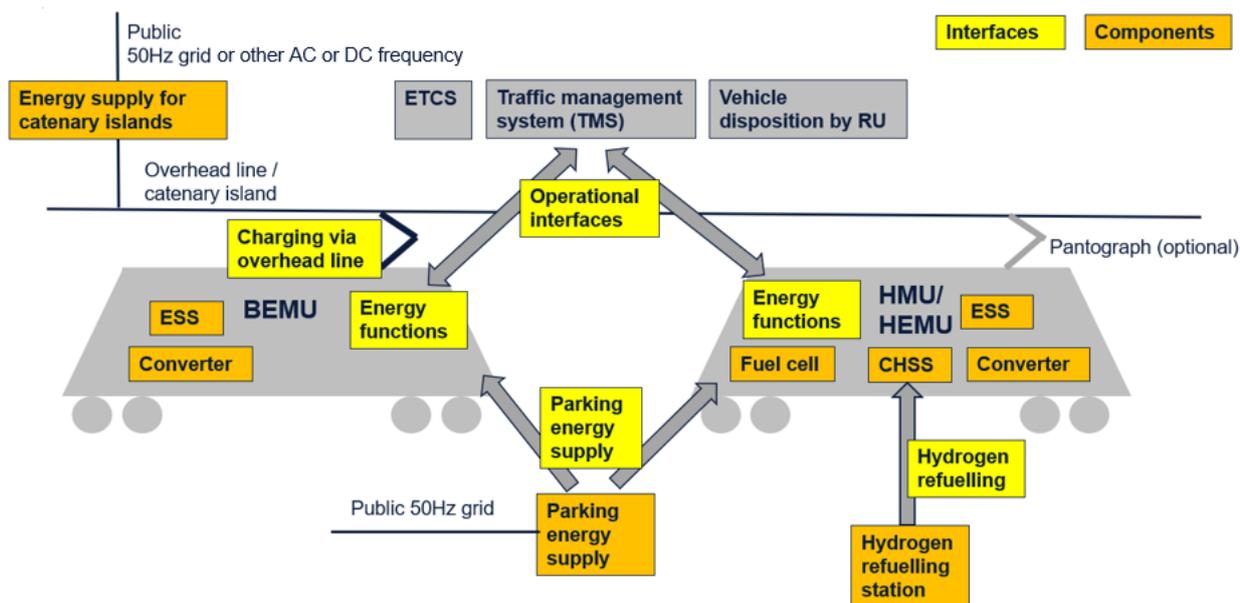


Figure 1: Interfaces of trains with alternative drives and related infrastructure

The pre-standardisation covers the following interfaces between train and infrastructure:

- BEMU charging via overhead line,
- Parking energy supply,
- Hydrogen refuelling.

Further work is covering the pre-standardisation of interfaces between train and operation /

Traffic Management System (TMS). This work is carried out in collaboration with Flagship Projects FP1 and FP2 as well as the system pillar.

Last not least, task 1.1 covers the pre-standardisation of interfaces of the vehicle components of the Energy Storage System (ESS) and Primary Power Sources (PPS) based on hydrogen energy supply, for trains with alternative drives:

- Traction batteries (ESS scope),
- Onboard fuel cell (PPS scope),
- Hydrogen storage system (HSS) (PPS scope),
- Battery converter (ESS scope).

The standardisation of vehicle components has several benefits:

- To allow a competition between different component suppliers,
- Simplify the exchange of the components after the end of lifetime (especially important for batteries),
- Avoid special interfaces for every vehicle class.

The working procedure is shown in Figure 2:

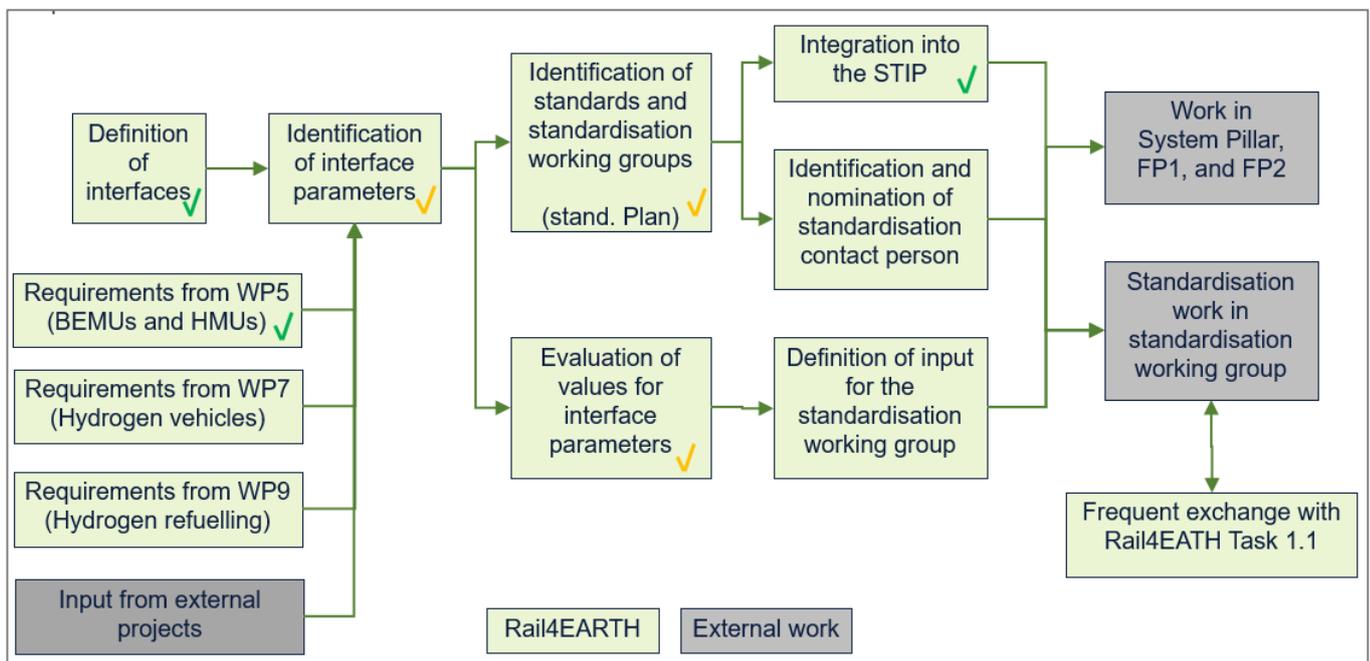


Figure 2: Working procedure for Task 1.1

After the definition of interfaces, the interface parameters for standardisation are identified. The parameters are taken from work carried out in WP5, 7 and 9. In these WPs the requirements for BEMUs, hydrogen vehicles and related infrastructure are defined. Further, they are taken from external projects like FCH2Rail or H2GoesRail.

The next step is the identification of existing standards and standardisation working groups. If there are no existing standards new ones are suggested. This information is integrated into the WP1 standardisation plan and into the common EU-Rail “Standardisation and TSI Input Plan”

STIP. The latter is important for collaboration with FP1 and the system pillar with respect the pre-standardisation of operational and TMS interfaces.

Since the standardisation work in the standardisation bodies and working groups is carried out outside of the project contact persons within these working groups must be identified who will introduce the output of Rail4EARTH into the working groups. It may also be feasible to arrange meetings with the working group convenor(s) to facilitate a better introduction of the Rail4EARTH work in advance of working group discussions as was done by WP9 with ISO TC197 WG5 (Gaseous hydrogen land vehicle refuelling connection devices) and WG24 (Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles).

The main work of task 1.1 is the evaluation of harmonised values of the parameters, e.g. common voltage and frequency or dimension of plugs. The pre-standardisation output will deal as an input into the standardisation bodies. It will be described in the final deliverable (Del. 1.3).

During the standardisation work in the standardisation bodies and the system pillar a frequent exchange with Rail4EARTH task 1.1 is required.

5.2 Input from other WPs and Projects

Task 1.1 “Pre-standardisation for trains with alternative drives” is based on work carried out within the following WPs of Rail4EARTH:

- WP5 Task 5.1 Operational requirements for BEMUs and HMUs/HEMUs,
- WP7 Development of hydrogen propulsion systems,
- WP9 Development of hydrogen refuelling systems,

Further, task 1.1 is based on work carried out in the projects FCH2RAIL and H2GoesRail, where hydrogen trains and related infrastructure are developed.

The input from these WPs and projects is described in the following chapters.

5.2.1 Input from WP5 for BEMUs and HMUs/HEMUs

The main objective of task 5.1. is seeking the European harmonisation of requirements for regional battery and hydrogen trains (BEMU and HMU/HEMU). The achievement of this objective will permit:

- Minimise the variety of vehicle types,
- Avoid the adaptation of vehicles for every application,
- Increase the number of similar trains,
- Avoid different infrastructure for different train classes,
- Allow a flexible vehicle operation.

And so, final benefits associated to the harmonization of the requirements will give the opportunity:

- To purchase a higher number of similar trains and,
- To avoid the special adoption for every application.

This will reduce the costs of vehicles and will contribute to the decarbonisation of the railway system.

However, the full common harmonization of all the European requirements may not be possible. Therefore, some options for certain applications are identified and considered.

Firstly, the procedure used for developing task 5.1. work is shown below:

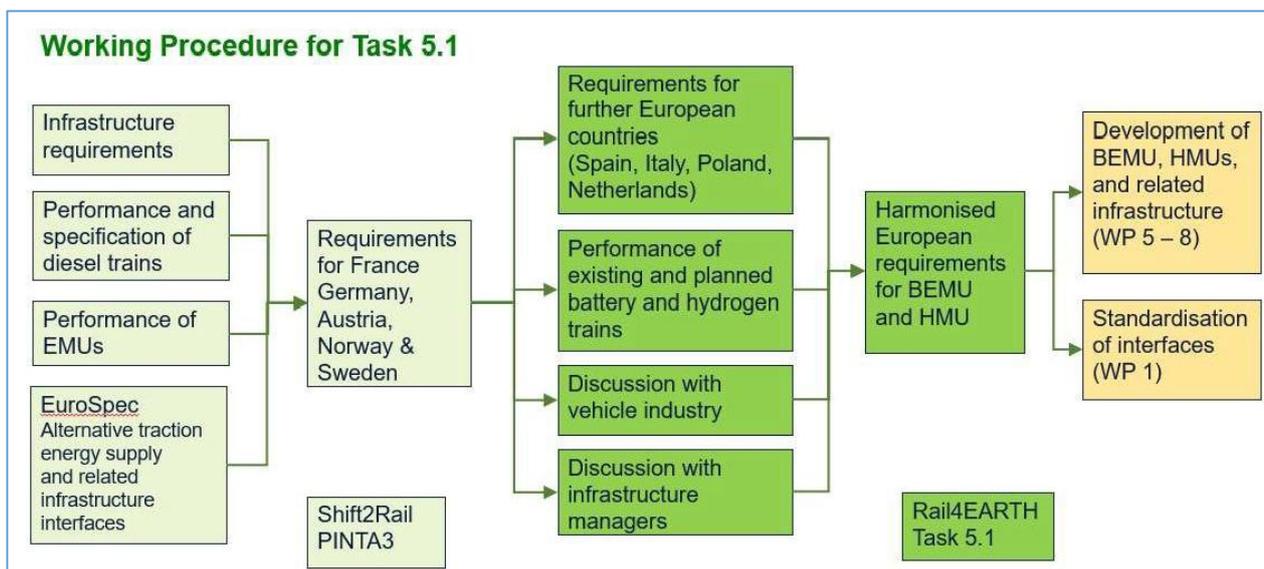


Figure 3: Working procedure for Task 5.1

As Figure 3 shows, the work of Task 5.1 (green) is based on the pre-study carried out in the Shift2Rail project PINTA3 WP3 (light green). In the PINTA3 project, the requirements for next generation BEMUs and HMUs/HEMUs were collected for France, Germany, Austria, Norway, and Sweden. They were taken from the following sources:

- Infrastructure requirements,
- Performance of diesel trains,
- Performance of EMUs,
- EuroSpec "Alternative traction energy supply and related infrastructure interfaces".

In task 5.1 of Rail4EARTH, the following work has been done:

- Collection the requirements from further countries (Spain, Italy, Poland, Netherlands),
- Performance of existing and planned BEMUs,
- Discussion of the requirements with industry with respect to realisability and vehicle effort,
- Discussion with infrastructure managers with respect to realisability and infrastructure effort,

The harmonized European requirements and the options for certain applications /countries have been obtained after a collaborative work between WP5 participants. These requirements, both if they can be harmonised or not, have been classified into six different groups:

- Infrastructure (without energy supply),
- Vehicle performance,
- Traction energy supply and battery charging,

- Parking energy supply and refuelling,
- ESS/ battery requirements,
- Other requirements.

The requirements of each group are described in the following tables. The **yellow** marked values are a challenge for the design. **Red** values are still open and must be clarified in WP1 during the next year.

Requirement	Value	Options	Country *	Comment
Max. non-electrified line segment / total line length • for short-range BEMU • for long-range BEMU • for HMU	70 / 200 km 200 / 320 km 730 km			<u>70% line share</u>
Average station distance for • Regional train • Regional express train and intercity	5 km 10 km	20 km	E, N	Intercity
Max. allowed axle load	18t	16 t 20t	I, P D, F	Only some lines HMU & long range BEMU
Max. gradient	40 ‰	50 ‰ 55 ‰	A I	
Max. gradient for long slopes (up to 5 km)	35 ‰			
Max. height difference	1000 m			
Platform height with level access	550 mm	760 mm	D, E, N, P, S	
Gauge	1435 mm	1668 mm 1000 mm	E E	

* France (F), Germany (D), Italy (I), Netherlands (NL), Norway (N), Poland (P), Spain (E), Sweden (S) and Austria (A)

Table 1: Common European infrastructure requirements

Requirement	Value	Options	Country*	Comment
No of coaches per train / train length	2, 3, 4 / 40 – 80m	6 / 120m	F, N	
Max. speed	160 km/h	140 km/h 200 km/h	D,E,N,P,S E	Some lines Intercity service
Interior design for service	Regional	Intercity	E, N	
Max. acceleration	1,1 m/s ²			
Typical traction power like EMU for 2 / 3 / 4 coaches • Maximum power • Continuous power • Average power (Ref speed profile)	1,5/ 2 / 3 MW 1/ 1,5 / 2 MW 0,3/ 0,5 / 0,7MW	4 MW 3 MW 1 MW	F, N	for 6 coaches

Table 2: Common European requirements for vehicle performance

Requirement	Value	Options	Country	Comment
Energy supply voltage and frequency on electrified lines (via overhead line and pantograph)	25kV 50Hz for F, E 15kV 16,7Hz for D,A,CH,N,S 1,5kV DC for E, F, NL 3kV DC for E, P	1,5kV DC & 25kV 50Hz 3kV DC & 25kV 50Hz	F, E I	Suitable for both voltage systems
Charging voltage and frequency for catenary islands and intermediate electrification segments (via overhead line and pantograph)	25kV 50Hz for F, D,A,CH,N,S 1,5kV DC for E, F, NL 3kV DC for E, I, P	15kV 16,7Hz 1,5kV DC & 25kV 50Hz 3kV DC & 25kV 50Hz	D,A,CH,N,S F, E I	Suitable for both voltage systems
Location of the pantograph	Approx. middle of the train			
Typical BEMU charging power for 2/ 3/ 4/ 6 coaches (same as max. power)	1,5/ 2/ 3/ 4 MW (fast charging)	1/ 1,5 / 2/ 3 MW		Slow charging
BEMU charging time for full charging • Short-range BEMU (< 70km) • Long-range BEMU	With max. power up to 15 min up to 40 min	With average Power up to 20 min up to 60 min		Slow charging

Table 3: Common European requirements for traction energy supply and battery charging

Requirement	Value	Options	Country	Comment
Shore energy supply for parking (for 2 and 3 coach BEMUs)	400V 50Hz 3AC, > 85kW			
Plug for shore energy supply	EN 50546 125A	CEE	Italy	
Location of the sockets for ext. energy	On both sides of the train (still open whether at the end or in the middle of the train)			
Target. HMU refuelling distance	1000 km (ref. speed profile)	1500 km		Less refuelling stations
Target refuelling time	15 – 30 min			
Location of the refuelling tap	Approximately in middle of the train on both sides (left & right)			

Table 4: Common European requirements for parking energy supply and hydrogen refuelling

Additional requirements can be found for regional low usage or secondary lines, according to Europe's Rail FP6 studies (Mascis, 2024).

5.2.2 Input from WP7 for Hydrogen Propulsion

The focus of WP7 (Guerra, 2023) is the development of technologies for improving the efficiency of the H₂ traction system for railway vehicles (nor fuel-cell nor batteries are developed within the WP). Next the main results and conclusions related to pre-standardisation of requirements and interfaces are briefly explained.

WP7 work has been conceived as a continuation of the preliminary works carried out in the S2R project PINTA3 WP3 Carbon Free Mobility. As for those previous works, WP7 activities have been done through a global participation of infrastructure managers, railway operators, and rolling stock manufacturers.

So, after the work developed within WP7, the state of the art of hydrogen trains has been updated to check and summarize the evolution in the performance of alternative propulsion systems based on hydrogen. The state-of-the-art analysis covers production, storage, and refuelling of hydrogen for railway vehicles.

As conclusions, the main general challenges for the definition of common interfaces and pre-standardization for hydrogen refuelling extracted from S2R project PINTA3 WP3 are:

- Standardisation of interfaces between infrastructure and rolling stock,
- Infrastructure for hydrogen supply/ refuelling,
- Risk assessment for refuelling stations,

The specific requirements are the following:

- Refuelling properties,
- Refuelling time,
- Refuelling amount,
- Safety,
- Operation by Staff,
- Refuelling control and communication,
- Location of the tank and dispenser,
- Physical Guards.

Finally, after the collaborative work done and data gathered during the meetings held, no specific issues needed from the railway environment have been detected that could differ from the land vehicle (automotive, buses, etc.) standardization framework. So, no new requirements/standard to further testing the land vehicle components must be developed.

However, regarding discussion on fast refuelling, the following outcomes have been obtained:

<p><u>Maximum refueling time:</u> a requirement for a maximum hydrogen refueling time of 15 minutes may lead to unnecessary high investment, operating, and energy costs.</p>	<p><u>Minimum refueling time:</u> to minimize H₂ refueling time, the vehicle type and basic H₂-tank specifications must be communicated from the vehicle to the HRS via a safe communication channel.</p>
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<u>Storage capacity</u> : requirements for hydrogen storage capacity in railway applications vary significantly. So, it is necessary to know in advance how much to fill.	<u>H2 tank temperature measurement</u> : a safe measurement is not possible and cannot be used to control the refueling process.
<u>Amount of H2 required</u> : <50 kg for shunting locomotives and 250 kg for regional trains.	<u>Pre-cooling of the hydrogen</u> : pre-cooling is required for fast refueling, especially for warm summer days.
<u>Pressure</u> : for the railway sector, the preferred pressure for compressed hydrogen stored in H2 tanks is 350 bar.	<u>Lifetime of H2 tanks</u> : It is limited by the number of refueling cycles; 20,000 cycles will be required.
<u>Large hydrogen tanks</u> : There are no standards for large hydrogen tanks (CH2) suitable for railway applications.	<u>Hydrogen fueling protocols</u> : There are no standards for hydrogen fueling protocols for trains.
<u>H2 tanks configuration</u> : the preferred H2 tanks configuration is in cascade (energy consumption reduction and stable and uninterrupted hydrogen supply guarantee).	<u>Measurement methods or communication protocols</u> : There are no standards to monitor flow, pressure, and temperature during fast filling of H2-tanks onboard trains.
<u>H2 unit tanks sizes and requirements for H2 flow, pressure, and temperature</u> : it will be needed to develop standard protocols.	<u>Stationary/moveable</u> : most hydrogen refueling demonstrators for trains are mobile and/or moveable (State-of-the-art).
<u>Couplings</u> : hydrogen trains use TK17 or TK25 type of couplings (State-of-the-art).	<u>Automotive standards</u> : they are not accepted by some authorization bodies.

Table 5: Requirements for hydrogen fast-refuelling

Based on these outcomes and findings, the main extracted conclusions and recommendations are listed next:

- Maximum refuelling time: the requirement of 15 minutes as the maximum hydrogen refuelling time for trains should be reviewed.
- Hydrogen demand profiles and hydrogen refuelling requirements: establishment based on actual and/or simulated energy demands and “standard” load and duty cycles for specific applications and operating under normal ambient weather conditions.
- Specifications and requirements for hydrogen storage system: establishment at high-level in regional trains (<250 kg) and shunting locomotives (<50 kg).
- Hydrogen refuelling procedures with respect to pressure, flow, and temperature: development for new trains and agreement on overall hydrogen refuelling rate at each nozzle.
- Technology and systems for safe monitoring (temperature and pressure): development for fast refuelling for H2 tanks located in the train.
- H2 tanks characteristics: establishment of H2 tank types and sizes for railway applications with requirements for 20,000 pressure cycles (20-year lifetime).
- Coupling: establishment of a standard European coupling for railway applications.
- Identification: establishment of standard and safe identification of the railway vehicle type.
- Communication rolling stock-HRS: establishment of standard.



- Stationary/moveable: commercial operation of hydrogen trains (i.e., several trains on the same line) will require large stationary hydrogen refuelling stations, H2 supply cannot just be based on mobile/moveable systems.
- Rail4EARTH contact person for the standardization bodies: nomination of a common contact person supported by each Rail4EARTH partner regarding hydrogen subject.
- Specific H2 standards for the railway sector: HRS for trains must be designed and operated according to specific train applications (different from those for cars, buses, and trucks).

5.2.3 Input from WP9 for Hydrogen Refuelling

In WP9 pre-standardization activities are divided between gathering standards connected with hydrogen refuelling stations for railways. The main areas of standards defined in WP9 combined with hydrogen refuelling stations are refuelled vehicles, refuelling process, refuelling interfaces, hydrogen storage on refuelling station and safety zone of refuelling Station and In-site Hydrogen Production.

In WP 9 a search of standards was carried out related to the following topics covered by WP9:

- HRS localisation model helping to choose the best localisation for refuelling station where standards and regulations are bringing boundary condition for that localisation,
- Risk analyses for hydrogen refuelling station,
- Model of hydrogen refuelling process focusing on fast refuelling,
- Developing a new concept of interface between vehicle and refuelling station,
- Demonstration of interoperable hydrogen refuelling station concept.

While many of the standards relevant to land vehicle hydrogen refuelling have been or are being developed for road vehicle applications, many of the requirements or recommendations are applicable to railway applications. However, operating conditions and environmental requirements may need to be adjusted to suit the rail industry requirements. Some standards for the automotive sector are national standards, e.g. SAE standards, however, they are often de-facto international standards and should be considered.

A lot of existing and planned international, European and North American standards have been identified, see the table below. In relation to the deliverable 1.1 the standards are reviewed and amended.

Standards for hydrogen technologies are constantly evolving in parallel with the technology to serve the needs of different applications and markets, with new editions being published, and the development of new parts or entire new standards. The increased number of standards in Table 6 of the latest report compared to earlier report is due to the following:

- The list was updated to include a number of new or revised standards which have been published since the previous version of the report
- Standards under development were included
- All relevant parts of a standard are listed, rather than simply referring to the standard series
- A wider scope is considered, for example, some electrolyser standards are included which may be relevant for on-site hydrogen production
- Relevant standards from CSA/ANSI which, like NFPA standards, are written for the North American market but are often taken as de-facto international standards with widespread adoption.

#	Standard name	Topic
1	ISO 14687: 2025 “Hydrogen fuel quality — Product specification” - This standard specifies the minimum quality characteristics of hydrogen fuel as distributed for utilization in vehicular and stationary or other applications as fuel.	Vehicles
2	ISO/TR 15916:2015 - This technical report provides guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications are	Hydrogen safety

	treated in separate International Standards. The TR is expected to be replaced by a Technical Specification with the same number and updated content in the near future.	
3	ISO 16110-1:2007 "Hydrogen generators using fuel processing technologies Part 1: Safety" - This standard applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than 400 m ³ /h at 0°C and 101,325 kPa, referred to as hydrogen generators, that convert an input fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen (e.g. a fuel cell power system or a hydrogen compression, storage and delivery system).	Hydrogen production / safety
4	ISO 16110-2:2010 "Hydrogen generators using fuel processing technologies Part 2: Test methods for performance" - This standard provides test procedures for determining the performance of packaged, self-contained or factory matched hydrogen generation systems with a capacity less than 400 m ³ /h at 0°C and 101,325 kPa, referred to as hydrogen generators, that convert a fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen (e.g. a fuel cell power system, or a hydrogen compression, storage and delivery system).	Hydrogen production
5	ISO 17268: 2020 "Gaseous hydrogen land vehicle refuelling connection devices" - standard for devices for connecting and refuelling hydrogen in the gaseous state in motor vehicles. Note: At the time of writing, July 2025, expected to be replaced by imminently by ISO 17268-1: 2025 "Gaseous hydrogen land vehicle refuelling connection devices Part 1: Flow capacities up to and including 120 g/s"	Interface
6	ISO/CD 17268-2.2 "Gaseous hydrogen land vehicle refuelling connection devices Part 2: Part 2: Flow capacities greater than 120 g/s" – draft standard defining the design, safety and operation characteristics of gaseous hydrogen land vehicle refuelling connectors having flow capacities greater than 120 g/s.	Interface
7	ISO19880 series "Gaseous hydrogen — Fuelling stations" – series of standards for gaseous hydrogen refuelling station components and fuel quality control	Refuelling station
8	ISO 19880-1:2020 "Gaseous hydrogen — Fuelling stations Part 1: General requirements" - a standard specifying the minimum requirements for the design, installation, commissioning, operation, inspection and maintenance to ensure the safety and, where appropriate, the performance of public and non-public service stations supplying light road vehicles (e.g. electric vehicles equipped with fuel cells) with hydrogen gas). Many of the generic requirements of this document are applicable to trains.	Refuelling station
9	ISO 19881: 2025 "Gaseous hydrogen — Land vehicle fuel containers" - This standard contains requirements for the material, design, manufacture, marking and testing of serially produced, refillable containers intended only for the storage of compressed hydrogen gas for land vehicle operation.	On-board storage
10	ISO 19882: 2025 "Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers" - This standard establishes minimum requirements for pressure relief devices intended for use on hydrogen fuelled vehicle fuel containers .	On-board storage
11	ISO 19885-1: 2024 "Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 1: Design and development process for fuelling protocols" – standard for the design and development of fuelling protocols for compressed hydrogen gas dispensing to vehicles with compressed hydrogen storage o	Refuelling
12	ISO/CD 19885-2 "Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles - Part 2: Definition of communications between the vehicle and dispenser control systems" – draft standard to focus on the communication system needed to implement the fueling protocols defined in ISO 19885 series to fuel hydrogen vehicle	Refuelling

13	ISO/CD 19885-3 “Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles, Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles” – draft standard for high-flow hydrogen fuelling protocol(s) for 35 or 70 MPa NWP compressed gaseous hydrogen powered heavy-duty road vehicles (10-200kg hydrogen capacity). Use is intended for but not limited to heavy-duty road vehicles.	Refuelling
14	ISO 19887-1:2024 Gaseous Hydrogen — Fuel system components for hydrogen-fuelled vehicles Part 1: Land vehicles – standard establishes requirements for newly produced compressed hydrogen gas fuel system components, that are intended for use on hydrogen gas powered land vehicles:	Onboard components
15	ISO/WD 19887-2 Gaseous Hydrogen — Fuel system components for hydrogen-fuelled vehicles Part 2: Rail vehicles – this draft standard establishes the minimum requirements for fuel system components intended for use on hydrogen-fuelled rail vehicles. It references ISO 19887 for the main hydrogen component requirements and focuses on the specific details applicable to rail vehicle applications. This standard is applicable to components incorporated in Hydrogen Fuel Systems specified in IEC 63341-2 “Railway applications – hydrogen and fuel cell systems for rolling stock - Part 2: Hydrogen fuel system”	Onboard components
16	ISO/TS 20100 (Withdrawn) - former technical specification specifying the characteristics of outdoor public and private refuelling stations that dispense hydrogen gas used as a fuel for land vehicles of all types. Replaced by ISO 19880-1.	Refuelling
17	ISO 22734-1: 2025 “Hydrogen generators using water electrolysis, Part 1: Safety” - a standard specifying the safety requirements for devices for generating hydrogen using water electrolysis.	Hydrogen production
18	IEC 60079-10-1:2020 “Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres”- This standard is concerned with the classification of areas where flammable gas or vapour hazards may arise and may then be used as a basis to support the proper design, construction, operation and maintenance of equipment for use in hazardous areas. Related to ATEX in the EU.	Explosion safety
19	IEC FDIS 63341-1 (FDIS approved April 2025) “Railway applications - Hydrogen and fuel cell systems for rolling stock - Part 1: Fuel cell power system” - applies to fuel cell power systems installed onboard rolling stock for railway applications and are used for traction power or as an auxiliary onboard power source.	Vehicle
20	IEC FDIS 63341-2: 2025 (FDIS approved April 2025) “Railway applications - Hydrogen and fuel cell systems for rolling stock - Part 2: Hydrogen fuel system” - applies to on-board hydrogen fuel systems (HFSS) used to supply fuel cells for te traction power or the auxiliaries supply of railway vehicles. It applies to hydrogen storage in gaseous form only and addresses the on-board mechanical, fluid and electrical interfaces between the on-board hydrogen fuel system and fuelling station. The fuelling station, fuelling protocol and communication for the fuelling protocol are not in the scope of this document.	Vehicle
21	EN ISO 80079-36:2016 & AC:2020 “Explosive atmospheres Part 36: Non-electrical equipment for explosive atmospheres — Basic method and requirements” - This standard specifies the basic method and requirements for design, construction, testing and marking of non-electrical Ex equipment, Ex Components, protective systems, devices and assemblies of these products that have their own potential ignition sources and are intended for use in explosive atmospheres.	Explosion safety
22	Standard EN 17127:2024 ” Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols” - external hydrogen refuelling points distributing hydrogen gas and the refuelling procedures used.	Refuelling
23	EN 62305 series - this series of standards provide the requirements for protection of a structure against lightning and physical damage and life hazard	Safety

	(all parts)	
24	SAE J2578_202301 “Recommended Practice for General Fuel Cell Vehicle Safety” – US recommended practice identifies and defines requirements relating to the safe integration of the fuel cell system, the hydrogen fuel storage and handling systems (as defined and specified in SAE J2579) and high voltage electrical systems into the overall Fuel Cell Vehicle. The document may also be applied to hydrogen vehicles with internal combustion engines. (Intended for road vehicle applications)	Vehicle safety
25	SAE J2579_202301 “Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles” – US standard specifying requirements for road vehicle hydrogen storage tanks.	Onboard storage
26	SAE J2600_201510 “Compressed Hydrogen Surface Vehicle Fueling Connection Devices” – US standard for the design and testing of nozzles, connectors, and receptacles for refuelling road vehicles with compressed hydrogen.;	Interface
27	SAE 2601_202005 “Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles” – US standard establishes the protocol and process limits for hydrogen fueling of vehicles with total volume capacities greater than or equal to 49.7 L. These process limits (including the fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure) are affected by factors such as ambient temperature, fuel delivery temperature, and initial pressure in the vehicle’s compressed hydrogen storage system.	Refuelling
28	SAE J2601/5_202502 “High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles” - This US Technical Information report (TIR) establishes high-flow fueling protocols, including their process limits for fueling of compressed gaseous hydrogen vehicles at peak flow rates from 60 to 300 g/s with compressed hydrogen storage system (CHSS) volume capacities between 248.6 and 7500 L which have been qualified to UN GTR #13. The TIR will be upgraded to a standard after field testing.	Refuelling
29	CSA/ANSI HGV2 2:23 “Compressed hydrogen gas vehicle fuel containers” – the standard contains requirements for the material, design, manufacture, marking, and testing of serially produced, refillable containers intended for compressed hydrogen gas storage for on-road vehicle operation and which are permanently attached to the vehicle, have a capacity of up to 1000L water capacity and have a nominal working pressure not exceeding 70MPa.	Onboard Storage
30	CSA/ANSI HGV 3.1-2022 “Fuel system components for compressed hydrogen gas powered vehicles” - Canadian/US standard	Onboard Storage
31	CSA/ANSI HGV 4.1-2020 “Hydrogen-dispensing systems” – Canadian/US standard for safe operation, substantial and durable construction, and performance testing of the mechanical and electrical features of newly manufactured hydrogen gas- dispensing systems for vehicles, intended primarily to dispense fuel directly into the vehicle fuel storage container.	Refuelling station
32	CSA/ANSI HGV 4.3-2024 “Test methods for hydrogen fuelling parameter evaluation” - Canadian/US standard specifying the minimum testing requirements for verifying the fuelling protocols specified in SAE J2601 and the communications protocols in SAE J2799. This Standard applies to dispensing systems, referred to as "dispensers", designed to fill vehicle storage systems in	Refuelling station

	accordance with SAE J2601.	
33	CSA/ANSI HGV 4.5-2023 “Priority and sequencing equipment for hydrogen vehicle fueling stations” - Canadian/US standard for priority and sequencing equipment used in compressed gaseous hydrogen fuelling stations and specifies general, materials, construction, and assembly requirements.	Refuelling station
34	ANSI/CSA HGV 4.8-2012 (R2023) “Hydrogen gas vehicle fueling station compressor guidelines” - Canadian/US standard for safe operation, substantial and durable construction, and performance testing of the mechanical features of newly manufactured compressors for use in gaseous hydrogen vehicle fueling stations.	Refuelling station
35	CSA/ANSI HGV 4.9-2020 “Hydrogen fueling stations” - Canadian/US standard specifying the design, installation, operation, and maintenance of site-built and modular gaseous hydrogen fuelling stations (HFS) for on-road vehicles.	Refuelling station
36	CSA/ANSI HGV 4.10-2021 “Standard for fittings for use in compressed gaseous hydrogen fueling stations” - Canadian/US standard specifies methods for testing and evaluating fittings for use with compressed hydrogen gas and hydrogen-rich gas mixtures	Refuelling station
37	CSA/ANSI HPRD 1-2021 “Thermally activated pressure relief devices for compressed hydrogen vehicle (HGV) fuel containers” – Canadian/US standard for thermally activated pressure relief devices for containers complying with the CSA/ANSI HGV 2 standard.	On-board storage
38	CSA/ANSI B107-2024 “Enclosed hydrogen equipment – Safety” - Canadian/US standard addresses safety requirements related to hydrogen and its use inside an enclosure intended for stationary outdoor operation, such as assemblies of hydrogen equipment integrated into enclosures with a minimum floor area of 7.4 m ² and a maximum floor area of 41.8 m ² regardless of whether the enclosure contains internal compartments.	Hydrogen safety
39	NFPA 2: 2023 Hydrogen Technologies Code - US code providing fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH ₂) form or cryogenic liquid (LH ₂) form.	Hydrogen safety

Table 6: Identified standards in WP9 related to hydrogen refuelling station.

Many standards for road vehicles fulfil the needs of railway sector, however, there are aspects of the automotive standards that need to be adapted to the specific needs of the railway sector:

- Rail specific service life, including pressure cycle life
- Rail specific environmental factors, e.g. operating temperature ranges, vibration spectra
- Rail specific crash loadings
- Higher level of flow up to 300 g/s,
- Different approach for refuelling: fast or economical,
- Higher quantity of hydrogen to be stored and larger /more safety valve vents



- Additional hazards must be considered in Risk assessment.

5.2.4 Input from FCH2RAIL Project

Within the *Clean Hydrogen Partnership* funded **FCH2RAIL project** (Fuel cell hybrid power pack for rail applications, Grant Agreement No. 101006633, <https://www.fch2rail.eu/en>), two public deliverables (D7.1 (Guerra, 2023) and D7.4) covered the analysis of the regulatory framework (RCS – regulations, codes and standards) related to hydrogen refuelling of trains. The analysis in these deliverables was done within the context of the FCH2RAIL demonstrator tests and focussed on:

- The identification of relevant RCS and
- Whether the single RCS leave a gap in terms of the applicability of hydrogen trains and refuelling of hydrogen trains.

Contributors to the deliverables were CAF, TÜV Süd Rail, DLR, CNH2, Stemmann Technik and ADIF.

The focus of this chapter are the main results of the FCH2RAIL deliverables concerning hydrogen refuelling station (HRS) in terms of

- a. interface parameters and
- b. pre-standardisation input.

In addition to the HRS, the deliverables also cover the analysis of regulatory gaps with respect to train, pantograph, and infrastructure.

Since the FCH2RAIL deliverable D7.4 (Esteban Rodriguez, FCH2RAIL Del. D7.4–Complementary gaps in analysis framework, 2024) is an update of the preceding deliverable D7.1 (Esteban Rodriguez, FCH2RAIL Del. D7.1–Gaps in regulatory framework prior to the demonstrator train test, 2022), the next sections refer only to the FCH2RAIL D7.4.

a) **Interface parameters:**

Interface parameters mentioned in the FCH2RAIL project Deliverable D7.4 regulatory gap analysis regarding HRS (not exhaustive) are:

- Temperature (ambient and fuel),
- Pressure,
- Flowrate,
- Communication,
- Leakage control,
- Refuelling protocol,
- Communication protocol,
- EMC,
- Dispenser, hoses.

b) **Pre-standardisation input:**

The following section covers the results of FCH2RAIL **Deliverable 7.4** about pre-standardisation of the HRS (not exhaustive):

5.1 Analysis related to the Train

The report [...] concludes that a total of 90 Regulations, Codes and Standards (RCS) – of which more than half are Railway Regulations Codes & Standards (RCS) – have been allocated 360 times to 26 generic Causes.

- 16 Railway RCS [...] were identified that require no modification as they adequately mitigate the related hazards, when applied,
- 16 Railway RCS [...] were identified that require modification in order to achieve an acceptable mitigation,
- 56 Non-railway RCS [...] were identified that are partially suitable to mitigate the related hazards, however there were some implications or constraints, that require amendment by railway RCS, such as EN 50155,
- 18 Technical issues [...] have been identified where currently no RCS exists,
- If no applicable RCS exists and the requirement is not entirely specific but more generic, generating a new standard or amending existing ones might be appropriate. This applies for the gaps identified regarding hydrogen refuelling, since these aspects will be key for an economic and successful application of the new technology.

[...]

5.2 Analysis related to the HRS

From a total of 82 RCS in total, 45 RCS applicable to the project have been analysed, from which it can be concluded that:

- 36 RCS do not need modification,
- 7 RCS need to be modified to adapt to project requirements. In these 7 RCS, 4 new gaps have been identified within the RCS analysed based on field experience with the train demonstrator,
- 4 technical issues have been found where currently there is no RCS that specifies how to mitigate the effects that may generate a hazard, a new one found based on field experience with the train demonstrator,
- If there is no RCS that can be adapted to some of the project requirements, it would be convenient to expand and/or modify an existing one, specifying the nature of the problem associated with the use of hydrogen in the railway sector.”

Within the FCH2RAIL D7.4 each identified RCS had been analysed with respect to its impact or relevance for hydrogen trains and for hydrogen refuelling. Further, the RCS had been evaluated in terms of gaps in the RCS and the priority to mitigate these identified gaps. Hydrogen refuelling related RCS and their gaps mentioned in the FCH2RAIL deliverable D7.4 are given in Table 7: FCH2RAIL Deliverable D7.4 regulatory gap analysis regarding HRS. (not claimed to be complete):

RCS (regulation, code, standard)	RCS title	Identified gap
ISO 19880-1 to ISO 19880-8	Gaseous hydrogen — Fuelling stations) with the respective parts	Targets road vehicle refuelling. Gaps identified in terms of refuelling protocols for railways, safety distances, communication protocol and unsuitable mechanical designs.
ISO 19885-3	Gaseous hydrogen - Fuelling protocols for hydrogen-fuelled vehicles - Part 1: Design and development process for fuelling protocols	High-flow (HF) refuelling protocol under the supervision of the ISO/TC197. Could be a valid option also for trains.
EN 17127	Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols	Only applicable for road vehicles. Connectors currently used in railway vehicles do not comply to EN 17127.
EN ISO 17268	Gaseous hydrogen land vehicle refuelling connection devices	Connectors currently used in railway vehicles do not comply to EN 17268.
SAE J2601-1	Fuelling Protocol for Light Duty Gaseous Hydrogen Surface Vehicles	Not applicable for railways and valid only for pre-cooled hydrogen refuelling at max. 60 g/s
SAE J2601-2	Fuelling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles	Not applicable for railways. Also, high flow (HF) refuelling protocols for heavy-duty vehicles are lacking (> 10 kg of H ₂ storage capacity and/or mass flow rates of up to 7.2 kg/min). Only ambient temperature refuelling foreseen. Validated fast refuelling protocols missing
TSI LOC & PAS		with respect to EMC susceptibility needs to be analysed/tested (TSI LOC & PAS Chapter 3.2.1.4.3)
TSI Energy and TSI Infrastructure		Requirements for HRS are not part of these TSI. H ₂ fire detection and extinguishing issues are also not specified in the TSI.
CSM	Common Safety Methods	the concrete definition of the type of ASBO or ISA required for hydrogen refuelling is not defined
ATEX (with respect to portable HRS)		railway regulation on safety zone limits between HRS and Railway Safety Zone are missing
/	General	Requirement of infrastructure manager Adif for a protocol and regulations to ensure an interoperable communication system that records essential data during refuelling.

Table 7: FCH2RAIL Deliverable D7.4 regulatory gap analysis regarding HRS.

5.3 Pre-Standardisation of Interfaces Between Train and Infrastructure

The interfaces between vehicle and infrastructure cover the following interface groups:

- BEMU charging,
- Parking energy supply,
- Hydrogen refuelling.

5.3.1 BEMU Charging

Requirements for BEMU Charging:

The operational requirements for BEMU charging are developed in task 5.1 from the European railway undertakings taking part in Rail4EARTH, see (Fernandez, 2023).

Battery multiple units (BEMUs) run on electrified and non-electrified lines. On electrified lines they are supplied with electrical energy via pantograph and overhead line. The energy is used for traction, auxiliary consumers, and battery charging. In addition, fast battery charging is required at termination stations, some intermediate stations, and parking areas. Catenary islands with short overhead lines are the preferred solution for fast charging since no additional vehicle side equipment is required.

Charging Infrastructure Types

The different kind of charging infrastructure are defined in

- prTS 50729: 2024 “Railway applications - Fixed installations and rolling stock - Interface requirements between charging infrastructure with dedicated contact line sections and electric traction units with onboard electric traction energy storages and current collectors”

Catenary islands correspond to the charging infrastructure types III and IV:

Charging infrastructure type III: The contact line islands are dedicated contact line sections which are located within and around railway stations on non-electrified railway lines. The contact line system is extended a few km from the railway stations depending on the contact line system. This type of infrastructure allows on one hand the movement of the electric traction units and on the other hand the charging of the onboard electric traction energy storage of the electric traction units

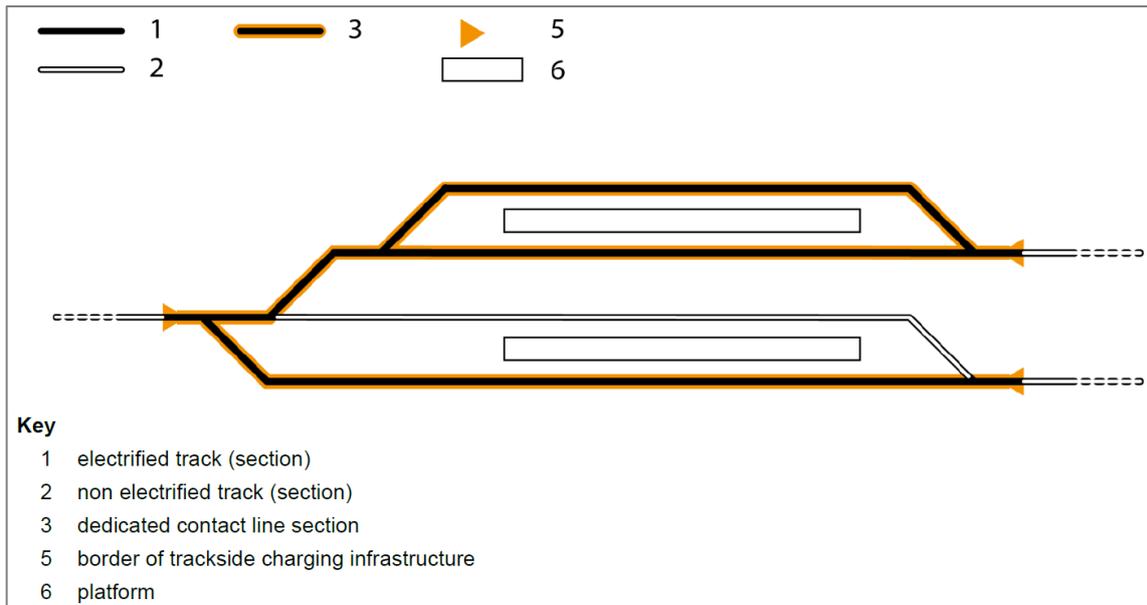


Figure 4: Charging infrastructure type III according to prTS 50729

Charging infrastructure type IV: The dedicated contact line sections are in railway stations on non-electrified railway lines. The contact line system is only located over platform tracks, marshalling tracks, depot tracks and associated track connections. This type of infrastructure is dedicated to charge the onboard electric traction energy storages of the electric traction units in standstill. This is the basis for the rating of the charging substation. A restricted low speed operation (e.g. coupling and de-coupling of electric tractions units) in the frame of the rated power of the charging substations may be allowed.

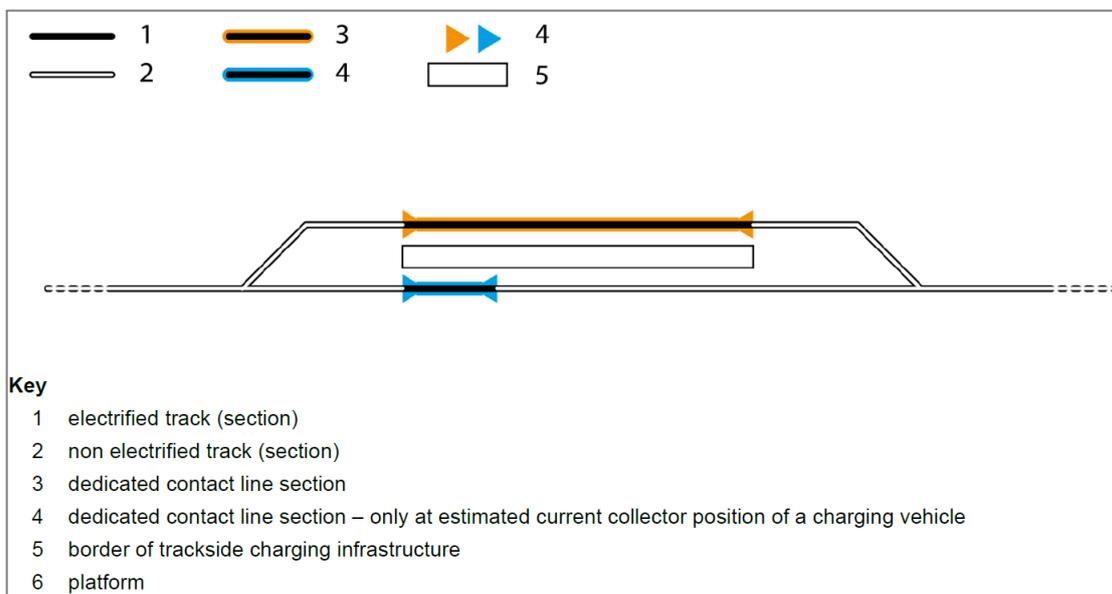


Figure 5: Charging infrastructure type IV according to prTS 50729

Requirements for Charging Time and Power

The charging should be done as fast as possible to meet the required operational termination time (down to 15min in some cases). But fast charging requires high charging power. To limit the vehicle effort, it was decided in task 5.1 see (Fernandez, 2023) to charge with the max. rated BEMU power, e.g.

