D1.1
Energy Management & Pre-Standardisation for Alternative drive trains and related railway system
Intermediate Report N° 1

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1. Executive Summary

The present document constitutes the Deliverable D1.1 "Energy Management & Pre-Standardisation for Alternative drive trains and related railway system intermediate report n°1" 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 first version of the document which reports the status of the SP3-WP1 of Rail4EARTH after 16 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 first intermediate WP1 progress report, some chapters are not fully completed because the work will be continued in 2024 and 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
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
CAF	Construcciones y Auxiliar de Ferrocarriles, train manufacturer
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
CSM	Common Safety Methods
C-DAS	Connected-Driver Advisory System
DAS	Driver Advisory System
DB	Deutsche Bahn, train operator
DC	Direct Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt, research centre
DMU	Diesel Multiple Unit
EMC	Electromagnetic Compatibility
EMU	Electrical Multiple Unit
ESS	Energy Storage System
ESU	Energy Storage Unit
ETCS	European Train Control System
FCH2Rail	Within the Clean Hydrogen Partnership funded "Fuel Cell Hybrid PowerPack for Rail Applications" Grant Agreement No. 101006633
FINE2	European project funded within Shift2Rail. Furthering Improvements in Integrated Mobility Management (I2M), Noise and Vibration, and Energy in Shift2Rail
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"
HMU	Hydrogen Multiple Unit
HRS	Hydrogen Refuelling Station
HSS	Hydrogen Storage System

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
OHS	Occupational Health and Safety
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
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
SoE	State of Energy
SP	System Pillar
STS	Hitachi Rail STS, train manufacturer
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
VOLTAP	Fast charging station developed by Furrer+Frey in partnership with Stadtwerke Tübingen
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 leaded 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.

4. Objective/Aim

This document has been prepared to provide intermediate results and report the status and progress of WP1 activities until M16.

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 are also 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 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 will last not least pushes the decarbonisation of the railway system.

An overview of the interfaces and components of trains with alternative drives and related infrastructure is shown in Figure 1.