- About 1,5 MW for a 2-coach train
- About 2 MW for a 3-coach train

For a train running along the regional reference speed profile according to EN50591 (CENELEC, EN 50591 Railway applications - Specification and verification of energy consumption for railway rolling stock, 2019) the charging time was calculated, when it is charged with average power (slow charging) and max. power (fast charging), see Figure 6:

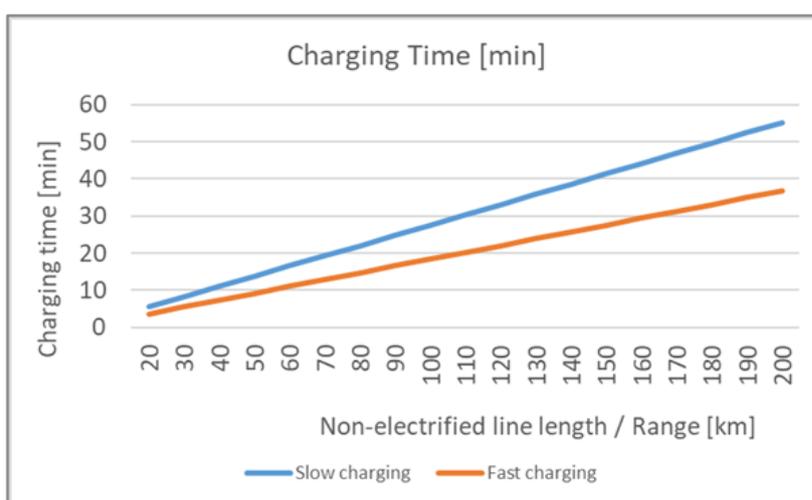


Figure 6: Charging time for slow and fast charging.

Even with max. power (fast charging) the required charging time of 15 min is only achieved for a non-electrified line length of up to 80km (short-range BEMU). Long-range BEMUs up to 200km require a charging time of up to 40min, corresponding to 300 km range for 60 min charging. To compare with electric car application, the charging time may vary significantly. Depending on the type of charger used, conventional one or fast charge. According to the website “ev-database.org” and based on the characteristics available for 336 electric cars, the average fast charge is 600 km for 60 min (recovering 600 km range for 1 hour duration of fast charge). Best fast charge range recovery can target more than 1200 km equivalent.

This is an operational draw-back of long-range BEMUs and required the purchase of additional trains for many applications.

BEMU Charging Via Overhead Line

In general, the overhead lines of catenary islands and intermediate electrification sections are supplied with the same voltage system of the electrified lines of the country and region:

- 1,5kV DC in France, Spain, and Netherland,

- 3kV DC in Poland and some lines in Spain,
- 25kV 50Hz for some lines in France and Spain.

For the charging of 3-coach BEMUs 2 MW charging power is required. This corresponds to the following currents:

- 1330 A for 1,5kV
- 667 A for 3kV
- 80 A for 25kV
- 133 A for 15kV

While in most countries the voltage system of overhead current islands is identical to the general system of the country, there is an exception for countries with 16,7Hz overhead line frequency. Here a supply of the overhead islands with 50Hz is the preferred solution to reduce the infrastructure effort at the charging stations. For 50Hz the energy can be taken from the local electrical grid without an expensive converter. 16,7 Hz 15Hz is preferred if the line is supposed to be electrified in the next years.

The different possible voltage systems have been discussed within the project and with external stakeholders in Germany (DB InfraGO, EBA, Bundesverband SchienenNahverkehr). The result of the comparison is shown in the table below:

Voltage system	Required current (for 2MW)	Max. current & power	Solutions for 2MW power	Application in Germany	Infrastructure effort	Vehicle effort	Legal permissibility	Suggestion for harmonisation
15 kV, 16,7 Hz	133 A	80 A / 100 A, 1,2 MW	Overhead current rail or double wire	Schleswig-Holstein, VRR	High (converter)	Low (Special pantograph)	TSI standard	
25 kV 50 Hz	80 A	80 A, 2 MW	-	Ost-Brandenburg (parking)	Low	Medium (transformer with additional tap)*	TSI standard	
15 kV 50 Hz	133 A	80 A, 1,2 MW	Overhead current rail or double wire	Erzgebirgsbahn, Ammertal-bahn (trial)	Low/ medium	Low (Special pantograph)	Not allowed in TSI and declined by EBA for roll-out	

Table 8: Comparison of AC voltage systems for catenary islands

For 25kV supply voltage requires a charging current of 80A for 3-coach BEMUs. This value is allowed at standstill as a continuous current according to EN 50367. The infrastructure effort is low since no special measures like double wire line are required. A conventional overhead line can be used. There are no amendments of standards on the infrastructure and vehicle side required since 25kV 50Hz is a TSI voltage system in Europe. The drawbacks is that on vehicle side a transformer with additional windings and tap as well as a switching circuit is necessary. Further, the high voltage insulation must be dimensioned for 25kV. But most vehicles are already equipped with this kind of transformer.

For 15kV voltage requires a charging current of 135A for 3-coach BEMUs. This would require a special solution, e.g. an overhead current rail instead of a standard catenary, e.g. the VOLTAP system (Dschung, 2023), see Figure 7. If the vehicle position in the station is fixed the infrastructure effort is low since only a short overhead current rail is needed. The infrastructure effort increases for longer overhead supply in case of different orientated trains, coupled trains,

or supply for more than one track, since the max. mast distance for overhead current rails is lower than with conventional overhead line. Therefore more masts including grounding are required. On the vehicle side there is no additional effort.

15kV 50Hz is no standardised voltage system in Europe and not permitted according to the TSI. The amendment of a new voltage system contradicts the harmonisation process in Europe and is declined for rollout by the German authorisation body EBA and the German Infrastructure Manager DB InfraGO.

Result for AC Catenary

The **result** of the discussion within the project and with external stakeholders in Germany was that 25kV 50Hz is the preferred solution for catenary islands incl. acceleration ranges (a few km) since

- It allows fast charging
- Is a standardised voltage system in Europe
- Is a cost-effective solution

For AC catenary no changes of standards (TSI, EN...) are required since 25kV 50Hz is a TSI voltage system. But the preferred voltage system should be stated in the EuroSpec "Specification for alternative traction energy supply and related infrastructure interfaces" (EUROSPEC, 2022).

For charging of 4- and 6-coach trains (3/ 4 MW) additional measures must be applied to handle the higher currents:

- For 25kV: Current rail instead of standard catenary or two pantographs,
- For 15kV: Two pantographs.



Figure 7: Example for fast charging via overhead current rail for catenary islands (VOLTAP system)

Charging via DC Catenary

For DC catenary 2 MW charging power means

- 1300 A overhead current for 1,5 kV DC catenary (300 A permitted for standard catenary and pantograph originally),
- 650 A overhead current for 3 kV DC catenary (200 A permitted originally).

The latest revision of TSI LOC&PAS from 2023 opens the opportunity to increase the maximum current at standstill for DC systems for charging of ESS, if the register of infrastructure allows it for dedicated locations and conditions. The text has been modified as following:

“For trains equipped with electric energy storage for traction purposes:

- The maximum current per pantograph at vehicle standstill in DC systems can be exceeded only for charging electric energy storage for traction, in allowed locations and under the specific conditions defined in the register of infrastructure. Only in that case, it shall be possible for a unit to enable the capacity to exceed the maximum current at standstill for DC systems.”

Furthermore, the TSI LOC&PAS from 2023 add an open point concerning the evaluation method for the fast charging:

“The assessment method including the measurement conditions is an open point”.

Even if regulation modification is less restrictive than previous version, there's still a technical challenge for fast charging of BEMUs. To handle these currents several measures are required:

- Overhead current rail,
- Pantograph with contact strip,
- Increased vertical pantograph pressure,
- Second pantograph,
- Supervision system to protect the interface between the overhead line and the pantograph.

To allow these higher currents tests, verification, certification, and adoption of standards is required (EN 50367 and pr:TS 50729).

DC Charging via Charging Plug:

An alternative solution of charging via DC catenary is the charging via plug.

Whereas, in other mobility applications (buses, trucks, ships, etc.) and beyond the massive electrification of these vehicles, development of new generation of plugs for the charging has been proceeded. Different power characteristics and communication control are available to manage the charging process of the batteries.

There are few references of traction battery charging plugs. One special case in railway is for heavy rail battery locomotive WABTEC “FLXdrive”, with special charging plug 480V AC 3ph . This plug allows to have a slow charge of traction batteries. According to BNSF report, the charging process can take up to 11 hours to fully charged the batteries (G.Anderson, 2021). Another more recent example is in Croatia and train manufacturer “KONCAR”, using a MCS plug (Megawatt Charging System) developed for the heavy vehicles sector. On this new 2 car trainset, there's no conventional high voltage traction system to collect the energy from the railway infrastructure. To recharge the 736-kWh nominal battery, a MCS plug has been installed to allow the charging during standstill.

But all systems require a manual operation by the train driver. Further, it reduces the time for charging and requires longer termination times.



Figure 8: On the left, battery locomotive charging plug in Stockton (USA), on the right, charging plug connect to the battery locomotive.



Figure 9: KONCAR's battery train in Innotrans 2024 and MCS charging plug for traction batteries

Underfloor charging system:

A charging via plug without manual operation is possible with the underfloor Fraunhofer charging system developed for developed for road vehicles, see figure below (Fraunhofer, 2025) (MEGA-LADEN, 2024).

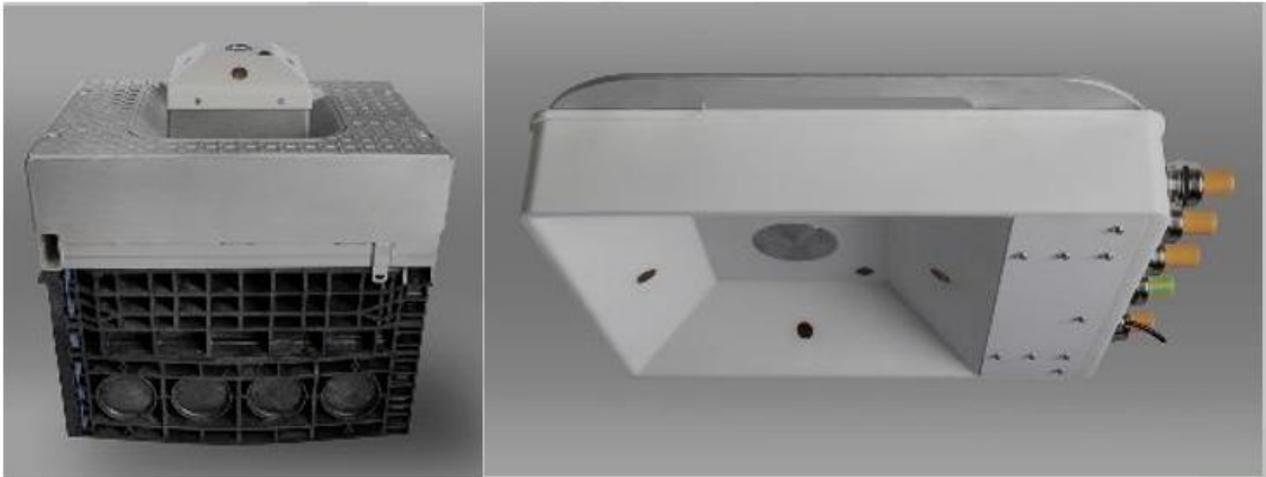


Figure 10: Fraunhofer underfloor charging system (left: on-ground part, right: vehicle part)



Figure 11: Mega-Laden charging system

The system connects to the vehicle by means of a retractable plug, which moves up from track level to a connector counterpart mounted at the vehicle underbody. The targeted application area is charging electric trucks in distribution centers during loading and unloading of goods.

For railway application, the plug would be installed between in the middle of the track and move up to establish contact to the vehicle once in standstill. This requires accurate positioning of the vehicle at the stop. The fixed position of the plug on the infrastructure side requires standardized positions for the counterpart at the vehicle underbody.

The plug system, designed for operations up to about 1.5 kV and currents up to 1 kA and above, meets the charging power requirement. Depending on the BEMU power electronics topology, connection to the traction DC link and charging control via the battery DC/DC converter is possible. Alternatively, direct connection to the traction battery circuit and charging control via external.

The proposed Fraunhofer system offers the advantage of automated operation and fast charging with high transmitted power, but the robustness against the environmental impact like snow and ice still must be proved. According to on-going state-of-the-art, no railway projects have been identified with this solution.

5.3.2 Shore Energy Supply for parking of BEMUs and FCMUs

Requirements for Shore Energy Supply

For lines with short non-electrified line segment (less than about 30km) there is no fast charging required at the termination station. The train can reverse without charging. But at these stations an external energy supply for supplying the HVAC system and auxiliary consumers during parking at night or during longer daytime stops (Pre-conditioning) is required. Further, a slow battery charging should be possible for special cases:

- Train parking for a longer period (e.g. several weeks)
- Operational irregularity (e.g. deviation or longer intermediate stop)
- Battery failures (e.g. one battery string is broken down)
- Battery charging in maintenance shops

In contrast to fast charging within the short termination time a manual operation of the supply can be accepted. Therefore a cable and plug supply as widely used for the supply of DMUs can be used, see figure below:



Figure 12: Parking energy supply for DMUs (32A, 22kW)

The external energy supply is not only required for BEMUs, but also for FCMUs since for FCMUs it is more economic to use external electrical power supply than taking the energy from onboard hydrogen.

In comparison to the DMU supply the required power is higher since DMUs are pre-heated by diesel and not from the external energy supply. Therefore a supply station with higher power and different plug is required.

The maximum required power in parking mode is required for night-time heating at the lowest outside temperatures. The maximum required power for applications in central Europe is 120 kW for a 3-coach train. But according to the analysis in the FINE2 project (Ernst, 2020) it is possible to reduce the power to 85kW with special vehicle-side measures to allow a cost-efficient supply.

Possible Solutions for Shore Supply

In the PINTA3 project (Mannvev, 2022) four different solutions for external energy supply have been analysed:

- 400V 50Hz 3AC with CEE plug 125A,
- 400V 50Hz 3AC with EN50546 plug,
- 1.500V 50Hz AC with UIC 552 plug,
- Automobile plug,
- Underfloor plug (Fraunhofer)

In the PINTA3 project it was shown that the most economical solution is the supply with 400V 50Hz 3AC 125 A, see figure below:

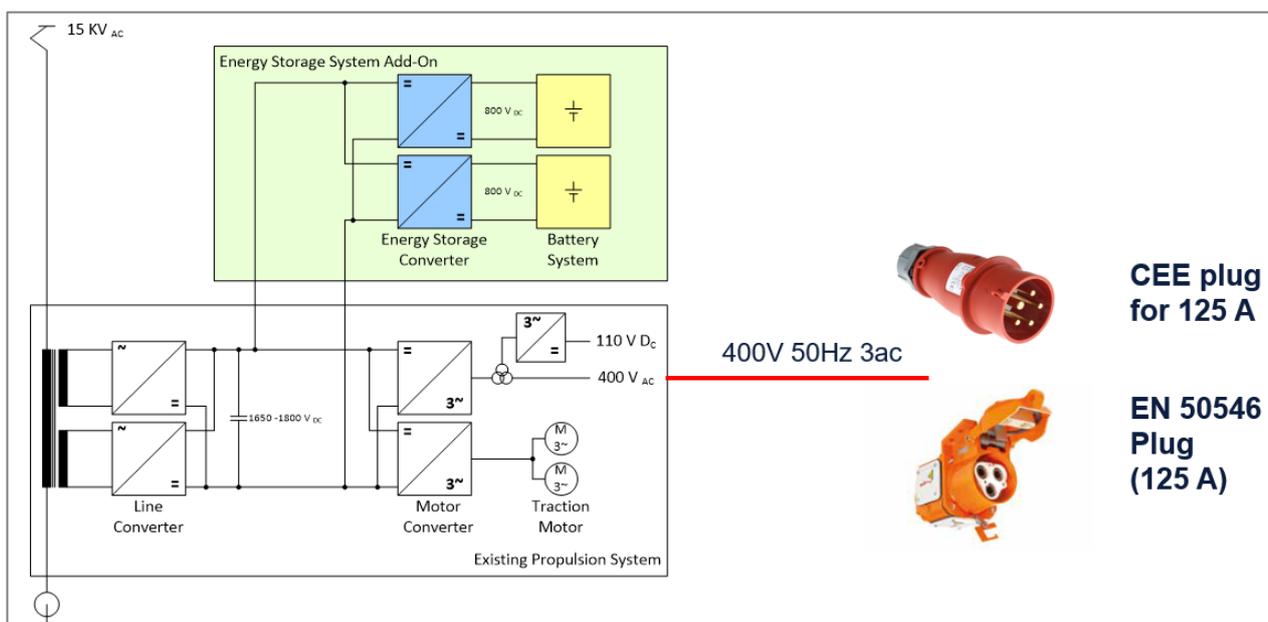


Figure 13: Connection of the shore energy supply to the electrical circuit of the vehicle

For the connection there are two different plugs in discussion: the CEE 125A plug or EN50546 plug (CENELEC, EN 50546 “Railway applications – Rolling stock – Three -phase shore (external) supply system for rail vehicles and its connectors, 2022). The table below shows the comparison between different plugs:

	CEE	EN 50546	UIC	Automobile	Fraunhofer
Plug					
Plug type/ standard	CEE 125A	EN 50546 for 125A	UIC 552	IEC/EN 62196-3 Combo 2	
Voltage	400V 50Hz 3ac	400V 50Hz 3ac	1,5 or 3kW dc ac	400 or 800V dc	About 1.000V dc
Power (3 coaches)	86kW	86kW (400kW)	120 kW – 300kW	120 kW – 300kW	120kW – 2.000kW
Vehicle effort	low	low	medium (transf. tap)	low	expensive socket
Infra effort	low	low	Special components	controlled rectifier	plug, Rectifier
Robustness	medium	high	high	low	medium
Pilot contact	no	yes	no	yes	no
Mech. lock	no	yes	yes	?	Not required
Autom. operation	no	no	no	no	yes
Railway certification	open	To be done	yes	no	no
Long-term standard	yes	yes	Only for plug (different voltages)	Not clear	Not clear
Result/ Ranking	2	1	2	3	4

Table : Comparison between different solutions for shore energy supply

Results for Shore Supply

The comparison shows that the **EN 50546 plug is the best solution** with respect to robustness, mechanical lock, and pilot contact. In 2024 the EN 50546 was updated in collaboration between the railway stakeholders to open the introduction of a common European railway supply for shore energy supply in parking areas and maintenance shops.

There is already a plug on the market. But it still must be tested under railway conditions.

Since the plug is only able to supply the energy for 3-coach trains, trains with more coaches require two supply cables and sockets.

The harmonised **location of the socket** is still not finalised. The location should consider that the train can orientated in different directions. Therefore there should be a socket at both sides of the train (left and right). But the location of the socket along the train is still not clarified:

- Approximately in the middle of the train,
- At one end,
- On both ends.

Future works

For the next and final period, the following studies shall be conducted:

- Description about new auxiliary loads to supply related to ESS and fuel cell power system (especially for cooling & heating → E.g. BTMS),
- Analysis of FINE2 project report on auxiliary consumption values,
- Warning about developing long range with bigger batteries to avoid increasing by twice the consumption of the ESS's auxiliaries.

5.3.3 Hydrogen Refuelling

For pre-standardisation of the gaseous hydrogen refuelling interface the requirements from the following hydrogen vehicles should be considered:

- Regional trains (BEMUs, HMUs/HEMUs),
- Shunting locomotives,
- Light main line locomotives (for freight and passengers),
- Maintenance and inspection vehicles,
- DMUs and diesel locomotives refurbished for operation with hydrogen.

Future technologies with higher pressure than 350 bar or liquid hydrogen will not be covered in this project. But these technologies are probably required for heavy main line application.

5.3.3.1 Requirements for Hydrogen Refuelling

The requirements for hydrogen refuelling agreed in task 5.1 are taken from Del. 5.1 (Fernandez, 2023) and the pre-study carried out in the Shift2Rail project PINTA 3 WP3 (Mannevy, 2022).

The **refuelling time** target for HMUs/HEMUs should be like the diesel refuelling time of DMUs in the order of 15min. But this would lead to high infrastructure cost. Therefore project partners agree that a refuelling time of up to **30min** can be accepted. This time should be fulfilled for the fuel amount required for 1000 km distance.

Since hydrogen refuelling stations are often not located near the application line, the refuelling distance should be as low as possible to minimise additional operational train runs for refuelling. Therefore a target for the **refuelling distance** of about **1000km** is required by most operators (in France 600km are enough). Here the following conditions must be considered:

- Two-coach train
- Running along the regional train profile according to EN 50591 with the defined timetable
- HVAC consumption for climatic zone 2
- 50% passenger load
- Parking hydrogen consumption when the train is not connected to the electrical shore supply

To reduce the number of refuelling stations even a higher refuelling distance is the target for innovations 1500 km option.

1000 km range corresponds to a **fuel amount of about 250 kg H₂**. During longer parking, an external energy supply can be assumed. This energy consumption value is only an orientation. In praxis it depends on the weight, the driving characteristics of the vehicle, the profile and the distance of the route and the environmental conditions.

- Elevation profile
- Numbers of stops
- Speed profile
- Equipment of trains
- Environmental conditions (heating, cooling, head wind, adhesion)

The combination of refuelling distance and time is a challenge for the development in WP8 (vehicle) and WP9 (infrastructure).

The trains must be filled with **compressed hydrogen** of fuel cell grade according to the following standards:

- EN 17124: 2022 Hydrogen fuel -- Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen -- Proton exchange membrane (PEM) fuel cell applications for vehicles
- ISO 14687: 2025 Hydrogen fuel quality — Product specification

The pressure must not exceed 35 MPa or **350 bar** at 15° C, corresponding to a density of 24 g/l and a state of charge (SoC) of 100%.

With respect to the **location of the receptacle** along the vehicle a position approximately in the middle of the train on both sides (right and left) is the preferred solution to allow a flexible vehicle operation and limit the number of receptacles. For 3- and 4-coach trains more receptacles are required.

To allow a fast refuelling the parallel refuelling with via **two receptacles** (one for each tank) can be accepted from operator view.

To minimise the refuelling process time, it should be desirable to install a **chiller** at the dispenser to refuel the hydrogen as cool as possible, taking care with the compatibility with some process elements as sensors or electrical valves. For minimising the energy consumption of the HRS the cooling temperature should be controlled in dependence on the ambient temperature.

To ensure **safety** during the refuelling process following topics must be considered:

- Parts of the refuelling station exposed to hydrogen must be explosion-proof,
- The hose may not exceed a length of 10 m Occupational Health and Safety (OHS),
- Prevent overfilling and overheating scenarios of the communication between hydrogen refuelling station (HRS) and train for service stations with non-discriminatory access, the CHSS-model must be known at service station (to know the relation piping-temperature to train-tank-temperature),
- End of refuelling must be defined in the “refuelling process”,
- Tear-off safety device (in case of moving the vehicle during refuelling process),
- HRS and vehicle must have the same electric ground,
- The hydrogen refuelling process is based on the following standards:
 - SAE J2601 - Hydrogen Refuelling Protocols for Light-Duty Vehicles
 - SAE J2601-2 - Hydrogen Refuelling Protocols for Heavy-Duty Vehicles
- Since the capacity for railway vehicles is greater, other standards and various projects are being developed to meet their needs. Currently, the ISO 19885-3 standard, titled "Gaseous Hydrogen - Refuelling Protocols for Hydrogen-Powered Vehicles. Part 3: High-Flow Hydrogen Refuelling Protocols for Heavy-Duty Road Vehicles," is being developed. This standard is being overseen by ISO/TC 197 and is expected to represent a viable alternative for railway systems

To enable the same **operational performance** than refuelling of diesel driven vehicles, the refuelling must be possible by the same staff (concerning education). In general, the driver refuels the vehicle. This means that the refuelling can be done by one person.

This means that the person must be able to do the following **refuelling actions**:

- The operator should get info whether the HRS is ready to refuel,
- Connecting both couplings,
- The weight of the refuelling equipment must be lower than 15 kg,
- Max. weight depends on work safety rules /OHS – rules,
- The height of the receptacle must be within a certain range,
- The distance from the dispenser to the receptacle of train may not exceed 8 m,
- Starting refuelling process by manual action after connection,
- Abort the refuelling process in case of unexpected events,
- Interruption of refuelling can be triggered manually,
- Emergency switch which closes the connection and unpressurised the hose,
- The rest of refuelling process must be automatically done,
- The operator may be informed about the remaining time,
- The refuelled mass must be counted accurately and precisely,
- There must be a signal at the end of the refuelling process e.g. light-signal. Further, the operator should be stated if all was fine and targeted SoC achieved. If refuelling has been cancelled, it also should explain why (leak tightness test failure, over flow, etc),
- In case of unknown vehicle only a safety refuelling mode must be applied.

As a rule, the **refuelling process** must be approved between HRS and the petrol station user (HRS or operator staff).

Collaborative Work within WP1, WP7, and WP9

For the clarification of a common European interface for hydrogen refuelling, a common project expert group was established, consisting of different stakeholders (Industry, railway undertakings, and infrastructure managers)

- WP1 Pre-standardisation
- WP7 Vehicle-side development
- WP9 Hydrogen refuelling station

The scope of work is limited to the refuelling process according to the figure below:

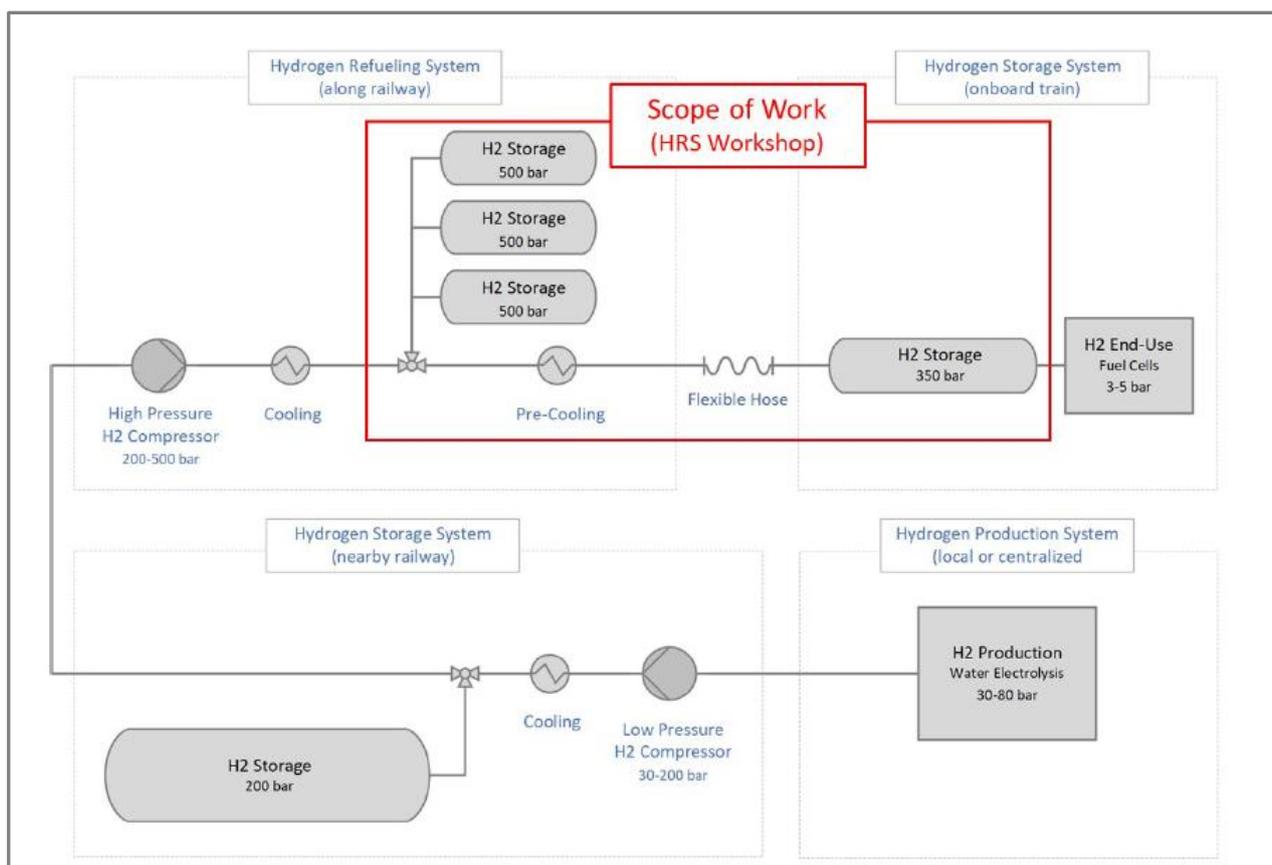


Figure 14: Scope of work for pre-standardisation of hydrogen refuelling interface

5.3.3.2 Mechanical Interface

Requirements for Mechanical Interface

The following **requirements** for the mechanical interface (nozzle and receptacle) were agreed between the partners:

- Compressed hydrogen of 350 bar
- Refuelling time of up to 30min can be accepted to reduce the effort for the hydrogen refuelling station (HRS)
- 30 - 100 kg hydrogen amount for shunting locomotives and up to 250 kg for regional trains
- Flow rate for a regional train 8,3 kg/min or 140g/s or 70g/s per vehicle/ receptacle (for parallel refuelling with two nozzles)

State-of-the-art Mechanical Interface

Key components related to this interface include the hydrogen dispenser, which features nozzles, filling hoses, breakaway systems, sensors, and communication systems between the train and the refuelling station, as well as filter systems, among others.

Nozzles

Nozzles are the components through which communication occurs between the vehicle and the refuelling station. Currently, there are no specific nozzles or receptacles for refuelling railway vehicles; however, due to the similarities with refuelling heavy-duty road vehicles, the latter could be adopted for the railway sector.

The nozzles and receptacles must be compatible to ensure proper refuelling, making pressure and mass flow rate critical factors in defining these components. This compatibility is governed by the

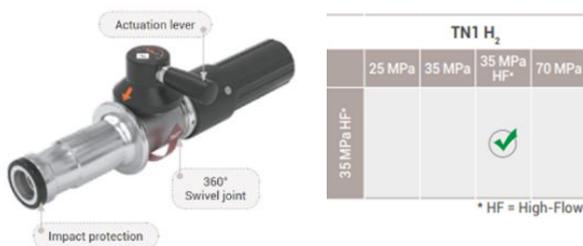
- ISO 17268 “Gaseous hydrogen land vehicle refuelling connection devices” and
- SAE J2600 “Compressed Hydrogen Surface Vehicle Fuelling Connection Device standards”, as specified in the PHRYDE project.

WEH, a leading manufacturer of hydrogen refuelling nozzles and receptacles, states that the receptacle must be compatible with nozzles operating at a pressure equal to or lower than that of the receptacle. In the railway sector, since the hydrogen refuelling technology focuses on a pressure of 35 MPa, the selected nozzles and receptacles should be designed for this pressure.

In one of WEH's catalogues, "Hydrogen Refuelling Technology: High-Performance Components for Hydrogen Vehicles and Service Stations," the potential nozzles and receptacles applicable in the railway sector are specified as follows:

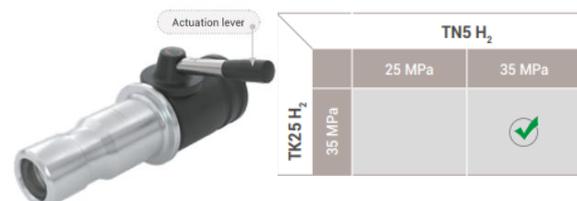
- TK16 H2 High-Flow Nozzle: this nozzle is compatible with the TN1 H2 receptacle due to its pressure range, as shown in the figure below. Additionally, as it allows for a higher refuelling flow rate, filling times are consequently reduced. This nozzle allows communication with the refuelling station and complies with SAE J2600 and ISO 17268 standards.
- TK25 H2 Nozzle: This nozzle is compatible with the TN5 H2 receptacle, also due to its pressure range, as shown in the figure below. This nozzle complies with SAE J2600 and ISO 17268 standards.
- TN1 H2 High-Flow Receptacle and TN5 H2 Receptacle: These receptacles are compatible with the TK16 H2 and TK25 H2 nozzles, respectively. Their main features include the ability to facilitate high flow rates while their efficient design also reduces refuelling noise. Additionally, they are equipped with a particle filter to prevent contamination and have a soft protective cap to avoid potential leaks. It is important to note that both receptacles should be installed at a height between 0.7 m and 1.5 m above the rail height. The main distinction between the two lies in the data interface; the TN1 H2 allows for operation with communication, while the TN5 H2 does not.

TK16 H2 High-Flow



Receptacle TN1 H₂ High-Flow

Nozzle TK25 H2



Receptacle TN5 H₂



Figure 15: State-of-the-art nozzles and receptacles

With respect to standardisation, it should be stated that the nozzle and hose should be compatible with the technical parameters defined in ISO 17268 independent of the supplier. No special supplier and product should be preferred.

Hoses

Hoses are responsible for connecting the refuelling nozzles to the breakaway device or refuelling station. WEH offers hydrogen refuelling hoses in various diameters and lengths. For the mentioned nozzles, the selected hoses can withstand a temperature range of -20 °C to +90 °C, according to the catalogue of WEH (WEH, 2025). These hoses are typically braided and corrosion resistant.

Filters

To ensure that the hydrogen supplied to the railway vehicle is free from impurities and contamination, filters must be installed as close as possible to the breakaway. According to standard 19880-2, a filter capable of removing particles larger than 5 µm is required, with a minimum retention efficiency of 99%.

Breakaway

The breakaway is a safety device installed between the hydrogen dispenser and the refuelling hose. In the event of unexpected tensile forces, such as if the vehicle starts to move with the nozzle connected, this device separates all connections between the hydrogen dispenser and the hose while sealing both ends using shut-off valves. This helps reduce damage to the entire hydrogen refuelling system. The device activates when a force exceeding 1000 N is applied. Additionally, it includes a particle filter to prevent contamination. WEH offers two models of breakaways (TSA5 H2 and TSA6 H2); however, neither is suitable for the railway sector, as the breakaway force is between 222-667 N.

Results for standardised mechanical Interface

The following **standardised solution** for the mechanical interface was agreed between the project partners:

- **H35HF hydrogen receptacle** (high flow for commercial vehicle applications) according to Fig. 4.2 of EN ISO 17268:2020-05)
- Product name: nozzle TK 25 (refuelling station) and receptacle TN5 (train)
- Flowrate > 120 g/s
- Same coupling used in European state-of-the-art hydrogen trains like Mireo Plus H (Siemens) and iLint (Alstom)

5.3.3.3 Refuelling Control and Communication

Requirements for Refuelling Control

- The control system must guarantee safe within the fuelling window (see graph below):
 - > Limiting the pressure and temperature in the vehicle tank
- The control system must guarantee fast refuelling of at least 140g/s average flow rate for two hoses
- The safety requirements are SIL 2 (from the risk assessment of DB) to prevent overheating of the tank, especially the liners.
- The inhomogeneous temperature distribution within the tank must be considered.
- The control system should be located within the refuelling station
- A safe communication between the HRS and the vehicle should be avoided for simplification
- Pressure and temperature sensors within the HRS should be installed as close as possible to the breakaway device. Regarding tolerances, a tolerance of ± 2 °C is allowed for ambient temperature, and the pressure sensor tolerance must be within 1% of the total scale.

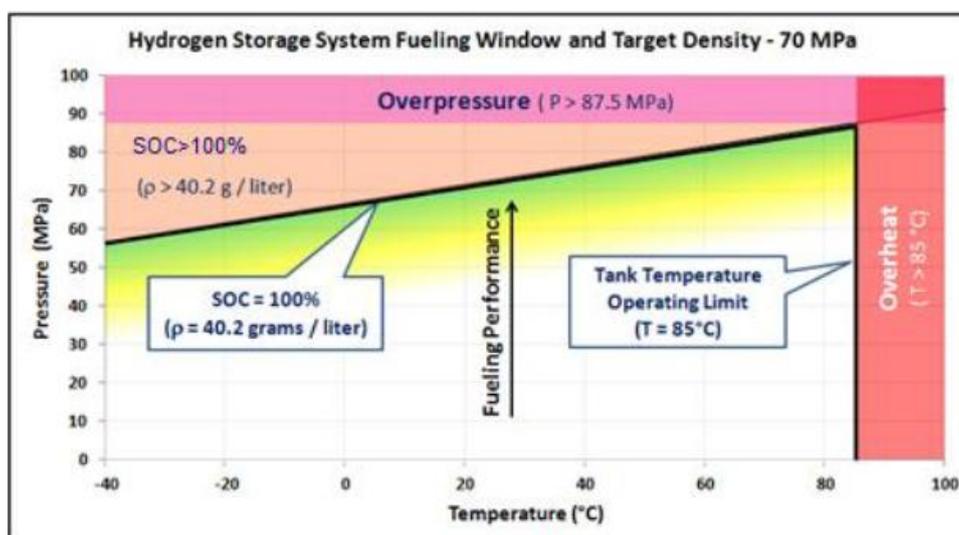


Figure 16: Hydrogen fuelling window and target density for 70MPa

Communication and Temperature Measurement

To achieve a fast refuelling and 100% SoC a safe communication between HRS and vehicle as well as a safe measurement of the hydrogen vehicle storage system is required to ensure that refuelling occurs within the protocol limits for compressed hydrogen storage systems in vehicles (according to ISO 19880-1), especially to prevent an overheating of the hydrogen in the vehicle storage system,

This is practice for HRS for road vehicles. This communication is unidirectional, meaning it transmits data from the vehicle to the station, thereby enhancing the refuelling process.

Two kinds of communication are possible:

- Wireless,

- By wire

the TN1 H2 allows a communication by wire, while the TN5 H2 (required for rail vehicles) does not.

Preferred Solution for Refuelling of Rail Vehicles

Different solutions for refuelling of rail vehicles were discussed between the project partners. The result of the discussion is:

- There are no temperature sensors on the market that allow a safe measurement of the tank (Esteban Rodriguez, FCH2RAIL Del. D7.4–Complementary gaps in analysis framework, 2024)temperature according to the safety requirements for rail vehicles. Therefore a fast refuelling by measuring of the tank temperature during the refuelling process is not possible
- The preferred solution for rail application is the refuelling without dynamic communication between HRS and vehicle
- To achieve a safe and fast refuelling the HRS must know the vehicle data with respect to the max. pressure, max. temperature and mechanical parameters of the tank (refuelling table, see graph below).
- The refuelling table of the vehicle should be stored within the HRS refuelling control system.
- This requires a safe identification of the vehicle type/ class (SIL 2)
- A possible solution vehicle identification are vehicle-side RFID tags that transmit the vehicle number to the HRS. For safe identification a second source is required, e.g. the verification of the vehicle class by the operator

Refuelling Table

An example for a static refuelling table can be taken from SAE J2601-5 (Automotive standard)

Input data from the refuelling station are

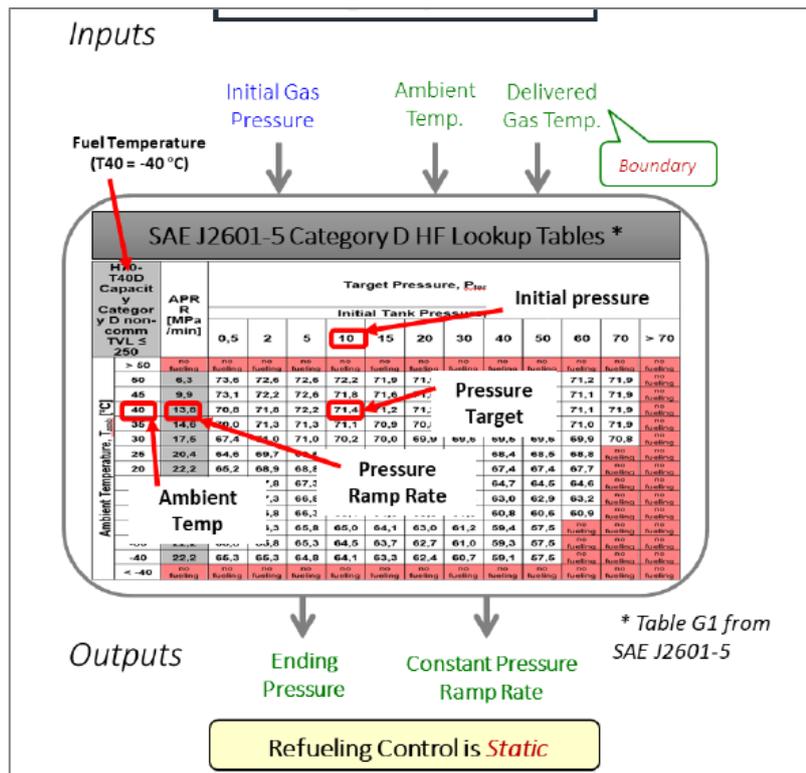
- Initial gas pressure
- Ambient temperature
- Delivered gas temperature

Output data are

- Ending pressure
- Constant pressure ramp rate

Problems to be solved are

- The ambient temperature of the refuelling station can be different to the ambient temperature of the vehicle tank, in particular if they are on the roof and under a protective hood exposed to the sun.
- The authorisation body in Germany (EBA) does not accept automotive standards for railway application



H70-T20D Capacity Category D non-comm TVL ≤ 250 L	APRR [MPa/min]	Target Pressure, P_{target} [MPa]												
		Initial Tank Pressure, P_0 [MPa]												
		0,5	2	5	10	15	20	30	40	50	60	70	> 70	
Ambient Temperature, T_{amb} [°C]	> 50	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	
	50	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	
	45	1,4	71,0	72,2	72,6	71,8	71,6	71,5	71,2	71,0	70,9	71,1	71,9	
	40	2,3	70,0	71,8	72,2	71,4	71,2	71,2	70,9	70,8	70,8	71,1	71,9	
	36	2,6	70,0	71,3	71,3	71,1	70,9	70,8	70,6	70,6	70,7	71,0	71,9	
	30	3,3	68,6	71,0	71,0	70,2	70,0	69,9	69,6	69,5	69,6	69,9	70,8	
	25	4,2	67,3	69,7	69,6	69,3	69,0	68,9	68,6	68,4	68,5	68,8	no fuelling	
	20	5,2	66,0	68,9	68,8	68,4	68,1	67,9	67,5	67,4	67,4	67,7	no fuelling	
	10	7,2	63,4	67,8	67,3	66,3	65,9	65,6	65,1	64,7	64,5	64,6	no fuelling	
	0	11,2	57,7	67,3	66,8	66,9	64,9	64,0	63,4	63,0	62,9	63,2	no fuelling	
	-10	12,2	56,9	66,8	66,3	66,4	64,5	63,5	61,5	60,8	60,6	60,9	no fuelling	
	-20	13,0	56,1	66,3	65,8	65,0	64,1	63,0	61,2	59,4	57,5	no fuelling	no fuelling	
	-30	13,8	55,4	65,8	65,3	64,5	63,7	62,7	61,0	59,3	57,5	no fuelling	no fuelling	
-40	14,6	54,7	65,3	64,8	64,1	63,3	62,4	60,7	59,1	57,5	no fuelling	no fuelling		
< -40	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling	no fuelling		

Figure 17: Example of a refuelling table from SAE J2601-5

Static Vehicle Data

For the calculation of the refuelling table the following static vehicle data are required according to ISO 19885 Part 1 Annex 2:

- number of containers in vehicle fuel system,

- container volume(s) or total volume of the vehicle fuel system at reference conditions specified by the fuelling protocol (e.g., water volume at atmospheric pressure and room temperature, compressed gas volume at 100 % NWP and 15 °C),
- container L/D(s),
- container type(s),
- minimum and maximum allowable container temperature(s),
- maximum allowable or target fuelling rate expressed as mass flow (g/s) or pressurization rate (MPa/s),
- container thermal characteristics (e.g., specific heat, conductivity, ...),
- pressure drop coefficients and thermal mass of the onboard fuelling lines,
- maximum fuelling pressure,

Vehicle Identification by Means of RFID Tags

A possible solution hardware solution that is already applied for railway vehicle identification is the SOFIS Tag by Siemens.

Physical Principle: An interrogating pulse from the Sofis reading device is transmitted to the piezoceramic interdigital converter located in the ID tag. The reflected acoustic signals returning to the inter-digital converter are converted to electromagnetic oscillations and emitted via the antenna. The pulses form a pulse train, also called pulse response. This pulse train can be received by the antenna of the Sofis reading device and evaluated using a downstream signal processor in line with the intended purpose.



Figure 18: SOFIS Tag (Siemens)

Standardisation of Hydrogen Refuelling for Rail Vehicles

Suggested Standard:

- ISO 19885 “Gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles”

The automotive standard should be amended for railway applications by a part 4 for railway application “Very high flow hydrogen fuelling and communication for railway application”. Alternatively, amendment of part 2 “Definition of communications between the vehicle and dispenser control systems”

The following topics shall be integrated into the standard

- Safe and secure vehicle identification
- Definition of standardised tank volume ranges and parameters for different vehicle types, e.g. regional train, shunting locomotive, maintenance vehicle
- Definition of standardised refuelling tables for the different tank volume ranges in analogy to SAE 2601-5

5.4 Pre-Standardisation of Operational Interfaces

5.4.1 Required Data for Energy Functions

For BEMUs and FCMUs several energy functions must be implemented to control the energy flow, minimise the energy consumption, and supervise the pantograph. Important energy functions are:

- Range calculation of BEMUs
- BEMU charging via overhead line
- Lift and drop of pantograph
- Connected or hybrid driver assistant system (C-DAS)
- Shore energy supply during parking

The energy functions require static and dynamic infrastructure data and parameters of the traffic management system (TMS). The communication between vehicle and landside should be standardised with respect to the communication channel and the parameters.

For the energy functions the following **infrastructure parameters** are required:

- Permitted speed profile
- Location of the stations
- Gradient
- Location of the electrified and non-electrified sections
- Overhead line voltage and frequency
- Permitted continuous overhead line current
- Location of the overhead islands

For the energy functions the following **operational parameters** are required:

- Timetable
- Max. permitted charging time and/or pre-planned end time of parking, e.g. taken from the vehicle circulation plan

For the energy functions the following **vehicle parameters** are required:

- Vehicle position
- Vehicle orientation
- Pantograph position
- ESS parameters (kWh, SOC ...)
- Traction parameters (Max. power, continuous power, efficiency ...)
- Vehicle parameters (Mass, length, no of coupled units, aerodynamic resistance ...)