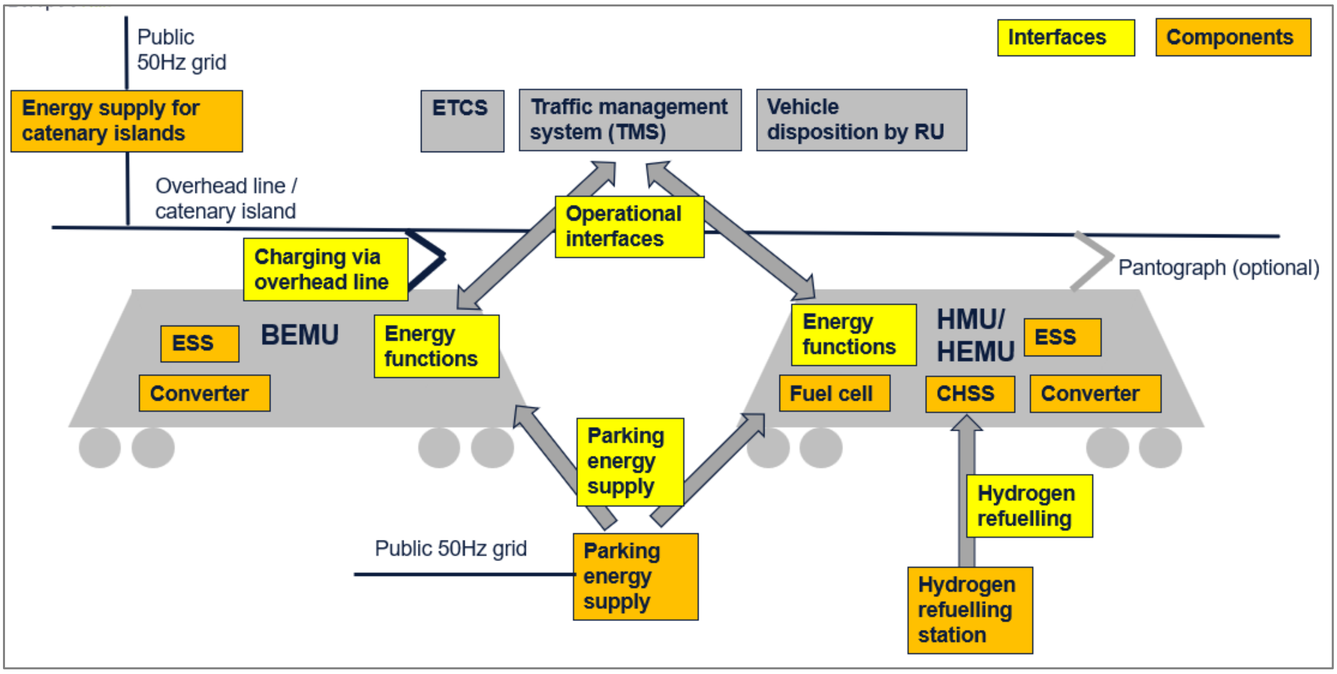


Figure 1: Interfaces of trains with alternative drives and related infrastructure

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 requirements, performance, and interfaces of the vehicle components of the Energy Storage System (ESS) of trains with alternative drives:

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

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:

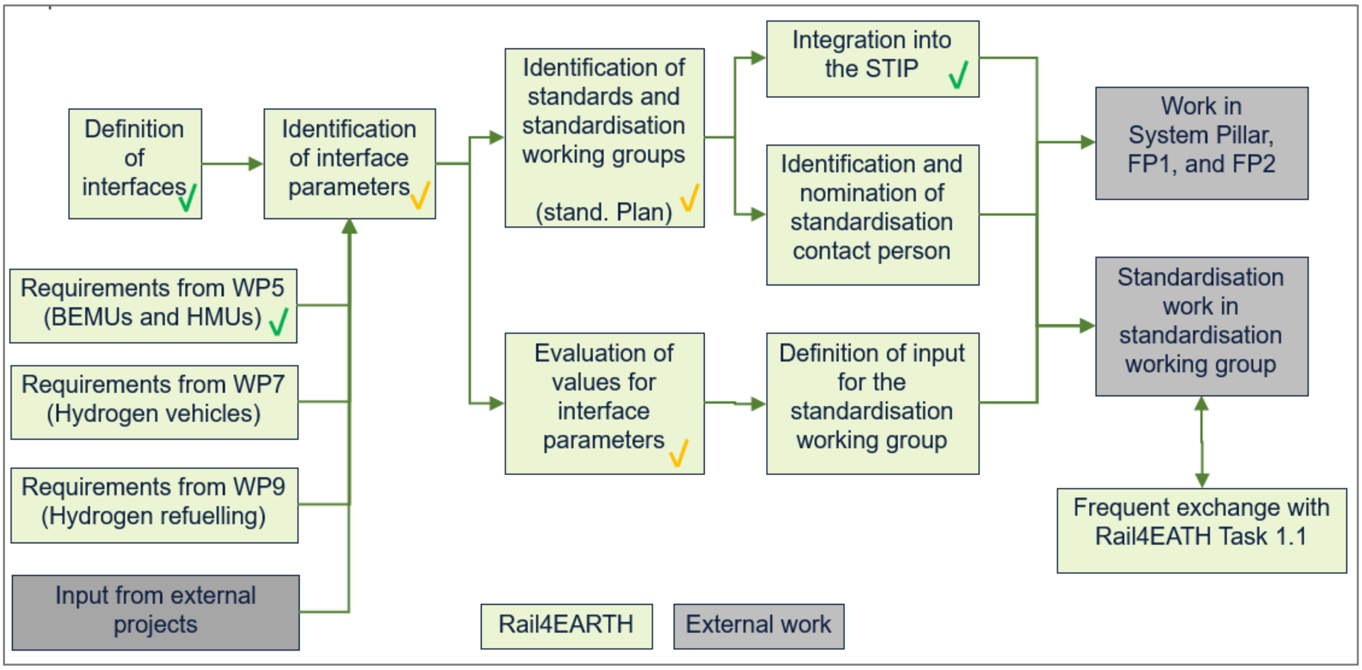


Figure 2: Working procedure for Task 1.1

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 of these working groups must be identified who will introduce the output of Rail4EARTH into the working groups.

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 successive deliverables (Del. 1.2 and 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-standarisation 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:

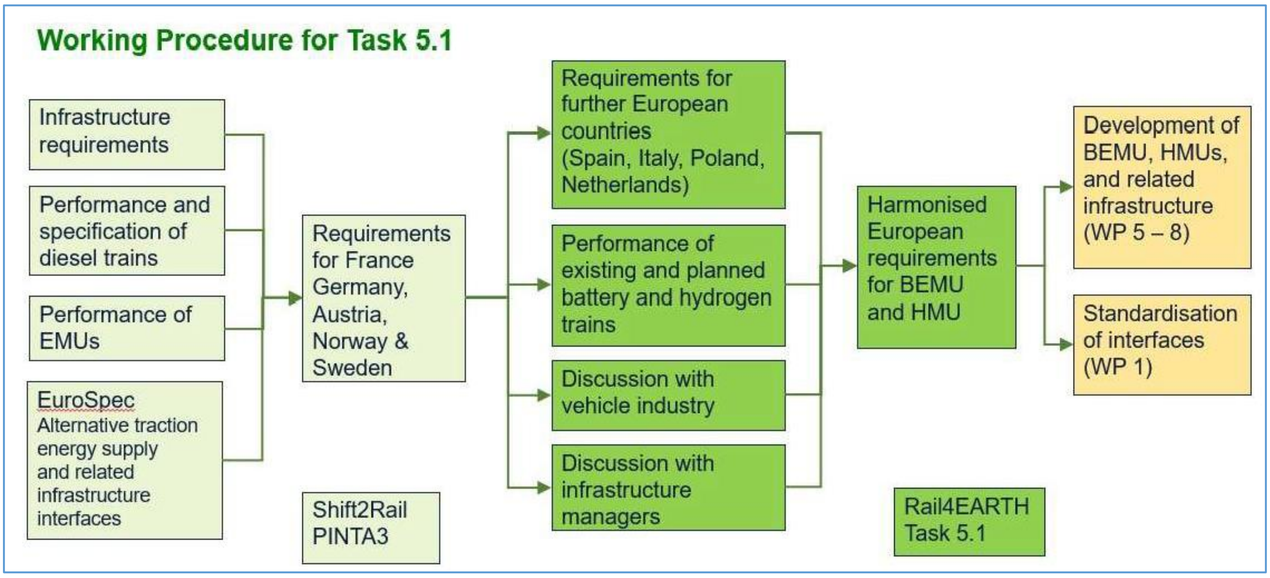


Figure 3: Working procedure for Task 5.1

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".

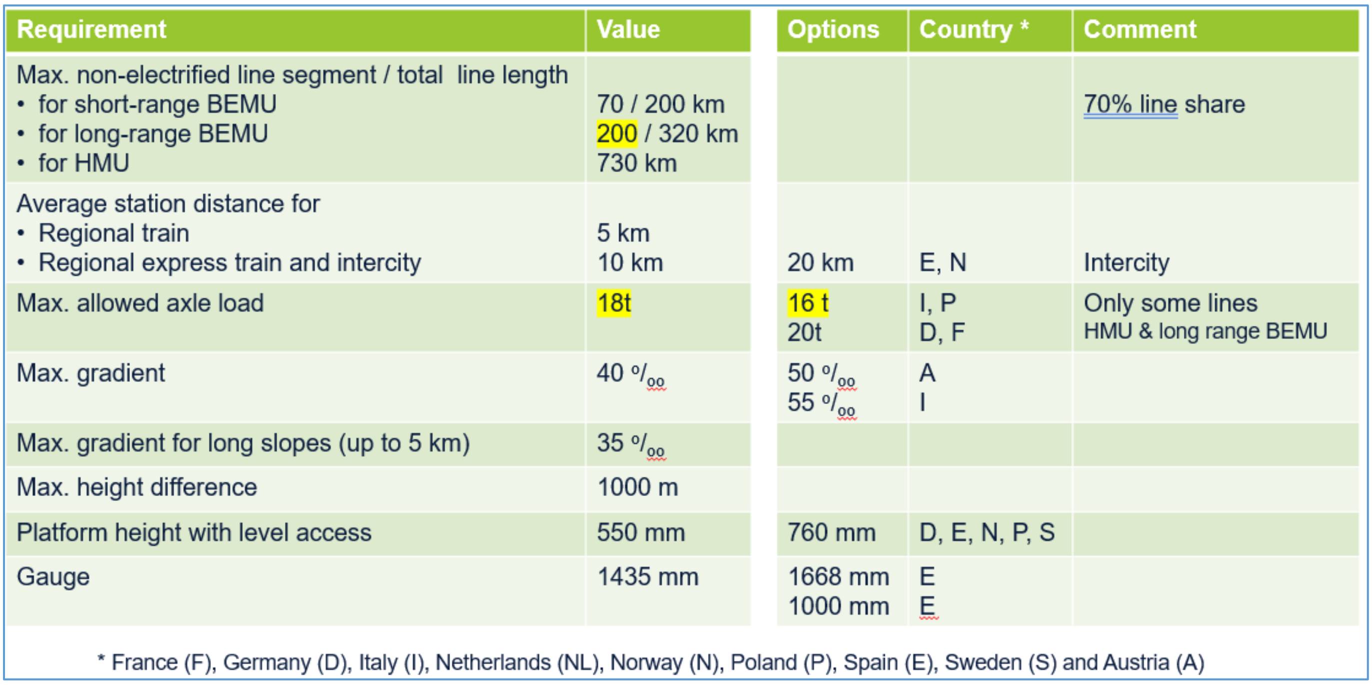
In task 5.1 of Rail4EARTH, the following work has been done:

- 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.

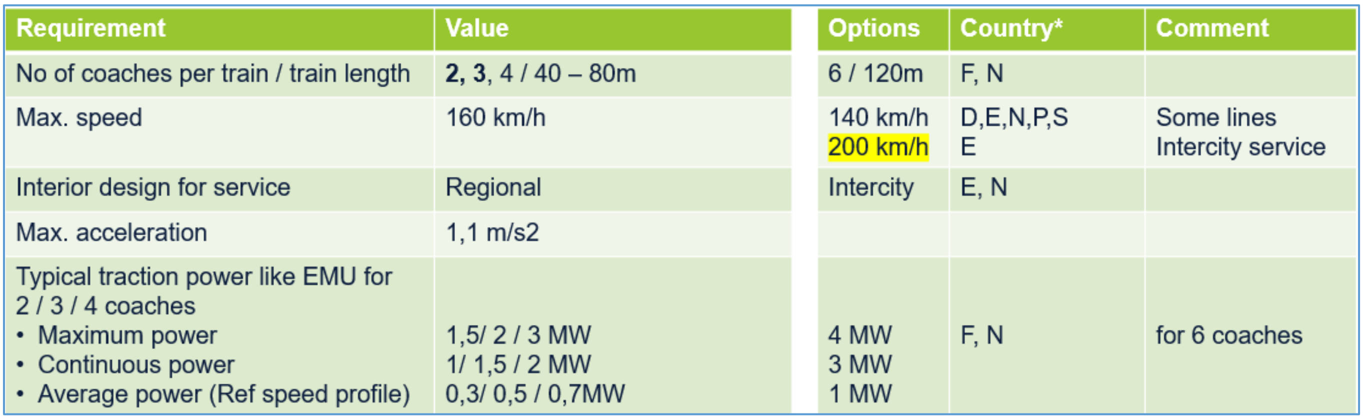
The requirements of each group are described in the following tables. The yellow marked values are a challenge for the development. Red values are still open and must be clarified in WP1 during the next year.



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			70% line share
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 °/oo	50 °/oo 55 °/oo	A I	
Max. gradient for long slopes (up to 5 km)	35 °/oo			
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/s2			
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 (via overhead line and pantograph)	25kV 50Hz for F 15kV or 25kV 50Hz for 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
External energy supply for parking (for 2 and 3 coach BEMUs)	400V 50Hz 3AC, > 85kW			
Plug for external energy supply	CEE 125A	EN 50546		
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 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

5.2.2 Input from WP7 for Hydrogen Propulsion

The focus of WP7 [9] is the development of vehicle components for hydrogen propulsion. 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, further discussion on fast refuelling will be necessary. Hence WP7 participants will work on this point during the next period of the project regarding pre-standardization.

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.

The following existing and planned standards are identified:

#	Standard name	Topic
1	ISO 19880-1:2020 - 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).	Vehicles
2	Standard PN-EN 17127:2021-04 - external hydrogen refuelling points distributing hydrogen gas and the refuelling procedures used.	Refuelling
3	ISO 17268 standard - standard for devices for connecting and refuelling hydrogen in the gaseous state in motor vehicles.	Interface
4	ISO 22734-1 standard - a standard specifying the design, safety requirements and operational requirements for devices for generating hydrogen using water electrolysis.	Hydrogen production
6	SAE J2600 standard - standard for the design and testing of nozzles, connectors, and tanks for refuelling with compressed hydrogen.;	Interface
7	SAE J2579 standard – a standard specifying requirements for hydrogen storage tanks.	Storage
8	ISO/TS 20100/, ISO 19880-1:2020 standard - standards specifying the characteristics of outdoor public and private refuelling stations that dispense hydrogen gas used as a fuel for land vehicles of all types, do not cover home and backyard applications to power land vehicles.	Refuelling
9	ISO 19880 series – This standard defines the minimum design, installation, commissioning, operation, inspection and maintenance requirements, for the safety, and where appropriate, for the performance of public and non-public refuelling stations that dispense gaseous hydrogen to light road vehicles (e.g. fuel cell electric vehicles).	Refuelling
10	ISO 19881:2018 - This document 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.	Storage

11	ISO 19882:2018 - This document establishes minimum requirements for pressure relief devices intended for use on hydrogen fuelled vehicle fuel containers	Storage
12	ISO/DIS 19885-1 [35] should be mentioned Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 1: Design and development process for fuelling protocols.	Vehicles
13	EN 17127:2020 - This standard defines the minimum requirements to ensure the interoperability of hydrogen refuelling points, including refuelling protocols that dispense gaseous hydrogen to road vehicles (e.g. Fuel Cell Electric Vehicles) that comply with legislation applicable to such vehicles.	Vehicles
14	ISO 17268:2020 - This standard defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refuelling connectors. Under revision.	Vehicles
15	ISO 22734:2019 - Hydrogen generators using water electrolysis Industrial, commercial, and residential applications. This document defines the construction, safety, and performance requirements of modular or factory-matched hydrogen gas generation appliances, herein referred to as hydrogen generators, using electrochemical reactions to electrolyse water to produce hydrogen.	Hydrogen production
16	SAE J2600_202301 - This document defines the design and testing of nozzles, tanks and connections for refuelling with compressed hydrogen.	Interface
17	IEC 60079-10-1:2020 - 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.	Safety zone
18	EN ISO 80079-36:2016 & AC:2019 - 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.	Safety zone
19	EN 62305 - this series of standards provide the requirements for protection of a structure against lightning and physical damage and life hazard (all parts)	Safety zone
20	ISO 16110-1:2007 - This standard applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than 400 m3/h at 0°C and 101,325 kPa, herein 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
21	ISO 16110-2:2010 - 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 m3/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
22	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 treated in separate International Standards.	Safety zone
23	SAE J2579_202301 - This document defines design, construction, operational, and maintenance requirements for hydrogen fuel storage and handling systems in on-road vehicles.	Vehicles

24	ISO 14687:2019 - This standard specifies the minimum quality characteristics of hydrogen fuel as distributed for utilization in vehicular and stationary or other applications as fuel, this applies to all modes of transport and hydrogen applications as fuel, land, water, air and space.	Vehicles
25	NFPA 2 Hydrogen Technologies Code - The purpose of this code is to provide fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH2) form or cryogenic liquid (LH2) form.	Safety zone

Table 5: Identified standards in WP9 related to hydrogen refuelling station.

Most of standards for road vehicles fulfil needs of railway sector. Despite that there are areas that need to be adopted to consider the railway sector:

- Higher level of flow up to 300 g/s,
- Different approach for refuelling: fast or economical,
- Higher quantity of hydrogen to be stored,
- 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 [9] and D7.4 [11]) 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 covers the analysis of regulatory gaps with respect to train, pantograph, and infrastructure.

Since the FCH2RAIL deliverable D7.4 [11] is an update of the preceding deliverable D7.1 [10], 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 with regard to 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 result of FCH2RAIL **Deliverable 7.4** with regard to 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 6: 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 H2 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. H2 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 6: 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 via overhead line,
- Parking energy supply,
- Hydrogen refuelling.

5.3.1 BEMU Charging via Overhead Line

The operational requirements for BEMU charging are developed in task 5.1 from the European railway undertakings taking part in Rail4EARTH, see [1].