Most parameters are static. They may be transferred to the vehicle once and can be stored in the TCMS. But some parameters are dynamic, they change during the run of the train. They must be updated continuously.

5.4.2 Standardised Data Exchange Between Vehicle and Landside

Possible standards for standardisation of the data exchange between vehicle and landside (TMS / infrastructure) are identified:

- CCS/ TMS Data model (developed in EU-Rail)
- UNISIG ATO-OB / ATO-TS FFFIS Application Layer, Subset-126 of ATO over ETCS
- UIC IRS 90940 SFERA protocol

In all three standards most of the required data are already implemented.

The different standards are compared with respect to suitability for the data exchange of alternative drives:

The preferred standard is the SFERA protocol defined in IRS 90940, since

- it enables a data exchange on lines without ETCS
- it is a already established standard for data exchange for connected driver assistant systems (C-DAS)

In contrast

- UNISIG ATO-OB Application layer require ERTMS (not equipped on most regional lines) and
- The CCS/TMS data model is not yet established

The SFERA protocol addresses the standardisation of data exchange flows with Driver Advisory Systems (DAS). This protocol has been designed to allow operators to work seamlessly across borders and speed up the implementation of advice to driver connected to real-time traffic management (Connected DAS or C-DAS) while remaining compatible with ATO over ETCS.

Most of the required parameters are already defined in the SFERA protocol:

Subsystem	Parameter	Dynamic/ static	IRS 90940 SFERA protocol	Remark
Infrastructure	Location of the overhead line	S	JourneyProfile / SegmentProfileList / TemporaryConstraints/ TractionTotalCurrent/ maxCurValue	
Infrastructure	Max. continuous overhead current	S + D	JourneyProfile / SegmentProfileList / TemporaryConstraints/ TractionTotalCurrent/ maxCurValue	Only max. current defined, continuous current missing
Infrastructure	Overhead line voltage type (voltage and frequency)	S	SegmentProfile / SP_Characteristics / RatedVoltage / RatedVoltageChange / voltageValue	
Infrastructure	Speed profile	S + D	JourneyProfile / SegmentProfileList / TemporaryConstraints/ AdditionalSpeedRestriction / ASR_Speed	
Infrastructure	Gradient	S	SegmentProfile / SP_Characteristics / GradientSteepest / GradientSteepestStart / gradientValue	
Infrastructure	Location of charging islands	S	JourneyProfile / SegmentProfileList / TemporaryConstraints/ TractionTotalCurrent/ maxCurValue	
Infrastructure	Station location	S + D	JourneyProfile / SegmentProfileList / TemporaryConstraints/ startLocation	
TMS	Station stop time	S + D	JourneyProfile / SegmentProfileList / TimingPointConstraints / TP_latestArrivalTime	
TMS	Station dwell time	S + D	JourneyProfile / SegmentProfileList / TimingPointConstraints / StoppingPointInformat	

Table 9: Required parameters already defined in the SFERA protocol

Communication Channel

With respect to the communication channel, the idea is to use the communication channel already used for data exchange of the C-DAS. But here additional data have to be added.

Next Steps

Next steps for the pre-standardisation of the operational interface are:

- Evaluation of existing solutions of C-DAS data exchange on lines without ETCS
- Evaluation of the infrastructure data sources in different countries
- Clarification of a amending data exchange parameters not yet implemented in the C-DAS data exchange
- Amendment of IRS 90940 by further exchange parameters required for alternative drives

5.4.3 Range Calculation

The most important energy function is the range calculation.

The decarbonization of railway vehicles with the introduction of new technologies such as lithium-ion batteries or hydrogen introduced a reduction of the energy capacity on-board. Range in operation with these alternative drive technologies can be impacted significantly. As shown in S2R PINTA3 WP3, the autonomy in operation is quite different from one technology to another (Ap.Chamaret, Analysis, trends and expectations for low carbon railway, 2022).

Train characteristics	Battery train	Hybrid Hydrogen/Battery train	Hybrid Diesel/Battery train
Type of operation	Mainly Regional Sub-urban	Regional	Mainly Regional Freight
Maximum speed	160 km/h (Regional)	160 km/h (Regional)	160 km/h (Regional) 100 km/h (Freight)
Type of Energy supply	Traction batteries Electric (panto / 3rd rail)	Mainly H2 + Traction batteries Electric (panto)	Electric Diesel + Traction batteries Batteries only* ("Silent mode")
Range in Catenary Free Operation	80 km (from 40 – 150 km)	800 km (from 400 to > 1000 km)	> 1000 km
Traction Battery capacity per train	550 kWh	270 kWh	130 kWh
Battery technology	LTO or NMC	LTO or NMC	LTO or NMC
Fuel cell power	N.A	325 kW	N.A
Hydrogen storage	N.A	350 Bar	N.A
Combustion engine	N.A	N.A	Stage IV or V

Table 10: S2R PINTA3 WP3 performance of alternative drive trains

The most critical technology in terms of range in operation is the battery train (BEMU) with a reduction of a factor 10 at least compared to conventional diesel trains. For hydrogen vehicles (HMU), this topic is much less critical, especially HEMUs (dual-mode hydrogen and catenary operation).

For heavy rail vehicles, such as freight locomotives, the alternative drive technologies are more limited due to high power and high energy required. A heavy rail locomotive has generally a weight around 90 t (e.g. ALSTOM TRAXX = 88 t, SIEMENS VECTRON = 88 – 90 t). Connecting with several wagons, it's inducing a train characteristic of more than 1000 tons. Based on European standard EN 50591 "specification and verification of energy consumption for rolling stock", the standard convoy is composed of 18 wagons type Zans, representing a total weight of 1449 tons. Compared to regional alternative drive trains, the gap is close to 10 times higher. So, heavy rail



freight involved developing more energy density and power in discharge of energy storage system, to avoid extra loads and volumes to allocate for the on-board traction system.

Manufacturers	Names	Weight (t)	Max Power at wheel (kW)
ALSTOM	TRAXX	88	6400
SIEMENS	VECTRON	88	6400
18 wagons Zans (EN 50591)	Standard EN 50591	1449	-
Total Heavy Rail Freigh	Loco + Wagons standard EN 50591	1537	6400
SIEMENS	MIREO Plus B	120	1700
ALSTOM	CORADIA STREAM H2	216	1170
HITACHI	BLUES (catenary + hybrid diesel/battery)	162	1330

Table 11: Weight and Max tractive power comparison between heavy rail locomotive and alternative drive trains multiple units (BEMU, FCMU and DEBMU)

Currently, for freight application, alternative drive development has been proceeded on the level of “low powered locomotive” (between 1 and 2 MW). Several locomotive manufacturers design electric low power locomotive with an additional battery set (e.g. VOSSLOH Modula EBB, ALSTOM TRAXX SHUNTER, etc.). For this application, the energy capacity is also limited (from 100 up to 500 kWh). Therefore, range in operation and power are reduced:

- Range: between 1 and 2h of shunting operation,
- Power: till 500 kW (between 2 and 4 times lower than in electric mode).

The conditions to attempt these performances are strongly dependent on the usage of the locomotive. In freight operation, the loading and convoys are changing regularly, much more than for passengers’ transportation with alternative drive multiple units. Potential lack of energy might be chaotic if it happens on a non-electrified section by delaying. So, it requires an accurate range estimation prediction to give more confidence to the operator for using alternative drive locomotives.

Range calculation is very complicated and requires a lot of operational, infrastructure, TMS, and vehicle parameters.

How to calculate the range in operation?

Today, most of the vehicles are using simplified range calculation. This simplified range calculation is based on available energy on-board, divided by a fixed consumption factor.

Example below for diesel trains:

$$Re = Ead/Ecf$$

With:

- Re: Range estimation, in km,
- Ead: Energy available in diesel, representing the quantity of diesel fuel reserve in the tank, in litre,
- Ecf: Energy consumption factor, representing a predefined energy consumption value, expressed in litre/km.

The energy consumption factor is based on results from simulation and/or tests on a railway line.

The value obtained can then be applied for any type of service or line. This approach is basically enough for diesel trains due to the high energy density and large volume of fuel.

This method is very simple to apply, whereas it's not considering real energy consumption of the vehicle during operation. The energy consumption may vary significantly when the train is in service due to many parameters such as:

- Train characteristics,
- Efficiency (traction system and auxiliary converters),
- Energy supply type,
- Aerodynamics,
- Auxiliary loads,
- Energy management functions,
- Train load,
- Operational conditions (journey profile, driving style, timetable, etc.),
- Environmental conditions (external temperature, wind speed, etc.),
- Infrastructure characteristic (line profile, electrification sections, etc.).

So, this is not an accurate method to estimate the remaining range of BEMUs in operation.

Range Calculation for Trains with Alternative traction

As explained previously, new alternative drive trains are much more sensible with respect to range calculation. The range calculation will apply to any kind of alternative drive trains (regional, suburban, freight). Especially for freight use cases, it is important to consider in the calculation process the configuration of wagons used.

On battery train, a so called “**predictive range estimation**” can be installed. This new autonomy calculation is based on:

- Energy available inside the traction batteries,
- Route information,
- Simulation model.
- Optionally: Verification at the different traces and mission profiles, if it is possible to add variation in the autonomy with derating
- Optionally: Potential corrections due to stationary parameters that may affect the expected consumption of auxiliaries (HVAC, pneumatics, lighting)

The range in operation is calculated as following:

- Train is in the departure station and waiting for commercial service,
- Train driver enter the information about the service into the driver terminal,
- An on-board program will check whether the service information is available in the database,
- If yes, each service is associated to a predefined simulation to determine how much energy is necessary in operation. It gives an estimated energy consumption in operation simulated (EoS),
- In the meantime, the amount of energy available in the traction batteries is collected (Eab),
- Range calculation is proceeded $Re = Eab/Eos$

This method of “predictive range calculation” involves many data to use in a simulation tool to create a data base. The simulation model implies the modelling of rolling stock characteristics (aerodynamic, efficiency, auxiliary loads, etc.) with its energy storage system, infrastructure characteristics (gradient, station location, voltage, etc.), route profiles (timetable, driving style, etc.). Furthermore, it also enables to include the recharging in the estimation of energy consumption. On partially electrified lines, the battery uses the energy from the traction batteries on the non-electrified section, but it can recharge when the vehicle is on a catenary section. So, if another catenary free section comes along the operation, it gives more energy available to pass the non-electrified zone.

Compared to the methodology historically used on diesel trains, this approach of “predictive range calculation” is much more accurate by considering route information of the operation.

Since the predictive range estimation is based on simulation with predefined assumptions the results differ from real conditions during service. For example, the auxiliary loads are a fixed parameter in simulation, while according to real conditions, such as weather, number of passengers on-board, etc., auxiliary consumptions will vary along the service line. Another limitation of this method is concerning the risk of events during operation. Many kinds of disturbances, such as signaling failure, exceptional attendance, fatalities, etc. and so may impact the energy consumption of the vehicle and the remaining range in operation.

Due to the inaccuracy of “predictive range calculation”, a recommendation to develop a “**real-time range calculation**” for alternative drive trains. Realtime range calculation may allow to collect all available data from sensors on-board to estimate the energy consumption and so the range in operation. It could inform the train driver about an estimated range in operation based on actual energy consumption at least. Therefore, real-time range calculator should be able to consider the parameters defined previously about influencing the energy consumption.

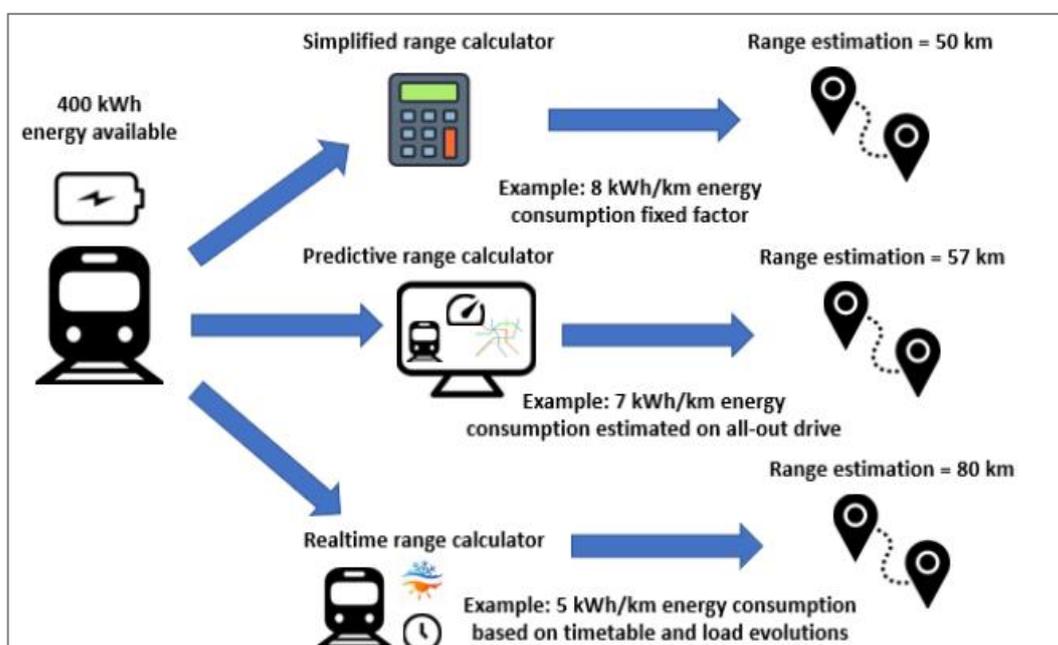


Figure 19: Range calculator methodologies for battery train

The example presented here was based on a battery train, but the same approach can be applied to other type of alternative drive trains, such as hydrogen trains. The main difference will be on the available energy on-board, with multiple sources:

- Hybrid hydrogen train = Energy available from hydrogen tank + Energy available from traction batteries
- Hybrid diesel train = Energy available from fuel tank + Energy available from traction batteries

Additional Functions to Improve Operation of Alternative Drive Trains

Accurate range calculation is a fundamental function for alternative drive trains as seen before. Furthermore, additional functions could be interesting for smarter operation of the battery train, such as fleet management supervision.

Battery vehicle fleet management is now developed in the mobility sector, especially for e-buses. Several companies and European projects have worked to develop remote monitoring and decision-support tools for the operator. Efficient management of the fleet allow to maximize the usage of vehicles, while ensuring nominal conditions. It also helps to prevent potential disturbances and reduce the effect on the traffic. Additionally, other useful information such as energy consumption or ageing status of the batteries can support the operator to optimize his assets.

Future works:

In the next period, WP1 will work on potential definition of common requirements for alternative drive trains fleet management.

5.5 Pre-Standardisation of the Energy Storage System (ESS)

As described in S2R PINTA3 WP3 report, all alternative drive trains are equipped with an Energy Storage System (ESS). The ESS is a subsystem, defined in international standard IEC 62864-1:2016, constitutes of:

- One or more Energy Storage Units (also called “ESU”)
- A converter, to adapt the voltage between the ESU and the DC link of the vehicle,
- Control and monitoring system for the supervision of the ESS,
- Protection devices,
- Thermal Management System (mostly named “Battery Thermal Management System”),
- Etc.

For alternative drive based on hydrogen fuel, the fuel cells are considered in the scope of the “Primary Power Source” (PPS) subsystem. It is the same classification of diesel electric engine or DC or AC contact line. For fuel cells and diesel electric engines, both are based on supplying electric energy by consuming fuel stored on-board (hydrogen and diesel, alternative fuels). Whereas for DC or AC contact line, the train collects energy from external sources (by catenary and pantograph or by 3rd rail and shoe). The figure below is an excerpt from the standard and provides a simplified overview of an alternative drive train:

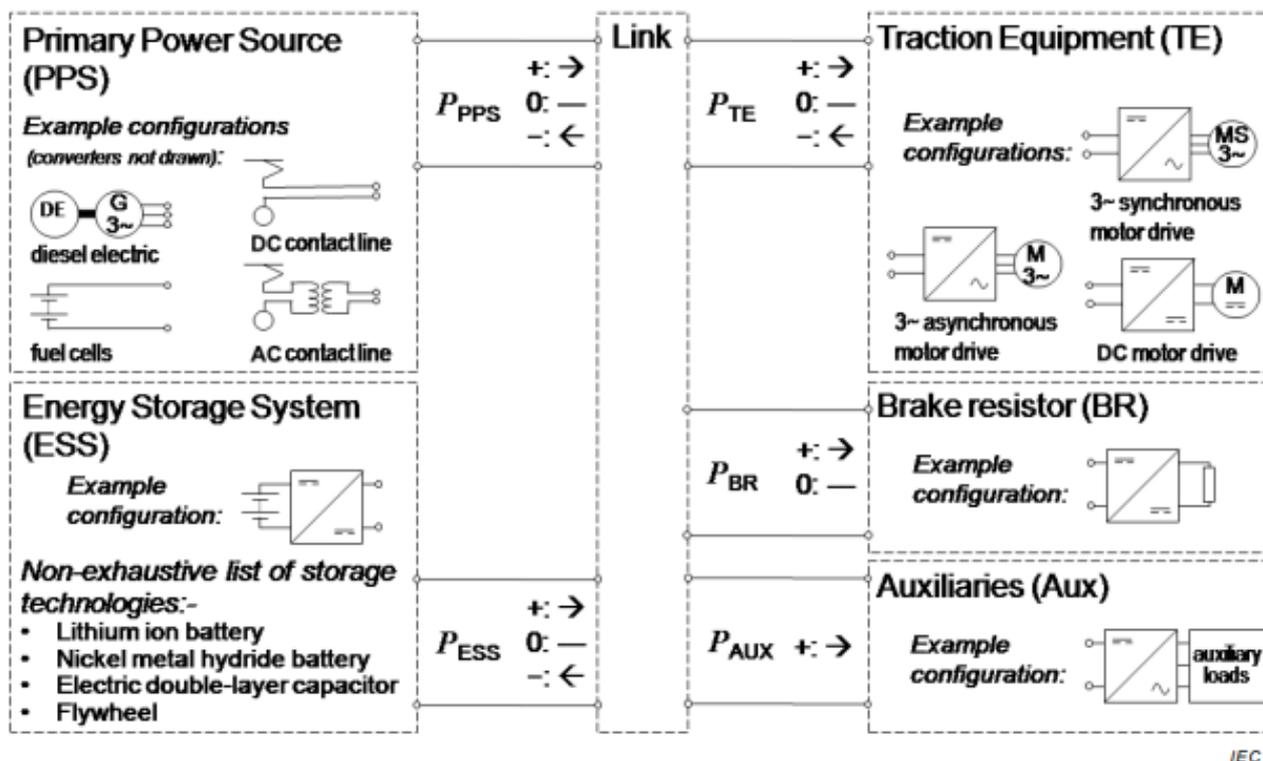


Figure 20: Block diagram of an alternative drive trains according to IEC 62864-1 (source: IEC)

For the following components of the ESS and PPS existing standards are identified:

- Traction batteries (ESS scope),

- Onboard fuel cell (PPS scope),
- Hydrogen storage system (HSS) (PPS scope),
- Battery converter (ESS scope).

The following standards for these vehicle components are identified:

Interface	Standard	Objective	Rationale
Battery ESS	IEC 62928 Onboard lithium-ion traction batteries	Definition of common interfaces to standardise ESU on-board to improve maintainability and reducing LCC	If modification of IEC 62928:2018 is selected, then a new chapter in the standard shall be added to describe these new interfaces If creation of a new standard (or a series with IEC 62928:2018-2), this new document shall include the content for interfaces requirements
Onboard fuel cell system	IEC 63341-1 Railway applications - Rolling stock - Fuel cell power system	Define common European requirements and performance of fuel cell power systems for all kind of rail vehicles running with hydrogen (HMU, locos and maintenance vehicles)	
Onboard hydrogen storage system	IEC 63341-2 Railway applications - Rolling stock - Compressed hydrogen storage system	Define common European requirements and performance of the CHSS for all kind of rail vehicles running with hydrogen (HMU, locos and	
	IEC 63341-3 Railway applications - Rolling stock - Test methods	Define common European test procedures for hydrogen components in all kind of rail vehicles running with hydrogen (HMU, locos and maintenance vehicles)	
Power converter	IEC 61287-1 Power converters installed on board rolling stock	Define service conditions, general characteristics and test methods of electronic power converteres onboard of rolling stock	No adoption with respect to trains with alternative drives required

Table 12: Standards for vehicle components related to alternative drives

The work in Task 1.1 is limited to the pre-standardisation of battery ESS interfaces.

5.5.1 Battery ESS

The following battery interfaces are identified:

- High voltage ESU interface
- Cooling interface
- Low-voltage ESU interface
- Communication interface
- ESS parameters

The pre-standardisation of these interfaces is the focus of this deliverable.

For clarification of the interfaces three introducing chapters are written on:

- The benefit of standardised interfaces for the stakeholders
- Definition of the ESS components and structure
- Examples of ESS component structure and enclosures

5.5.1.1 Benefit of Standardised Battery Interfaces

The standardisation of battery interfaces has a benefit for different areas and stakeholders:

- For operation /railway undertaking
- For maintenance / entity in charge of maintenance
- For battery exchange at the end of lifetime /vehicle owner and industry
- For second life battery usage

Benefits for operation / railway undertaking:

- Providing standardised information of the **battery status** (SOX, failure) for range calculation and train driver information
- Optimisation of **battery charging**

Benefit for maintenance / entity in charge of maintenance ECM 3 and 4 as well as vehicle revision

- **Fast exchange of ESUs** in case of damage -> plug and socket for power and control connection as well as quick coupling for cooling connection
- Providing **present and historical information** about the battery parameters in a standardised data format for
 - Battery status and failures
 - Data useful for predictive maintenance in case of deviation of battery parameters to prevent failures
 - Required maintenance activities
 - Estimation of remaining battery lifetime for estimation and scheduling of battery change (vehicle owner)
- **Storage and charging of ESU** as a spare part in the maintenance shop, e.g plugs for power, control and data connection as well as data format and structure

Benefit for battery exchange at the end of lifetime and second life battery usage /vehicle owner

and industry

- Low effort and cost for adoption of the new battery type to the vehicle class and interfaces, e.g. control interfaces as well as battery data and data communication format
- Low effort and cost for adoption of the vehicle interfaces to the new battery type
- No need for an updated certification, e.g. same safety information (control line)
- Possibility to use a battery of a newer generation (from the same battery supplier) or to change the battery supplier, if not existing any more or to allow competition for battery purchase
- Increasing number of same battery types for railway application with the same specification to reduce the purchasing costs
- Use of the battery for a second life application, e.g. for stabilisation of the power grid

5.5.1.2 Definition of the ESS Components and Structure

According to IEC 62928 Railway Applications – Rolling stock - Onboard Lithium-ion traction batteries the following ESS-components are defined:

Cell	<u>Secondary cell</u> where electrical energy is derived from reaction of lithium-ions or oxidation/reduction of lithium
Cell block	Group of cells connected together in parallel configuration with or without protective devices and monitoring circuitry. Not ready for use in application as <u>it is not fitted in a housing, and has no control device</u>
Battery pack/module	Energy storage device, which is comprised of one or more cells electrically connected. <u>It incorporates protective housing*</u> . It includes at least monitoring circuitry to provide information to a battery system
Battery branch	Group of battery packs/modules connected together with <u>voltage equal to that of the battery system</u> . The battery branch is the smallest electrically isolatable subsystem (by means of contactors, switchgears, circuit breakers, etc.). A battery branch may be contained in a single or multiple enclosures**.
Battery system	System which incorporates one or more cells, modules or battery packs, including BMS and BTMS, as well as disconnecting and/or isolating devices (contactors, disconnectors, fuses, etc.).
ESU	Physical system, which is comprised of an energy storage technology, especially lithium-ion traction battery system.
ESS	Physical system which consists of one or more ESUs and other equipment to connect to the DC-link (converters, control and monitoring system, inductors, protection devices, cooling

	systems...)
Battery box***	<p>Not defined in the IEC 62928 but mentioned as follows:</p> <p>The battery box is the unit in the battery system directly accessible by the user. The battery system can be separated in several battery boxes (mechanical enclosures). In some battery boxes cells need not to be included (e.g., separated BMS)</p>

Table 13: Wording of ESS components

*Protective housing: It is not specified if the housing has to fulfill any degree of protection according to IEC 60529. Could be understood as only some basic protection is required as the battery pack/module will be part of a battery branch that could be contained in a enclosure.

**Enclosure: It is not specified if the housing has to fulfill any degree of protection according to IEC 60529. It could be understood as a protection against access to hazardous parts, against solid foreign objects and protection against water is required.

***Battery box: mechanical enclosure

But it is mentioned in chapter 11.3 of IEC 62928 that “The degree of protection shall be selected from those defined in IEC 60529. IP requirement shall be fulfilled at least at the higher mechanical integration level, e.g. battery box, traction converter box including a part of battery system, etc.”.

Hierarchy of the Battery System

Battery system → Battery branch → Battery pack/module → Cell block → Cell

Functional configuration of the cell, cell block and battery pack/module are shown in the figure below (Figure 3 of IEC 62928):

- Some functions incorporate cells
- The monitoring circuit is mandatory for battery pack
- The control circuitry and protective devices may be included as optional functions.

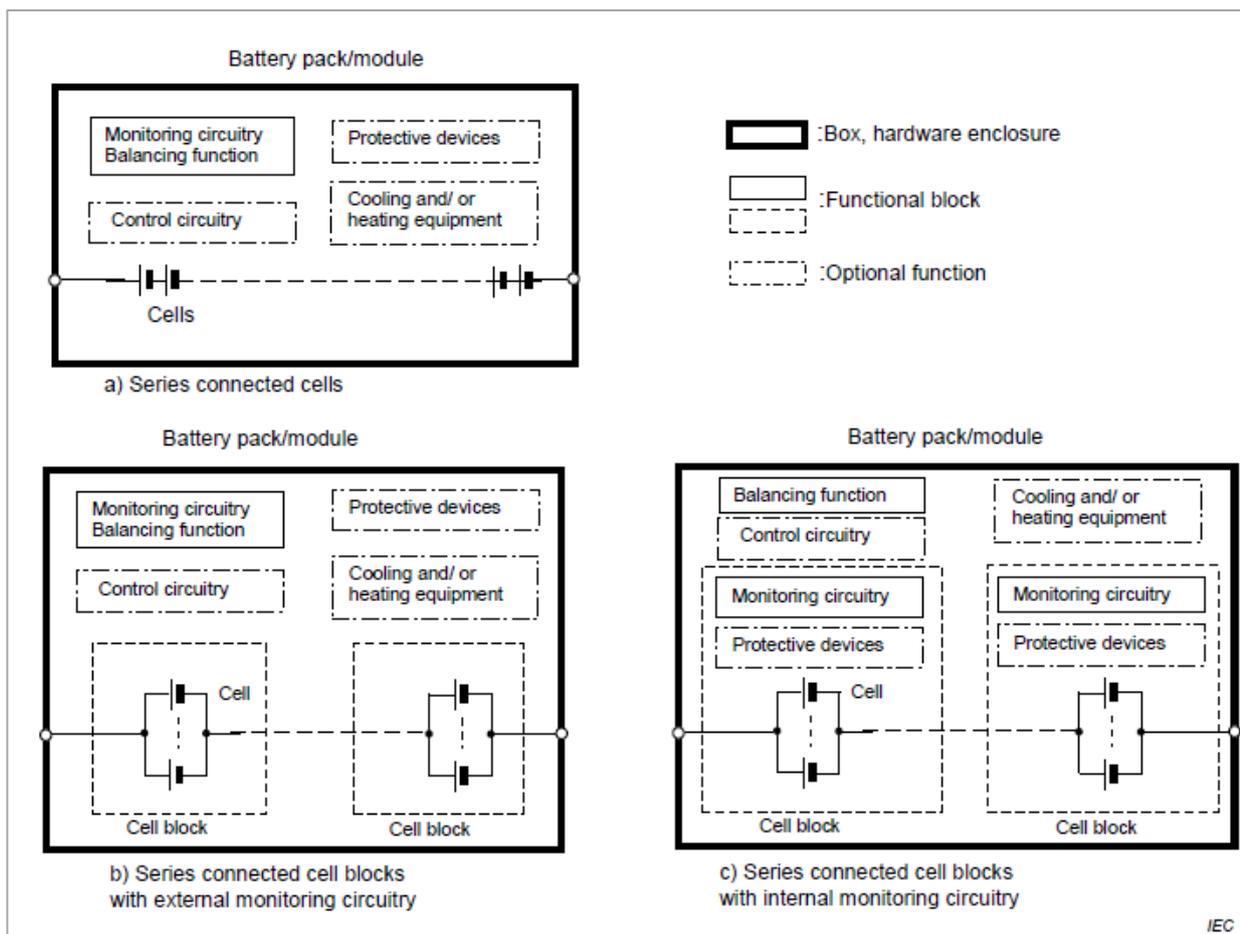


Figure 21: Illustration of definitions for cell, cell block and battery pack/module

Levels

Levels according to IEC 62864-1:2016. Railway applications – Rolling stock – Power supply with onboard energy storage system – Part 1: Series hybrid system (see figure below):

- Level 1: vehicle/system interface
- Level 2: system interface
- Level 3: Components (ESU converter, motors...)
- Level 4: Subcomponents (Lithium-ion battery, EDLC, etc. within ESU).

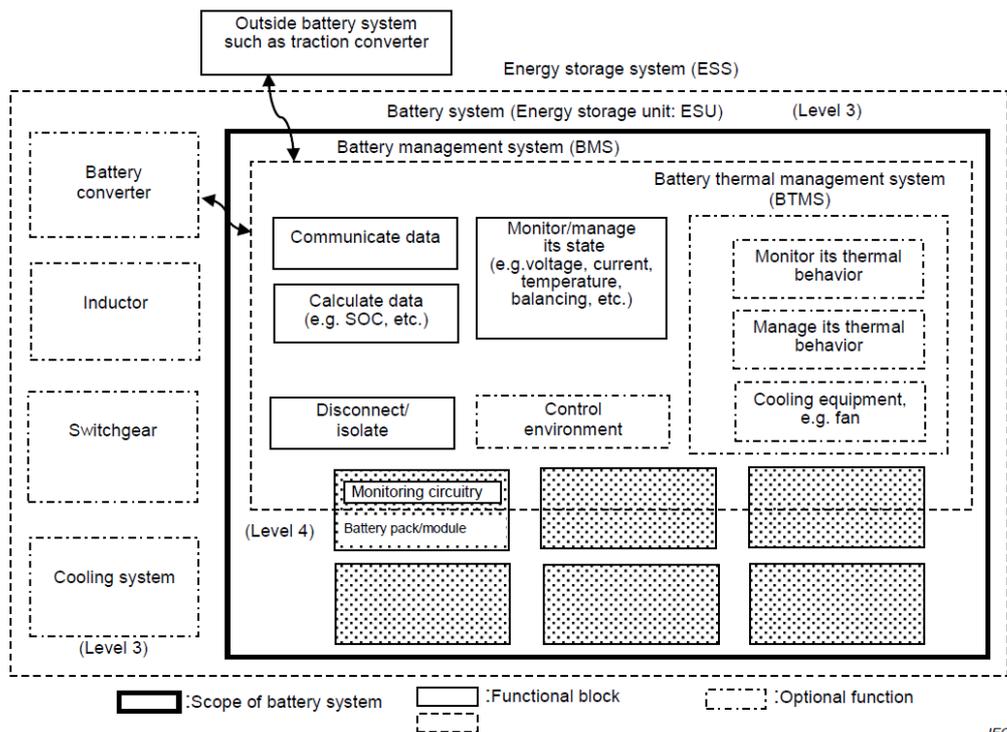


Figure 22: Functional block of battery system (source: IEC)

5.5.1.3 Examples of ESS Structure and Enclosures

There are different possibilities for integration of the ESS components into enclosures (see the following figures):

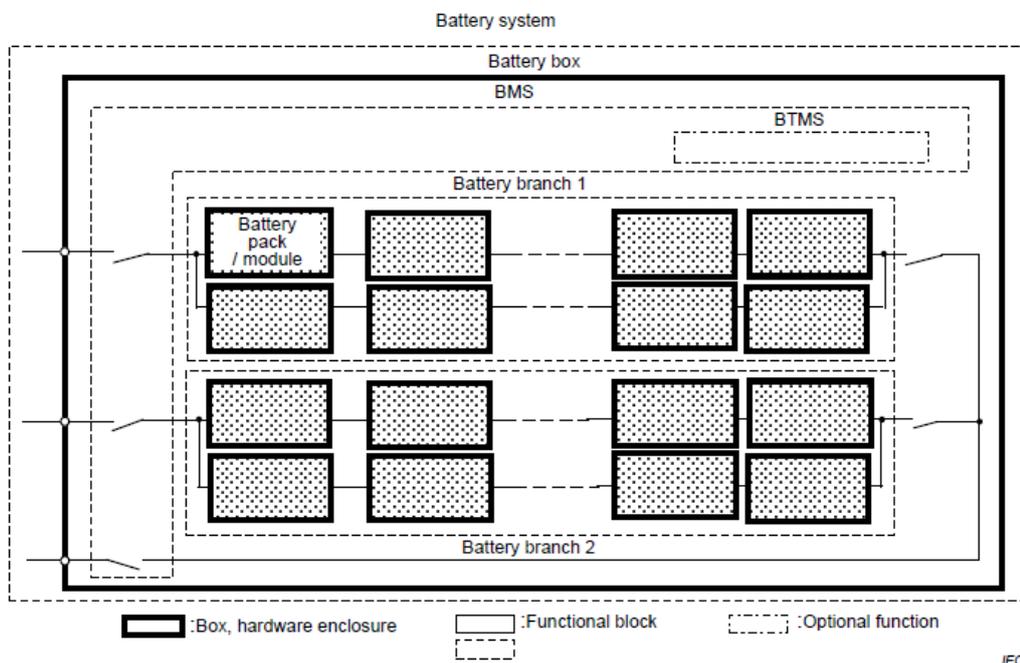


Figure 23: Example of configuration for conductor inside of the battery box

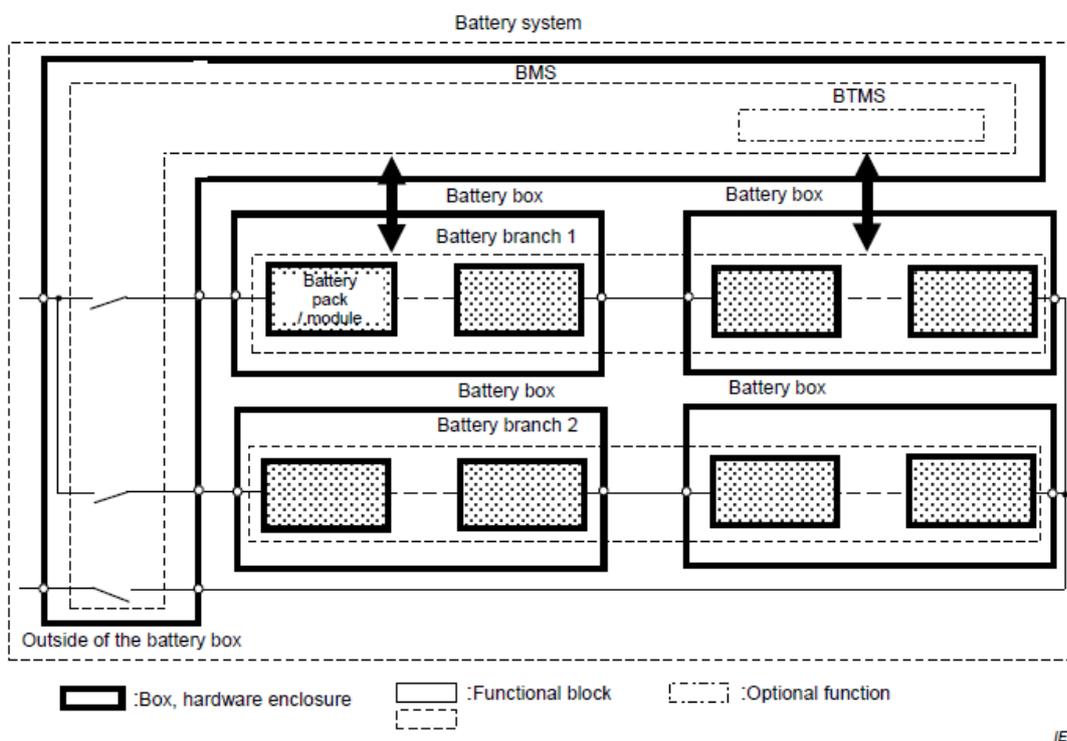


Figure 24: Example for series connected battery pack/ modules installed in separate boxes

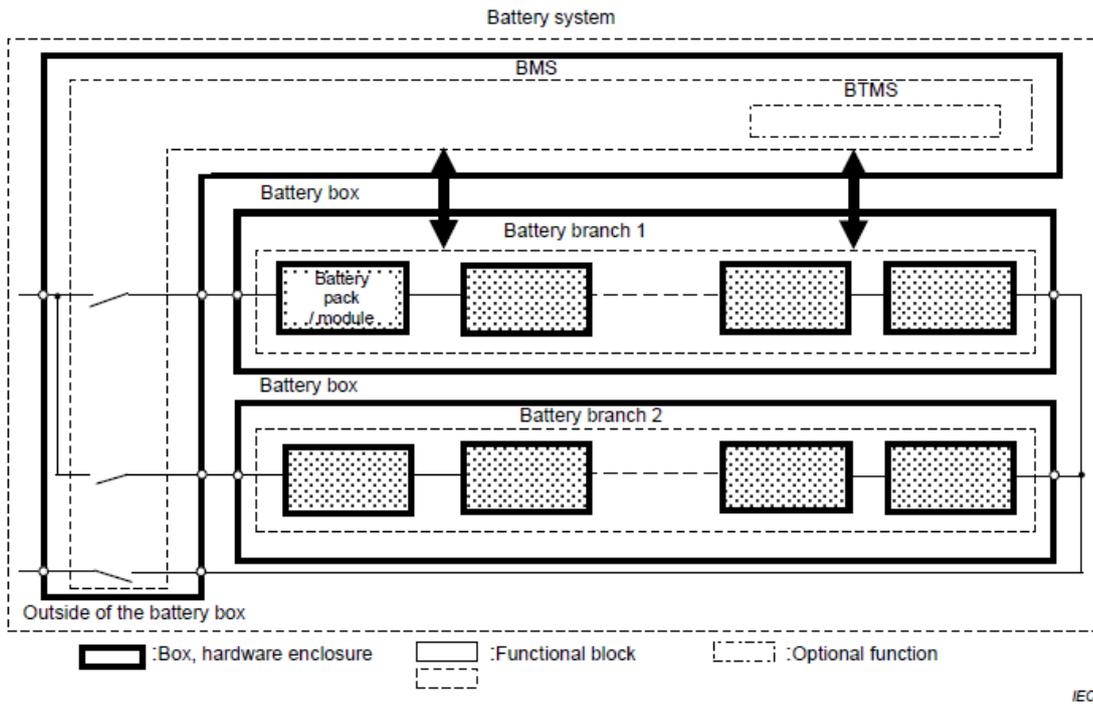


Figure 25: Example for series connected battery pack/ modules with each battery branch installed in separate boxes

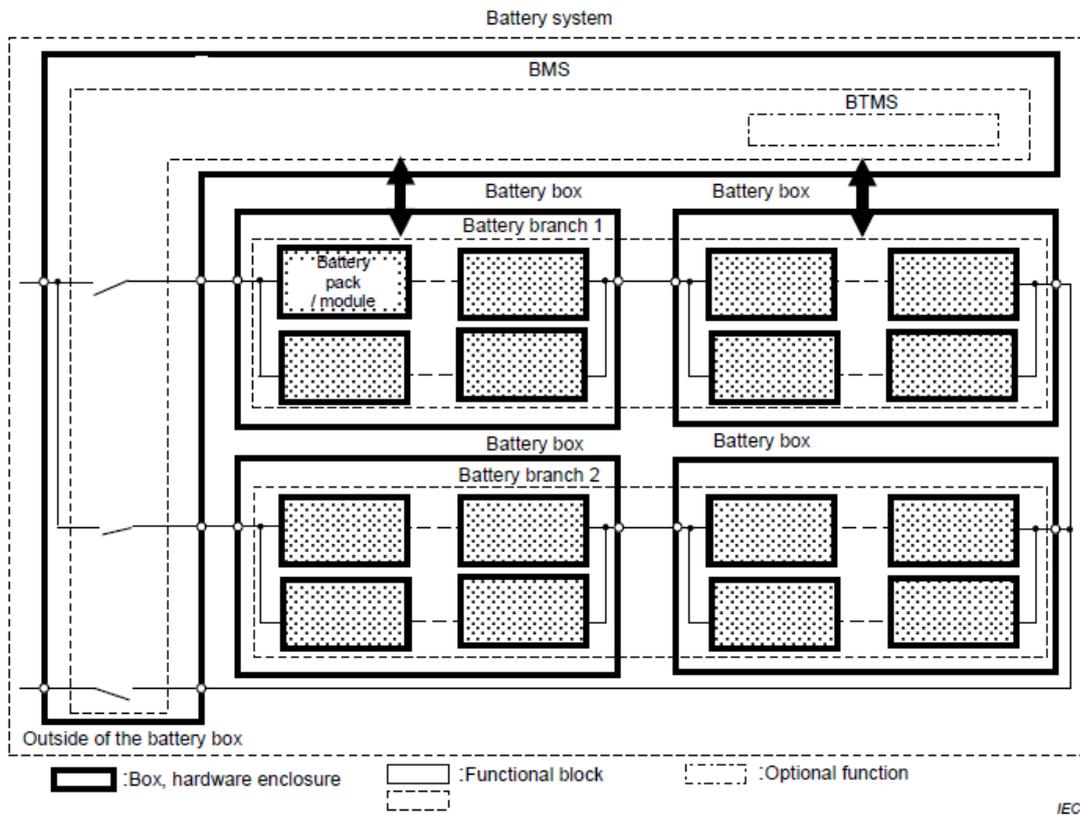


Figure : Example for parallel connected battery pack/ modules installed in separate boxes

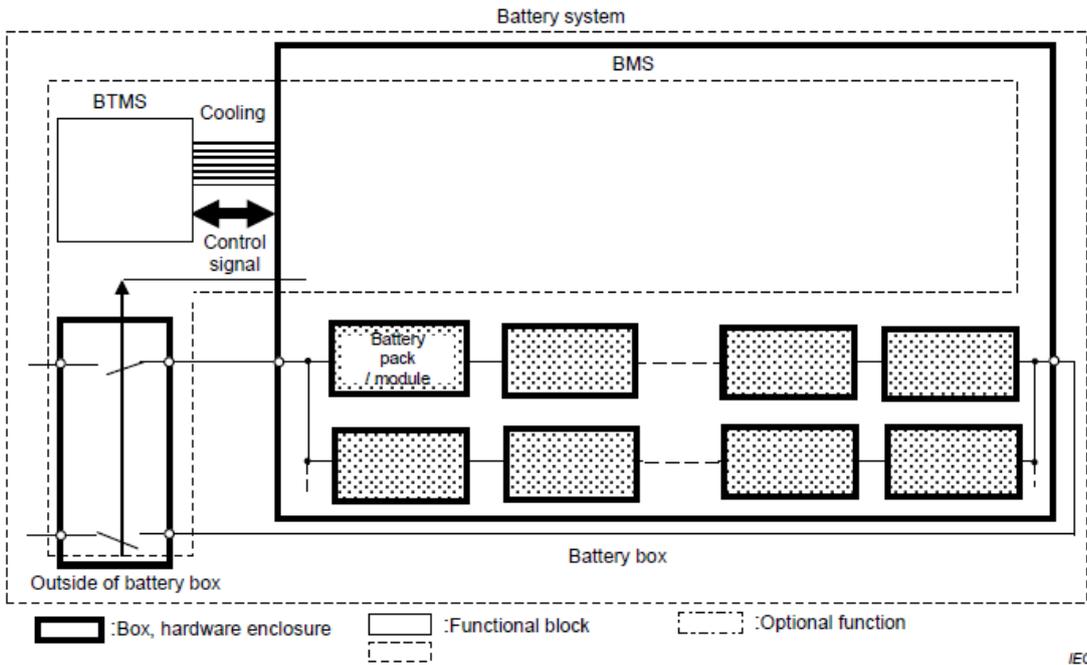


Figure 26: Example of configuration of a BTMS outside of battery box

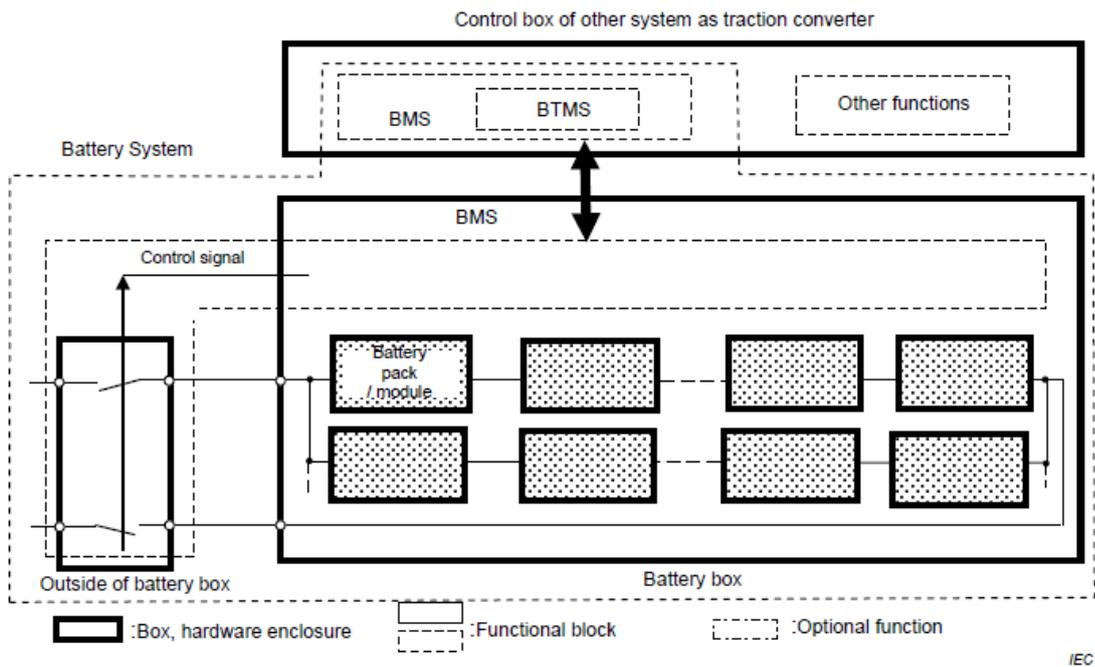


Figure 27: Example of configuration of a BMS and BTMS included in another system outside of battery box

5.5.1.4 High Voltage ESU Interface

State-of-the-art Interfaces

High voltage connection can be achieved by means of cable glands, cable entry frames, or plugs & sockets. None of the next scenarios will permit unplugging the ESU in charge. It should be guaranteed that the ESU is not in charge/discharge when being disconnected.

The connection via **cable glands** is a robust and compact system, very well known in railway. The screen of cables can be easily mounted. IP69 can be achieved. It is a standardized system for railway applications.



Figure 28: High voltage connection via cable glands

The connection via **entry frames** is an alternative solution vs cable gland. the screen of cables can be easily mounted. IP54 to IP68 can be achieved depending on manufacturer, model and technology. These systems require mounting experience to achieve good tightness.



Figure 29: High voltage connection via entry frames

The connection via **plugs & sockets** allows quick assembly and disassembly.

Connector can be coded to avoid voltage inversion connection.

If there is not good contact guaranteed inside the plug it can be a hot spot.

IP65 can be achieved.

If IP20 for plugs is selected there is a lower risk of electrocution if the connection is done with presence of voltage in the cables. Typically, rectangular connectors, HARTING HAN family with double pole or similar from other brands can be used. Also available single pole circular connectors.

For plug and socket connections, standard connectors are used to output the + and – Battery power. Both polarities are grouped inside one connector with 1000V and 300 A capabilities. This

connector must be selected to avoid any voltage inversion during plugging. The figure below presents an example of Harting Connector.



Figure 30: High voltage connection via plug & socket

Plug & socket is the only solution that allows a fast exchange of the ESU for maintenance.

Future Interfaces

The different solutions for high voltage connections are discussed in working groups. The following results are achieved and agreed with the WP-partners:

- Plug and socket is the preferred solution from industry and operators to reduce the time for
 - ESU change in the maintenance shop and to maintain the ESU spare part (Charging about every 6 months).
 - to maintain the ESU spare part (Charging about every 6 months).
- Screwed connections of the whole ESS can be accepted since it is not changed for maintenance
- The standardisation of one certain plug type for the ESU is not desired to prevent the dependence on one supplier (Lessons learned from "Mennekes-desaster" in automotive-industry) and the standardisation is not necessary since ESUs of different suppliers are not exchanged
- A European standard for the requirements of plugs and sockets incl. type tests is desired. There is only an old existing French standard
- Pilot contacts are not required, since the plugs are only disconnected when the voltage is turned off. Pilot contacts make only a sense for plugs that are disconnected frequently like shore power supply plugs. Further, they increase the complexity and reduce the availability.

5.5.1.5 Cooling Interface

State-of-the-art Interfaces

Most of the battery packs are water cooled. So, in addition to the electrical connector, some hydraulic interface are present for each kind of packs.

If liquid cooling is mandatory to cool down an ESU, liquid interface can be made by means of quick couplings or by means of hydraulic fittings. In any case, it must be ensured that the hydraulic system to the ESS can be completely shut off to prevent leaks.

The size of **quick couplings** will depend on liquid flow and operating pressure.



Figure 31: Example of quick couplings of different size

To realize the function water must go in and out, so two hydraulic interfaces are needed and usually they are realized with quick lock connectors, coming from supplier like Stäubli (see example below).

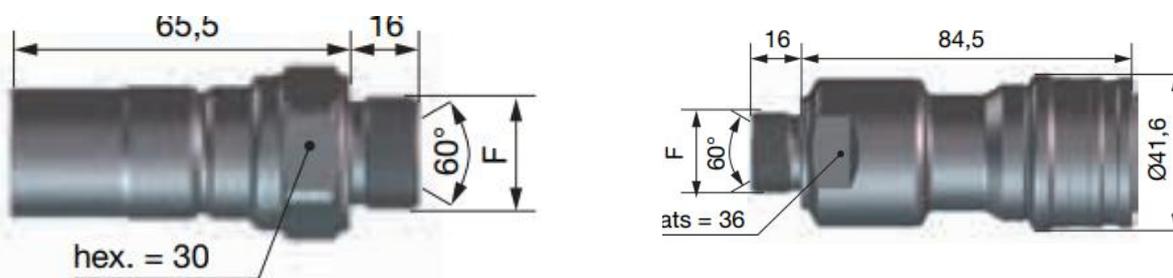


Figure 32: Example of hydraulic interface (Stäubli male SPT12.7154/L/CG and female SPT12.1154/L/JS3/CG)

Hydraulic fittings should be leak-proof to prevent leakage when replacing an ESU. Connection thread dimension in inches.

Future Interfaces

The following results are achieved and agreed with the WP-partners:

- For a long battery life, the batteries should be operated within a moderate temperature range. This is the task of the Battery Thermal Management System (BTMS).

- For the connection between the BTMS and the ESUs hydraulic hoses and hydraulic plugs are required.
- Operators prefer quick couplings for fast change of the ESU and avoid leakages when the cooling connection is disconnected
- Care must be taken for choosing coupling supplier with high quality especially with respect to leakages
- The standardization of the coupling type is not desired to prevent the dependence on one supplier and is not necessary since ESUs of different suppliers are not exchanged
- Imperial thread (in inches) is typically for liquid connectors and preferred instead of metric thread
- The standardization of the thread size seems to be complicated since the size depends on the required flow rate of the ESU
- Electrical pre-heating from external energy sources is not necessary for traction batteries that are heated by the BTMS.
- An electrical pre-heating system supplied by the internal battery might be used but does not require a standardisation of an interfaces because it is an internal interface.

5.5.1.6 Low Voltage ESU Interface

The low voltage interface of the ESU is required for safety relevant signals and for communication between ESU and BMS

State-of-the-art Interfaces

It is recommended that LV cabling is splitted according to characteristics of the signals. Low voltage values of 24Vdc & 110Vdc are used. Digital input and output signals can be installed in the same connector as LV DC power supply.

Typically, HARTING brand, HAN product family or similar from other brands can be used. Also available as circular connectors like those from ITT. All of them permit modular configuration of the pins.



Figure 33: Example of low voltage connections

The low voltage connectors are usually designed to carry LV signals and network signals.

The LV signals for the battery packs are usually on 24V level. In the case that the auxiliary battery of the train has a voltage of 110V, a 110V/24 dc/dc converter is required.

For LV connection usually standard railways connectors are used, e.g. from Harting which can manage LV signals and CAN message signals inside the same connector thanks to the modular approach (see figure below).

For CAN communication, a dedicated connector called “MEGABIT” is used to ensure “circular” shielding (see figure below)



Figure 34: HARTING Megabit connector for CAN communication

Future Interface:

The following results are achieved and agreed with the WP-partners:

- Plug and socket for the low-voltage interface is the preferred solution to reduce the time for ESU change in the maintenance shop
- The standardisation of the low-voltage plug is not desired to prevent the dependence on one supplier and is not necessary since ESUs of different suppliers are not exchanged

- For safety-related control functions some conventional electrical control lines are required for the notification of critical conditions of the ESU to the BMS, e.g.
 - Fire alarm
 - Error signal
- State-of-the-art low voltage supply of the BMS is 24V due to the available (automotive) components on the market. There is no intention to change it.
- The common low-voltage supply voltage of 24V and the safety-relevant signals should be integrated into the standard IEC 62928 “Onboard lithium-ion traction batteries”

5.5.1.7 Communication Interfaces

Two kinds of communication networks are required (see figure below):

- Communication within the ESS, e.g. between the master BMS and BMS of the ES
- Communication between the ESS and the vehicle / TCMS (train control and monitoring system).

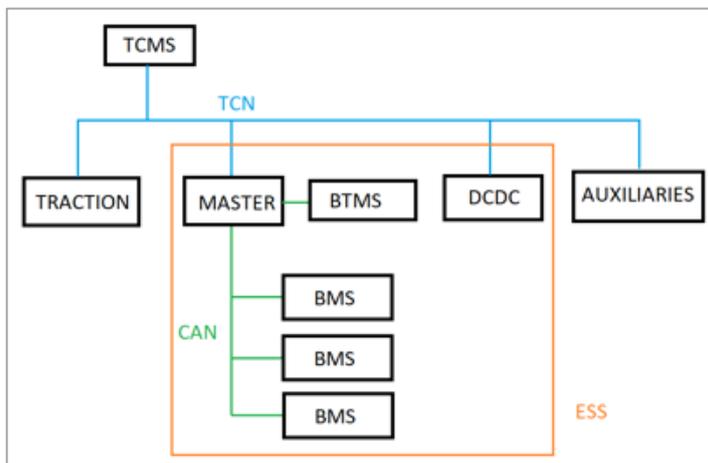


Figure 35: ESS internal and external communication

State-of-the-art Interfaces

- For BMS-internal communication most battery suppliers and vehicle integrators use CAN communication
- For communication between ESS and vehicles most vehicle suppliers use the TCN (Train control network)

Future Interfaces

The preferred solution agreed with the WP-partners:

- For BMS-internal communication: CAN bus (CAN OPEN Protocol) since it is safer than IP-communication
- For communication between ESS and vehicles: TCN (train control network)

Both physical communication networks are already standardized:

- ISO 11898-1 for CAN
- EN 61375-1 & 3 for TCN

5.5.1.8 ESS Parameters

Many ESS parameters are measured by the Battery Management System (BMS) and transmitted to the TCMS via the Train Communication Network (TCN). TCMS provides the relevant information to the respective users (Train driver, maintenance personnel, etc.)

In special cases (Maintenance and Troubleshooting) a special Diagnosis Interface may be used

Stakeholders for the ESS information are:

- Train driver
- Train operator (ECM 3)
- Entity in Charge of Maintenance (ECM 4)
- Train dispatcher
- Train Control and Management System (TCMS)
- Battery supplier

The definition and standardisation of the parameters is very important since they are used by many stakeholders.

For every parameter the following values should be defined:

- Unit
- Tolerance
- Sample rate
- User (destination stakeholder)
- Necessity

To avoid different definition the basis for defining the parameters shall be the definition in the European battery regulation (pass, 2025).

The preferred standard for standardisation of the ESS parameters is the IEC 62928: 2017 (Onboard lithium-ion traction batteries).

The following table contains the first draft of a parameter list:

ESS Parameter	Unit	Tolerance	Sample rate	Corresponding / related Data Attribute(s) from European Battery Passport
SoC	%	±1%	10 sec	State of Charge
SoH	%	±1%	daily	<ul style="list-style-type: none"> • Remaining Capacity • Expected lifetime in calendar years • Expected Lifetime: Number of charge-discharge cycles
SoE	%	±1%	10 sec	-
SoP (State of Power)	%	±1%	10 sec	Remaining power capability
ESU Current	A	±5%	1 sec	-
Temperature	°C	±1		-

<ul style="list-style-type: none"> • Pack Avg. Temp • Pack Cell Max. Temp • Pack Cell Min Temp 				
Cell Voltages (for each Cell-Module, including location) <ul style="list-style-type: none"> • Max. Cell Voltage • Min. Cell Voltage • Avg. Cell Voltage 	mV	±1	60 sec	-
Insulation Resistance <ul style="list-style-type: none"> • HV+ to Chassis • HV- to Chassis 	kΩ	±10%	Once when ESU is switched on	-
Cumulated charged and discharged ESU Energy	kWh	±5%	60 sec	Energy throughput
Status, Error and Warning Messages	-	-	Depending on specific message and criticality	

Table 14: Draft list of ESS parameters

5.5.2 On-board Fuel Cell

The activities towards a new standard on on-board fuel cell systems are being held in the frame of IEC Technical Committee 9 “Electrical equipment and systems for railways”.

More specifically, the standard in progress is IEC 63341-1 RAILWAY APPLICATIONS – ROLLING STOCK – FUEL CELL SYSTEMS FOR PROPULSION -PART 1: FUEL CELL POWER SYSTEM.

This standard applies to Fuel Cell Systems for traction and auxiliaries purpose used on rolling stock. The standard applies to any rolling stock types (e.g. light rail vehicles, tramways, streetcars, metros, commuter trains, regional trains, high speed trains, locomotives, etc).

The standard focuses on:

- The scope of supply and the description of the interfaces (fluidic, electrical and mechanical),
- The description of environmental conditions,
- The design requirements and the functional requirements to ensure the fuel cell system compliancy with a railway application,
- The definition of the standardization process to validate the fuel cell system capacity required for a specific mission profile,
- The safety and protection requirement to design and install a fuel cell system for railway applications,
- The protection of persons and the environment inside and outside the vehicle against hydrogen related hazards,
- The marking and labelling requirements,
- The requirements related to storage, transportation, installation and maintenance,
- The tests (type and routine) to validate the fuel cell system.

5.5.3 Onboard Hydrogen Storage System (HSS)

The activities towards a new standard on on-board hydrogen storage systems are being held in the frame of IEC Technical Committee 9 “Electrical equipment and systems for railways”.

More specifically, the standard in progress is IEC 63341-2 RAILWAY APPLICATIONS – ROLLING STOCK – FUEL CELL SYSTEMS FOR PROPULSION -PART 2: HYDROGEN STORAGE SYSTEM

This standard applies to Compressed Hydrogen Storage Systems (CHSS) installed onboard rolling stock for railway applications. The CHSS is used to supply the Fuel Cells for the traction power and the auxiliaries supply of railway vehicles as defined in IEC 62864-1. This standard applies to storage for hydrogen in gaseous form, being the technology currently used for land transport vehicles. Therefore, liquid hydrogen storage systems are not treated in the present revision of the standard. The standard applies to any rolling stock type (e.g. light rail vehicles, tramways, streetcars, metros, commuter trains, regional trains, high speed trains, locomotives, etc.). This standard addresses also the mechanical, fluidic, and electrical interfaces between On-board CHSS and Refuelling Station. Nevertheless, this standard does not specify Refuelling Station itself nor the Refuelling Protocol, that are specified in other standards such as ISO 19880-1 or future one for Railway applications.

5.5.4 Onboard Converters

All the Power electronic converters on board of rolling stock shall comply the Standard IEC 61287. This standard defines the service conditions, general characteristics and test to be performed. This standard is applicable to power electronic converters mounted on board supplying traction circuits (including converter for BEMUs).

See below a summary of main requirements for these converters:

- All the converters on board for railways applications shall comply with the standard IEC 62498-1 (altitude, temperature, and other environmental conditions),
- Converters can generate perturbances in telecommunications and radio systems. All the requirements established in the standard IEC 62236-3-2 (electromagnetic compatibility- Rolling Stock) are applicable and shall be complied,
- All the components of the converter shall be tested according to the following standards:
 - Power semiconductor devices. IEC 60747,
 - Electronic control and components with low current. IEC 60571,
 - Semiconductors control unit. IEC 61287-1 and IEC 60571,
 - Power transformers and inductance coils. IEC 60310,
 - Power electronics capacitors. IEC 61881 and IEC 60384-4,
 - Power resistors. IEC 60322.
- In the main components of the converters a partial discharge test shall be performed according with the IEC 60270 standard,
- In all the converters dielectric test, cooling system test and mechanical protection listed in IEC 61287 standard shall be performed,
- For each type of converter, a list of tests listed in the standard IEC 61287 shall be performed (for instance commutation test).

These standards must be applied for the converters in trains with alternative drives. Discussions are ongoing to define if the standard for power electronics converter should be modified or amended with respect to BEMUs, HMUs/HEMUs and any other type of alternative drive trains, such as heavy rail vehicles.

T

6 Smart Energy Management

Leader: SNCF; Contributors: CAF, CEIT, DB, FSI, PKP, TRV, SMO

6.1 State of the Art of Energy Management Functions

On the way to improve alternative drive trains with higher range in operation and with better energy efficiency, reducing the cost in operation, the management of energy is the key. These functions of energy management can be various, impacting traction system, auxiliary loads, or other equipment. So, the proposal is to start by a state of the art of energy management functions. To do this activity, a first look on previous studies on this topic, such as Shift2Rail PINTA3 WP3 report (Mannnevy, 2022). Also, in a common activity with Rail4EARTH WP5, the collaboration allows to make a state of the art of energy management functions impacting alternative drive trains.

6.1.1 Energy Management Functions in S2R PINTA3 WP3

In the 1st European railway R&D program S2R, PINTA is a project from Innovation Pillar 1 focusing on traction system improvements, as well as brakes and Heating Ventilation Air Conditioning (HVAC). The project has the main objectives to demonstrate innovative solutions to offer on the market. These new systems will contribute to improve main Key Performance Indicators (KPI) defines in the project, such as energy efficiency, noise reduction, reduction of volume / weight, etc. to obtain a better Life Cycle Cost (LCC) at traction, braking and HVAC level first, but also a train level.

In 2019-2020, the context in Europe and for rail sector to shift diesel trains to low carbon emission technologies, had enforced the PINTA3 project to be involved on the topic of decarbonization. Therefore, a new Work Package (WP), WP3, has been created with the objective to build a first roadmap on carbon free mobility for railway.

Vehicle energy management system (VEMS¹) was defined as following in the report “The energy management system is the control unit that organically coordinates the on-board energy sources to satisfy the power demand of the vehicle. An efficient Energy Management Strategy should ensure an optimal power split between the different energy sources, but it might also perform adequately in real-time, respect the specific operation constraints of each power source, and be robust enough against unexpected driving cycle variations.” This definition is focusing on the energy management for traction. So, it is not covering the whole scope of energy management at vehicle level, including traction of course, but also auxiliary loads.

In the S2R PINTA3 WP3 report (Mannnevy, 2022), the energy management strategies (for traction) were classified in 3 categories:

- Rule-based (RB)
- Optimization-based (OB)
- Learning-based (LB)

The figure bellow shows the main differentiation of these strategies:

¹ Vehicle energy management system (VEMS) is used to avoid confusion with EMS, already used for Energy Measurement system in standardisation.

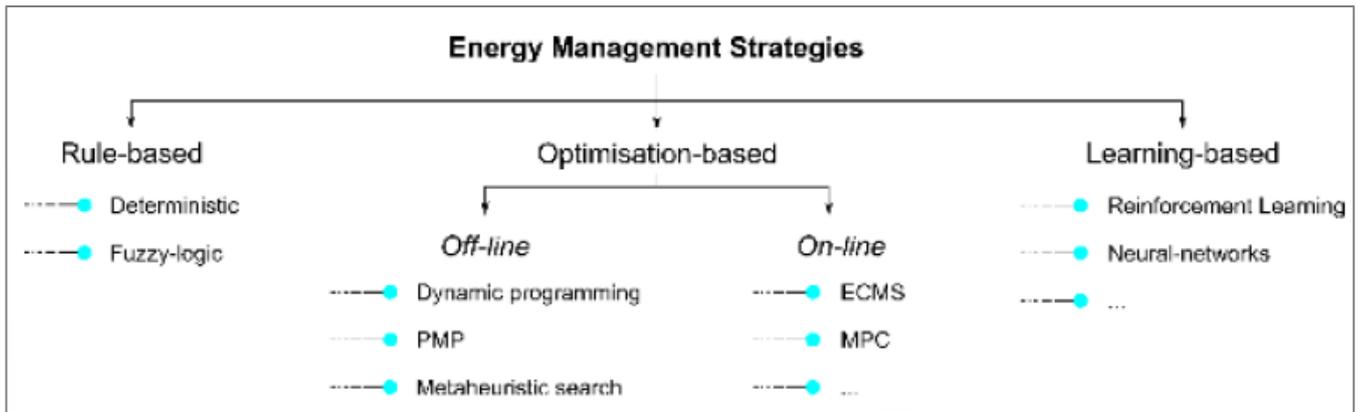


Figure 36: Classification of Energy Management Strategies according to S2R PINTA3 WP3

Some energy management strategies may have different sub-strategy. The table hereafter resumes these different sub-strategies:

RB energy management	CPF-1 Strategy	Conventional Power Follower with fuel cell power constant
RB energy management	CPF-2 Strategy	Conventional Power Follower with fuel cell power stop if bellow fuel cell reference power
RB energy management	SOC-AD Strategy	SOC Adaptive by changing fuel cell operational point according to the SoC of the battery
RB energy management	D-AD Stratgy	Demand Adaptive by adapting fuel cell reference to average demand value on different line sections
OB energy management	GA-SOC-AD S1(mh2 low)	Genetic Algorithm for SoC Adaptive and multi-objective optimization → Low hydrogen consumption
OB energy management	GA-SOC-AD S1(DoD low)	Genetic Algorithm for SoC Adaptive and multi-objective optimization → Low ESS DoD
OB energy management	GA-SOC-AD S1(Δ PFC low)	Genetic Algorithm for SoC Adaptive and multi-objective optimization → Low fuel cell power variation
OB energy management	GA-D-AD S1(mh2 low)	Genetic Algorithm for Demand Adaptive and multi-objective optimization → Low hydrogen consumption
OB energy management	GA-D-AD S1(DoD low)	Genetic Algorithm for Demand Adaptive and multi-objective optimization → Low ESS DoD
OB energy management	GA-D-AD S1(Δ PFC low)	Genetic Algorithm for Demand Adaptive and multi-objective optimization → Low fuel cell power variation oriented
OB energy management	DP Strategy	Dynamic Programming
LB energy management	ANFIS Strategy	Adaptive Neuro Fuzzy Inference System

Table 15: List of energy management strategies evaluated in S2R PINTA3 WP3

These different strategies were evaluated on case of study of a hybrid hydrogen/battery train on the railway line between Tardienta and Canfranc (Spain).

For each strategy, an analysis and a comparison based on:

- Hydrogen fuel consumption,
- DoD of the batteries (related to battery lifetime),
- Average power variation of the fuel cell (related to fuel cell lifetime),
- Robustness (represents the ability of the strategy to adequately work when the drive cycle changes),
- Real-time implementation (represents the ease to deploy the strategy in the real application).

With the aim to ease the analysis, mH₂, DOD and Δ PFC values have been normalized and rounded to integer values between 1-5 in relation to the maximum and minimum values obtained in all the strategies. Therefore, the values represent the capability of the strategies to save hydrogen, increase the battery life, and increase the FC life. The following figure shows the comparison results of each strategy.

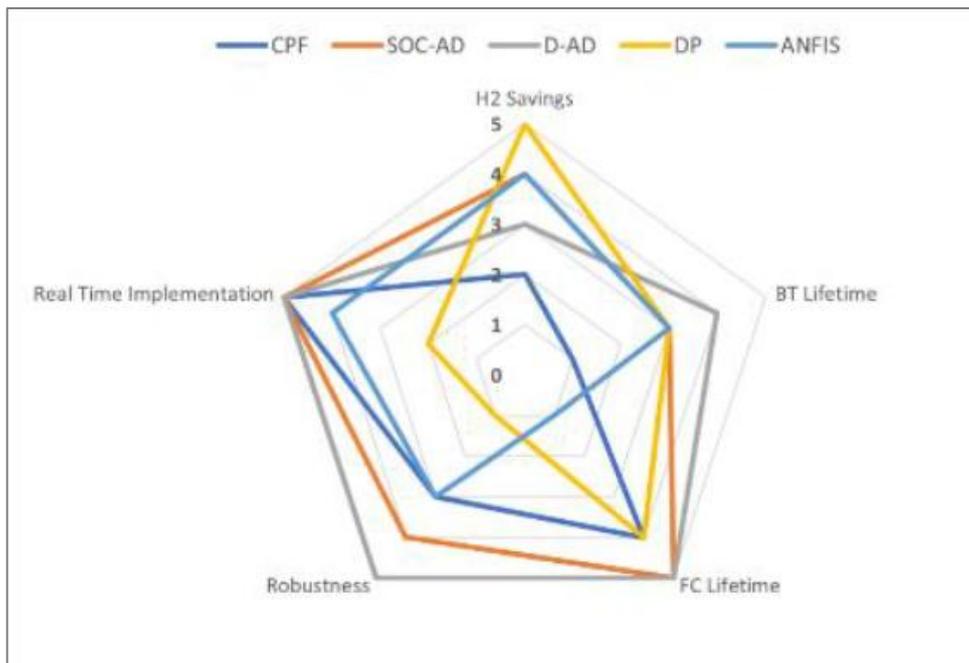


Figure 37: Comparison results of energy management strategies for traction hybrid hydrogen/battery train

Focusing on the hydrogen consumption, the best solution is obtained by the DP optimization. Then, appropriate approximations are obtained with ANFIS, and all the solutions related to the SOC-AD strategy.

Regarding the battery life, D-AD strategy (in all its variations) is the strategy with the best performance. The SOC-AD strategy optimized to reduce the DOD also gets a good performance in this indicator, getting close to some of the solutions of D-AD. DP and ANFIS strategies also obtain a relatively high DOD, even if they obtain a better result than the CPF strategy, which is the one with the highest DOD.

The parameter related to the FC Life is relatively high with all the strategies, except in the ANFIS case. Similar values are obtained in DP, SOC-AD and D-AD approaches, which seem that they adequately ensure a soft FC operation. Logically, the best result is obtained in the CPF approach

without variations in the FC reference value.

Regarding the robustness of the strategies, the most robust approach is found to be the D-AD (with all its variations). The cause is that this is the strategy that ensures the lowest discharge of the battery, and thus the risk of running out of battery energy is lower than in the rest of cases. In the SOC-AD strategy, a good robustness is also obtained, since the FC operation point is adapted depending on the battery SOC.

Finally, all the RB strategies show an appropriate capability to be implemented in real time, as well as the optimized GA-SOC-AD and GA-D-AD strategies (since the optimized values are some of the parameters of the rules). The ANFIS controller can be also adequately implemented in real time, but it requires a much higher computational burden.

As it can be seen in the table SOC-AD and D-AD strategies, after their optimization, can obtain better results than the Conventional Power strategies. Also, its implementation is easier than Dynamic Programming or Learning based strategies. Considering that there is no strategy better than others in all the fields, vehicle characteristics and the working profile must be analyzed before taking a final decision about what strategy should be implemented.

6.1.2 Energy Management Functions in ERJU RAIL4EARTH WP5 (on-board)

As explained before, the collaboration with RAIL4EARTH WP5 team to define and classify energy management functions to apply on battery trains (WP5 is focusing only on the vehicle side and the BEMU technology). These functions will support the improvement of battery trains performance in terms of range in operation and energy efficiency. State of the art listed the following functions for rolling stock:

No	Energy Function
1	Eco-parking mode
2	Preconditioning of passenger compartment
3	Preconditioning of battery
4	BEMU charging
5	Driver advisory system
6	Shore parking energy supply
7	Lift & drop of pantograph
8	ESS protection and diagnostics
9	Train driver information
10	Peak-shaving
11	Optimized regenerative braking

Table 16: List of energy management functions defined in RAIL4EARTH WP1 & WP5

Detailed descriptions of these functions are given in the deliverable D5.2 (Fernandez, 2023). The definition of each energy management function with a description of the function, a block-diagram to visually identify the interfaces of the energy management function. Then, a list of requirements will be proposed and impacts on standardisation and regulations will be estimated.

6.1.2.1 Eco Parking

Description:

Eco-parking mode (or eco-stabling mode) is a train mode when vehicle is at standstill. Generally, after a duration of several minutes (e.g. 30 min), this mode is activated to reduce the energy consumption of the rolling stock. This train mode is linked with different on-board subsystems to change the control. Typical components on board are impacted:

- HVAC system (e.g. temperature target is removed, and temperature window is active)
- Traction system (e.g. switch-off traction auxiliary components or activation of passive control on power electronics converter)
- Auxiliary loads (e.g. Lights reducing performance, low-voltage battery charging, safety components, etc.)
- Door's status, to avoid energy losses due to open doors during parking.

Eco-parking can be activated / de-active manually (by the train driver), remotely or automatically.

In case of extreme weather conditions, some subsystems regulations might be different to manage. From a system vision, infrastructure manager might require reducing the current level at standstill to ensure overall energy distribution or protect the infrastructure. For alternative drive trains, eco-parking mode is a main energy function to obtain low energy consumption during parking phase. The Eco-parking mode is mandatory when the train is parked on non-electrified line sections when there is no energy supply or a shore supply with limited power (see energy function "Shore supply"). As the energy source is on-board (traction batteries for battery trains or fuel-cell and hydrogen storage system for hydrogen trains), special regulation can be used to optimize the energy consumption. Especially, a limitation might be defined to avoid "too low energy capacity on-board" and therefore, automatically stop the eco-parking mode and switch-off completely the vehicle.

NB: similar limitation can be also introduced for other train modes such as pre-conditioning.

Block-diagram:

The eco-parking mode has a link with several systems on-board and on-ground. Interfaces parameters with infrastructure is necessary if energy systemic management is expected. It allows to check voltage system type (depending of voltage types, different line current limitation can apply) and monitor vehicle line current to confirm the demanding limitation of the infrastructure manager.

On vehicle level, most of the interfaces are with the train control and monitoring system (TCMS), to manage at first the eco-parking function activation/deactivation. While mainly, the interfaces will be through the TCMS to activate/deactivate the economic mode of subsystem, such as traction system, HVAC and Passenger Information System (PIS).

Concerning alternative drive vehicles, eco-parking mode activation can be in interface with battery management system (BMS) or Monitoring and Control System for the fuel cell power pack (MCS-H2) to supervise the remaining energy on-board. This ensures to avoid too high energy consumption during the parking phase, potentially impacting the next service of the train.

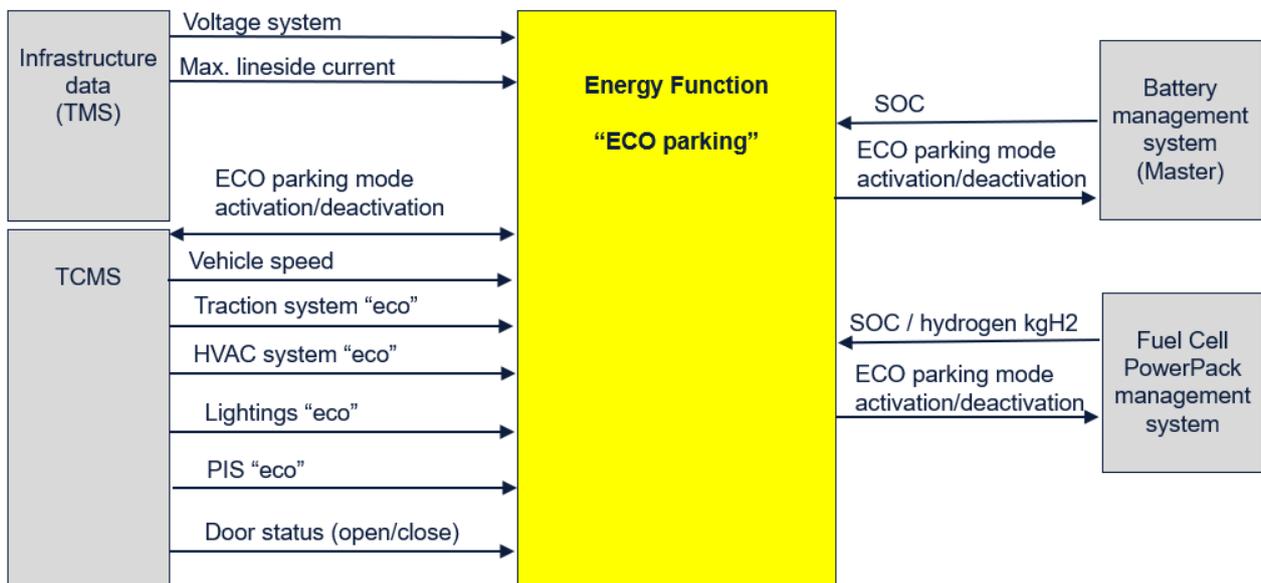


Figure 38: Eco-parking function block-diagram

Requirements:

Topic	Classification *	Requirement	Rationale
General	RE	When the train is parked, an energy saving mode (Eco-parking mode) should be activated. This mode should cover the following functions: <ul style="list-style-type: none"> - Activation of the eco-parking mode - Switching-off the HVAC system or enlarging the temperature regulation band - Switching-off auxiliaries loads that are not required for parking 	<ul style="list-style-type: none"> - Minimising the unloading of the battery - Minimising the power when the train is supplied by external shore supply (limited power) - Saving energy
General	RE	At the end of the parking mode, when the train journey starts with passengers the desired comfort parameters for passenger operation should be reached	
Activation	RE	Three modes for activation and de-activation of the eco-parking mode have to be foreseen: <ul style="list-style-type: none"> - Manual by the train driver - Remote - Automatic 	
Automatic mode	RE	In the automatic mode the eco-parking mode should be activated when the train is parked without passengers. This function is mandatory for automatic train operation (ATO). The mode should be de-activated when the preparation of the vehicle for passenger operation starts (a view minutes before the doors are opened for the passengers).	
HVAC	OR	Under defined ambient temperature conditions, the HVAC system should be turned off when the eco-parking mode is activated. The HVAC should be turned on a certain optimized time before the passenger operation starts (pre-conditioning mode). The time should be calculated by the energy management system depending on the environmental conditions to reach the required temperature when the train starts.	The HVAC has high no-load power (compressor, fan)
HVAC	OR	At extreme weather conditions (very low or very high temperature) the HVAC should not be turned off and should kept on during parking. But in this case the reference temperature should be enlarged (lower value for cold outside temperature and higher value for hot outside temperature).	
Auxiliary loads	RE	During parking the following auxiliary loads should be switched off: <ul style="list-style-type: none"> - WiFi system for the passengers - Saloon lights - Traction system (especially converter and transformer cooling and traction control) - HVAC of the driver cabin 	
Auxiliary loads	RE	The auxiliary loads should be turned-on when the eco-parking mode is de-activated. Only the HVAC system of the driver cabin should be activated in advance (during the pre-heating mode)	

Table 17: Requirements list for "Eco-parking" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
ISO 19659-3 “Railway applications - Heating, ventilation and air conditioning systems for rolling stock - Part 3: Energy efficiency”	Proposal has the goal to improve energy efficiency by standardizing energy management functions of HVAC and oriented the design of HVAC for alternative drive trains.	Current revision do not consider energy management functions related to HVAC, and also do not consider alternative drive trains special features.	Train mode: - Clarify the existence of eco parking mode inside the HVAC when train is in « parking mode » - Add the topic of train with alternative drive technology, with limited energy on-board and therefore, could impacting the way to proceed pre-conditioning New section « energy management functions of HVAC »: - Description of energy management functions (long stop eco, short stop eco, etc.) - Requirements on interfaces? Performance? Assessment methods: - Add rules to validate energy management functions

Table 18: Suggestion of standard evolution related to "Eco-parking" energy management function

6.1.2.2 Vehicle’s Preconditioning

Description:

Pre-conditioning is mode related to HVAC system. This mode is link with the train mode « pre-service. Pre-conditioning has a definition given in ISO 19659-3:

- Pre-conditioning is the process which enables the interior temperature to be lowered or raised to a defined comfort level including pre-cooling and pre-heating. This mode will depend on the ambient temperature conditions at which the train is operating. During hot conditions pre-cooling is required and in cold conditions, pre-heating is required. This mode of operation is without passengers on the train. This mode is an option. If the customer requires this mode, the detailed requirements shall be specified in the technical specification.

Generally, the pre-conditioning specification is defined by a maximum duration to reach the interior temperature target → E.g. Pre-conditioning shall be activated for a maximum duration of 30 min to reach the interior temperature target, in the full range of ambient temperature conditions (-20°C to +40°C).

A new proposal for pre-conditioning might be as follows:

- Be auto-adaptive to external temperature conditions,

- Have a communication to activate/deactivate the thermal pre-conditioning from the ground.

For alternative trains, limited on-board energy capacity and power limitation are important to consider for the pre-conditioning mode. Therefore, additional requirements could be used to manage the energy consumption and the power limitation during the pre-conditioning of the vehicle (see example of requirements in the section “requirements”).

Block-diagram:

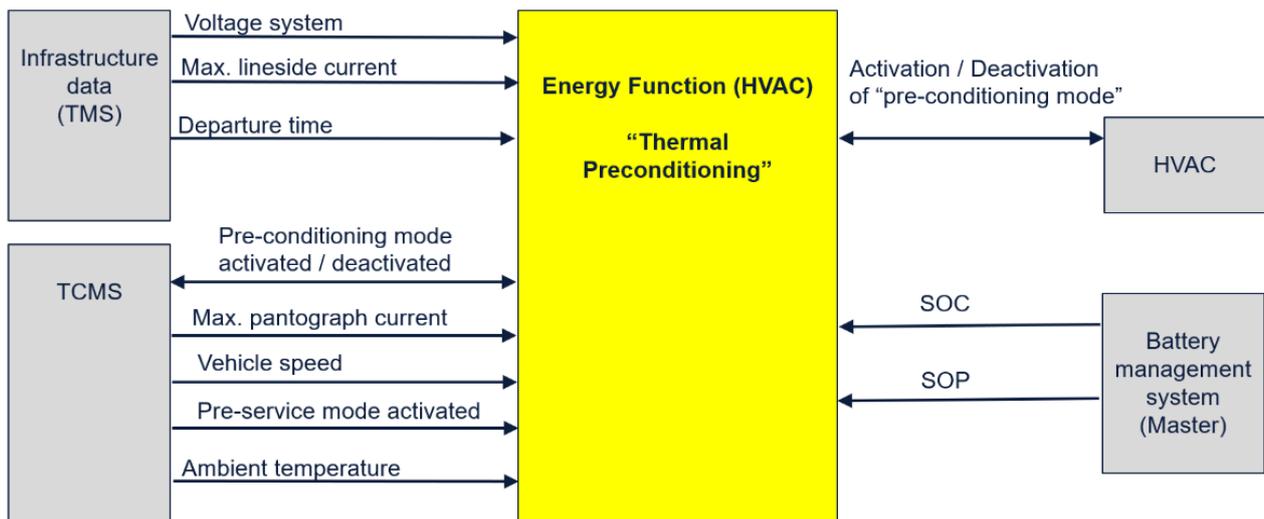


Figure 39: Vehicle's preconditioning function block-diagram

Requirements:

Topic	Classification *	Requirement	Rationale
General	INFO	The train pre-conditioning mode occurs during parking without passengers and before the train is operated with passengers. This mode is defined in the ISO 19659-3 /Ref. xxx, ISO 19659-3, Railway applications - Heating, ventilation, and air conditioning systems for rolling stock - Part 3: Energy efficiency document: <i>Pre-conditioning mode: Pre-conditioning is the process which enables the interior temperature to be lowered or raised to a defined comfort level including pre-cooling and pre-heating. This mode will depend on the ambient temperature conditions at which the train is operating. During hot conditions pre-cooling is required and in cold conditions, pre-heating is required.</i>	
Pre-conditioning time	RE	The pre-conditioning time must be calculated in dependence of <ul style="list-style-type: none"> - The inside temperature - The outside temperature - The HVAC power for heating and cooling (limited if the train is supplied by the external shore supply) - The thermal vehicle parameters - The foreseen time for passenger operation 	
General	RE	Have a communication to activate/deactivate the thermal pre-conditioning from the ground	
Alternative drive	OR	If train pre-conditioning is requiring too much energy (SoC window limitation to define), the train shall automatically deactivate the "pre-service mode" and switch to off-line mode.	

Table 19: Requirements list for "Vehicle's preconditioning" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
ISO 19659-3 "Railway applications - Heating, ventilation and air conditioning systems for rolling stock - Part 3: Energy efficiency"	Proposal has the goal to improve energy efficiency by standardizing energy management functions of HVAC and oriented the design of HVAC for alternative drive trains.	Current revision do not consider energy management functions related to HVAC, and also do not consider alternative drive trains special features.	Train mode: - Add the topic of train with alternative drive technology, with limited energy on-board and therefore, could impacting the way to proceed pre-conditioning Assessment methods: - Add rules to validate energy management functions

Table 20: Suggestion of standard evolution related to "Vehicle's preconditioning" energy management function

6.1.2.3 Battery's Preconditioning

Description:

Pre-conditioning of batteries is the process which enables the Energy Storage System ESS temperature to be lowered or raised to a defined operational level including pre-cooling and pre-heating. This mode will depend on the ambient temperature conditions at which the train is operating. During hot conditions pre-cooling is required and in cold conditions, pre-heating is required. In service, cooling could be required in cold conditions, due to high power demands of the ESS (such as fast charging).

This process is activated in different train operational modes (parking, before entering in commercial service, during service, etc.).

Objectives of battery preconditioning are:

- Optimized battery temperature with warm up or cool down battery temperature to be in operational temperature range of the lithium-ion battery. Depending on li-ion battery types, this range might range slightly. It is particularly important in case of extreme ambient temperature conditions.
- Improving lifetime by avoiding battery temperature to be out of the nominal range to preserve the lifetime
- Anticipating special mode, especially the fast charge of battery can influence significantly battery temperature and ageing. Therefore, preconditioning of the battery before fast charge can be selected to prepare the battery for this special mode.

Block-diagram:

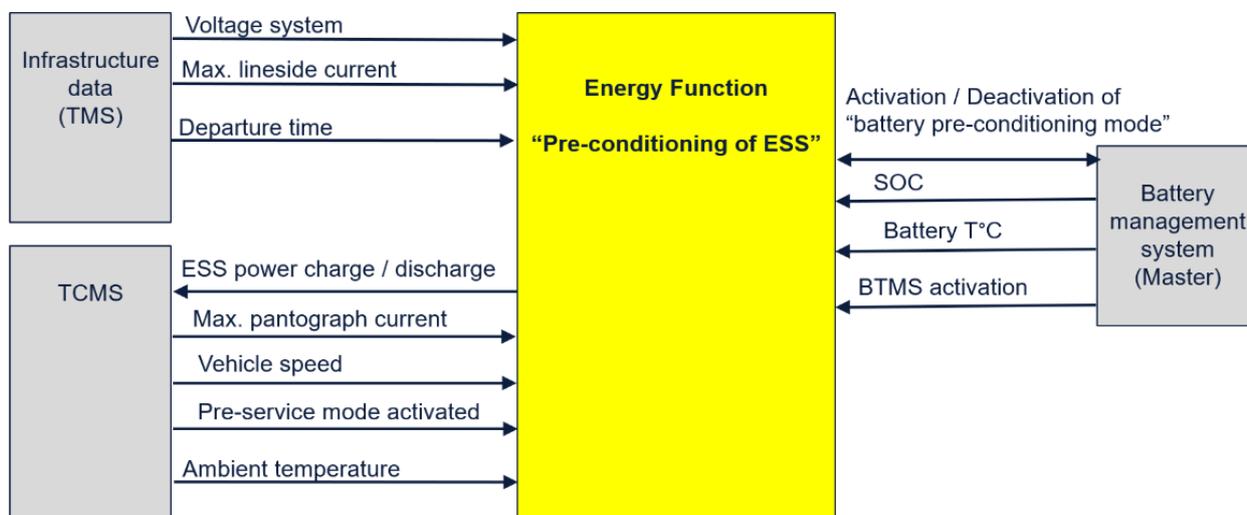


Figure 40: Batterie's preconditioning function block-diagram

Requirements:

Topic	Classification *	Requirement	Rationale
	INFO	The ESS thermal management system is 'active' when the temperature is observed and heating/cooling of the ESS is controlled, including when the vehicle is off. The thermal preconditioning function heats the ESS from a temperature at which performance is restricted to a temperature where full performance is available; it is 'active' when the temperature is observed and heating is controlled.	
	INFO	The Customer has to choose between ID 65 and 66.	
	CH	The time required to thermally precondition the ESS from the lowest contractually agreed temperature to the fully operational temperature shall be stated by the supplier.	Create information to adapt the operation and system boundaries to the train.
	CH	The time required to thermally precondition the ESS from the lowest contractually agreed temperature to the fully operational temperature shall be no more than XX minutes.	Adapt the train to the operation and system boundaries.
	RE	The ESS shall have thermal preconditioning incorporated.	To warm the battery from extremely low temperatures to allow safe operation.
	RE	While the vehicle is connected to an external power supply, the ESS thermal management system shall be active.	To ensure that the ESS is ready and to prevent low temperature battery state with external power supply.
	RE	While the vehicle is not connected to an external power supply, the ESS thermal management system shall be available.	To allow the ESS to be made ready and to prevent low temperature battery state without external power supply.
	RE	The ESS thermal preconditioning function shall have the ability to get activated and deactivated from onboard the vehicle.	To allow the ESS to be made ready by local control.
	OR	The ESS thermal preconditioning function shall have the ability to get activated and deactivated by a timer control onboard the train adjustable by the operator.	The timer can specify the activation time, or time at which the ESS shall be ready to use.
	OR	The ESS thermal preconditioning function shall have the ability to get activated and deactivated from a remote location, such as from an operations centre via a communication system by the operator.	To allow the ESS to be made ready by remote control.
	OR	The ESS thermal preconditioning function shall deactivate automatically when a set time has elapsed.	To prevent unexpected discharge.
	OR	The automatic activation of the ESS thermal preconditioning function shall have the ability to get inhibited/permitted by geolocation.	This allows repeated preconditioning events to be prevented then the train is in storage.
	RE	The ESS thermal preconditioning function shall deactivate when the SOC reaches a lower limit,	To prevent low SOC.

		which is to be agreed between the supplier and the operator.	
	OR	If the ESS thermal preconditioning function is activated by remote or timer control, then it shall not discharge the ESS to an SOC level which prevents the vehicle from being placed fully into service and meet performance requirements.	This may require one or multiple geolocation based SOC levels below which automatic preconditioning is inhibited, but permitted to be activated onboard, after which there is still sufficient SOC to place the train fully into service and reach the next charging location.
	RE	Regular battery conditioning activities shall not affect the vehicle's ability to be placed into service at any time.	To ensure the vehicle does not become unavailable.
	RE	The thermal preconditioning of the ESS shall not lead to uncontrolled harmful discharge of the ESS.	The performance of the ESS has to be kept available for commercial service.

Table 21: Requirements list for "Battery's preconditioning" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
IEC 62864-1 « Railway applications - Rolling stock - Power supply with onboard energy storage system - Part 1: series hybrid system »	The proposal has the goal to improve energy efficiency and operation of train with on-board ESS.	Current revision do not consider preconditioning test methodology of the ESS	Add tests to check and validate the ESS's preconditioning (performance, control, etc.).

Table 22: Suggestion of standard evolution related to "Battery's preconditioning" energy management function

6.1.2.4 BEMU charging

Description:

Traditionally, the traction batteries of a BEMU are charged during braking and from the overhead line via pantograph, line-side converter, and battery converter. Two kinds of landside energy supply must be distinguished:

- Main line
- Charging infrastructure (e.g. catenary island, charging station, etc.)

In both cases the max. charging power must be limited by

- The maximum allowed battery power and current
- The maximum allowed average lineside power according to the infrastructure dimensioning.

During parking at the termination station, the batteries should be charged with a defined power that a certain SOC is reached when the train leaves the station. The SOC should be that high that the train can be supplied during the non-electrified line section of the trip foreseen. The optimum charging power and target SOC must be calculated according to:

- Termination/ charging time,
- Max. allowed battery charging power and current,
- Max. allowed current of the pantograph, line side converter and transformer,
- Max. allowed current of the infrastructure (main line or charging infrastructure),
- Number of BEMUs charged at the same time,
- Prediction of next service (characteristics of the future operation and charge/discharge zone).

The charging current should be as low as possible to achieve a long battery lifetime.