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. The charging should be done as fast as possible to meet the required operational termination time (down to 15min). But fast charging requires high charging power. To limit the vehicle effort, it was decided in task 5.1 (see [1]) 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 [2] the charging time was calculated, when it is charged with average power (slow charging) and max. power (fast charging), see Figure 4:

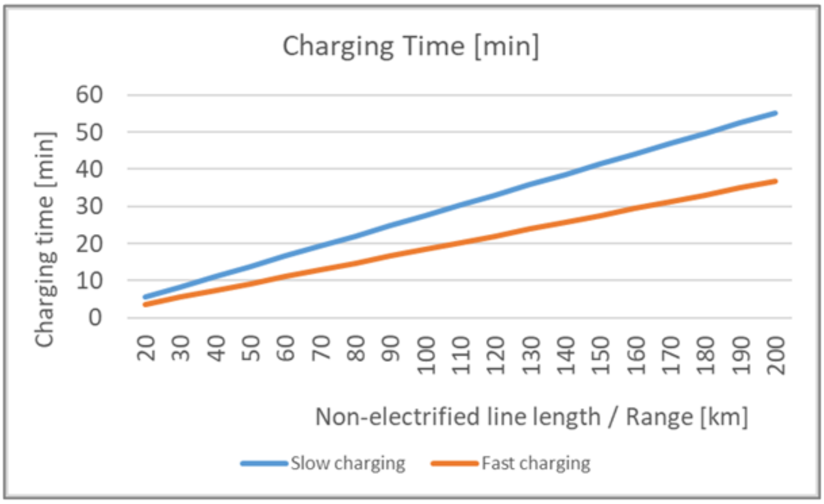


Figure 4: Charging time for slow and fast charging.

Even with max. power (fast charging) the required charging time below 15 min is only achieved for a non-electrified line length of up to 80km (short-range BEMU), so an equivalent fast charge range of 320 km for 60 min charging. 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.

In general, the overhead lines of catenary islands 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.

An exception are countries with 16,7Hz overhead line frequency. Here a supply of the overhead islands with 50Hz is chosen 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:

- 15kV or 25kV **50Hz** (instead of 16,7Hz) for Austria, Germany, Switzerland, and Sweden

But the common supply voltage for these countries (15 or 25kV) is still open. It will be clarified in task 1.1 in 2024. Table 7**Erreur ! Source du renvoi introuvable.** shows the comparison between both voltages for catenary islands for the supply of 3-coach BEMUs with up to 2 MW.

Voltage and frequency	**Required current**	**Kind of catenary**	**Infrastructure effort**	**Vehicle effort** (in addition to switched absorber circuit and changed software for 50Hz)	**Standardisation effort**	**Supply of acceleration range**
25 kV **50 Hz**	80 A	Common catenary, but isolation for higher voltage	Low (Components from the European and industry market)	Medium (Heavier transformer with additional tap and switching circuit)	Low (TSI standard)	Low (Components from the European and industry market)
15 kV **50 Hz**	135 A	Catenary with overhead current rail	Low for fixed parking area for one train (short catenary island)	Low (No additional effort)	High (New voltage system, must be integrated into standards)	High (Requires 15kV **16,7Hz** substation, since 15kV 50Hz is not a permitted voltage system)
			Medium for flexible parking area and coupled trains (long catenary island), since the current rail requires shorter mast distance than common catenary			

Table 7: Comparison of 15kV and 25kV voltage for catenary islands

For 25kV supply voltage requires a charging current of 80A. This value is allowed at standstill as a continuous current according to EN 50367. The infrastructure effort is low. A conventional overhead line con 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 drawback is that on vehicle side a transformer with additional windings and tap as well as a switching circuit is necessary.

For 15kV voltage requires a charging current of 135A. This requires an overhead current rail instead of a standard catenary, e.g. the VOLTAP system [3], see Figure 5. 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. Therefor more masts including grounding are required. On the vehicle side there is no additional effort. Since 15kV 50Hz is no standardised voltage system, it must be added to the European standards, especially TSI energy and pr:TS 50729 (CENELEC CLC/SC9XC/SG25), see [4]. The main drawback of 15kV 50Hz is that an extension of the electrification along the acceleration range (a few kilometres) is not possible, since 15kV 50Hz is not permitted as an overhead line voltage. In this case a 15kV 16,7Hz substation is required. This leads to much higher costs.

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

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 challenges 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).

Parameters for standardisation

The following parameters and systems for BEMU charging shall be the focus of pre-standardisation:

- Voltage and frequency (for different countries),
- Max. power and current,
- Contact line system,
- Contact line protection system,
- Pantograph protection system,
- EMC to the feeding grid,
- Electrical safety,
- Stray current protection,
- protection against influence on signalling system.