Block-diagram:

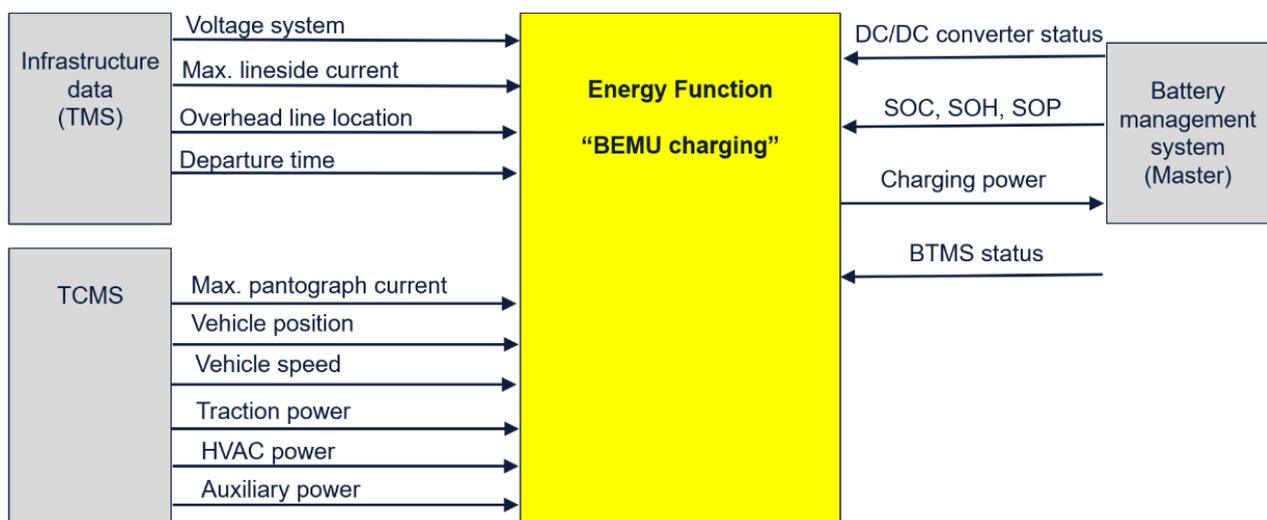


Figure 41: BEMU charging function block-diagram

Requirements:

Topic	Classification *	Requirement	Rationale
General	RE	The vehicle is capable of processing charging behavior commands (target SOC, timeline, preference, urgency) from the shore side.	Ensure operational freedom for charging fleets.
Charging source	RE	The battery must be charged from one of the following energy sources - Electrical braking energy - Overhead line via pantograph	
Charging begin	RE	The battery charging via overhead line must begin at once when the pantograph is lifted and the overhead line voltage is detected	For avoiding time at the termination station without charging
Charging cut-off	RE	The battery charging via overhead line must be stopped a few seconds before a non-electrified line section is expected	To guarantee the dropping of the pantograph without current
Charging cut-off	RE	The battery charging via overhead line must be stopped before the pantograph is dropped	To guarantee the dropping of the pantograph without current
Charging cut-off	RE	The battery charging via overhead line must be stopped at once when no overhead line voltage is detected	To prevent the supply of the overhead line from the vehicle when it is not connected to the grid
Location of overhead line	RE	The location of the overhead line must be provided by the infrastructure manager. The information must be provided before the train run starts at the operation day	
Location of overhead line	OP	The location of the overhead line must be provided by the infrastructure manager. The information must be provided and updated in case of non-available catenary line.	To adapt the driving and potentially the charging strategy to ensure enough range in operation
Charging power	RE	At termination stations, the charging power must be controlled to guarantee required SOC for the next trip until the departure time of the train	To start the operation on non-electrified lines with enough SOC
Limited charging power	RE	At termination stations, the charging power must be limited to guarantee required SOC for the next trip until the departure time of the train	To extend the lifetime of the battery
Limited pantograph current	RE	The current per pantograph must be limited to the time-dependent max. allowed current of the overhead line	To prevent an overheating of the overhead line during standstill
Max. pantograph current	RE	The value of the time-dependent max. allowed current of the overhead line in dependence on the location of the vehicle and the pantograph must be provided from the infrastructure manager. The information must be provided before the train run starts at the operation day	To prevent an overheating of the overhead line during standstill
Limited charging power	RE	The charging power must be limited to the max. allowed power of the battery pack depending on the state of the battery pack (e.g. number of active battery modules) and the outside and battery temperature	To prevent an overheating of the ESS To guarantee a long lifetime of the ESS

Charging time	RE	If the charging/ termination time provided by the TMS is too short to charge the batteries to the required SOC, the required termination and departure time should be signaled to the TMS	To charge the batteries to a sufficient SOC
Charging cut-off	RE	When a battery failure is detected, the battery charging has to be stopped at once	To avoid damage of the batteries
Charging restart	RE	The battery charging must restart again when the battery failure is eliminated	
Limited grid power	RE	When more than one train is charged in the same overhead line section the max. allowed supply current of the substation must be considered	
Limited grid power	RE	In order to facilitate stable operation in weak railway power supply networks or under extraordinary operating conditions, according to EN 50388 trains must be equipped with an automatic device that adjusts the power consumption depending on the catenary voltage in stationary state. Figure 1 of EN 50388 shows the highest permissible current as a function of the catenary voltage.	To prevent an overload of the catenary and energy supply
Max. pantograph voltage	RE	When the train is in regenerative braking, energy is generated, which is first consumed by the auxiliary systems (HVAC, lighting, etc.). The remainder is used to charge the batteries. If the battery system is fully charged, according to the defined SOC, the regenerated energy is sent to the grid. If the grid is unable to receive the energy, it is dissipated using an internal braking resistor.	To prevent overvoltages at the pantograph during regenerative braking under conditions with catenary systems is unable to receive energy

Table 23: Requirements list for "BEMU charging" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
TS 50729 « Interface requirements between charging infrastructure with dedicated contact line sections and electric traction units with onboard electric traction energy storages and current collectors »	The proposal is to optimize the BEMU charging and the infrastructure power supply	Current revision does not consider communication between train and infrastructure to manage the charging power level of the battery train	Definition of an architecture for the communication between train and infrastructure, and the data to be exchanged

Table 24: Suggestion of standard evolution related to "BEMU charging" energy management function

6.1.2.5 Driver-Advisory System

Description:

Driver Advisory Systems (DAS) are IT tools which provide live information to the drivers to help them arrive at stations on time while reducing energy consumption. DAS uses various types of input data, such as live positioning, infrastructure characteristics, the pre-planned or real-time timetable, rolling stock data, etc.

The Connected DAS (C-DAS) is an evolution of S-DAS which has a connection to the TMS to give and receive updates about the timetable, speed limit and delays. The C-DAS receives updates from the TMS to maintain a constantly updated understanding of the environment relating to the trip (e.g. conflicts, new timetables etc.), and in turn may keep the TMS informed on the status of the train journey.

For battery trains the DAS is most important since reduced energy consumption increases the range of battery trains. An additional driving style should be added for battery trains: If the battery SOC is too low to reach the next electrified section based on the defined driving profile, recommendations should be provided by the DAS to support the driver on the appropriate decision to take (e.g. additional charging time in station before the future non-electrified section, suggestion to stop in a railway station for passengers evacuation, etc.) while reducing as much as possible the delay.

Block-diagram:

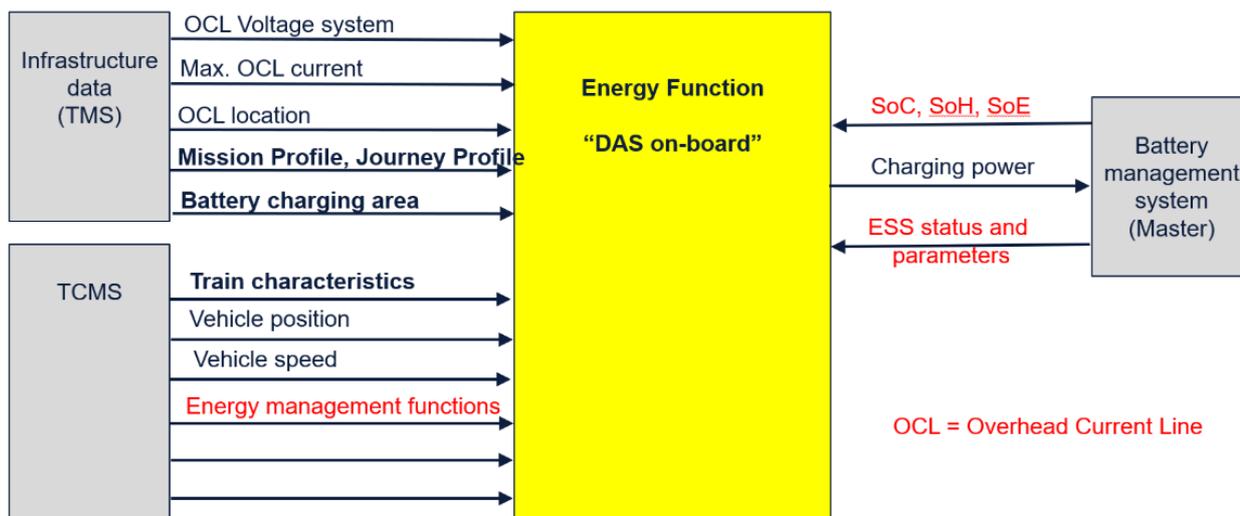


Figure 42: DAS for alternative drive trains block diagram

Requirements:

Topic	Classification *	Requirement	Rationale
General	INFO	Driver Advisory Systems (DAS) are IT tools which provide live information to the drivers to help them arrive at stations on time while reducing energy consumption. DAS take into account various types of data, such as live positioning, infrastructure characteristics, the real-time transport plan, rolling stock data, etc.	
General	RE	The vehicle shall have a driver advisory system to support energy- optimized driving.	Save energy e.g. by efficiency-optimized acceleration and driving (including load shift between drives), reduction of maximum running speed if there is a travel time buffer and/or longer rolling phases (coasting), and earlier use of braking to reduce the use of mechanical brakes, etc.).
General	RE	The train should be equipped with one of the following DAS systems in dependence of the requirements of the operator: <ul style="list-style-type: none"> - Standalone DAS - Connected DAS - DAS for ATO For BEMUs C-DAS or DAS for ATO is recommended, if there is a wayside TMS that can provide the necessary information, to increase the range of the BEMU	Energy saving Increasing the range of the BEMUs
Standalone DAS	INFO	A Standalone DAS (S-DAS) has no connection to Traffic Management Systems while driving, but it has an information source for the position of a train (e.g. GNSS). The S-DAS is pre-loaded with static information describing the train journey. In some cases there is also dynamic information, e.g. timetable updates by the operator.	
Connected DAS	INFO	The Connected DAS (C-DAS) is an evolution of S-DAS which has a connection to the TMS to give and receive updates about a train's journey. The C-DAS receives updates from the TMS in order to maintain a constantly updated understanding of the environment relating to the trip (e.g. conflicts, new timetables etc.), and in turn may keep the TMS informed on the status of the train journey.	Preferred solution for minimum delays and minimum energy consumption (important for long range)
Driving style	RE	The C-DAS should consider the following optimised driving styles: <ul style="list-style-type: none"> - Driving exactly according to the working time table with small time reserve (DB: Planfahren) - Following the (delayed) train ahead with reduced speed to avoid unnecessary stopping (DB: Nachfahren) - Increasing the speed ahead of areas with temporary reduced max. speed to avoid delays 	

		- Energy-optimised driving with cruising and/or coasting (Eco-driving)	
Driving style	OR	The energy-optimised driving may use the following measures: - Coasting: Before braking, a coasting takes place by switching off the traction - Cruising=Speed reduction: Running at a constant speed below the permitted (line) speed - With momentum over the top : Rolling out (traction is switched off) in front of downhill slope - Purely electric braking: The use of mechanical brakes is avoided, the braking energy is used on board of the train or recuperated - Avoid acceleration and braking in unnecessarily quick succession.	Use as much measures as possible and wise to reduce energy consumption
Driving style	RE	In the case of not enough remaining battery capacity an energy saving driving style is mandatory while ignoring the timetable	Avoid the breakdown of the vehicle without battery energy
Data format	RE	The data exchange between vehicles and infrastructure should be according the standards - UIC SFERA IRS 90940 ed. 3 and - railML®,	To avoid adaptation for the application in different countries

Table 25: Requirements list for "DAS for alternative drive trains" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
IRS 90940 "SFERA protocol: Train operation data exchange with on-board devices"	The proposal is to add further requirements related to alternative drive trains	Ongoing	Ongoing

Table 26: Suggestion of standard related to DAS for alternative drive trains to update

6.1.2.6 Shore supply

Description:

During longer stops in parking areas or termination stations without an overhead line the train

needs an external energy supply for supplying HVAC and the auxiliary consumers. The preferred standardized solution is the supply via cable and plug according to EN 50546 with a supply voltage is 400V 125A 50Hz 3AC. To prevent an overload of the plug, cable and infrastructure the continuous train power must be limited to 85kW. This must be considered for the pre-conditioning of the vehicle (power and pre-conditioning time; see Pre-conditioning of the train). Concerning the cable and plug the following energy functions of the train must be implemented:

- When the plug is disconnected the voltage at the socket should be switched off automatically to protect the staff against electric shock,
- The voltage at the socket should be switched on automatically when the plug is connected, the correct external voltage is measured, and the communication signals that the infrastructure is ready for energy supply,
- A communication between the landside infrastructure and vehicle may be foreseen.

The following energy functions of the landside external energy supply should be implemented:

- The supply station shall confirm there is electrical contact before applying power
- The supply station shall immediately remove power if an abnormal power or control condition is detected or the watch-dog signal is determined to be absent.

In addition to the external energy supply during parking, the external energy supply should be used in the maintenance shop to test the auxiliary consumers and functions without connection of the vehicle to the overhead line.

Block-diagram:

Ongoing, to be displayed in next period 3.

Requirements:

Classification *	Requirement	Rationale
RE	At termination stations without overhead line a shore supply for BEMUs must be foreseen.	
INFO	The shore supply is required for the supply of the HVAC system of the train, auxiliary consumers and for the pre-heating or cooling of the batteries	
RE	The shore supply is required during longer parking of the train during longer termination times or during overnight parking	To prevent the discharge of the batteries during parking
RE	The shore supply must be foreseen at the location of terminating train (at the platform) and/ or in the parking area	
RE	The shore supply is provided via plug and socket according to: FprEN 50546: 2024 "Railway applications - Rolling Stock - Three-phase shore (external) supply system for rail vehicles and its connectors"	
RE	The shore supply voltage system is 400V 3AC 50Hz	

RE	In general, the medium power system shall be used for the supply of BEMUs: 125a per conductor, 86kVA	For 2- and 3-car trains 86kVA is enough. The 600A system is not required.
RE	Three control lines can be used to control the shore supply: - PP Shore supply connected - PP Shore supply enable - CP 125A shore supply	
RE	When the shore supply is not connected to the vehicle the socket must be free of voltage (vehicle entrance switch off)	
RE	When the shore supply control line PP "Shore supply connected" is active the vehicle entrance switch shall be turned on	
RE	The vehicle consumer power (HVAC, auxiliaries, battery heating) shall be controlled to limit the shore supply power to the rated value (e.g. 86A for continuous current)	
RE	The consumer control consider the importance of the different consumers in the following order: 1. Auxiliary loads 2. Battery heating/cooling 3. HVAC	
RE	During overnight parking or longer daytime parking, the HVAC system must be controlled in the sense that the temperature of the passenger area reaches the required temperatures at the planned starting time of train operation with passengers. During overnight parking or longer daytime parking without passengers the temperature of the passenger areas can be lower or higher than the required value for passenger operation.	To save energy and to limit the power of the shore supply
RE	The control of the HVAC power during parking shall be optimized with respect to energy consumption and limitation of the shore supply power, for example: - Pre-heating a certain time before passenger operation depending on the outside temperature (short pre-heating time at high outside temperatures, long preheating time at low outside temperatures)	

Table 27: Requirements list for "Shore supply for alternative drive trains" energy management function

Impacts on standardisation / regulations:

No change on standardization and regulations suggested.

6.1.2.7 Lift and drop of pantograph

Description:

Traditionally the lift and drop of the pantograph is controlled by the train driver according to signals along the line.

To prevent the damaging of the pantograph and overhead line, when the pantograph is lifted at areas without overhead line, a technical supervision system must be foreseen that

- blocks the lifting of the pantograph when there is no overhead line
- automatically drops the pantograph if there is no overhead line

For the case of the failure of the supervision system, there must be a possibility for the train driver to request the lift of the pantograph with a special manual operation

For ATO operation the lift and drop must be done automatically.

Lift and drop of pantograph might be done automatically by dedicated beacon added on the line

→ This kind of system is typically used in tramway-train for the switching railway line and city line (e.g. switch from 25kV 50Hz to 750V DC).

Block-diagram:

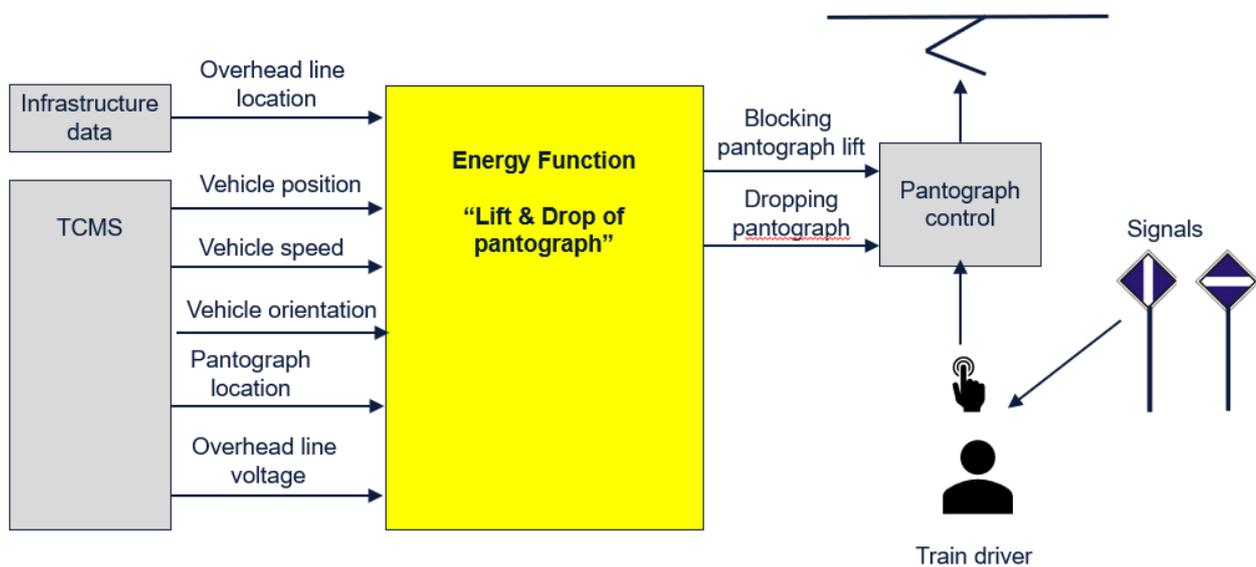


Figure 43: Lift & Drop of pantograph block diagram

Requirements:

Topic	Classification *	Requirement	Rationale
Pantograph control	INFO	Without automatic train operation the lift and drop of the pantograph is controlled manually by the train driver	Simple state-of-the-art solution
Overhead line signalling	INFO	The location where the lift and drop should be signalled to the train driver by landside signals, for example signals according to the German standard Ril 301	Already established solution for areas with change of voltage system
Automatic lift and drop	RE	In automatic train operation GoA 4 the lift and drop of the pantograph must be carried out automatically.	
Pantograph protection	RE	A technical protection system must be foreseen that blocks the lift of the pantograph at areas without overhead line	To prevent the destroying of the pantograph and overhead line, when the pantograph is lifted at areas without overhead line
Pantograph protection	RE	The protection system must be foreseen that drops the pantograph automatically, - if no overhead line voltage is detected (non-fed overhead line at the end of the overhead line section) or - there is no overhead line above the pantograph according to the vehicle position and infrastructure data	To prevent the destroying of the pantograph and overhead line, when the pantograph is lifted at areas without overhead line
Pantograph protection	INFO	The protection system requires the following data: - Position of the vehicle - Position of the pantograph along the vehicle - Position of the overhead line	
Pantograph protection	RE	The train driver must have the possibility to override the protection system in case of malfunction	

Table 28: Requirements list for "Lift & Drop of pantograph" energy management function

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
EN 50388-1:2022 Railway Applications - Fixed installations and rolling stock - Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability - Part 1: General	Amendment of requirements and measures for battery trains - to prevent the lifting of the pantograph at non-electrified line sections and - to protect the collision of the pantograph with the overhead line at transition points from non-electrified to electrified line sections	Protection of damage to the pantograph and catenary in case of falsely lift of the pantograph of battery trains	Proposal of requirements to add in the standard

Table 29: Suggestion of standard related to lift & drop of pantograph to update

6.1.2.8 ESS protection and diagnostics

Description:

Ongoing, to be developed in the next period.

Block-diagram:

Ongoing, to be developed in the next period.

Requirements:

Ongoing, to be developed in the next period.

Impacts on standardisation / regulations:

6.1.2.9 Train driver information

Description:

Ongoing, to be developed in the next period.

Block-diagram:

Ongoing, to be developed in the next period.

Requirements:

Ongoing, to be developed in the next period.

Impacts on standardisation / regulations:

Ongoing, to be developed in the next period.

6.1.2.10 Peak-shaving

Description:

Ongoing, to be developed in the next period.

Block-diagram:

Ongoing, to be developed in the next period

Requirements:

Ongoing, to be developed in the next period.

Impacts on standardisation / regulations:

Ongoing, to be developed in the next period.

6.1.1. Optimized regenerative braking

Description:

Depending on whether a BEMU is running on electrified or non-electrified section, the following considerations should be considered:

- Reduce peak shaving to reduce line losses and improve the available capacity of the line (increase the intensity of traffic),
- Add optimised functionality should not affect line safety,
- Optimise the charging policy (charging speed and frequency) in electrified lines according to the line infrastructure (line availability, requirements of electrified line), SOC, expected line voltage and line length).

Regenerative braking optimisation for the BEMU and EMU, to update the battery recharge policy Considering the power consumed in the auxiliaries, define one mode focused on performance and another mode centred on saving, both based on SOC and the availability of energy in the

regeneration phase

Block-diagram:

Ongoing, to be developed in the next period.

Requirements:

Ongoing, to be developed in the next period.

Impacts on standardisation / regulations:

Ongoing, to be developed in the next period.

6.1.2.11 Energy management functions interfaces

Description:

The proposal is to define standardised interfaces of the energy management functions defined previously. Standardised interfaces should allow more flexibility and modularity between subsystems / components on a vehicle.

Block-diagram:

Not applicable

Requirements:

Not applicable

Impacts on standardisation / regulations:

Standard	Objective	Rationale	Input from Rail4EARTH
New standard or modifications of existing documents (e.g. subsets?)	Definition of standardized interfaces for energy management functions (e.g. eco parking modes, peak-shaving mode, etc.)	Reduce cost and simplify the exchange of subsystem or components	Suggestion

Table 30: Suggestion of standard related to energy management function interfaces

6.2 Optimization of Charging Process for Battery Trains

Battery train performance is strongly linked with charging capability. The charging of battery

trains shall be considered from a system view. BEMU's and battery trains (e.g. Battery locomotive, lightweight battery train, etc.) charging can be proceeded in different cases:

- **Battery train charging under catenary line: Train is running under electrified line**, with a current collector to feed electricity from infrastructure into the train. During train moving or at standstill, the electrical energy supplies the traction system and auxiliary loads, while charging the traction batteries,
- **Battery train charging under catenary line and by regenerative braking**: Similar conditions to the previous case, but specifically when train is decelerating to stop. During this braking phase, electrical traction motors are providing energy (motor is now generator), so called regenerative energy. This regenerative energy can be stored into the traction batteries. Therefore, no and less energy is requested for the charging from the catenary line,
- **Battery train charging by external shore**: This is a particular case because it concerns only charging during parking. As explained previously in the deliverable, the technology of plug for rail vehicle is today mainly dedicated to supply auxiliary loads.
- **Battery train charging by regenerative braking on non-electrified line**: One of the main reasons for the electrification of vehicles is the capability of battery to be recharged during braking, or while travelling with constant speed or accelerating in a downhill zone. This is improving the energy efficiency by valorising the energy produced by traction motors in deceleration. Especially on non-electrified, train need to use on-board energy source, such as combustion engine combined with fuel tank, or fuel-cells combined with hydrogen storage tanks. Whereas these 2 types of on-board energy sources are not regenerative. Therefore, having an energy storage system able to regenerate is improving the efficiency.

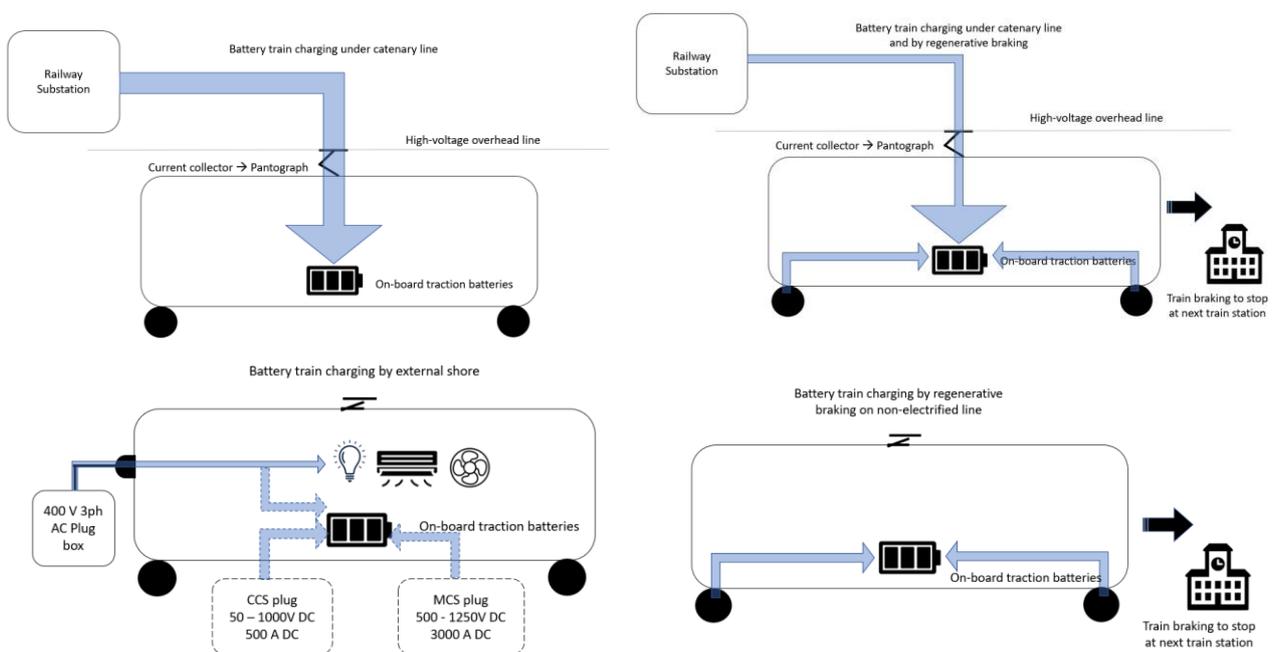


Figure 44: Simplified diagram of recharging options for battery train

Additionally, the shift from fossil fuel in the railway sector, and more generally to the whole

mobility and transport, involves looking at the full scheme of energy production and conversion. To reduce the carbon emissions of energy production, renewable energies are used and grow significantly. As reported by the European Environment Agency, the share of renewable energy increased from 10,2% to 24,5% between 2005 and 2023. This trend is expected to be even bigger to reach the target for 2030 of 42,5% (EEA, Share of energy consumption from renewable sources in Europe, 2025).

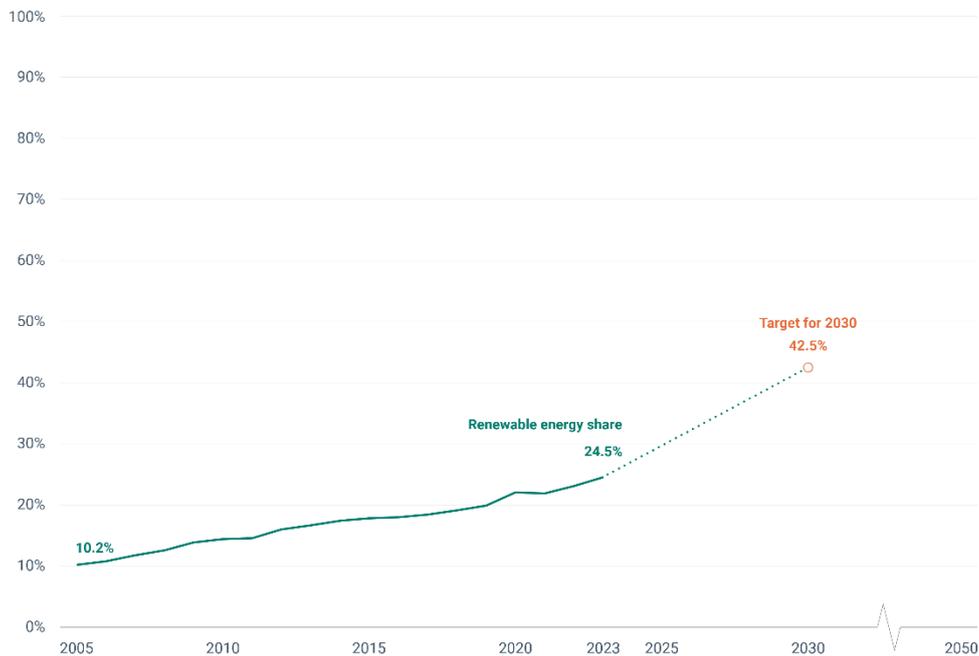


Figure 45: Evolution of renewable energy share in Europe since 2005 and target level for 2030

Renewable energy brings the question of unbalance in energy production. Compared to other kinds of energy production type, a major unbalance in the production power capacity is obtained with renewable energy production, such as photovoltaic type or wind turbine. The figures below show example of solar and nuclear production power profile in France on a same day based RTE (France’s transmission system operator) report:

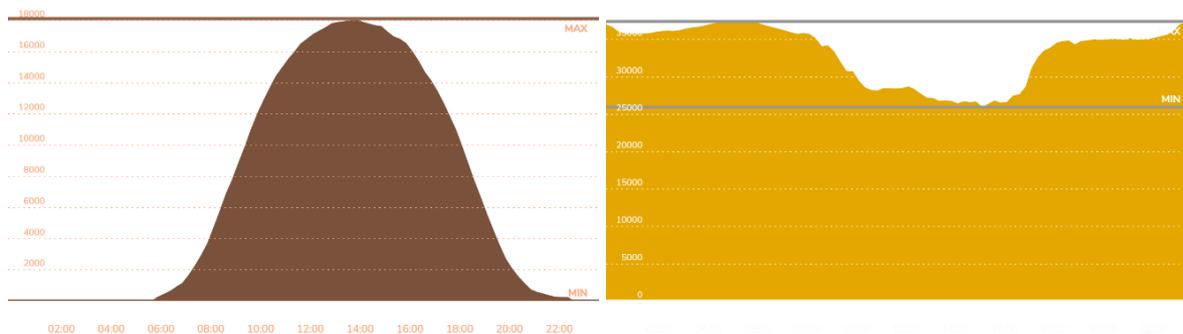


Figure 46: On the left, production power profile of photovoltaic in France on July 1st 2025. On the right, nuclear production profile in France for the same day.

The projection in the future of more renewable energy sources, with a huge variation of power capacity, might affect the supply of loads, such as the railway system. Therefore, there're two major perspectives to avoid this phenomenon:

- Being able to store the energy → The energy storage allows us to use energy during periods of demand. It can be interesting to use on-ground storage devices especially when the production capacity is higher than the demands.
- Being able to manage the energy → The management gives more flexibility on the loads side. Typically, the management of energy will try to reduce or prioritize the energy demands during “low production capacity”. It may introduce the energy management function of “peak shaving”.

In this work package, the focus on only the 2nd point related to energy management, dedicated to recharge batteries traction. Different types of charging strategies can be used and will be developed in the next sub sections.

6.2.1 Optimization of the Battery Train Charging on Current Battery Trains

On current battery trains, the charging power for traction batteries is generally controlled but not optimized. It means that the traction batteries are controlled with a DC/DC converter to regulate the power in charge or discharge. The following control scheme is applied:

- On non-electrified sections the battery train uses energy from the traction batteries
- When an electrified section is identified, the battery train switches from battery to catenary mode,
- In the generic strategy the recharging of the traction batteries starts automatically.

Prioritization is defined to determine how much power can be transferred into the battery. Currently, charging batteries is not the priority. Preference is given to the power demands of the traction system, to ensure the tractive performance of the drive, and of the auxiliary loads, to keep nominal conditions of traction and comfort functions.

Therefore, the recharging power applied following this formula:

$$P_{\text{chargESS}} = P_{\text{linemax}} - P_{\text{traction}} - P_{\text{auxiliary}}$$

- P_{chargESS} : Charging power for the Energy Storage System (ESS),
- P_{linemax} : Maximum power from the infrastructure line,
- P_{traction} : Power requested by the traction system of the rolling stock,
- $P_{\text{auxiliary}}$: Power requested by the auxiliary loads on-board.

The charging power of the ESS may vary significantly according to the actual condition of the other parameter. For example, when the train is at standstill, P_{traction} is zero, so higher power may be allowed for the charging of ESS. However, at standstill, the maximum power of the infrastructure line is reduced. So, based on the power values of P_{linemax} , P_{traction} and $P_{\text{auxiliary}}$, the remaining power is used for the charging of ESS.

In terms of optimization strategy, current battery trains are focused on a strategy to keep the Rail4EARTH – GA 101101917

SoC / SoE at the maximum. This strategy makes sure that the traction batteries may be reused with the highest available energy in a shorter time. The figure below shows an example of this type of strategy on a line with a non-electrified section, and then a long-electrified section until the terminus. The electrified section is under 1.5 kV DC.

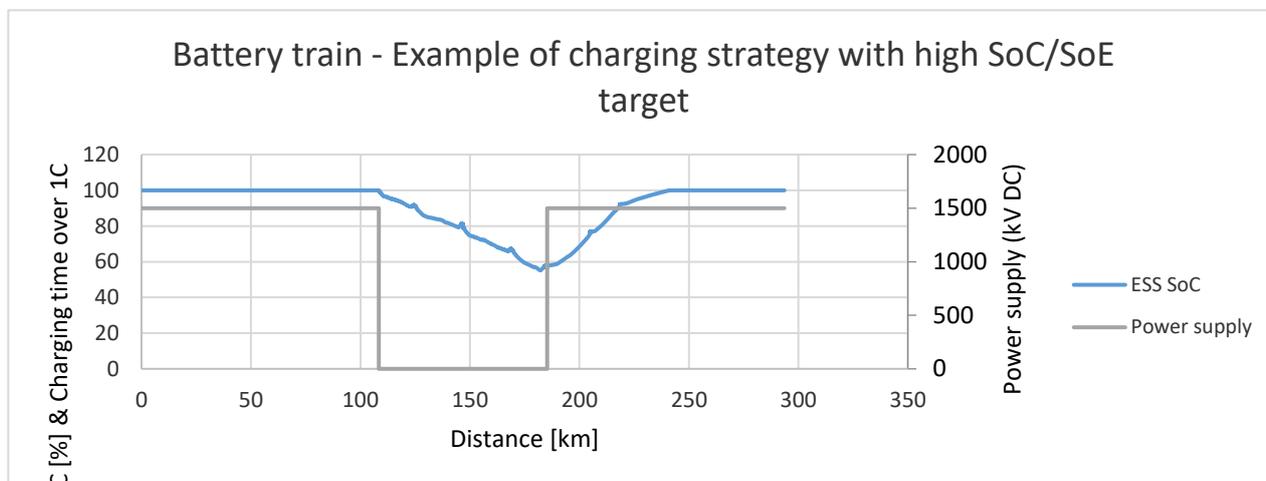


Figure 47: Example of battery train charging strategy for max SoC/SoE

After using the traction batterie on the non-electrified section, the battery train start to charge immediatly when the pantograph is risen on the electrified line. The strategy requests to reach as fast as possible to recharge the traction batteries to maximum SoC/SoE, while respecting the prioritization explained previously. So, the line power (grey curve) increased to maximum during powering and coasting. But, when trains decelerate, the line power is reduced due to regenerative power produced by the traction motors. Regenerative braking power is used first to recharge the traction batteries to avoid consuming energy on the catenary line. The SoC reached its maximum at 242 kilometers, around 50 km before the end of the line. So, an important margin for this case gives the possibility to use other kinds of charging optimization strategies. In this case of study, the total SoC discharged is 51%. By considering a full cycle equivalent (FCE) as 100% discharge of SoC, around 0,5 FCE for this journey profile. To estimate the ageing of the battery, the definition of operational conditions, such as the number of journey profiles per day and a few operational days per year is needed. But also, the battery characteristics, especially concerning his cycle life for 100% discharge. With these conditions, it is possible to evaluate ageing related to cycling profile.

Additionally, this charging strategy is creating higher losses due to the fast-charging approach. The charging over defined rated current (commonly call C-rate) will give extra loss to evacuate by the battery thermal management system, so by extra energy consumption of auxiliary load. At the same time, other negative impacts can be detected, such as ageing of the batteries, or high noise emission related to the cooling of the batteries.

6.2.2 Optimization of the Battery Train Charging from Infrastructure Side

From the infrastructure side, this max SoC/SoE strategy involved is stressful for the electrical energy supply system on-ground. This is due to a constant maximum power at the line to the battery train. When a fleet of battery trains in the same area are supplied altogether by one substation, the phenomenon can be quite hazardous. As different trains are requesting maximum power from the infrastructure line, an unbalancing may happen when a train starts to limit its power, and therefore another increases its power demand.

So, it is recommended to reduce the charging power, especially in case of many battery trains at the same spot.

Furthermore, for DC voltage power supply, due to high current in the line, the non-management of the charging power of trains with on-board traction batteries might affect the infrastructure conditions. To preserve the traction power supply, new TS 50729 (publication in 2025) require limiting the charging power while moving with a speed up to 8 km/h. The charging current shall be equivalent to the maximum current allowed at standstill (e.g. in 1.5 kV DC → 300 A DC; in 3 kV DC → 200 A DC). Similar studies were conducted in France with a recommendation to reduce the charging power up to 35 km/h. The figures below show the difference between no limitation and with limitation of the charging power during an acceleration phase:

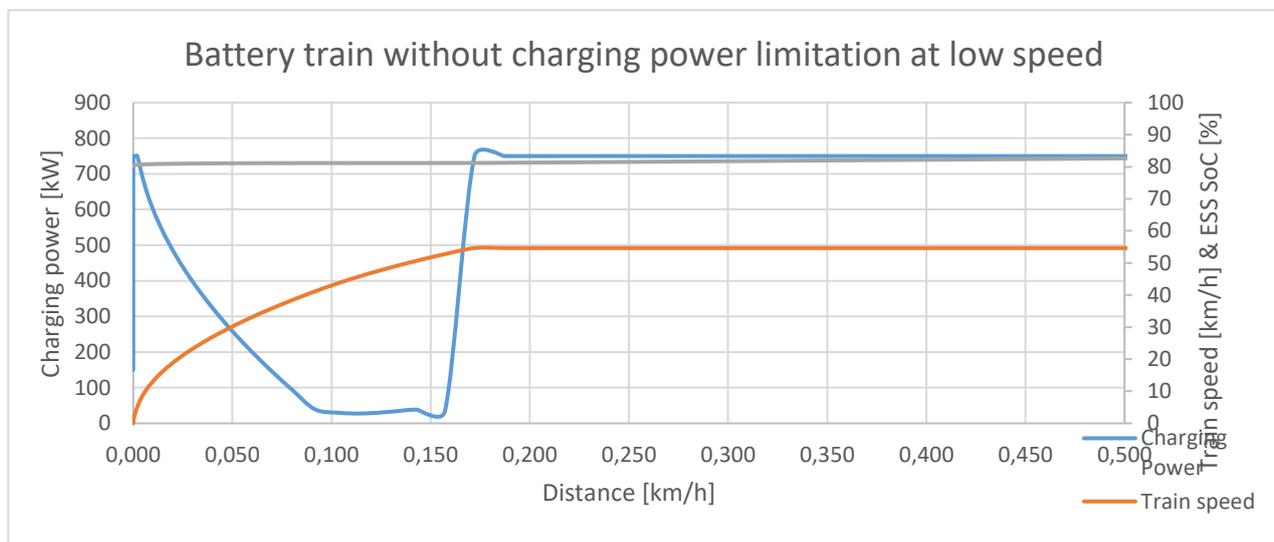


Figure 48: Battery train without charging power limitation during acceleration under 1.5kV DC

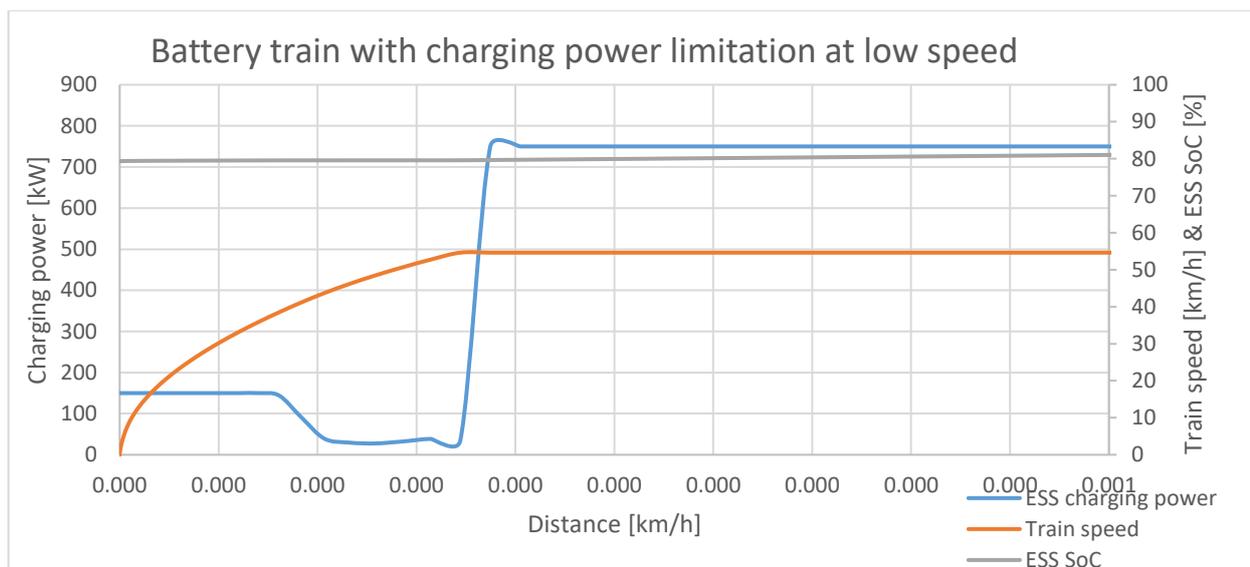


Figure 49: Battery train with charging power limitation during acceleration under 1.5kV DC

5.1.1. Optimization of the Battery Train Charging With Respect to Battery’s Lifetime

From battery’s lifetime side, the charging strategy may significantly affect the ageing of the lithium-ion battery. Ageing of li-ion battery is depending on different factors:

- Calendar,
- Cycling,
- Temperature,
- Depth of Discharge,
- Charging current (C-rate),
- Abusive charging/discharging,
- Manufacturing process.

The charging strategy could have an impact on cycling and temperature factors. As seen previously on the SoC/SoE max strategy, this option introduces more cycling of the energy capacity with regular discharge/charge of the batteries. With respect to temperature, the charging strategy can impact the power level. Maximum SoC/SoE strategy involves fast charging of the batteries as much as possible. Therefore, fast charging creates additional losses in the batteries and so the temperature is increasing. So, improving the control strategy of charging with prioritization on cycling and temperature reduction shall be developed.

Based on the example given in section 6.2.1 and current battery train charging strategy with max SoC/SoE prioritization, the charging time over 1C represents 43% of the total charging time. Most of the charging power time over 1C is under the electrified section of the line, to recharge the traction batteries after the non-electrified section. Some charging power over 1C also happens on non-electrified section, related to high braking power when train stops at stations. To reduce these peaks, adapted driving strategies can be used to avoid too high regenerative power.

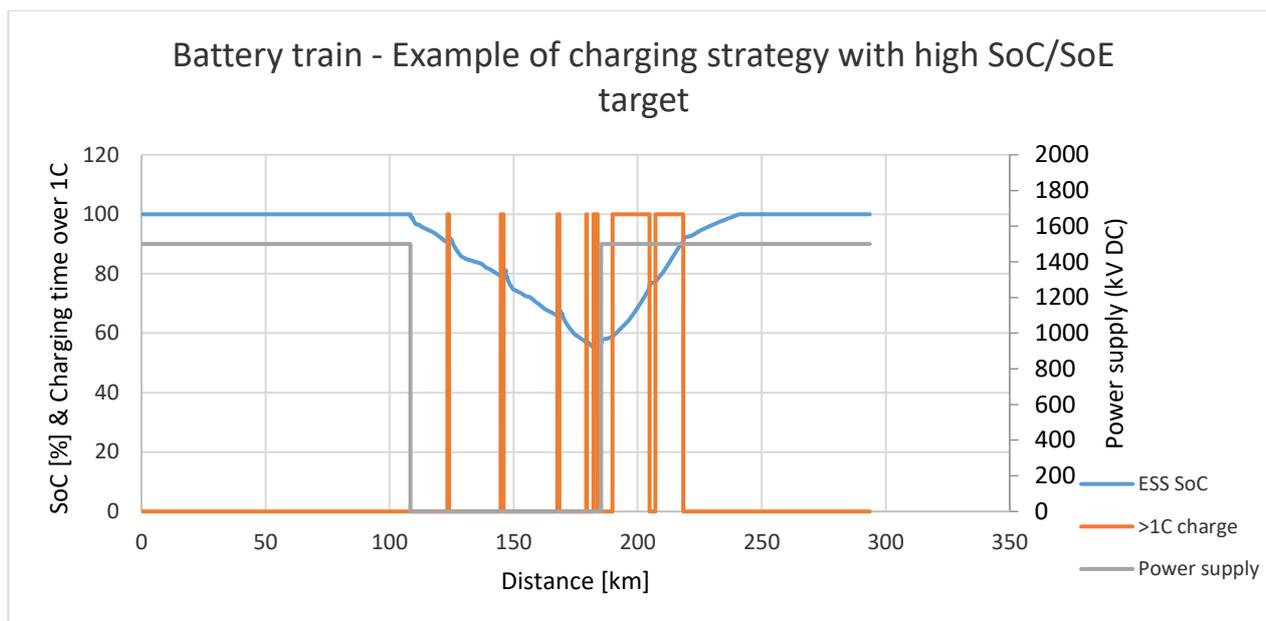


Figure 50: Battery train with charging strategy oriented to high SoC/SoE objective

A new charging strategy based on “1C charging limit” to reduce the heating effect of the charging into the traction batteries can be introduced. At the same time, there’s also a benefit from systemic point of view:

- saving energy on railway infrastructure by lower loss on the line,
- reducing power consumption on the infrastructure and grid helps to stabilize the power distribution,
- In case of voltage leaks on the line, this reduction can support to reinforce the railway traffic thanks to nominal voltage conditions

The figure below shows the new SoC curves obtained by this charging strategy:

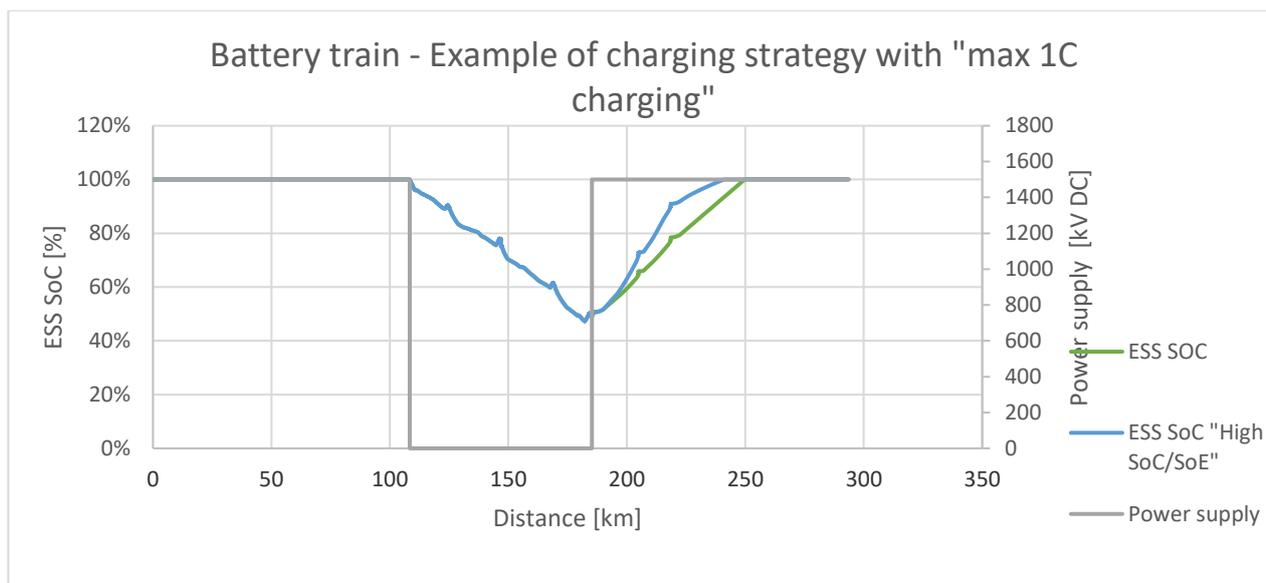


Figure 51: Battery train with charging strategy to reduce charging thermal temperature (max 1 C-rate)

According to this new charging strategy, a reduction from 43% to 8% has been achieved of the charging time over 1C, inducing lower temperature inside the batteries, preserving the lifetime, while reducing the auxiliary consumption of the battery thermal management system for the cooling purpose. On this use case, the impact of this charging strategy is really low concerning operation, with an additional 10 km to reach the maximum SoC value (equivalent to 4 min additional time). There's still an important margin (around 50 km) until the end of the service, therefore, a more optimized charging strategy can be use.

This type of strategy shall be tested on different kind of use cases to determine if this charging control profile can be compliant with operational requirements.

In terms of standardisation, it's impacting the energy management function "BEMU charging". Following additional requirement can be proposed:

Topic	Classification *	Requirement	Rationale
Optimized charging		Data characteristics from infrastructure and operational and current vehicle speed and ESS SoC/SoE shall be sent to the ESS control system to manage the charging strategy	To send appropriate data to create on-board management of ESS charging power, considering the prediction of energy consumption.
Optimized charging		The charging power strategy of the ESS shall prioritize the reduction of power, while ensuring the ESS SoC/SoE compliance with the mission profile or journey profile	Reduction of charging power will support slower ageing, as well as other benefits such as low BTMS consumption, lower loss on catenary line, etc.

Table 31: Additional requirements for optimized charging with "BEMU charging" energy management function

5.1.1. Optimization of the Battery Train Charging With Respect to Energy Costs

From energy costs perspectives, charging strategies can influence the energy billing, depending on the price of energy when the charging is proceeded. The fluctuation of energy price shall be an input parameter of the charging strategy to optimize the process accordingly. Many studies on this optimization strategy were published for electric car chargers or electric buses fleet.

Typical input data needed for this strategy are:

- Charging location,
- Energy consumption of the vehicle,
- Price of electricity over time.

This strategy will be studied in the next period.

5.1.1. Optimization of the Battery Train Charging With Respect to grid production (Rail2Grid)

As explained previously, the evolution of renewable energy production will create a more discontinuous power production profile. The management and storage of energy will be fundamental to response to loads demands. Based on a similar concept from the car sector, known as vehicle to grid (V2G), railway might be an additional player of the energy ecosystem to support the balance between demand and answer. This requires developing a completely new architecture, based on charge and discharge control of the on-board batteries of railway vehicles. Some studies have been published over past few years to demonstrate the benefits of such concept (Aruto Watanabe, 2024).

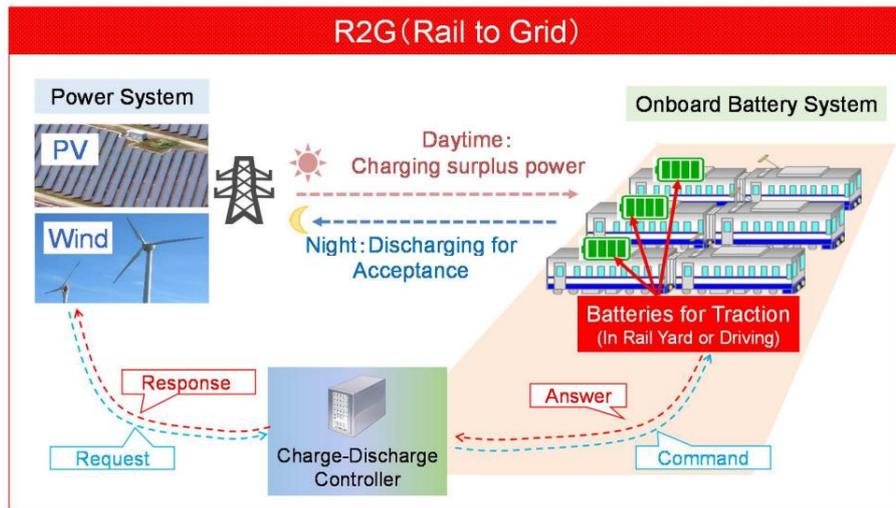


Figure 52: Schematic overview of R2G by RTRI Japan

More detailed study will be done during the next period.

6.3 Preconditioning of Vehicle and ESS

6.3.1 Current situation of preconditioning of vehicle

As described in the chapter related to energy management functions, the existing preconditioning function of railway vehicles is not optimized for alternative drive trains. A look at the typical curve of preconditioning of a train to have a better understanding of this issue. On the figure below, the interior temperature (2) evolved over time (1). First, the train stop, and the interior temperature is set for condition in operation but without passengers on board (9). During this first phase (10), the train is “In service without commercial operation mode”. When the parking mode starts (3), the interior temperature can decrease due to the stopping of the heating system. This management is representing the “eco-parking mode” explained in a previous chapter of this document. During this second phase (11), the interior temperature will vary, depending on several factors, such as external temperature, solar radiation, train car-body insulation, etc. The interior temperature can drop up to a minimum value defined (8). If this minimum value is reached, the HVAC system is activated to maintain the interior temperature, in a third phase (12). When the request of preconditioning is activated, it switches to a fourth phase with heating system powering to warm the interior temperature up to the value defined for defined for train condition “In service without commercial operation mode” (9). To achieve this temperature target, the HVAC system dimensioning is crucial to secure this objective in the expected duration (generally given by train operators, between 30 and 60 min).

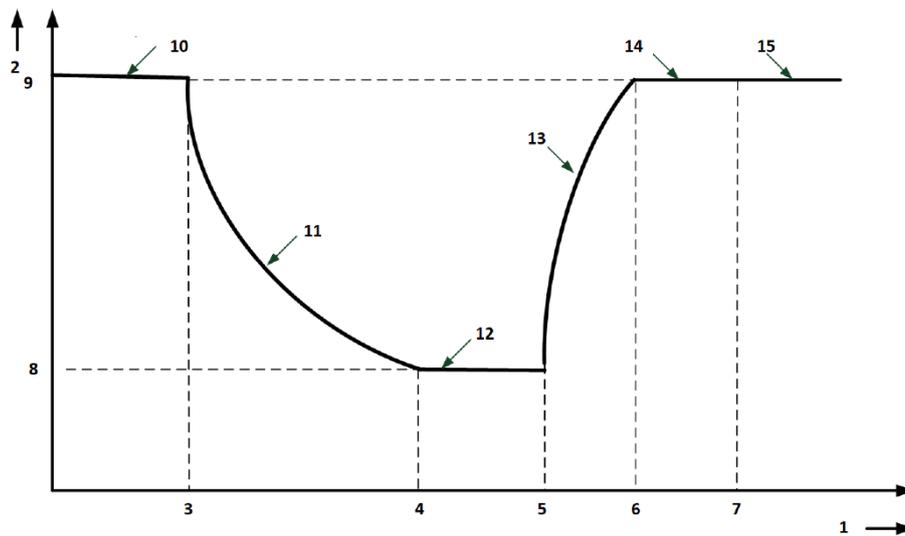


Figure 53: Train pre-conditioning (pre-heating) curve of interior temperature function of time (based on IEC 63593)

Whereas the current preconditioning of train vehicles does not consider the energy source and its potential limitations (in terms of available energy on the one hand, but on the other hand, in terms of available power to deliver). Therefore, a link between the vehicle's preconditioning function and the energy storage system control is strongly recommended. On the following figure, an estimation of the impact of vehicle preconditioning on the on-board energy capacity is stated. When arriving at terminus station on the non-electrified section, the battery train keeps the auxiliary supply activated in parking. This is necessary to allow time for passengers to get off the train and for the driver to finalize safety checks before switching off the train. A duration of at least 7 minutes is considered for this calculation. For the simulation, it was not efficient to calculate while train off, so the calculation starts directly as if several hours spent in real conditions. As the train is not energized anymore, internal temperature will increase and decrease, depending on external temperature conditions. On the selected battery train for this analysis, the HVAC design has been developed for 30 min maximum preconditioning. So, a phase of 30 min maximum preconditioning is introduced in the simulation. The values of electrical power of auxiliary loads and of preconditioning of the vehicle have been resumed the table below:

France BEMU train 1st gen (4-cars)	Value	Units
Average auxiliary power assumption	75	kW
Maximum auxiliary power assumption	150	kW
Maximum preconditioning duration	30	min
Maximum preconditioning power	300	kW

Table 32: Preconditioning and auxiliary load power for France BEMU 1st gen train

These values are consistent with previous studies on HVAC and auxiliary loads energy

consumption (FINE2, 2023). Based on this table, the following figure has been produced to evaluate the impact on energy consumption and on-board capacity during the operation.

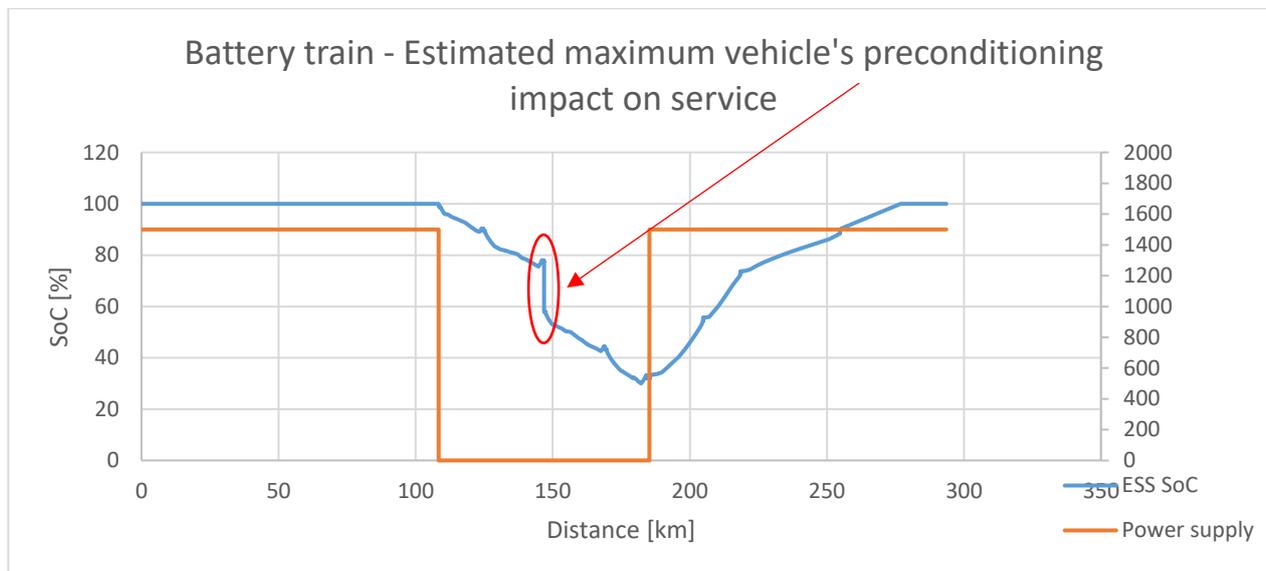


Figure 54: Impact of train's preconditioning on the operation of a battery train

On this scenario, the energy consumption during parking on the non-electrified terminus station represents 19% of SoC. The first 2% of SoC is used for supplying the auxiliary load when arriving at terminus station (7 min duration as explained before). The second part with the vehicle's preconditioning phase is the most energy demanding. Consequently, the DoD of the batteries moves from 51% to 77%, affecting the battery lifetime related to cycling by a reduction of 66%. From an operational point of view, the energy consumed during standstill, mainly for the preconditioning of the train, is also limiting the margin in case of events on the line.

So, a smarter management of train preconditioning is recommended after this analysis.

A specific preconditioning strategy for alternative drive trains by considering on-board energy capacity in the preconditioning process is key to ensure good conditions for the next commercial service.

This strategy can be used as well for conventional trains, to preserve infrastructure. On existing infrastructure, by reducing energy consumption and the power level of the preconditioning. For new infrastructure, especially dedicated to non-electrified station, it may allow significant cost reduction by avoiding high voltage substation and overhead lines, if the preconditioning of the train can be supplied by an external shore.

Additionally, there's requirements related to noise emission during parking in city center. Preconditioning strategy can be adapted to have a smoother preconditioning to limit "full speed" of the HVAC system and therefore, important noise emission.

Another alternative is to install a shore supply for energy supply of the auxiliary loads of the train. As described in the chapter related to energy management functions, the shore supply can deliver an intermediate power level at 400V AC 3ph. Based on common requirements, the performance of EN 50546 plugs can reach around 85 kVA. Therefore, several plugs might be

necessary to be able to deliver the power requested for the preconditioning, or to limit the preconditioning power, but impacting the duration and the operational management.

6.3.2 Preconditioning analysis for Northern Europe

Battery vehicles have specific challenges in Nordic countries related to the climatic conditions that occur during a considerable part of the year. When parking, idling, or stabling, trains are typically standing still for minutes or hours in an open environment, so train and OESS conditions will be those of the environment while needing to ensure acceptable internal climate when operation starts.

For lower temperatures, the maximum charge of the batteries can be significantly reduced, and charging speed can also be affected. Apart from the technical challenges there are operational ones too, as the energy needs to be used for heating purposes (defrosting, HVAC) while in diesel trains heat losses can be used for this, see Deliverable 5.1 section 7.3. “Optimization of the usage of the thermal energy” (Fernandez, 2023). Thermal preconditioning is of course intertwined with the more general thermal energy usage aspects but are especially critical when considering that the approximate percentage of time of different trains in service is around 30%, with the rest of the time in parking or stabling situations (Vinberg E. M., 2018).

Existing battery cells typically used in road EVs have an allowed temperature range from approx. -40 °C to 60 °C, but to maximize their life, capacity, and overall performance the suggested operating temperatures range is between 10 °C and 35 °C. To achieve this, Battery Thermal Management System (BTMS) are used, which manages the heat generated in the cells for the battery to operate efficiently. Most of these systems are targeting safety related issues like overheating, and not that much the thermal preconditioning of batteries before vehicle operation.

When specifically considering battery preheating for low temperature operation, there are recent publications on the existing techniques and solutions (S. Wu, 2020) which can be classified as Internal and External Heating techniques. While for External heating there is always a need for a connection to additional components on the infrastructure side, Internal heating can be performed while not connected to any heating or electric infrastructure, while also still being able to connect to additional components for increasing the external energy input in the vehicle before operation.

For vehicle preheating considerations in the system energy optimization, there is a limited number of publications studying energy use of stabled or parked vehicles. For metro systems, heating has been found to account for 11% of the total energy consumption of vehicles (J. P. Powell, 2014). For intercity services in Sweden, the estimations of auxiliary energy usage vary between 19% in summer and 30% in winter (Vinberg E. M., 2018). Independently of the technical systems proposed for vehicle environment preheating, the operational cycles including parking, idling, and stability need to be considered.

From an energy optimization perspective, there are different interesting analyses to be performed:

Balancing battery performance with increased energy due to battery heating: optimal operational temperatures affect the battery chemical processes, and thus maximum storage levels, energy consumption, and more, leading to different energy use and train range optimization possibilities.

The possibility of connecting before starting operation or at intermediate operative stops allows for extra net energy that would not need to be utilized from the on-board ESS, be it for the preconditioning of batteries or the whole train. Different technical solutions will enable a variety of energy and thermal flows, affecting the optimal strategies in combination with different operational cases.

Battery and vehicle preconditioning are then key features for vehicles to have, especially in the Nordics. TRV and KTH plan to perform preliminary needs analysis for the Nordic countries, and these Energy Functions will be modelled and implemented into their own simulation tool as a key feature, together with Power Peak Shaving EFs.

6.4 Auto Adaptative Train Energy Consumption Functions

At first, a proposed definition of “auto adaptive energy management function”, as no one has been defined previously according to standardization documents reviewal. It’s important to note that 2 parts must be considered:

- 1) “Auto adaptative”, can also be called “Self-adaptive”, means to be able to adapt automatically
- 2) “Energy management function”, as described previously, energy management function managed by a command.

So, the definition suggestion is “Function used on a vehicle and on infrastructure with the objective to reduce energy consumption, while being able to automatically adapt to change operational/environmentally conditions (or boundaries). Function can be based on different approaches, such as rule-based, learning-based or hybrid, to manage the performance to achieve the objective.”

Auto adaptative functions are already existing in railway applications and more globally to the mobility sector. Rail/wheel adhesion control is a typical example of auto adaptative function. This function is described by previous study, such as Shift2Rail “The Slip control system reacts preventing the total blockage of the axles and possibly bringing each axle into a controlled sliding situation until the best recovery of the available adherence” (Matteo Frea, 2019). In other transportation mode, a very well-known auto adaptative function is the adaptive front light system for road vehicles. This function allows to automatically adjust the front lights of the vehicle to compensate road curves, improving the visibility for the drivers. The simplified scheme made by car manufacturer Nissan bellow explain the principle of this auto adaptative function:

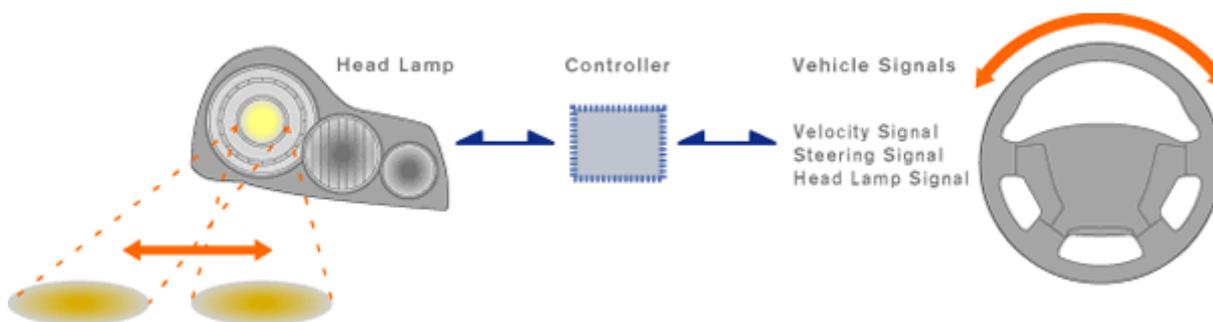


Figure 55: Auto-adapting front lightning system by car manufacturer NISSAN

Regarding auto adaptative functions related to energy saving, the first step is to analyze the table of energy management functions identified in RAIL4EARTH project.

No	Energy Function	Auto adaptative Energy management function
1	Eco-parking mode	Yes, if connected to a weather database, eco-parking mode can adapt the regulation to control the interior conditions.
2	Preconditioning of passenger compartment	Yes, if the vehicle's preconditioning is adapting his power and/or duration automatically, based on conditions such as external temperature or on-board energy available.
3	Preconditioning of battery	Yes, if the batterie's preconditioning is adapting his power and/or duration automatically, based on conditions such as external temperature or on-board energy available.
4	BEMU charging	Yes, the battery train charging can be auto adaptive. For example, if the battery charging is adjusted to the route profile or mission profile, it's naturally changing the charging power level depending on predictive load profile
5	Driver advisory system	Not in case of Stand-Alone DAS (S-DAS). Yes in case of Connected DAS (C-DAS). C-DAS is calculating and providing adapted speed profile to optimize the trains traffic, while reducing the energy consumption. The speed profile is updated automatically according to several parameters likes train characteristics (load condition, tractive performance, etc.), train traffic conditions, signaling, etc.
6	Shore parking energy supply	Not auto adaptative
7	Lift & drop of pantograph	Not auto adaptative
8	ESS protection and diagnostics	Not auto adaptative
9	Train driver information	Not auto adaptive for some train driver information. Range calculation can be auto adaptive if predictive (e.g. variation of the range according to current load conditions or auxiliary load consumption).
10	Peak-shaving	Yes, if peak-shaving is managing dynamically the loads according to a predefined strategy.
11	Optimized regenerative braking	Yes, if optimized regenerative braking is based on variable parameters to prioritize on-board regenerative braking (e.g. SoC window keep free for future braking and regenerative energy is changing depending of predictive regenerative braking to save or varying due to current temperature level or ageing of the batteries)

Table 33: Analysis of RAIL4EARTH energy management functions list for compatibility to be auto adaptive

Additionally, other auto adaptative energy management functions are used in railway, such as:

- CO2 sensors for HVAC control → Automatically adapt the HVAC power according to the number of passengers into the rolling stock.

- Automatic Train Operation → Automatically adapts the speed of the vehicle depending on several parameters to ensure the safety of the operation, while optimizing the energy consumption,
- Lights intensity → Automatically adapts the interior lights intensity depending on the external conditions,
- Etc.

Leader: SNCF; Contributors: FSI, TRV

The study purpose is to evaluate different kind of solutions on alternative drive trains to determine the most optimized combination, based on system-level indicators. The objective is to define a methodology to compare solutions of alternative drive trains (e.g. Battery trains, Diesel-Battery trains, Hydrogen trains, etc.) on several scenarios and use cases. Based on this methodology, a comparison of different solutions to optimize energy performances and cost savings can be achieved.

7.1 Methodology approach

The objective is to develop a methodology to compare different solutions of alternative drive trains and their related systems (e.g., charging infrastructure, refuelling stations, etc.) in the preliminary phase. The methodology will have a systemic vision, considering rolling stock, infrastructure, and operational aspects.

The comparison primarily focuses on energy savings to define the best way to optimize energy consumption according to a given scenario. This type of study to compare energy consumption or CO2 emissions of different kinds of traction system technologies is more and more common (Kapetanović, 2024) (Buffarini, 2022). Complementary, the approach will also include other aspects such as cost and compliance with operational requirements.

As a first step towards introducing a standard methodology, the criteria are limited to energy, cost, and operations. The solutions to evaluate and compare will be described in the form of "use cases" and "scenarios." Use cases describe a real or virtual railway line associated with a type of operation (regional, suburban, intercity, etc.). These cases should be representative of other types of railway lines in a country or region. Scenarios, within each use case, allow for the examination of a specific condition. For each scenario, it is necessary to evaluate the impacts from operational, infrastructure, and rolling stock perspectives. All scenarios and associated impacts will be evaluated according to the defined methodology. The overall analysis of all scenarios will provide information on how much they influence the criteria defined in the methodology for system-level optimization.

The comparison will be based on simulations and calculations to produce the results.

Additionally, real data measurements may be used to support the accuracy of the estimations.

One of the major expected outcomes of the methodology is to define harmonized processes and references to create a fair analysis. A reference to current standards regarding energy consumption specifications and energy efficiency for railway applications. The contents of the Committee Draft (CD) of IEC 63593 "Specification and verification of energy consumption" and

IEC TS 63498 "System energy efficiency" are major inputs to develop such future standard methodology.

The estimations will be based on an annual period, extrapolating energy consumption over one or several cycles as a baseline and then combining with operational data to create energy consumption per day, week, and year, as well as cost (CAPEX/OPEX) and CO2 equivalent emissions. Regarding cost evaluation, consideration of costs at the vehicle and infrastructure level for the operational phase. Construction and recycling phases are not considered in the first step but may be studied in the future.

7.1.1 General criteria definition

In line with the systemic vision for this study, a proposal to define general criteria based on the three fundamental components of the rail system: rolling stock, operations, and infrastructure. Given that focus on alternative drive trains, the intention is to incorporate two additional criteria concerning the Energy Storage System technology and Energy/CO2 emissions.

For each criterion, sub criteria will be defined to deeply analyse the performances. According to sub criteria results, a criteria ranking will be created. From 0 (lowest score) to 10 (highest score), use case and scenarios will get a ranking on the 5 main general criteria. The summation of the scores of these criteria is giving the total general evaluation. Higher the total general evaluation is, better the performance of the solution is estimated. This total general evaluation score is providing a proposal to classify the different solutions analysed. The ranking obtain can be readapted depending on other prioritized criteria. For example, a use case with a major hurdle for infrastructure works, the scoring of "infrastructure criteria" should be changed to comply with this input condition.

7.1.1.1 Operational criteria

7.1.1.1.1 Operation Criteria

From operational perspective, the definition of 6 criteria on:

- Driving style → Driving style might be different depending on operational condition. There's typically 3 different type of driving styles: all-out, scheduled, eco. Each driving style has his own characteristics and will be detailed later in the report,
- Journey Profile Compliance → For every use case and scenario, evaluation of timetable is respecting along the route,
- Mission Profile Compliance → Evaluating compliance with various service types potentially utilized in transportation planning.
- Maximum duration of service stops → This criterion is linked with the minimum State of Charge observed during the load cycle. At this minimum point, an estimation of the maximum time to spend at standstill due to a service stop is produce. To calculate this duration, the difference of SoC between the minimum SoC value and lowest nominal value of SoC (0%). The value obtain is giving a quantity of energy available inside the batteries. Then, according to

the assumption of auxiliary load power, the conclusion on the time to allow for supplying auxiliary loads during abnormal operation stop can be found.

- Final Energy Consumption per Offered Transport (KPI given in IEC TS 63498 CD): Measuring final energy consumption per potential passenger transport, in kWh per seat-kilometre, considering fully occupied seats and standing passengers. This calculation is based on the final net energy consumption measured at the point of common coupling and offered transport as the number of seats times total train kilometres.
- Share of Energy Consumption during parking phases (KPI given in IEC TS 63498 CD): Percentage of energy consumption for trains in parking mode, calculated based on energy used at the pantograph point and final net energy consumption at the point of common coupling.

Use Case	Operation Driving style	Operation Journey profile compliance	Operation Mission profile compliance	Operation IEC 63498 CD KPI2 (Wh/seat.km)	Operation IEC 63498 CD KPI5 (%) Share of energy consumption for parked trains	Operation Duration of service stop	Operation General Evaluation
Use case & scenario (solution)	Scheduled = 1 pt All-out = 2pt	Compliant with journey profile = 1 pt (scheduled driving style), 2 pt (all-out driving style)	Compliant with mission profile = 1 pt (scheduled driving style), 2 pt (all-out driving style)	Compare to reference value with full electrification If below = 1 pt If higher = 0 pt	Compare to reference value with full electrification If below = 1 pt If higher = 0 pt	Duration < 0 min = 0 pt 0 min < Duration < 60 min = 1 pt 60 min < Duration < 120 min = 2 pt Duration > 120 min = 3pt	Between 0 - 10

Table 34: Operational sub criteria ranking proposal

7.1.1.2 Rolling stock criteria

From vehicle perspective, a proposal the definition of 3 sub criteria on:

- Vehicle Energy Consumption à Calculation of energy consumption over electrified and non-electrified sections.
- Vehicle Cost (CAPEX and OPEX) à Establishing the investment and maintenance costs over the vehicle's lifetime. Alternative drive trains are currently more costly than conventional diesel or electric multiple units, with a standard rolling stock lifetime fixed at 30 years.
- Vehicle energy management functions (e.g. automatic lift/drop of panto, peak shaving, etc.)
→ Considering potential energy management functions activation during the cycle, affecting the energy consumption and consequently the batterie's SoC,

Use Case	Rolling stock Vehicle Energy consumption	Rolling stock CAPEX	Rolling stock OPEX	Rolling stock Vehicle Energy Management functions	Rolling stock General evaluation
Use case & scenario (solution)	Compare to reference value with diesel traction by ratio between diesel traction energy consumption and use case / scenario energy consumption, Ratio < 1 = 0 pt 1 < Ratio < 3 = 1 pt 3 < Ratio < 4 = 2pt Ratio > 4 = 3 pt	Vehicle purchase cost compared to reference value for diesel train by ratio between diesel train and use case / scenario vehicle type Ratio < 1 = 3 pt 1 < ratio < 3,5 = 2 pt 3,5 < ratio < 5 = 1 pt Ratio > 5 = 0 pt	Vehicle maintenance cost compared to reference value for diesel train, ratio between diesel train maintenance cost and use / scenario vehicle type Ratio > 2 = 3 pt 1,5 < Ratio < 2 = 2 pt 1 < Ratio < 1,5 = 1 pt	Using energy management functions to save energy for improving the performance, No function used = 1 pt Function used = 0 pt	Between 0 – 10 pt

Table 35: Rolling stock sub criteria ranking proposal

7.1.1.3 Energy storage system criteria

For the Energy Storage System (ESS), three additional parameters will be used to evaluate scenarios and related ESS technologies:

- ESS Estimated Lifetime: Estimating aging based on the Depth of Discharge (DoD) throughout the cycle, evaluating full cycle equivalents per year.
- ESS Estimated Cost (CAPEX and OPEX): Considering aging and substitution costs for cost analysis.
- ESS Auxiliary Energy Consumption: The auxiliary components necessary for ESS operation affect the train's energy consumption and operational range.

Use Case	ESS Estimated lifetime (cycling)	ESS CAPEX	ESS OPEX	ESS Auxiliary energy consumption	Rolling stock General evaluation
Use case & scenario (solution)	ESS lifetime estimation based on cycling affect ESS lifetime < 5 years = 1 pt 5 < ESS lifetime < 10 years = 2 pt 10 < ESS lifetime < 15 years = 3 pt ESS lifetime > 15 years = 4 pt	ESS purchase cost compared to reference value for diesel engine by ratio between diesel engine and use case / scenario vehicle type Ratio < 1 = 3 pt 1 < ratio < 3,5 = 2 pt 3,5 < ratio < 5 = 1 pt Ratio > 5 = 0 pt	ESS maintenance cost compared to reference value for diesel engine, ratio between diesel engine maintenance cost and use / scenario vehicle type Ratio > 2 = 3 pt 1,5 < Ratio < 2 = 2 pt 1 < Ratio < 1,5 = 1 pt	ESS auxiliary consumption power compared to train level auxiliary power Ratio < 10% = 2 pt 10% < Ratio < 25% = 1 pt Ratio > 25% = 0 pt	Between 0 – 10 pt

Table 36: ESS sub criteria ranking proposal

7.1.1.4 Energy and CO2 criteria

For energy criteria, the recommendation is to consider two parameters:

- Energy Price: The cost per unit of the energy source.
- CO2 Equivalent Emission Factor: Dependent on the energy source type, values should be selected according to European / national references (EEA, Greenhouse gas emission intensity of electricity generation, 2024) or specified by train operators or energy purchasers (SNCF VOYAGEURS, 2024) (Deutsche Bahn, 2025)

Use Case	Energy Energy price	CO2 equivalent emission factor
Use case & scenario (solution)	Energy price calculated from the infrastructure energy consumption. Energy price is compared to the reference value with diesel energy by a ratio Ratio < 25% = 5 pt 25% < Ratio < 50% = 4 pt 50% < Ratio < 75% = 3 pt 75% < Ratio < 90% = 2 pt 90% < Ratio < 100% = 1 pt Ratio > 100 % = 0 pt	CO2 equivalent emission calculated from the infrastructure energy consumption and according to CO2 equivalent factor, depending on the type of energy used. CO2 equivalent emission is compared to the reference value with diesel energy by a ratio. Ratio < 1% = 5 pt 1% < Ratio < 2% = 4 pt 2% < Ratio < 4% = 3 pt 4% < Ratio < 8% = 2 pt 8% < Ratio < 24% = 1 pt Ratio > 24% = 0pt

Table 37: Energy and CO2 sub criteria ranking proposal

7.1.1.5 Infrastructure criteria

Regarding infrastructure, key criteria are essential for proper comparisons, especially if new infrastructure is required to meet use case requirements, considering financial impacts. Five criteria are suggested:

- Infrastructure Electrical Energy Consumption → The final net energy consumption at the point of common coupling, defined as inflow minus outflow from the entire railway system. This sub criterion is based on IEC CD 63498.
- New Charging Infrastructure → Identifying the need for new charging facilities.
- New Charging Infrastructure Type → Classifying types of charging infrastructure, such as stations, electrified islands, partial electrification, and others for trains with on-board energy storage, or stationary, mobile, on-site stations for refuelling trains.
- New Charging Infrastructure Total Cost (CAPEX and OPEX) → Estimating the total cost of new infrastructure, including purchase, installation and maintenance.
- New Charging Infrastructure Lifetime → Estimating the lifespan of charging infrastructure using state-of-the-art studies, such as those from Clean Hydrogen Partnership regarding hydrogen refuelling stations.

Use Case	Infrastructure Energy Consumption	Infrastructure New charging infrastructure	Infrastructure New charging infrastructure type	Infrastructure New charging infrastructure cost (CAPEX)	Infrastructure New charging infrastructure cost (OPEX)	Infrastructure New charging infrastructure lifetime
Use case & scenario (solution)	Infrastructure energy consumption compared to reference value with diesel traction (for diesel, same value of energy consumption between rolling stock and infrastructure is used). Ratio < 2 = 1 pt Ratio < 4 = 2 pt	If new charging infrastructure is needed, therefore several impacts to be considered (cost, planning, etc.) No new charging infrastructure = 2 pt New shared charging infrastructure = 1 pt New dedicated charging infrastructure = 0 pt	Classification of charging infrastructure	Estimation of acquisition cost of the charging infrastructure, reference cost is the diesel refueling station Ratio < 25% = 0 pt 25% < Ratio < 50% = 1 pt Ratio > 50% = 2 pt	Estimation of the maintenance cost of the charging infrastructure, reference cost is the diesel refueling station Ratio < 25% = 0 pt 25% < Ratio < 50% = 1 pt Ratio > 50% = 2 pt	Estimation of the useful life of the new charging infrastructure compared to diesel refueling station Ratio < 1 = 0 pt 1 < Ratio < 2 = 1 pt Ratio > 2 = 2 pt

Table 38: Infrastructure sub criteria ranking proposal

To calculate the cost of additional infrastructure, a look on the estimation of charging infrastructure cost is needed. According to previous publications, such as Verband der Elektrotechnik, Elektronik Informationstechnik e. V. (VDE) (W.Klebsch, 2020) data related to CAPEX and OPEX costs for the different kinds of technologies (diesel, hydrogen, battery, electrification) have been collected. The working group check the assumptions with other publications and articles to define common data base for the evaluation. For example, on the electrification costs, several papers such as scientific paper (Streuling, 2021) or thesis on



electrification (A.Verdicchio, 2019).

7.2 Simulation Tool

7.2.1 SNCF Simulation Tool “SIM3PO”

SNCF simulation software named SIM3PO for “Simulation d’Infrastructure et de Matériel roulant au sein d’une Plateforme Polyvalente pour des calculs de Performance et d’Optimisation », translated as “Simulation of infrastructure and rolling stock inside a polyvalent platform for performances and optimisation calculations”. This tool gives the ability to simulate the energy consumption of rail vehicles according to different parameters (driving styles, characteristics of the rolling stock, etc.) inside a single platform including different libraries, functions, and models. SIM3PO tool is founded on 3 numerical tools:

- MATLAB/SIMULINK for the modelling and simulations,
- Gitlab for the management of the models and libraries revisions, including also a wiki, logbook for the validation of the models, studies review, etc.
- SharePoint used to save, organize and share information, with a list of projects with all related documents.

The simulation tool is based on an “Forward” approach, able to consider the potential limitations of vehicle or the degraded modes and check the impacts on the performance (acceleration, speed, time duration, etc.). From the power energy source “infrastructure” to the running speed of the train, the modelling is considering the physical limits of the traction system. Different algorithms have been set up for the driving style:

- All-out drive: Maximum traction and braking efforts of the vehicle is used while respecting the speed limitations of the infrastructure. Objective is to achieve the shortest running time,
- Scheduled driving: Respecting the transit point defined along the line, without any objective to optimize energy consumption,
- Eco driving: Respecting the transit point defined along the line, this driving style looking for energy consumption reduction, such as coasting,
- Speed follow-up: Used to reproduce a speed profile reference, from a train measurement or from a DAS or ATO definition.

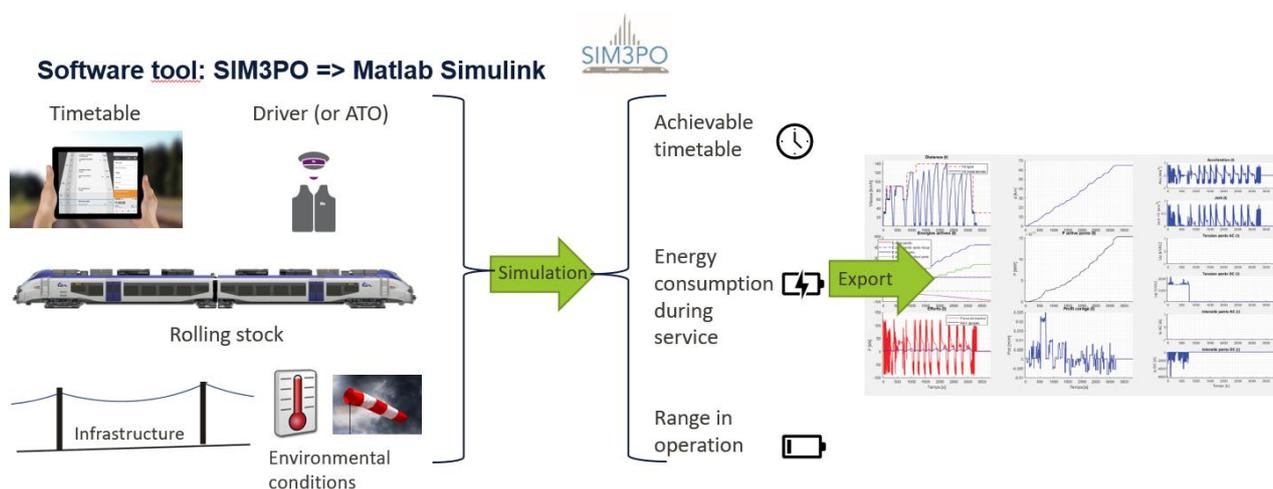


Figure 56: Simplified scheme of SIM3PO simulation tool.

SIM3PO simulation tool is also based on a modular architecture. The setting for each component is established on an object approach and also an library (including physicals and controls elements). With this approach, it is simpler to build train model by reusing previous modelling blocks from other train projects into the simulation tool. The figure bellows representing an example of libraries available in SIM3PO tool:

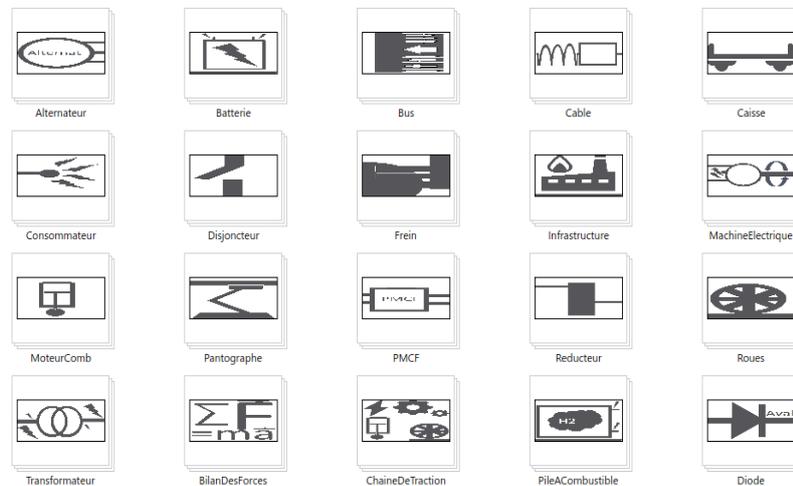


Figure 57: Libraries for rolling stock in SIM3PO tool

7.2.2 KTH Simulation Tool “Rail Vehicle Energy Calculator”

KTH simulation tool “Rail Vehicle Energy Calculator” is a MATLAB based simulation tool used to calculate the power and energy consumption of a rail vehicle traveling along a defined track. The user can characterise the simulation by defining various input parameters including the train’s characteristics, traction chain efficiencies maps, auxiliary power demand, track gradients and curves, driving style, and station locations etc. The tool can also simulate a mix of driving styles in the same simulation, by varying the percentage of traction, mechanical braking and regenerative braking utilised per track section, as well as applying coasting. Additionally, the user can define several constraints such as limitations due to comfort and available adhesion, timetable, track speed limit, maximum braking forces and regenerative brake limitations. To simplify the user input and computational burden, the tool also includes two additional pre-processing functions to aid in defining track breakpoints based on track gradient and speed limit, and to define curve equivalent radii.

The tool treats the train as a point mass object and computes the energy consumption using backwards computation from wheel via traction chain to energy source (catenary or battery), discretising the simulation based on distance step (can be user defined). For each discrete step the tool computes the instantaneous speed, torque, power demand, braking power and running mode. The computed results are post-processed and the results such as speed, torque, and power profiles as well as net and gross energy is exported to the user.

The tool has been developed for applications targeting energy related questions within railway

research. In its current version it includes both catenary and battery power train topographies, but it is possible to further develop the tool to cover other energy sources e.g. fuel cells.

7.3 Use Cases and Scenarios

In this chapter, the definition of use cases and scenarios for the optimization of energy at system level are presented.

Use cases is the description of a real or virtual railway line, linked with a type of operation (regional, suburban, intercity, etc.). The use cases should be representative to other kind of railway lines of a country or from a region.

Scenarios are defined for in each use case to evaluate a configuration of one or several solutions. All scenarios will be evaluated according to the methodology described in the previous part of the report. The global analysis of all scenarios will give a tendency and so, supporting the decision of appropriate technology.

A list of use cases and scenarios will be created continuously during the WP1 project. For France, a first use case of a regional uphill/downhill line will be described and analyzed.

For Sweden, TRV and KTH plan to study cases interesting for the Nordic countries. The proposal is to study partially electrified lines where a certain percentage of the track is electrified with conventional catenary, and the rest is not electrified. Then studies including end point charging, fast charging points, etc. vs. battery size will be performed, including also some selected energy functions like PPS and preconditioning. Specific situations centered around extreme temperatures or climatic conditions will also be proposed. Interesting cases are being identified at the moment.

7.4 Analysis and Comparison of the Results

7.4.1 Use case “France Regional Uphill/ Downhill line” (UC1)

The first use case (UC1) description is based on France regional service, with an uphill/downhill line proline. The length of the route is 35,6 km, and his electrified from the starting point in station A until 2,5 km. The voltage supply is 1.5kV dc in this scenario. The gradient is important on the uphill way, with a value of +5,2 mm/m, and so negative on the downhill way, - 4,6 mm/m. For the operation, there're 7 intermediate stops along the line, with an average distance between station of 4,4 km. The shortest distance between station is 1 km (between station B & C), and the longest one is 11,1 km (between station H & I). In each station, a stopping time of 1 min is used.

Station	Distance between station
A	0,0
B	3,5
C	1,0
D	2,0
E	2,6
F	4,8
G	6,9
H	3,9
I	11,1

Table 39: Distance between stations on France UC1

Based on the previous table, all intermediate stations are on the non-electrified zone of the line. Therefore, battery train shall be able to supply auxiliaries loads during the stopping time. The figure bellows shows the corrected gradient profile (blue curve) in mm/m unit, the electrification section (orange curve) and the stations on the line (grey dot).

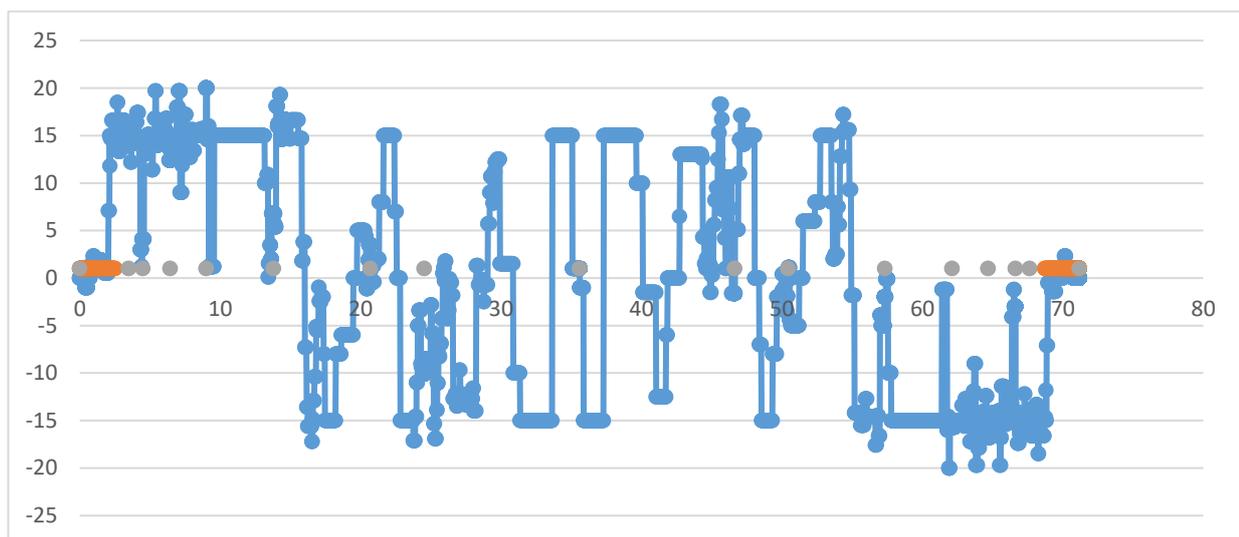


Figure 58: Uphill/Downhill line profile characteristics, including electrification and stations.