The result of the pre-standardisation for fast BEMU charging in catenary islands shall be integrated into the following standards:

Standard	Objective	Rationale
CLC/**prTS 50729**: 2022 Railway applications - Fixed installations - Requirements for charging infrastructure for accumulator electric traction units based on dedicated contact line sections	Definition of common interfaces between infrastructure and rolling stock for fast BEMU-charging via overhead line (voltage, frequency, max. current, communication, etc.) to optimise the charging process of trains with on-board ESS	If modification of TS 50729:2022 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 TS 50729:2022-2), this new document shall include the content for interfaces requirements
Deutsche Bahn **RIL 991.0131Z02** Oberleitungsanlagen; Laden von Battery Electric Multiple Units (BEMU) an der Oberleitung	Definition of the interfaces between infrastructure and rolling stock for fast BEMU-charging via overhead line (voltage, frequency, max. current, ….)	
EuroSpec Specification for alternative traction energy supply and related infrastructure interfaces - **Part 1**: battery driven system	Review of the EuroSpec based on the work in Rail4EARTH WP1 and WP5	Specification of common European interfaces between vehicle and infrastructure (fast charging, energy supply) instead of different possible solutions

Table 8: Standards for fast BEMU charging in catenary islands

All standards identified are reported to the common “Standardisation and TSI input plan” STIP developed by the system pillar.

5.3.2 Parking Energy Supply for BEMUs and HMUs

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. In contrast to the fast charging a manual operation of the supply can be accepted. Therefor a cable and plug supply as widely used for the supply of DMUs can be used, see Figure 6.

Figure 6: Parking energy supply for DMUs (32A, 22kW)

The external energy supply is not only required for BEMUs, but also for HMUs since for HMUs 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. Therefor 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 [5] it is possible to reduce the power to 85kW with special vehicle-side measures to allow a cost-efficient supply.

In the PINTA3 project [6] 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 7:

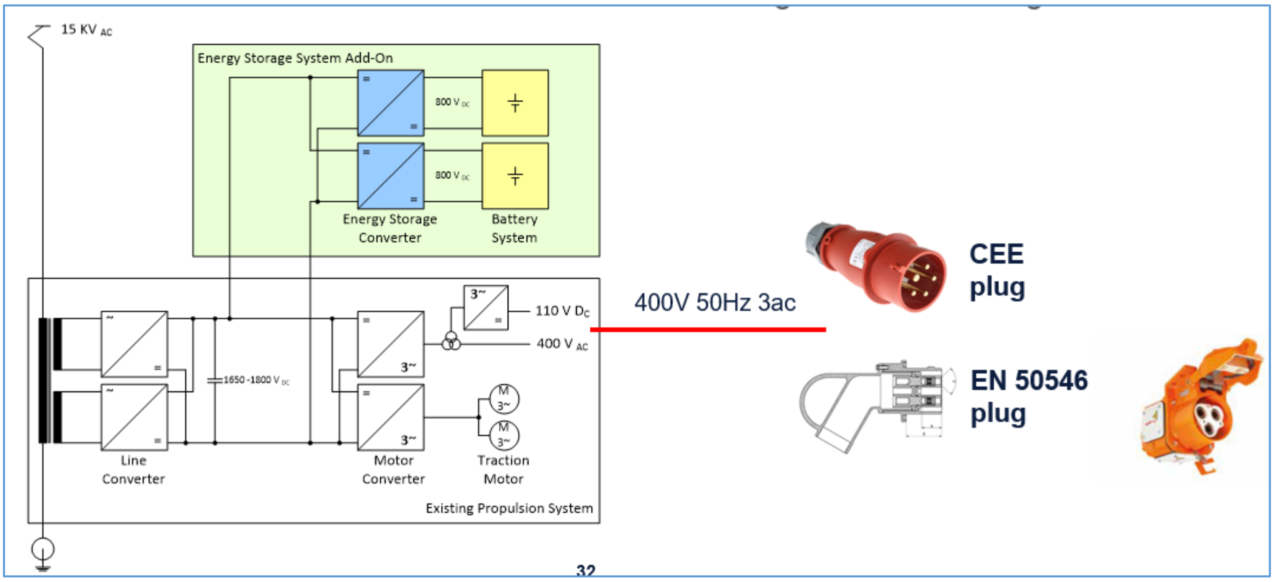


Figure 7: Connection of the parking energy supply to the electrical circuit of the vehicle