The reference to compare for the scenario based on alternative drive trains and their related system will be a diesel multiple unit (DEMU). The vehicle characteristics are as following:

	UC1 Diesel Train reference characteristics
Number of Cars	4 cars
Maximum Speed	160 km/h
Traction power (catenary)	1.8 MW

Traction power (diesel)	1 MW
Voltage supply	25kV AC + 1.5 kV DC
Diesel Engine Power	600 kW
Number of Diesel Engine per train	2
Auxiliary power (high/cold external temperature conditions)	150 kW
Auxiliary power (average external temperature conditions)	75 kW

Table 40: Characteristics of reference DEMU for regional operation in France

According to this use case and infrastructure and operational conditions to apply, the following general evaluation has been obtained based on the different criteria:

Use Case	Operation General Evaluation	Vehicle General Evaluation	ESS General Evaluation	Infrastructure General Evaluation	CO2 Emission General Evaluation	Total General Evaluation
UC1 – FR / DMU & No electrification	9	9	1	1	1	21

Table 41: Use case 1 - Reference Scenario general evaluation table

7.4.2 Use case 1 - Scenario 1 “1st Generation Battery Train in Operation, with existing infrastructure and operational conditions”

This first scenario will be focused on a 1st generation of battery train. By 1st generation, it means a BEMU based on mass production battery technology and so available on the market. Concerning infrastructure and operations, the current conditions will be applied to check if 1st generation battery train can be suitable without any modifications on these 2 aspects.

Operational impact analysis:

The first sub criterion is on the driving styles. All-out driving style means the requirement to run along the line in the shorter time condition, while respecting speed limits and according to maximum traction and braking power performances. Consequently, energy required for the vehicle is important to reach maximum speed. The “cruising driving” is another type of driving style. This style is more representative of normal driving conditions. The train is driven with the objective of being on time at each defined points on the route. Defined points could be train stations when the train stops, or area along the line, such as switches between single and double tracks.

An evaluation of the impact on the driving styles for the 1st use case and 1st scenario is given below:

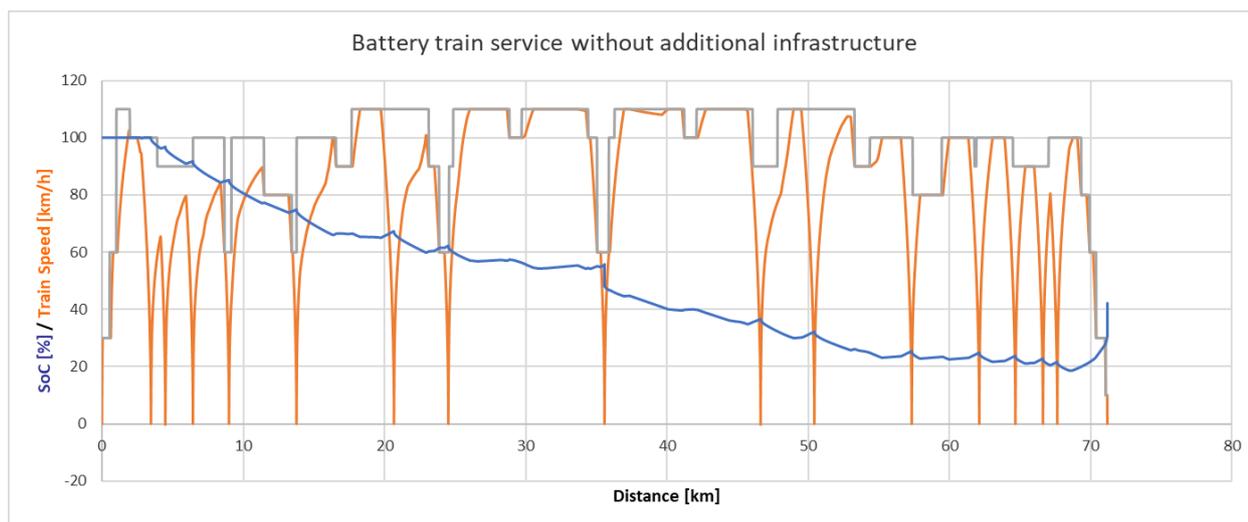


Figure 59: 1st gen regional battery train service in all-out driving, without additional infrastructure

In these conditions, the SoC drops at the end of the uphill route from 100% to 56% (-44%), after a trip duration of 38 min. The train is using the electrified section at the departure station A and then switch from electric to traction battery mode at 2,5 km. In this scenario, an assumption of signalling display on-ground to inform the train driver about the end of the electrified sections is considered. The train driver can switch the energy supply mode of the rolling stock from

catenary mode to on-board traction battery mode, while running. To prevent time reaction of the driver between the signalling and the end of the electrification of the line, an estimated loss of 200 m is considered. During the running, when train brakes, the regenerative energy can be stored into the traction batteries. Therefore, SoC increased at each braking phase, so typically at each stopping station.

In this scenario, the end station is not electrified, so energy from the traction batteries shall be used during the turnaround time to supply train auxiliaries for passenger's comfort and traction devices. The turnaround time duration is 13 min and the SoC reduced from 56% to 48%.

After this stop, train goes back downhill, with same stops than the one-way. The energy requested is lower than the uphill way, so the SoC decreased up to 18% (-30%), until to find back the electrified section, and so lift-up the pantograph to switch from battery to catenary mode and start to recharge the batteries at the same time. The trip duration is 37 min, in the same order of the uphill travel time. During the running of 2,5 km in catenary mode, the battery SoC moved from 18% to 31% in 3,5 min. Thanks to high power battery DC/DC converter, and because of train running, with higher current limitation level from the infrastructure (compared to current limitation at standstill), the charging time is reduced.

The cycle ending in station A, under catenary, with a turnaround time of 16 min. The battery can be recharged, but with lower charging power due to current limitation at standstill (in 1.5kV DC voltage, the maximum current at standstill is 300 A DC). The state of charge reached 42% at the end of the turnaround time, almost half of the SoC at the departure of the cycle. The conclusion is the incompatibility of these conditions to repeat cycles along the day on this line.

Use Case	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance / Shuttle service	Operation Journey profile compliance / Other service	Operation Duration of service stop	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 – FR / BEMU 1 st gen & No additional infra	All-out	Yes	No	-	51	1st gen BEMU	19%	-110%	42%	No	739,2	-	-	-	No

Table 42: France UC1 - S1 - Comparative criterion synthesis for all-out driving Operational impact

Now an observation of the effect of respecting the timetable given for commercial service on the line. On the uphill way, the time required is 46 min (+8 min compared to all-out drive). Train stops 1 min at each intermediate station on the line and the turnaround time at the end station is 13 min in station I and 16 min in station A at the end of the cycle, so same as previous simulation in all-out driving. After this turnaround time, train going back on the downhill way. The time for the downhill way is 43 min (+6 min compared to all-out drive).

The scheduled driving style based on a calculation to optimize the running speed of the train to reduce energy consumption. The strategy compares the margin between the minimum time to run, so the all-out time, and the time require in the timetable. At least, margin is calculated between each train stations where the train shall stop. But most of the time, additional points, so called “gate”, are defined along the line with time requirement to comply. These points can

be linked to the tracks or to signalling and are necessary to ensure traffic compliance with other trains. The margin is allocated between the gate to reduce the speed and obtain a low average speed.

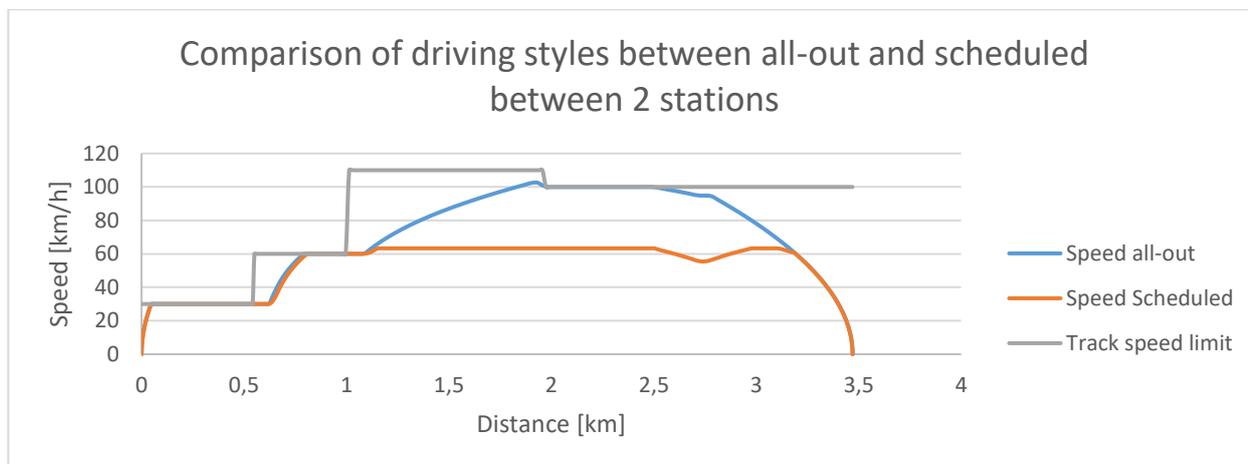


Figure 60: Comparison of driving styles between all-out and scheduled driving on the line between station A and B

This lower average speed gives a smaller amount of energy consumption of the train. The figure below shows the effect of this optimisation strategy of driving between 2 stations (A and B) with a reduction of the average speed of -15%.

An analysis of the results on the full cycle is done. On the uphill side, the train is respecting the required time of 46 min. The SoC drops from 100% at the departure station A1 to 60% when train's stop at station A9. On the downhill side, the time reached is 43 min, so compliant with the timetable. After losing 5% of SoC during the turnaround in station A9, the SoC fallen to 44% when arriving the station A1 and after charging during turnaround time, final SoC value is 58%. The SoC minimum value is 29%, just before switching from battery to pantograph mode on the way back to station A1.

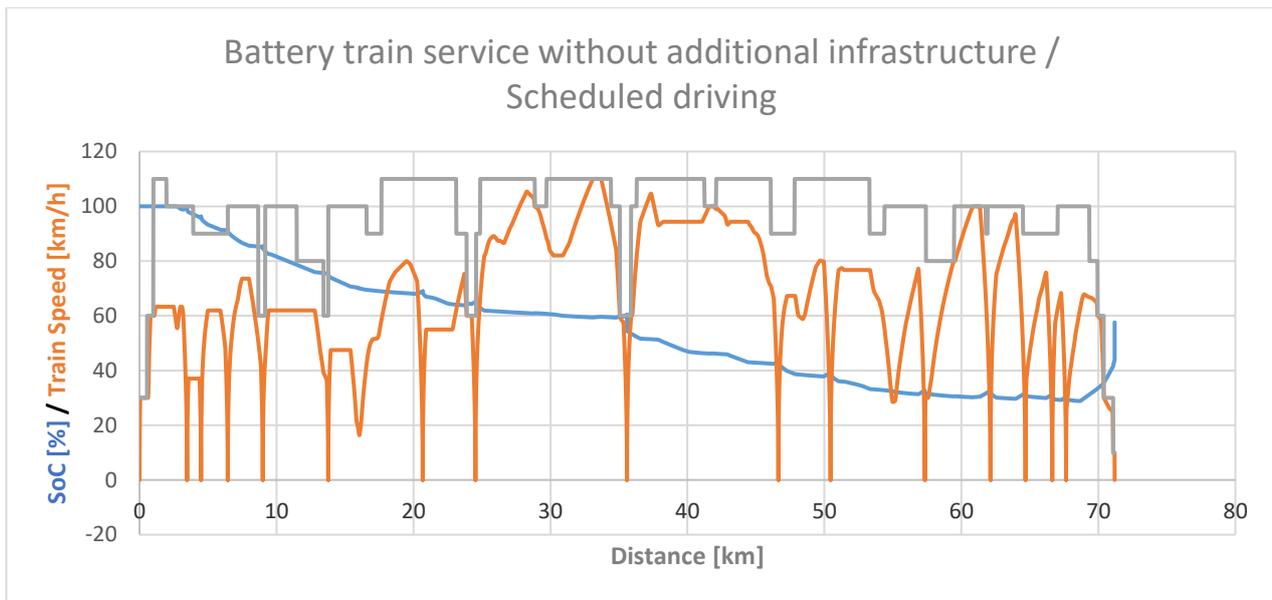


Figure 61: 1st gen regional battery train service in cruising driving, without additional infrastructure

Use Case	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance / Shuttle service	Operation Journey profile compliance / Other service	Operation Duration of service stop	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 – FR / BEMU 1 st gen & No additional infra	Scheduled	Yes	No	-	78	1st gen BEMU	29%	-73%	58%	No	490,56	-	-	-	No

Table 43: France UC1 - S1 - Comparative criterion synthesis for Scheduled driving impact

Turnaround time and mission profile:

As seen previously, the operational and infrastructure conditions are limiting the potential new cycle on the same line. So, adjustments of turnaround time and journey profile can be necessary to recharge the batteries for future service.

The first adaptation is on the turnaround time. By adding extra time, the train can continue to recharge the batteries. The main issue is to quantify how much energy shall be recharge for next service. If no value is defined, the worst case is to charge until the maximum SoC of the batteries. On the example given here, the battery can be charged at standstill under 1.5kV dc voltage. As the allowable maximum current at standstill is 300 A dc, it means 450 kW power to supply the vehicle. Whereas other train loads must be supplied and so required power. The 1st generation battery train selected here is a 4 cars trains, with an estimated average auxiliary power of 150 kW. In this condition, 1/3 of the maximum power is taken for the auxiliary loads, so it's limiting the charging power for the batteries and therefore, involving longer time to recharge. The figure bellows shows the duration to reach full charging.

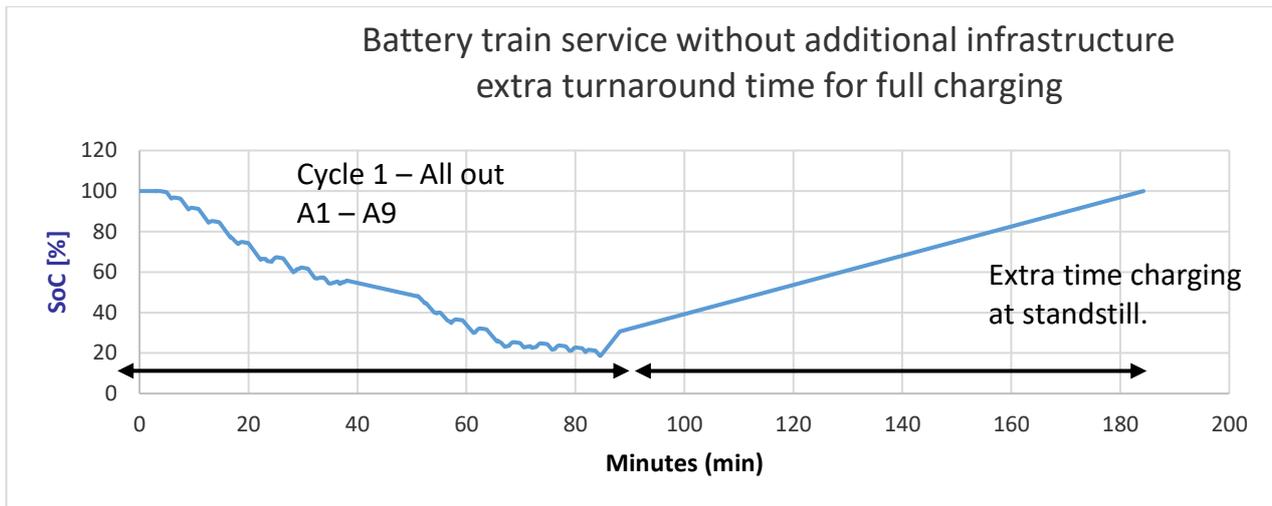


Figure 62: Evolution of SoC based on time duration of the cycle in all-out drive, with extra time for charging.

An extra time of 96 min is necessary to charge at 100% the batteries. This duration is longer than the duration of the full cycle in operation with all-out driving style (88 min). So, the limited performance of the charging at standstill under 1.5kV dc is very restrictive for the operation. It can oblige train operator to purchase more rolling stock to ensure the train traffic on the line. Therefore, extra cost for the operation is mandatory and can be a decision factor for the train operator.

Use Case	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance / Shuttle service	Operation Journey profile compliance / Other service	Operation Duration of service stop	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 – FR / BEMU 1 st gen & No additional infra & Extra time charging	All-out	Yes	Yes	-	51	1 st gen BEMU	19%	-110%	100%	No	739,2	-	-	-	No

Table 44: France UC1 - S1 - Comparative criterion synthesis for Extra time charge & All-out driving impact

This constraint is linked to shuttle service mission profile of the battery trains. Whereas other types of mission profiles can be selected. In this scenario, an observation of the influence of continuing the service at the end of the cycle on another line. The uphill/downhill line is between station A1 and A9 as seen previously. From same station A1, another line “B” is originally partially electrified. This line starts by an electrified section of 10 km from station B1, then is not electrified along 45 km, and finally another electrified section of 16 km until the terminus station B15.



Figure 63: Simplified map of the 2 lines of France uphill/downhill line regional train service

Simulation of the 2 lines with a first cycle on the uphill/downhill line (station A1 to A9) and after a second cycle on the other line (station B1 to B15). The goal is to check if the performance of the 1st gen BEMU on the second cycle is compliant with the service requested and the given infrastructure. A total distance of 213 km will be covered in this simulated scenario of mission profile.

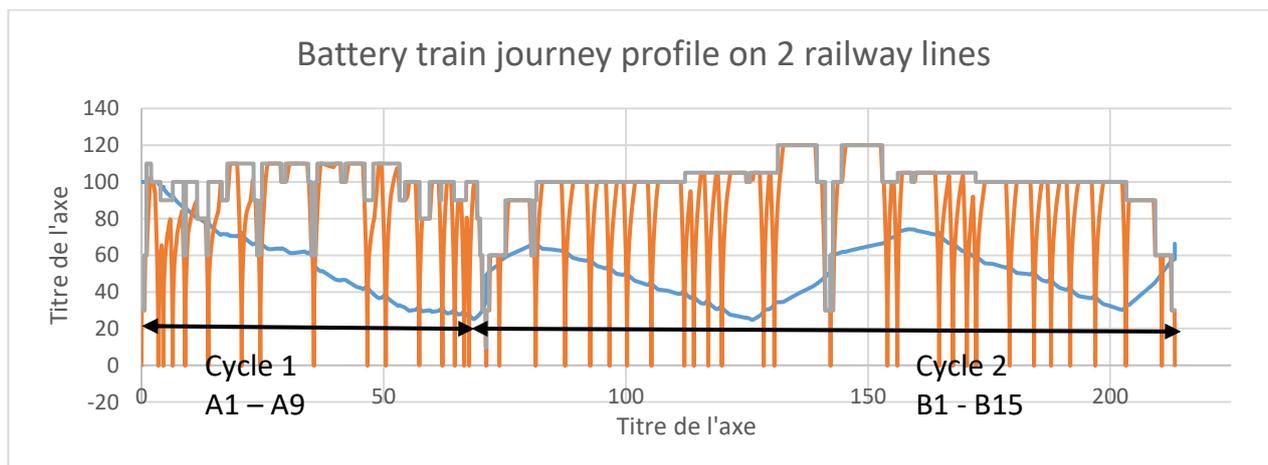


Figure 64: Journey profile simulation of 1st gen BEMU in all-out drive

As seen previously, After the cycle 1, the SoC ends at 49%. At the departure of the cycle 2, the battery train can be recharged thanks to the electrified section in the first 10 km. During train moving, the maximum current collected at the pantograph allows higher charging power for the traction batteries. Therefore, after 11 min of trip and before switching to battery mode, the SoC increased up to 68% (+19% compared to SoC at the departure time). The train will run now on the 45 km not electrified section, with 9 stops. The energy required for this section is important and SoC drops to 28% (-40%). As the electrification appears before a train station, the traction mode is changed while running. On the remained 16 km electrified, traction battery is charged to

reach 50% at the arrival in terminus station B15. The turnaround time in station B15 is 13 min, and the battery is charging at limited power at standstill. The SoC grow up to 60% before leaving the station B15. As the train goes back on the line under electrified section, the battery can charge during 16 km. The SoC is 74% when train is switching to battery mode and drops to 32% (-42%). Train is changing again of traction power mode from battery to catenary and can start to charge the batteries along the last 10 km of the line to ends in station B1. At the arrival in station B1, the SoC is 58% (+26%), and after 11 min of turnaround time, the SoC topped 66%. This mark is the end of cycle 2. This study of mission profile gave interesting feedback on the impact of different services for the battery train management. According to characteristics and results on the uphill/downhill line and the secondary line, the configuration comply the mission profile with 1st gen BEMU.

France Use Case I	Type of train	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance Shuttle service	Operation Journey profile compliance	Operation Duration of service stop	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Energy Management functions	New Infra Substation	New Infra Electrification length (km)	New Infra Total Cost (M€)
No additional infra	1st gen BEMU	All-out	Yes	No	Yes	78	29%	-73%	58%	No	-	-	-

Table 45: France UC1 – Scenario 1 - Comparative criterion synthesis for Journey profile & All-out driving impact

Degraded operational conditions:

During operation, an unnecessary stop may be required due to an event on the line (e.g., signalling failure, important traffic in station, fatalities, etc.). These stops can have a duration from few minutes to few hours. In France, SNCF Voyageurs published a list of events that may occurs and disturb the rail traffic:

- Passengers (Unaccompanied luggage, Illness on-board, Fraud, Exceptional attendance),
- Environmental conditions (Flooding, Dead leaf and lack of adhesion, Extreme weather),
- External conditions (Animals along the track, Fatalities, Fire along the track)
- Traffic (Radio alert, Traffic regulation)
- Train operator (Crew member delay or missing, Strike)
- Railway infrastructure (Overhead line incident, Railway crossing, Rail break, Signalling, Infrastructure maintenance activities)

From few minutes’ duration, such as exceptional attendance or passengers alarms activation on-board (average 10 min extra time).

The stop duration due to fatalities is estimated of 2 hours. When the event happens, the traffic is stop on both lines, and police and fireman are called. During the procedure, the train traffic is remaining closed. This event is one of the longest to impact the stop duration in operation.

Therefore, this could significantly impact the energy consumption. The train is stop and keep delivering energy to the auxiliary loads on-board. Based on a 4 cars battery train, the estimated auxiliary power during the service is 150 kW. This value is representing:

- HVAC system,
- Auxiliaries for traction/braking system and other comforts loads (plugs, lights, etc.),

- Auxiliaries for the Energy Storage System.

An assumption of 2 different duration of service stops: 60 min and 120 min.

According to previous simulations, an analysis is done to find the worst location for an abnormal service stop in the uphill way ↑ or the downhill way ↓. The station A2 ↓ is the worst case in terms of SoC, so of energy available inside the batteries.

SoC [%]	Stations
100,0	A1 ↑
98,7	A2 ↑
95,8	A3 ↑
91,0	A4 ↑
84,9	A5 ↑
75,1	A6 ↑
68,5	A7 ↑
64,5	A8 ↑
60,4	A9 ↑
54,6	A9 ↓
42,7	A8 ↓
38,6	A7 ↓
32,1	A6 ↓
32	A5 ↓
31,2	A4 ↓
30,7	A3 ↓
29,7	A2 ↓
44,1	A1 ↓
57,6	A1 ↑

Table 46: Evolution of SoC per station along the uphill/downhill use case (UC1) for the 1st gen battery train

So, an added an extra energy consumption at standstill in station A2↓ to simulate the effect of stop duration on the energy consumption. During the stop, auxiliary loads kept the same value. Therefore, this is representing an energy consumption of:

$$E_c = P_{aux} \times \Delta t \text{ with } P_{aux} = 150 \text{ kW} \ \& \ \Delta t = 1 \text{ h}; E_c = 150 \times 1 = 150 \text{ kWh}$$

Application for a stop duration of 60 min. In this case, the energy to deliver by the traction batteries during the stop is 150 kWh, equivalent to 23% of SoC.

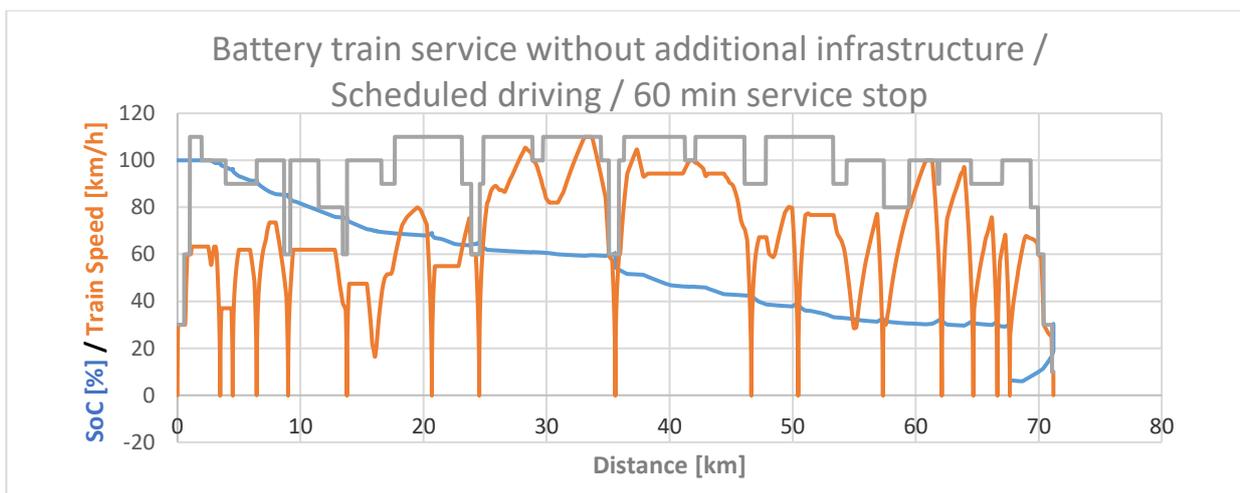


Figure 65: 1st gen battery in scheduled driving on the uphill/downhill line (UC1) without additional infrastructure (S1), with a stop of 60 min during the trip

In this situation, the available SoC after the stop is very low (7%) but thanks to the short distance to cover for finding the electrified line, the battery train can continue the service and end the cycle with an SoC of 30%.

Use Case	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance / Shuttle service	Operation Journey profile compliance / Other service	Operation Duration of service stop	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 - FR / BEMU 1 st gen & No additional infra & Service stop 60 min	Scheduled	Yes	No	Yes	19	1st gen BEMU	7%	-109%	30%	No	732,48	-	-	-	No

Table 47: France UC1 - S1 - Comparative criterion synthesis for Service stop 60 min & All-out driving impact.

Vehicle impact analysis:

As described in the beginning of the scenario 1, the vehicle selected here is a 1st generation BEMU. The average range in operation is estimated to 80 km. The table bellows is giving the main characteristics of the 1st gen BEMU used in this scenario:

	1st gen BEMU Train characteristics
Number of Cars	4 cars
Maximum Speed	160 km/h
Traction power (catenary)	1.8 MW
Traction power (battery)	1 MW

Voltage supply	25kV AC + 1.5 kV DC
Battery usable capacity per train (EoL)	400 kWh
Number of ESS per train	2
Auxiliary power (high/cold external temperature conditions)	150 kW
Auxiliary power (average external temperature conditions)	75 kW
Energy management functions (based on task 1.2/5.3 list)	ESS pre-conditioning External plug (auxiliary loads supply only)

Table 48: Characteristics of 1st gen BEMU for regional operation in France

According to the vehicle cost database, the estimated cost of 1st gen BEMU is 6,2 M€ (CAPEX) and 0,85 €/tkm in regular usage (OPEX). These 2 values will be used to calculate the ratio compared to diesel train for the sub criteria quotation.

Concerning vehicle energy management functions, no function has been used.

For the vehicle energy consumption, the value selected is based on cruising style and with a 150 kW auxiliary power load. The result obtain is 491 kWh of vehicle energy consumption.

Energy Storage System impact analysis:

For this example, the lithium-ion battery technology used is NMC. The table bellows is giving the main characteristics of the traction batteries:

	1st gen BEMU Train characteristics
Battery technology	NMC
ESS Battery technology expected cycle (100%DOD)	4500
Battery capacity	2 x 420 kWh
Battery auxiliary consumption	2 x 10 kW

Table 49: 1st gen BEMU ESS characteristics

To estimate the ageing of the battery, a simplified method by calculating the number of full cycle equivalent is used. In this scenario, the FCE is 0,73 for the round trip. Operational requirements are to run 4 round trip per day (mission profile) and for 365 days per year (annual profile). With these parameters, the annual FCE is obtained. By dividing the ESS battery technology expected cycle with the annual FCE, the result is the estimated lifetime of the battery for the scenario, here 4,2 years.

Concerning the ESS auxiliary consumption, an average assumption of 2 x 10 kW is considered. This value is equivalent to 13% of the global train auxiliary power consumption.

Infrastructure impact analysis:

In this scenario, the estimated energy consumption at infrastructure level is calculated through the energy used for charging the 1st gen BEMU under catenary sections, and the energy consumed by the train when running and when parking with panto. For a daily profile, the energy consumption from the infrastructure side is estimated at 2840 kWh. This value will be

compared with the result given in diesel traction, assessed at 8121 kWh (KPI “physical energy consumption” → -65% of energy consumption)

Concerning the other infrastructure sub criteria, as the scenario is based on the current infrastructure conditions, there’s high advantage by avoiding infrastructure works and investment.

Energy and CO2 impact analysis:

Based on the energy consumption from the infrastructure and on the energy price and CO2 equivalent factor data base, the estimation of energy price and CO2 emissions between the selected scenario and the reference value with diesel train can be done.

General evaluation of scenario 1:

According to the previous analysis on the several systemic criteria, the general evaluation table can be fulfilled:

Use Case	Operation General Evaluation	Vehicle General Evaluation	ESS General Evaluation	Infrastructure General Evaluation	CO2 Emission General Evaluation	Total General Evaluation
UC1 – FR / Scenario 1 “BEMU 1 st gen & No additional infra”	4	6	3	9	6	28

Table 50: Use case 1 - Scenario 1 general evaluation table

This scenario is providing interesting benefits from the infrastructure perspective with no modifications. Whereas the operational conditions and the ESS performances are low and might be not attractive.

Therefore, other scenarios will be analysed to enlarge the comparability.

7.4.3 Use case 1 - Scenario 2 “1st Generation Battery Train in Operation, with additional charging infrastructure and existing operational conditions”

In this scenario 2, the study on the impact of an additional charging infrastructure on the line is selected. The first case proposed to look on is a charging station at the station A9 (terminus/departure station). This new infrastructure facilities gives an opportunity to recharge the traction batteries during the turnaround time in station A9. 2 types of charging stations might be used:

- Slow charging stations: representatives to DC voltage catenary, with reduce power allows at standstill (450 kW total, including all the loads to supply into the rolling stock),
- Fast charging stations: representatives to AC voltage catenary, with high power allows at standstill (around 1500 kW, including all the loads to supply into the rolling stock), R&D studies are ongoing to develop fast-charging under DC voltage, by using different kinds of solutions on

the infrastructure side (e.g. rigid overhead contact line, two separated contact line, etc.) and/or rolling stock side (e.g. special pantograph strip, different contact force, etc.).

Furthermore, auxiliary loads are also supplied by the catenary line and so avoid using energy from the traction batteries. This scenario means to install a substation near the station, and to electrify the station, so to invest on the infrastructure side. The battery train remains as for scenario 1, as well for the operational conditions.

Operational impact analysis:

Same methodology is now applied for the second scenario on this 1st use case. First, an evaluation of the impact on the driving styles for the is given bellow:

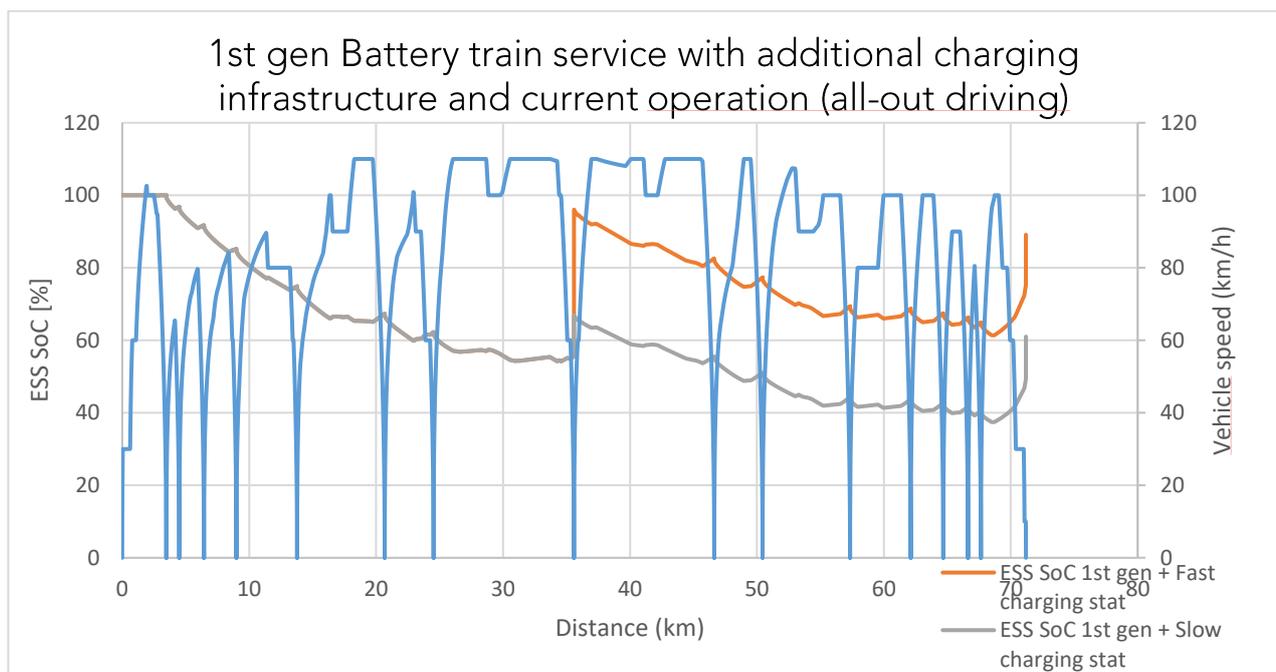


Figure 66: 1st gen BEMU on UC1 with additional charging station (scenario 2) & all-out driving

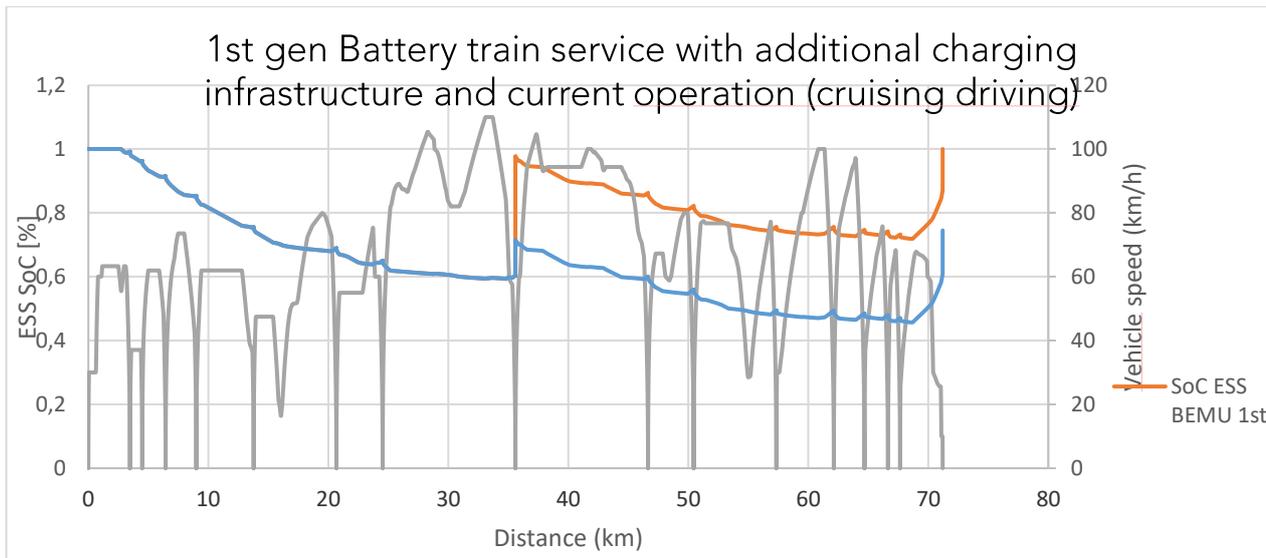


Figure 67: 1st gen BEMU on UC1 with additional charging station (Scenario 2) & cruising driving

The influence of the additional charging station in station A9 is significantly impacting the vehicle and ESS criteria, but also the operational side. For the rolling stock, the lower SoC is deeply reduced, with +22% for all-out driving and +40% for scheduled driving. This extra energy available along the route is supporting the operational parameter for duration of service stop. This is doubling the time duration in case of stop during the service. For the mission profile, the fast-charging station gives interesting results. With cruising driving style, the SoC get back to 100% at the end of the journey profile, so it allows to run several times the route profile as requested by the operation (4 round trip per day). With all-out driving, the SoC is reached 89% at the final station. It allows to circulate for next service on the same route profile, but with a reduction trip after trip of the SoC margin until 0%. For 4 round trips in all-out driving, the minimum estimated SoC is 21%.

The table hereafter resumes the main results obtain with this scenario:

Use Case	Operation Driving style	Operation Timetable compliance	Operation Journey profile compliance / Shuttle service	Operation Journey profile compliance / Other service	Operation Duration of service stop	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 – FR / BEMU 1 st gen & Additional charging station slow charge	All-out	Yes	No	Yes	110	1st gen BEMU	41%	-93%	64%	No	624,96	-	-	-	No
UC1 – FR / BEMU 1 st gen & Additional charging station slow charge	Scheduled	Yes	No	Yes	185	1st gen BEMU	65%	-73%	91%	No	490,56	-	-	-	No

Table 51: France UC1 – Scenario 2 - Comparative criterion synthesis for additional charging slow station & All-out / Cruising driving impact

Vehicle impact analysis:

The vehicle impact for scenario 2 is mostly the same as for scenario 1. The only difference is regarding the vehicle energy consumption. Due to the charging station, it saves energy during the parking time in station A9. The result obtain is 457 kWh of vehicle energy consumption (-7% compared to scenario 1).

Energy Storage System impact analysis:

Impact on the ESS related to the additional charging infrastructure is limited for the cycling ageing. The full cycle equivalent moves from 0,73 to 0,68, with a low impact on the lifetime of the batteries. Whereas the ageing calculation in the method do not consider other factors influencing the lifetime, such as the thermal effect. For the fast-charging station solution, high power charging will induce more losses and heat to evacuate. This will affect the ageing of the batteries.

Infrastructure impact analysis:

In this scenario 2, the estimated energy consumption at infrastructure level is higher than the scenario 1 due to the charging station. For a daily profile, the energy consumption from the infrastructure side is estimated at 3123 kWh with the additional fast-charging station. This value will be compared with the result given in diesel traction, assessed at 8121 kWh.

By adding a new charging infrastructure, an evaluation of the sub criteria is needed. The charging station in scenario 2 is dedicated to the line selected, so no shared cost can be applied with another line profile. The cost of the fast-charging station is estimated based on the infrastructure cost data base for CAPEX and OPEX. For fast-charging station purchase cost, an assumption of 1 M€ / MW is consistent with the studies and references. (EFACEC, 2024) (GWR, 2025). About OPEX, the same value as conventional electrification has been selected, with a percentage of the CAPEX cost of 3% according to other studies on this topic. For the lifetime estimation, an equivalent assumption to convention electrification has been also considered. This lifetime is estimated to be more than 60 years, based on publications (W.Klebsch, 2020) (Rail, 2024).

Energy and CO2 impact analysis:

Based on the energy consumption from the infrastructure and on the energy price and CO2 equivalent factor data base, the estimation of energy price and CO2 emissions between the selected scenario and the reference value with diesel train can be done.

General evaluation of scenario 1:

According to the previous analysis on the several systemic criteria, the general evaluation table can be fulfilled:

Use Case	Operation General Evaluation	Vehicle General Evaluation	ESS General Evaluation	Infrastructure General Evaluation	CO2 Emission General Evaluation	Total General Evaluation
UC1 – FR / Scenario 2 “BEMU 1 st gen & Additional fast charge station	8	6	3	5	6	28

Table 52: Use case 1 - Scenario 2 general evaluation table

This scenario is providing better performances on the operation compared to scenario 1, with capability to circulate in all-out for several round-trip, but also with more on-board energy margin in case of sudden stop in operation. However, the additional charging infrastructure is decreasing the infrastructure evaluation due to investment and maintenance cost. At general evaluation level, the scoring is identical between scenario 1 and 2. So, a third scenario will be developed in the section based on a long range BEMU assumption, according to RAIL4EARTH WP5 development.

7.4.4 Use case 1 – Scenario 3 “2nd Generation long range battery train with current infrastructure and operational conditions”

In this scenario 3, a study of the impact of a so called “long range BEMU” is chosen. The performances of the long range BEMU are based on the inputs from other Europe’s Rail studies, especially in RAIL4EARTH WP5. According to the works done in this project, the potential improvement in terms of energy density for next generation battery train, an increasing by 150% compared to current technology is validated. Another benefit from the WP5 works is to apply energy management functions to reduce the energy consumption. The following functions have been used for this scenario:

- Eco-parking
- Optimized HVAC

For the infrastructure and operational, the current conditions have been remained, as for scenario 1.

Operational impact analysis:

Same methodology is now applied for this third scenario on this 1st use case. First, an evaluation of the impact on the driving styles for the is given bellow:

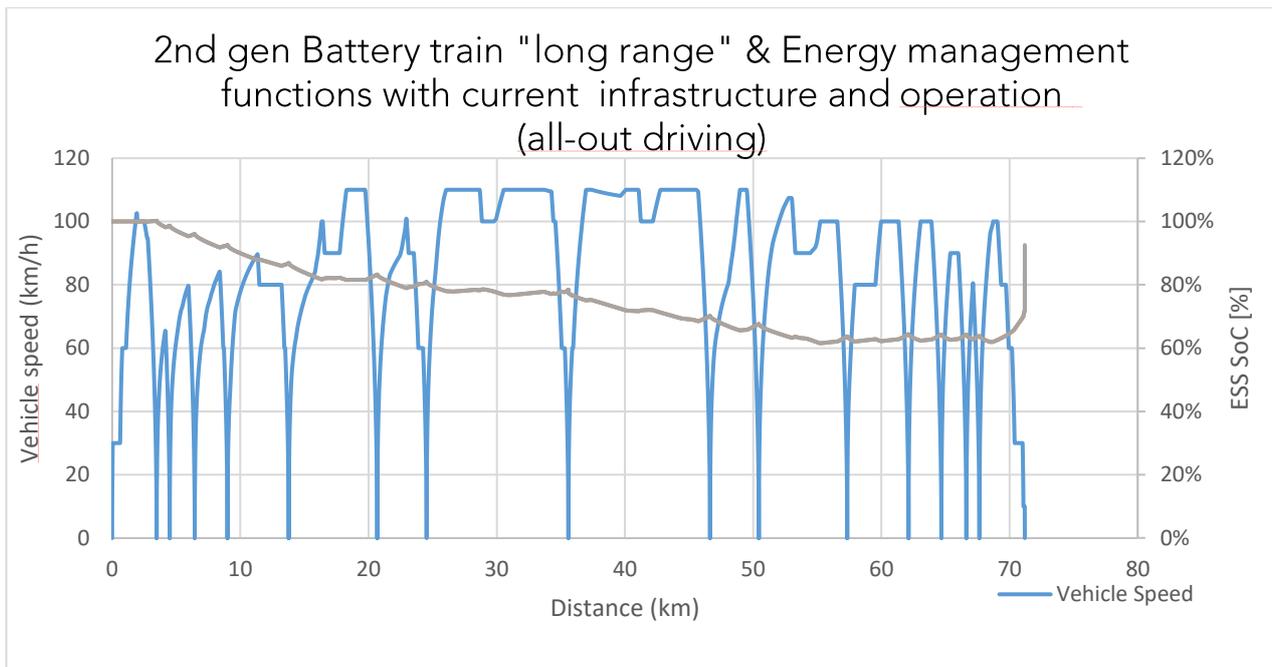


Figure 68: 2nd gen BEMU with energy management functions on UC1 & all-out driving

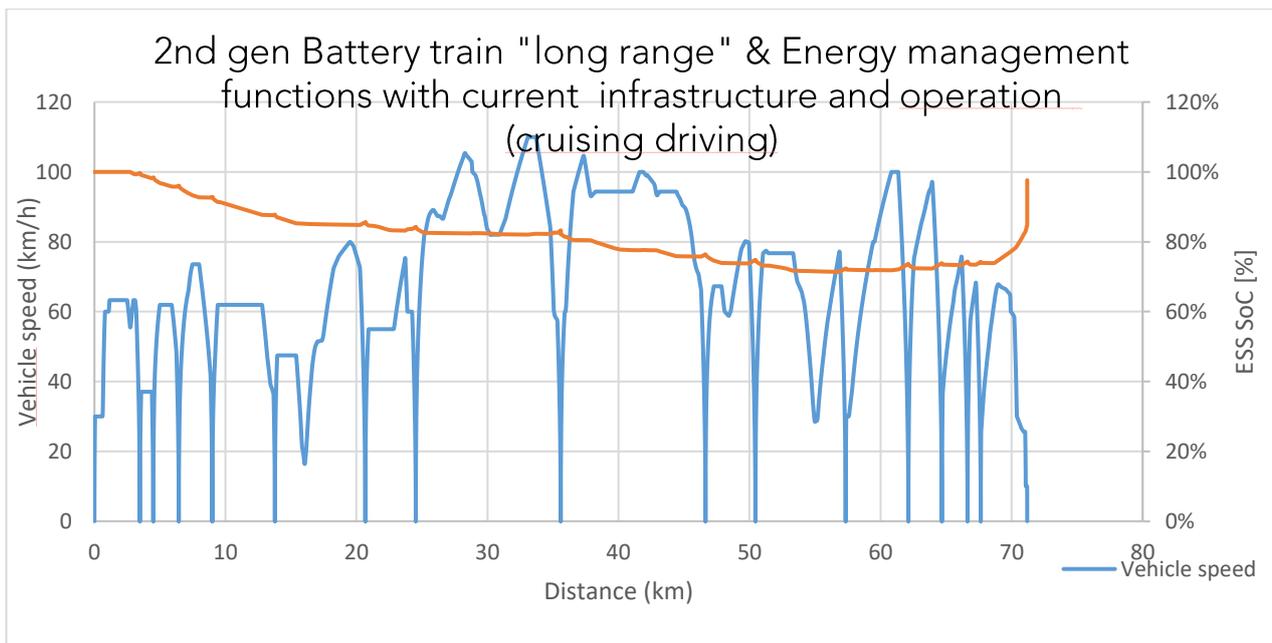


Figure 69: 2nd gen BEMU with energy management functions on UC1 & cruising driving

Thanks to the bigger energy density of the on-board ESS and to the optimized energy consumption during parking and on HVAC, major savings can be achieved. The lowest SoC attempt 71%, compared to 29% with scenario 1 (with cruising driving style). Based on cruising driving, the SoC get backs to 100% with the current infrastructure and service conditions. With all-out driving, the SoC balance at the end of the round-trip is almost on the top (93%),

therefore, it allows to run several times while ensuring good energy capacity margin in case of an event along the line.

Vehicle impact analysis:

The vehicle impact for scenario 3 is quite different compared to previous scenario. The energy consumption obtained is 296 kWh (-40% compared to scenario 1). Concerning the vehicle cost, an extra cost due to long range BEMU has been estimated:

- CAPEX long range BEMU: 7,15 M€
- OPEX long range BEMU: same as 1st generation BEMU

Additionally, as explained in the introduction of scenario 3, 2 energy management functions have been considered to optimize the energy consumption.

Energy Storage System impact analysis:

Concerning the traction batteries, only the battery capacity and number of cycle for 100% DoD have been modified according to RAIL4EARTH WP5 studies.

	2st gen BEMU Train characteristics
Battery technology	N.C
ESS Battery technology expected cycle (100%DOD)	3500
Battery capacity	2 x 630 kWh
Battery auxiliary consumption	2 x 10 kW

Table 53: 2st gen BEMU ESS characteristics

The estimated lifetime based on cycling effect has been strongly increased, in relation to the higher battery capacity and the reduction of the energy consumption of the vehicle through the energy management functions applied. The ageing is now evaluated to 11 years, based on cruising drive load profile.

Infrastructure impact analysis:

In this scenario, the estimated energy consumption at infrastructure level is calculated through the energy used for charging the 2st gen BEMU under catenary sections, and the energy consumed by the train when running and when parking with panto. For a daily profile, the energy consumption from the infrastructure side is estimated at 2163 kWh. This value will be compared with the result given in diesel traction, assessed at 8121 kWh.

Concerning the other infrastructure sub criteria, as described in the scenario 1, there's no impact due to no new charging infrastructure considered.

Energy and CO2 impact analysis:

A better score is achieved here because of the reduction in the infrastructure energy

consumption. Same values haven been selected to calculate the electrical energy cost (120 € / MWh) and CO2 emissions (0,052 kgCO2e / kWh).

General evaluation of scenario 1:

According to the previous analysis on the several systemic criteria, the general evaluation table can be fulfilled:

Use Case	Operation General Evaluation	Vehicle General Evaluation	ESS General Evaluation	Infrastructure General Evaluation	CO2 Emission General Evaluation	Total General Evaluation
UC1 – FR / Scenario 3 “BEMU 1st gen & Additional fast charge station	8	5	6	9	8	36

Table 54: Use case 1 - Scenario 3 general evaluation table

This third scenarios gives a higher ranking for the general evaluation compared to the 2 previous scenarios. Good scoring is obtained for operational, infrastructure and energy/CO2 emissions. Even if the vehicle scoring is a bit lower due to extra cost for 2Nd generation long range BEMU, the benefits from the other criteria more important.

7.4.5 Future Works on Scenarios Analysis

In the next period, additional new use cases and scenarios will be studied to validate the methodology. Based on the analysis of these future inputs, the methodology might be adjusted. At the end, a proposal for future standardization of this methodology will be submitted.

7.4.6 Use case 2 “Swedish case study”

Interesting non-electrified lines in Sweden have been located where partial electrification, battery trains, hydrogen trains, and similar solutions could potentially be implemented. These cases are shown in the figure below.

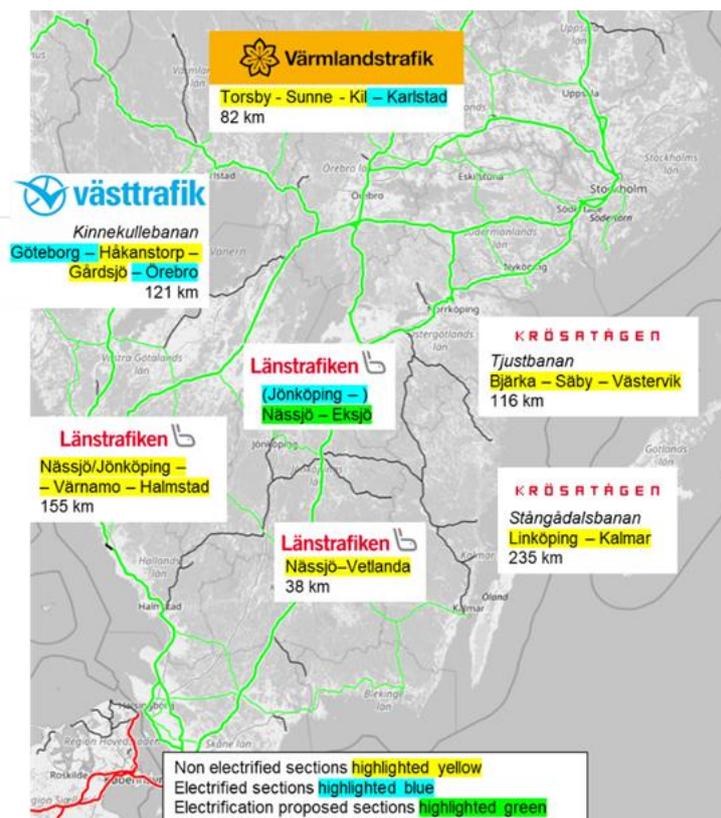


Figure 70: Map of southern Sweden with non-electrified lines in black, electrified lines in green. Textboxes with transport operators currently performed using diesel-electric EMU trains.

The lines in previous figure are nowadays partly or totally non-electrified, using Diesel Multiple Units - DMUs for passenger operations (typically ITINO trains, Y31 and Y32 in the Swedish nomenclature). The details of these lines are also listed in the following table:

Line	End stations	Track name	Operator	Non-electrified section	Non-electrified length (km)	Total (km)
63	Örebro-Göteborg	Kinekullebanan	Västtågen	(Gårdsjö) – Lidköping – Håkanstorp	121	339
74	Torsby-Karlstad	Fryksdalsbanan	Värmlandstrafik	Torsby-Kil	82	103
83	Västervik–Linköping	Tjustbanan	Krosatåg	Virtually all of it, catenary at Linköping end station	116	116
84	Kalmar–Linköping	Stångådalsbanan	Krosatåg	Virtually all of it, catenary at both end stations	235	235
85	(Jönköping–) Nässjö–Eksjö		Krosatåg	Nässjö–Eksjö (electrification project ongoing)	0	21
86	Nässjö–Vaggeryd – Värnamo – Halmstad		Krosatåg	Värnamo–Halmstad; Nässjö–Värnamo (electrification project ongoing)	115	195

	Jönköping– Vaggeryd– Värnamo–Alvesta– Växjö	Krosatåg	Jönköping–Värnamo (electrification project ongoing)	0	?
87					
88	Nässjö–Vetlanda	Krosatåg	Nässjö–Vetlanda	40	40

Table 55: Non-electrified commuter and middle-distance passenger operations in Sweden

Additionally, there are other non-electrified systems that don't have medium distance operations nowadays but have had in the past, or have seasonal train operations, such as Inlandsbanan, a railway line between Kristinehamn in central Sweden and Gällivare in the north, approx. 1 300 km long. Operations are typically tourism- or winter sports related.

From this list of options, first the lines being electrified are discarded. From the rest, Torsby-Karlstad (Operation A) is a good baseline for a non-electrified line with a distance between stations that is challenging for current battery trains to complete successfully without additional solutions. On the other hand, Örebro – Göteborg and its non-electrified section of Gårdsjö – Håkanstorp (Operation B) is a good case for analyzing system-level efficiencies of current solutions in a route that is nowadays viable with existing battery trains.

Preliminarily, the different scenarios to be studied are:

- System-level impact of battery aging – how does operations-related battery aging influence the infrastructure building decisions like catenary islands or fast charging points.

- Simulation of vehicle's complete operational cycle for Nordic conditions: eco-parking, thermal comfort (preconditioning, manual door opening...), operation, etc. Including the influence of possible infrastructure building decisions.

- Influence of line topology and geometry - from a functional perspective it is interesting to understand the topological differences between lines, so a study on the influence of track topology and geometry on energy consumption and BEMU system design.

- System robustness and resilience to unexpected disturbances – battery size needs for managing a certain range and level of thermal comfort in case of delays in challenging environmental conditions (e.g. extreme cold).

Operation A: Stångålsbanan (Stångdal Line)

The Stångåls line is a non-electrified and standard gauge line linking Linköping and Kalmar in the southeast of Sweden. 7 daily round passenger trips are operated by Krösatågen, plus a first- and a final partial trip each day. The line is 235 km long with 3km catenary before Kalmar station, and 1 km catenary before Linköping station. It has relatively high passenger traffic and is a relatively long route in need of refurbishing and maintenance: securing against vegetation and trees, and removing unattended level crossings. TRV considers these two to have much higher priority than electrification measures in the route.

This operational scenario is a challenging one for current battery techniques, making it a good choice for a combined system-level study of operational, infrastructure, and vehicle parameters.

Operation B: Kinnekullebanan (Kinnekulle Line)

The Kinnekulle Line is a non-electrified and standard gauge line extending for 121 km from Håkantorp, via Lidköping and Mariestad, to Gårdsjö. Commuter operations in the line cover Örebro - Lidköping – Göteborg, for a total of 339 km. 13 commuter round trips per day run partially or completely through the non-electrified section, with operations under the local Gothenburg rail traffic, Västtågen.

This operational scenario has a feasible orography and length for battery trains to cover, with good access to catenary sections at both ends of the non-electrified line, making it a good option for researching the energy optimisation measures for a realistic case.

Case study: System-level impact of battery aging

The capacity of the on-board ESS is a crucial factor for its overall function and an important aspect in enabling the introduction and competitiveness of BEMUs. When considering the degradation and lifespan of Li-Ion batteries, a common measurement is the loss of capacity. The factors that affect battery's rate of degradation can be divided into calendar and cycle ageing (A. Krupp, 2022), where the first refers to the ageing occurring during idle conditions due to parasitic reactions in the cell. Cycle ageing occurs during the battery's operation and is influenced by various usage-related factors such as operating temperature, high charge and discharge rates, depth-of-discharge (DoD) (Ou, 2023). A commonly used metric in the context of battery degradation is state-of-health (SOH), typically expressed as a percentage representing the ratio of the battery's current maximum capacity to its capacity at beginning-of-life (BoL). In electric vehicle applications, end-of-life (EoL) is often defined as the point at which the battery's capacity has declined to 80% of its initial rated capacity (X. Hu, 2020).

To model the degradation of the vehicle's batteries, a data-driven method based on the publicly available cycling data from the article "Degradation of Commercial Lithium-ion Cells as a Function of Chemistry and Cycling Conditions" was used. The dataset comprises measurements for different cell chemistries under varying DoD, discharge rates, and ambient temperature conditions, systematically modified to evaluate their impact on the decline in battery state-of-health (SOH), measured as the cells' capacity retention, relative to the number of cycles each cell had undergone. The cumulative number of equivalent full cycles ($EFC = \frac{Q_c}{Q_{bat}}$) is the ratio between the cumulative capacity supplied by the cell so far with respect to the cell's full capacity at BoL, in order to normalise battery ageing across tests with different DoD settings.

Additionally, SOH was computed at each test point based on the remaining capacity, providing a more interpretable indicator of the degradation trajectory. The target variable for the predictive model was then computed as the rate of degradation, expressed as SOH per equivalent full cycle.

After evaluating several models, a gradient boosting model based on decision trees was selected as the specific data-driven method. The boosting algorithm, with a decision tree as the weak learner, produced the best results due to its superior performance in capturing the nonlinear degradation patterns observed in the data. Key hyperparameters of the model such as learning

rate, tree depth, and number of estimators were fine-tuned with a grid search using Monte Carlo cross-validation.

To assess the impact of railway system-level parameters on battery degradation, and hence the overall system robustness, a series of scenarios were simulated in which elements of the infrastructure, operations, or ambient conditions were varied. These changes influence one or more critical factors related to battery ageing, namely:

- Depth of Discharge (DoD)
- Discharge current
- Operating temperature of the battery system

To examine the effect of ambient conditions, operation is simulated under three different ambient temperatures: $-20\text{ }^{\circ}\text{C}$, $15\text{ }^{\circ}\text{C}$, and $30\text{ }^{\circ}\text{C}$. Lithium-ion batteries can typically operate within a range of $-20\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$, with operation outside $15\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$ accelerating battery degradation. In the $-20\text{ }^{\circ}\text{C}$ scenario, it is assumed that battery thermal management systems and pre-conditioning before departure are applied to ensure reasonable operating conditions; a battery temperature of $5\text{ }^{\circ}\text{C}$ is then assumed. For simplicity, the thermal effects resulting from internal electrochemical reactions during charging and discharging are neglected, and the battery's operating temperature is assumed to remain constant throughout the journey. However, ambient temperature directly influences the train's auxiliary power demand, increasing under extreme temperatures. Consequently, colder ambient conditions, and to a lesser extent hot conditions, result in higher overall energy consumption over the course of the trip, and thus variations in DoD too.

The analysis is performed for Scenario A, Linköping – Kalmar. An ideal battery size is designed so that the capacity allows the vehicle to run the whole length of the Scenario. This is not a realistic battery, but it allows for a clearer understanding of the simulated aging effects in the system-level energy consumption.

The next figure shows the SoC of the consist for different environmental temperatures for a starting SoC of 100%. For $15\text{ }^{\circ}\text{C}$ there is less need for the HVAC system, and thus the SoC is the highest. For $30\text{ }^{\circ}\text{C}$ it needs AC to cool the cabin down, and for $-20\text{ }^{\circ}\text{C}$ heating is needed, with extra energy needs that affect the autonomy of the system. Note that these simulations still don't incorporate battery ageing, only energy consumption for different conditions.

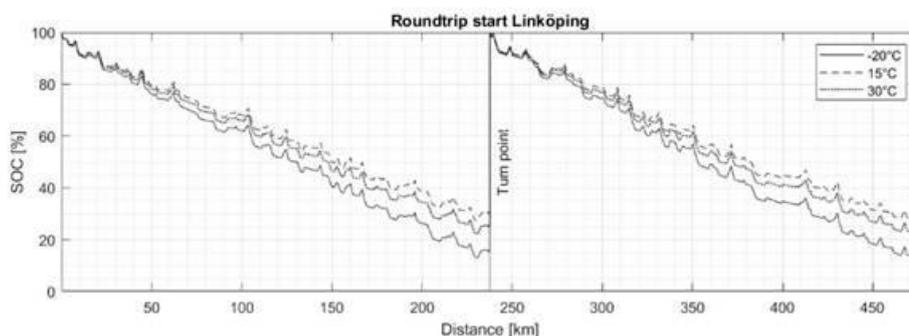


Figure 71: State of Charge for different environmental temperatures, base case with ideal battery capacity

To reduce the batteries required depth-of-discharge, two potential adaptations to the power infrastructure are considered, as illustrated in figure 72, involving partial electrification: (1) extending the existing catenary system from both end stations to shorten the unelectrified portion of the route, and (2) constructing a catenary island midway, effectively dividing the journey into two unelectrified segments. In both alternatives, the catenary extension is designed to limit the unelectrified segments to a maximum of 200 km, in alignment with the Rail4EARTH BEMU autonomy target.

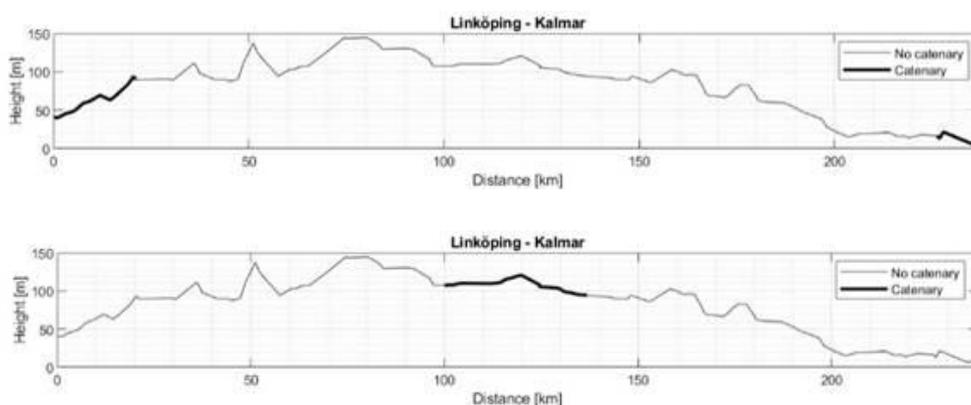


Figure 72: Adaptations to the power infrastructure

Figure 73 shows the effect of extended catenary sections on both ends of the line on the SoC of batteries for a starting SoC of 100%. The effectively directional, with most of the benefits coming at the end point of the trip. The extended section at the start the benefit is that battery is not emptied, but the catenary cannot be used for recharging as the batteries are full. At the end section the combination of regenerative braking plus extra catenary connection allows for almost completely replenishing battery capacity. This effect is symmetric, with similar behavior for the second half of the round trip, where the two catenary sections swap roles.

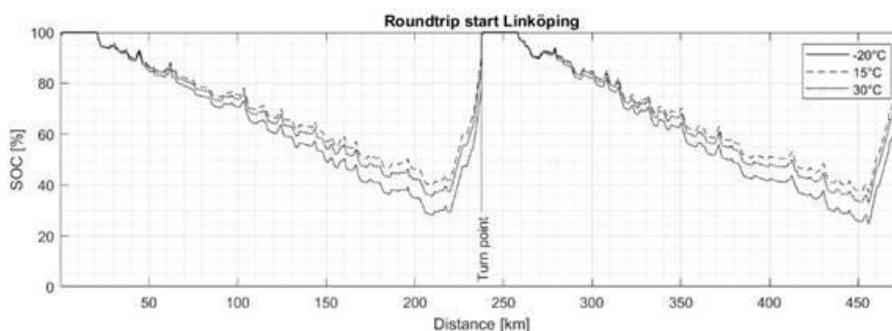


Figure 73: Case 1 partial electrification, extended catenary at end stations

Figure 74 shows the effect of the catenary island in the energy consumption for an initial SoC of 85%. In this case the Battery charging capacity at the catenary island in the central part of the stretch allows for a full recovery even when starting partially empty for a more efficient utilization of the storage capacity.

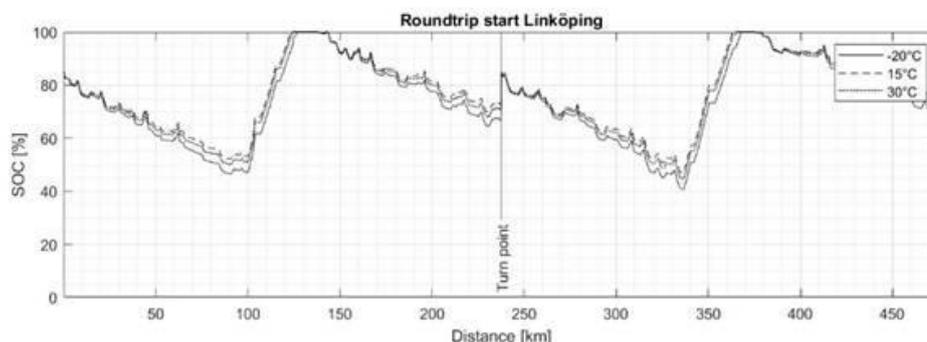


Figure 74: Case 2 partial electrification, catenary island

These simulations allow for different operational conditions to be applied to the system which significantly influence the DoD and the temperature of the battery, variables that significantly affect the State of Health of the batteries. Ongoing work continues with a systematic study of the effect of these operational and infrastructure effects on cycle ageing of the batteries using the described data-driven method and dataset, and subsequent understanding of the potential of different energy functions to influence aging and system level energy usage.

Case study: Simulation of vehicle's complete operational cycle for Nordic conditions

Previous studies have shown the importance of considering auxiliary energy consumption in Nordic conditions, such as (Vinberg E. M., 2018) where they analyse the energy consumed for both stages of train service i) with passengers and ii) through other stages of daily operations, such as stabling and parking, cleaning, inspection, and maintenance operations. The Swedish national passenger operator SJ reports that 1/3 of the energy consumption is due to these stages out of the commercial passenger transport operations.

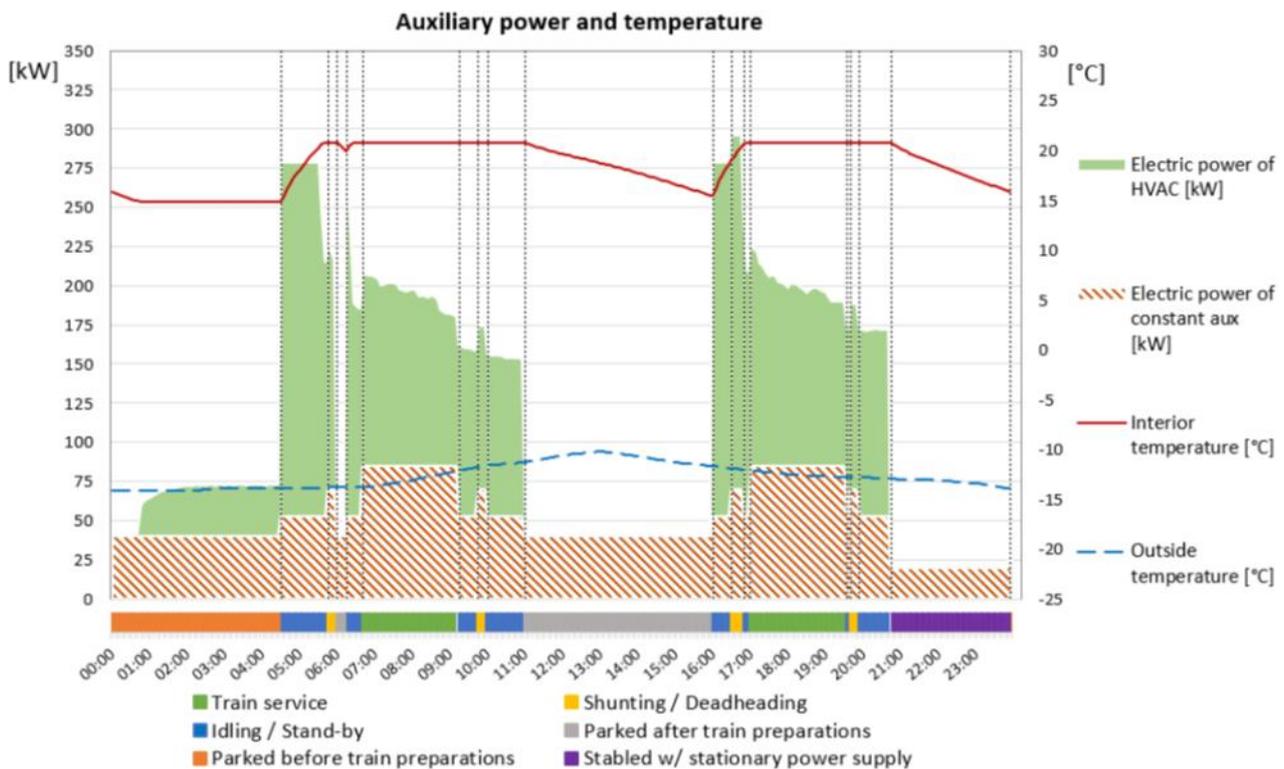


Figure 75: Simulated auxiliary power need for a X55 train going through a winter day. The coloured bar at the bottom illustrates the different operational situations. Constant auxiliary power (striped red) and varying auxiliary power (green) are included.

Energy calculation tools are limited in how they consider the auxiliary energy during the operational cycle, typically considering a flat rate for the simulated scenario. The criticality of thermal comfort in Nordic countries, plus the substantial toll that heat generation creates in the state of charge of batteries, highlights the need of a more complex model than the flat rate, and still simple enough to be used in parallel to the existing tools. Earlier studies that have modelled thermal management in passenger trains (Lidén, 2023) have developed models for analysing thermal effects in passenger trains and have shown the impact of operational and environmental variables in commuter trains around the Stockholm area.

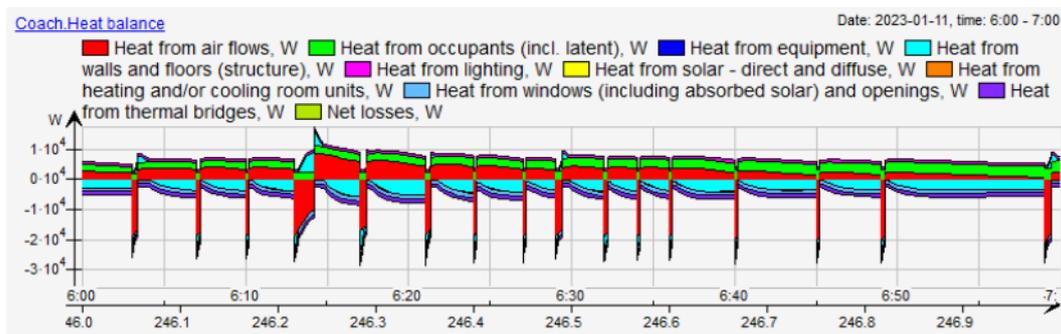


Figure 76: Example of heat balance of one coach during commuter operations in winter

Based in the models of this work, in WP5 D5.3 there have also been reported the influence of manual door opening for the extension of battery range. The estimations for a theoretical case are that, for the baseline simulation case with outside temperature of 20°C, the thermal losses due to outside air intake for the trip is 47.6 kWh, and is reduced to 33.3 kWh when assuming 30% of door opening time due to manual door opening. This is equivalent to 4.75 kW reduction of power per car. For an outside temperature of 0°C, the savings are obviously reduced, 1.7 kW per car.

All these showcase the need for a deeper understanding of the coupling between thermal comfort management and operational energy consumption. This case study will analyse the effect on the auxiliary energy consumption at a system level related to thermal comfort (vehicle preconditioning, manual door opening), eco-parking, operational variables, and partial electrification measures in the infrastructure.

Case study: Influence of line topology and geometry

Previous studies have focused in Scenario A, with a certain track design and topology. From a functional perspective, how do the topological differences between lines affect the battery and infrastructure dimensioning? The objective is to conceptually understand the pros and cons of battery electrification of non-electrified lines based on the.

This analysis will start in Q3 2025 and afterwards.

Case study: System robustness and resilience to unexpected disturbances

The objective is to study the battery design needs for managing a certain vehicle range and level of thermal comfort in case of delays in challenging environmental conditions (e.g. extreme cold). What is the impact of disturbances in battery trains in extreme cold conditions? Is there a need for a design of the system that ensures a certain statistical level of safety?

This analysis is planned to start in Q1 2026.

8. Exchange With Other Flagship Projects

FP4 WP1 have several exchanges with other Flagship Projects of Europe's Rail.

Link between FP4 WP1 and FP1:

Exchanges between FP4 WP1 and FP1 have been identified on the following topics:

- Influence of ATO/C-DAS, low carbon trains energy consumption
- Standardisation of data exchange related to energy
- Digital Twins in energy calculation

Influence of ATO/C-DAS, low carbon trains energy consumption

FP1 do not working on ATO & C-DAS in FP1 for alternative drive trains application. FP1 WP16 is working on ATO/C-DAS for trackside only. Concerning FP4, as shown previously in this report, WP1 work to suggest modifications of standards related to ATO/C-DAS for to consider the specificities of alternative drive trains.

Standardisation of data exchange related to energy

Several meetings between FP1 and FP4) to discuss on the data exchange related to energy.

Digital Twins in energy calculation

FP1 is working on Functional Mock-up Interface (FMI) and Distributed Co-Simulation Protocol (DCP), to develop more standard exchange of model, while ensuring IP protection.

FP4 is more focusing on the use of digital twin to create models of alternative drive trains (battery train, hydrogen train, etc.), based on simulation tools from each partner. The study from FP1 to improve standardisation is very interesting for FP4 as well to simplify models exchanges between numerical tools.

Link between FP4 WP1 and FP2:

Exchanges between FP4 WP1 and FP1 have been identified on the following topics:

- Pre-Standardisation of Interfaces Between Train and Operation
- Driver Advisory System
- Energy management

FP2 works do not deal with alternative drive trains. FP4 WP1 is studying the use cases related to alternative drive trains.

Link between FP4 WP1 and FP5:

Exchanges between FP4 WP1 and FP5 have been identified on the following topics:

- Analysis for energy efficiency
- Aerodynamic and C-DAS

No exchange has been proceeded today.

Link with System Pillar

Information collected from SP task 1 “SPT1-Railway system 2024 global task 1 architecture report”:

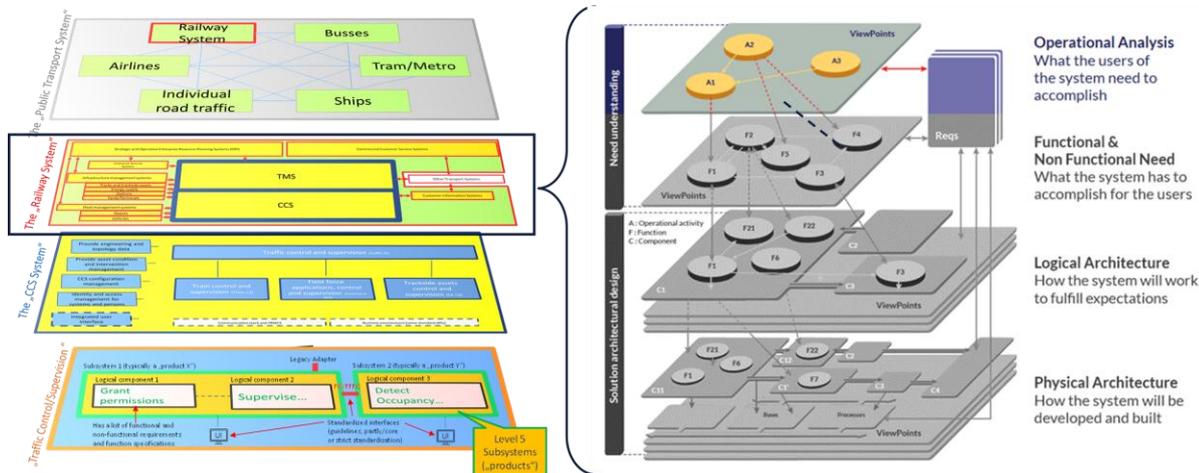


Figure 77: System pillar operational layers

SP task 1 objective is to inform the Operational Layer of the Railway System

The Operational Layer intends to create a model independent of the system being created. The idea behind it is to create a level of abstraction from the system under study, to focus on the needs of the stakeholders.

5 key Capabilities of the Railway System:

- Manage and Maintain Infrastructure: A detailed architecture report of the As-is architecture of this capability is described in Infrastructure Capabilities Architecture Report.
- Manage and Maintain Rolling Stock: A detailed architecture report of the As-is architecture of this capability is described in Maintain & Monitor Rolling Stock Architecture Report
- Manage Energy: A detailed architecture report of the As-is & To-be architecture of this capability is described in Manage Energy Architecture Report
- Operate train: A detailed architecture report of the As-is and To-be architecture of this capability is described in Operate Train Architecture Report
- Upgrade or renew Infrastructure network: A detailed architecture report of the As-is architecture of this capability is described in Infrastructure Capabilities Architecture Report

Between SP and FP4 WP1, the focus is on the “Manage Energy”.

The “Manage Energy” functional architecture is described according to the following method:

2.1 AS-IS : This section describes the workflow followed to describe the existing functional architecture of the "Manage Energy" capability.

2.2 TO-BE : This section describes the workflow followed to describe the TO-BE functional architecture of the "Manage Energy" capability as well as the recommendations raised by this new architecture.

2.3 Discussion of the architecture : This section describes the conclusion of the development of the architecture at a high level and the synthesis of contribution to the identified Common

Business Objectives (CBO).

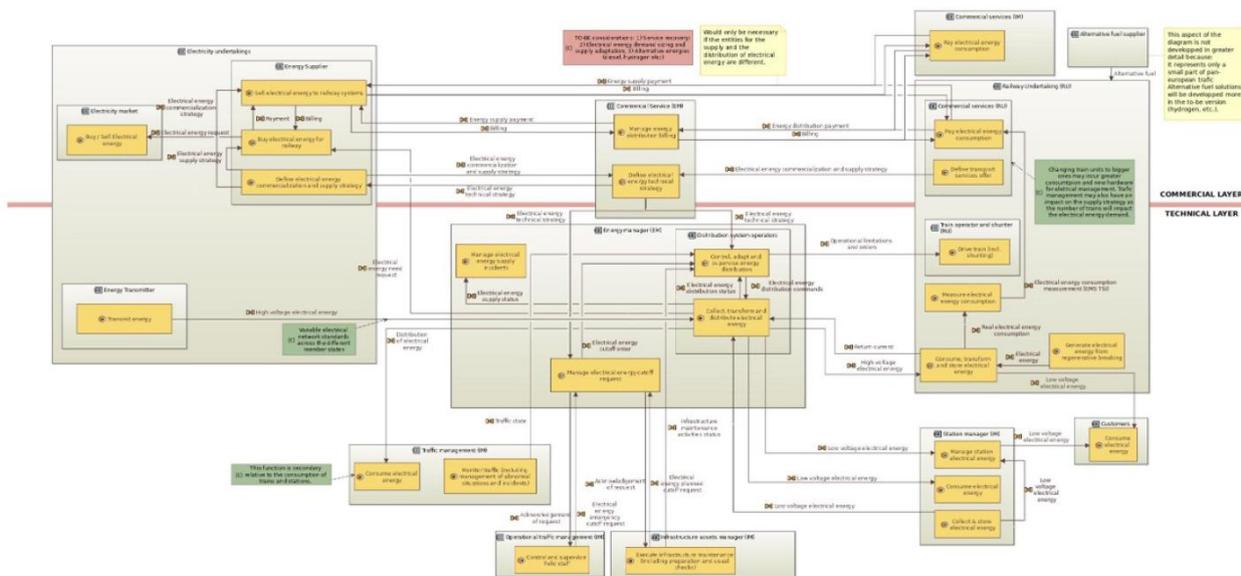


Figure 78: System Pillar "Manage Energy" As-exiSting (AS-IS) architecture

SP task 1 and FP4 WP1 have discussed on this architecture and suggestions to update the architecture with alternative drive trains (e.g. energy city used, hydrogen refuelling stations, exchange between train and traffic management for energy savings, etc.).

9. KPIs

Based on the progress of WP1, the estimation of the impact on each KPI is as followed:

- Physical energy consumption (train, infrastructure, station):
 - o Subtask 1.2.2 on “Optimization of energy management at railway system level”
The methodology proposal and applied to a first use case and 3 scenarios has shown significant energy savings compared to diesel train. Between the solutions themselves, the improvements between 1st generation BEMU and 2nd generation BEMU are providing a -24% energy savings, on the use case study.
- Physical CO2 equivalent emissions:
 - o Subtask 1.2.2 on “Optimization of energy management at railway system level” will enable to demonstrate CO2 equivalent emissions reduction. At that time, no simulation has been produced but will be developed in the next period.
- Life Cycle Costs reduction:
 - o Task 1.1 on “Pre-Standardisation for Trains with Alternative Drives” & subtask 1.2.1 on “Pre-standardisation of energy management functions (eco-mode on-board, preconditioning, peak shaving, Driver Advisory System, etc.) are contributing to this KPI by providing more standardized interfaces and

- components/subsystems for alternative drive trains. Cost savings have not yet been produced because works are still ongoing for the standardisation.
- Furthermore, subtask 1.2.2 “Optimization of energy management at railway system level” will give additional inputs to this KPI by comparing different scenarios and use cases to select the best option according to different criteria on operation, rolling stock and infrastructure. The first use case ongoing analysis shows already results on cost savings. Depending on the prioritization of the criteria, cost reduction may be achieved by avoiding extra electrification of railway.
 - BEMU autonomy target 200 km:
 - Task 1.1 on “Pre-Standardisation for Trains with Alternative Drives” & subtask 1.2.1 on “Pre-standardisation of energy management functions (eco-mode on-board, preconditioning, peak shaving, Driver Advisory System, etc.) are contributing to this KPI by:
 - Standardize the development of more accurate range calculation on vehicle,
 - Standardize the development of energy management functions to reduce energy consumption during train operation,

10. Conclusion

This document is the second public report to publish the intermediate results of the work done in WP1.

The objective of **Task 1.1 is the pre-standardisation of interfaces** for trains with alternative drives (battery or fuel cells) to

- allow a flexible vehicle operation,
- use the infrastructure for charging and refuelling for all vehicle classes,
- avoid the adaptation of vehicles for application in different areas, and
- avoid different infrastructure for different trains.

This will reduce the costs of vehicles and infrastructure and will last not least pushes the decarbonisation of the railway system.

The preferred solution for **charging of the batteries** is the charging via pantograph and overhead line to avoid additional components in the vehicle. For BEMUs catenary islands are required. For countries with AC overhead line the preferred voltage system is 25kV 50Hz, even for 15kV 16,7Hz countries to allow fast charging with high power and reduced infrastructure effort of the substation (no converter required).

The preferred solution for **shore energy supply** of BEMUs and FCMUs is the supply with 400V 3AC 50Hz as used for DMUs today but with higher current (125A instead of 32A) to allow the pre-heating of the train. The preferred standardised interface is the plug defined in EN 50546 instead of the CEE plug. It is designed for the railway environment and has an additional contact

for control functions required when more than one train is supplied by the same infrastructure.

The preferred standardised solution for the mechanical interface for **hydrogen refuelling** is the H35HF receptacle according to EN ISO 17268 part 5 with the TK25 nozzle and TN5 receptacle. To reduce the communication and control effort the refuelling should be controlled by using refuelling tables stored in the refuelling station instead of using a communication line between vehicle and station. For this solution a safe vehicle identification is required.

With respect to the pre-standardisation of the **operational interface** between vehicle and TMS the communication should be carried out via the SFERA protocol defined in IRS 90940, where most of the required parameters are already defined.

For **battery interfaces** plug and socket is the preferred solution for energy storage units (ESU) to allow a fast exchange of the ESU for maintenance. This covers the high voltage, low voltage and cooling interface. Standardised plugs are not required. But the standardisation of the control parameters is desired.

Next **steps of task 1.1** “Pre-standardisation of interfaces” until the end of the project (11/2026) will be:

- For BEMU charging: Identification of solutions for fast charging for DC catenaries
- For hydrogen refuelling:
 - simulation of the refuelling process for a typical regional train to verify the refuelling time and process
 - Clarification of a safe vehicle identification
- For the operational interfaces: clarification of the data exchange between vehicle and infrastructure
- For battery interfaces: Clarification the list of parameters to be transferred for control, supervision, and maintenance
- For pre-standardisation:
 - review the standards to be changed
 - Elaborate the input from Rail4EARTH for change request
 - Discussion with the standardisation contact persons
 - Update the STIP with respect to standards for alternative drives

For **task 1.2**, scope of this task is partially concerning pre-standardisation, for energy management functions, but also concerning studies to optimize the energy consumption at system level, based on numerical modelling and simulations.

For the energy management functions, a state of the art based on previous study in S2R PINTA3 WP3 and in RAIL4EARTH WP5 was created. The state of the art covers more than 10 energy management functions. The functions are defined, and proposal of requirements and potential standardisation / regulations modifications are suggested. Some energy management functions are not yet finalised and will be done during the final period of this project.

The charging process for BEMU was analysed and different strategies to optimize the charging have been studied and evaluated in terms of benefits. Works are still pending for the charging strategy based on energy cost and grid production.

Concerning the preconditioning, after the analysis of northern Europe case, a more general analysis has been produced of current preconditioning of vehicle, with the impact for alternative drive trains. Way of improvements are proposed for vehicle preconditioning. For the next period, same study should be done for ESS preconditioning.

Auto-adapting function has been defined and identification of energy management functions with potential for auto-adapting has been proceed.

For the optimisation of energy consumption at system level, the methodology has been rebuild compared to period 1. The newest methodology proposed cover a larger scope of comparison, with additional criteria on energy / CO2 and on Energy Storage System. Criteria on infrastructure, operation and rolling stock have been updated to be more consistent with the new approach. A ranking system is suggested to simplify the comparativeness of the solution. This methodology might be discussed in standardisation bodies for potential new standard to use. New use case will be studies in the next period to challenge the methodology.

Contacts with other FPs and SP will continue as well on the identified topics of exchange.

11. References

- A. Krupp, R. B. (2022). Calendar aging model for lithium-ion batteries considering the influence of cell characterization. *J. Energy Storage*, vol. 45.
- A.Verdicchio. (2019). New electrification with DC medium voltage for railway network. *New electrification with DC medium voltage for railway network, thesis University of Toulouse*.
- Agency), E. (. (2025, January). *Share of energy consumption from renewable sources in Europe*. Retrieved from <https://www.eea.europa.eu/>.
- Ap.Chamaret, P. P. (2022). Analysis, trends and ex-pectations for low carbon railway. *TRA2022*.
- Ap.Chamaret, P. P. (2022). Analysis, trends and ex-pectations for low carbon railway. *TRA 2022*.
- Aruto Watanabe, Y. T. (2024). Estimating Cost Benefit of Supply-Demand Adjustment Utilizing Railway Onboard Batteries Based on their Deterioration Test. *ESARS conference*.
- Buffarini, G. C. (2022). Technical-economic study to evaluate, for existing non-electrified lines, the adoption of new technology electric-hybrid (emission-free) train with on-board energy storage system as alternative to a total or partial electrification of the line. *WCRR 2022*. Birmingham.
- CENELEC. (2019). *EN 50591 Railway applications - Specification and verification of energy consumption for railway rolling stock*.
- CENELEC. (2022). *EN 50546 "Railway applications – Rolling stock – Three -phase shore (external) supply system for rail vehicles and its connectors*.
- CENELEC. (2025). *Railway applications. Fixed installations and rolling stock. Interface requirements between charging infrastructure with dedicated contact line sections and electric traction units with onboard electric traction energy storages and current collectors*.
- CENELEC. (2025). *Railway applications. Fixed installations and rolling stock. Interface requirements between charging infrastructure with dedicated contact line sections and electric traction units with onboard electric traction energy storages and current collectors*.
- Deutsche Bahn. (2025, June). *Die Klimawirkung Ihrer Reise einfach vergleichen: Der CO2Kompass*

- der Deutschen Bahn*. Retrieved from https://co2kompass.bahn.de/Grundlagenbericht_CO2Kompass_1.2.pdf
- Dschung, F. (2023). *Presentation of VOLTAP recharging infrastructure for Rail4EARTH*.
- EEA. (2024). *Greenhouse gas emission intensity of electricity generation*. Retrieved from <https://www.eea.europa.eu/>.
- EEA. (2025). *Share of energy consumption from renewable sources in Europe*. Retrieved from <https://www.eea.europa.eu/>.
- EFACEC. (2024, September). *Efacec selected to supply new train charging stations in Denmark*. Retrieved from <https://www.efacec.com/>.
- Ernst, J. (2020). *Project FINE2 Deliverable 2.3 Energy baseline update*.
- Esteban Rodriguez, B. N. (2022). *FCH2RAIL Del. D7.1–Gaps in regulatory framework prior to the demonstrator train test*.
- Esteban Rodriguez, B. N. (2024). *FCH2RAIL Del. D7.4–Complementary gaps in analysis framework*.
- EUROSPEC. (2022). *EuroSpec "Specification for alternative traction energy supply and related infrastructure interfaces" Part 1: Battery driven systems*.
- Fernandez, S. (2023). *Rail4EARTH – Del. D 5.1 Development of alternative propulsion based on ESS intermediate report n°1*.
- FINE2, S. (2023). *FINE2 Deliverable 2.2 Energy Baseline - Update*.
- Fraunhofer. (2025). *Fraunhofer charging system*. Retrieved from <https://www.ivf.fraunhofer.de>.
- G.Anderson. (2021). *BNSF ZERO-AND NEAR ZERO-EMISSION FREIGHT FACILITIES PROJECT (ZANZEFF) DATA ACQUISITION SUPPORT*.
- Guerra, E. d. (2023). *Rail4EARTH – Del. D 7.1 Development of alternative propulsion based on hydrogen intermediate report n°1*.
- GWR. (2025). *GWR fast charge white paper*.
- J. P. Powell, A. G.-G. (2014). Experimental assessment of the energy consumption of urban rail vehicles during stabling hours: Influence of ambient temperature. *Applied Thermal Engineering, vol. 66*.
- Kapetanović, M. N. (2024). Energy use and greenhouse gas emissions of traction alternatives for regional railways. *Energy Conversion and Management n°303*.
- Lidén, J. (2023). *Optimization of Comfort-Related Energy and Thermal Comfort for Commuter Trains : A Case Study of Stockholm Commuter Trains*.
- Mannevy, P. (2022). *Project PINTA3 Deliverable D3.1 "State of play and roadmap to achieve the full suppression of fossil fuel rolling stock"*.
- Mascis, A. (2024). *ERJU FP6 DELIVERABLE D5.1 STATE-OF-THE-ART REPORT FOR REGIONAL LINES ROLLING STOCK*.
- Matteo Frea, R. T. (2019). ADAPTIVE WHEEL SLIDE PROTECTION ALGORITHMS. *EuroBrake*.
- MEGA-LADEN. (2024). *Fully Automated Fast-Charging System for E-Trucks in the Megawatt Range*. Retrieved from <https://mega-laden.de/>.
- Ou, S. (2023). Estimate long-term impact on battery degradation by considering electric vehicle real-world end-use factors. *J. Power Sources, vol. 573*.
- pass, T. b. (2025). *European Battery Regulation*. Retrieved from <https://thebatteryass.eu/resources/>.
- Rail, E. (2024). *Energy saving in Rail: Consumption assessment, efficiency, improvement and saving strategies, overview report*.
- railML. (2022).

- S. Wu, R. X. (2020). The state of the art on preheating lithium-ion batteries in cold weather. *Journal of Energy Storage*, vol. 27.
- SNCF VOYAGEURS. (2024). *Information on greenhouse gases emissions for transport services*. Retrieved from sncf-voyageurs: <https://www.sncf-voyageurs.com/medias-publics/2025-01/sncfv-methodology-infoges-v2024.pdf>
- Streuling, C. P. (2021). Techno-Economic Assessment of Battery Electric Trains and Recharging Infrastructure Alternatives Integrating Adjacent Renewable Energy Sources. *MDPI Sustainability*.
- UIC. (2022). *SFERA IRS 90940 v2 Data exchange with DAS following the SFERA protocol*.
- UIC. (n.d.). *IRS 90940 v3 SFERA protocol: train operation data exchange with on-board devices*.
- UNISIG. (2023). *ATO-OB / ATO-TS FFFIS Application Layer, Subset-126 of ATO over ETCS*.
- Vinberg, E. M. (2018). *Energy use in the operational cycle of passenger rail vehicles*. MSc Thesis.
- Vinberg, E. M. (2018). *Energy Use in the Operational Cycle of Passenger Rail Vehicles*.
- W.Klebsch, N. P. (2020). *Evaluation of climate-neutral alternatives to diesel multiple units, VDE report*.
- WEH. (2025). *Catalogs & Brochures*. Retrieved from <https://shop.weh.com/>.
- X. Hu, L. X. (2020). Battery Lifetime Prognostics. *Joule*, vol. 4.

12. Appendices