For the connection there are two different plugs in discussion: the CEE 125A plug or EN50546 plug [7]. Table 9Table 9: Comparison between CEE and EN50546 plug. shows the comparison between both plugs:

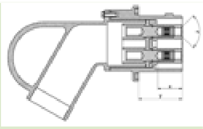
	CEE	**EN 50546**
Plug		
Plug type/ standard	CEE 125A	EN 50546
Voltage	400V 50Hz 3AC	400V 50Hz 3AC
Power (3 coaches)	86kW	86kW
Vehicle effort	low	low
Infra effort	low	low
Robustness	medium	high
Control/ data line	no	yes
Mech. lock	no	yes
Railway certification	To be clarified	To be done

Table 9: Comparison between CEE and EN50546 plug.

The comparison shows that the EN 50546 plug is the better solution with respect to robustness, mechanical lock, and a control/ data line. There is already a plug on the market. But it still must be tested under railway conditions. This is planned outside of Rail4EARTH. After the tests it should be decided which plug should be established as the European standardised solution for external energy supply for pre-conditioning of BEMUs and HMUs. Beside the technical criteria the costs and availability / second source must be considered. Italy already mentioned that they are in favour of the CEE 125A plug, since it is already introduced.

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. Therefor there should be a socket at both sides of the train (left and right). But it 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.

The following parameters for parking energy supply shall be the focus of pre-standardisation:

- Voltage and frequency,
- Max. power and current,
- Mechanical plug type and dimensions,
- Control lines,
- Control communication,
- Environmental conditions,

The result of the pre-standardisation of the parking energy supply shall be integrated into the standards:

Standard	Objective	Rationale
EN 50546: 2020 update Railway applications – Rolling stock – Three -phase shore (external) supply system for rail vehicles and its connectors	Review of the EN based on the work in Rail4EARTH WP1	Specification of common European interfaces between vehicle and infrastructure for energy supply for pre-conditioning of BEMUs and HMUs (performance, plug, etc.)
EuroSpec Specification for alternative traction energy supply and related infrastructure interfaces - **Part 1**: battery driven system	Review and amendment of the EuroSpec based on the work in Rail4EARTH WP1 and WP5	Specification of common European interfaces between vehicle and infrastructure (fast charging, energy supply) instead of different possible solutions

Table 10: Standards for parking energy supply

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.

Requirements for Hydrogen Refuelling

The requirements for hydrogen refuelling agreed in task 5.1 are taken from Del. 5.1 [1] (see chapter 5.2.1) and the pre-study carried out in the Shift2Rail project PINTA 3 WP3 [6].

The **refuelling time** for HMUs/HEMUs should be like the diesel refuelling time of DMUs (about 15min). It should be fulfilled for the fuel amount required for 1000 km distance. For other applications like maintenance or shunting locos the refuelling time can be longer to reduce the costs of the refuelling station.

Since hydrogen refuelling stations are often not located near the application line, the refuelling distance should be as high as possible to minimise additional operational train runs for refuelling. Therefor a **refuelling distance** of at least 1000km is required. 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.

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 H_2 . 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, see EN 17124:2019. 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.

To allow a fast refuelling the parallel refuelling with via **two receptables** can be accepted from operator view. For more than 3 coaches even more receptables can be an option.

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.

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

- The refuelling station 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),
- Maximum SoC must be reached,
- 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,
- Save and secure communication between the vehicle and the HRS.

To enable the same **operational performance** than refuelling of diesel driven vehicles, the refuelling must be possible within the same time and by the same staff (concerning education). In general, the driver refuels the vehicle. This means that the refuelling must 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 receptable 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,
- 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.

Traditionally the vehicle is identified by a transponder mounted in the vehicle.

In any case that the refuelling process uses a **communication** between the vehicle and the refuelling station and the vehicle can be accurately identified via this communication, the transponder can be replaced by this communication.

Pre-standardisation for Hydrogen Refuelling

The following parameters and systems for hydrogen refuelling shall be the focus of pre-standardisation:

- Mechanical dimensions and type of nozzle and receptable,
- Hydrogen pressure,
- Refuelling speed/ flow rate,
- Environmental conditions,
- Number and location of the receptable at the vehicle and infrastructure,
- Communication hardware, protocol, and parameters,
- Test procedure,
- Leakage control,
- Risk management,
- Required refuelling distance /range,
- Refuelling time.

Further, the measurements accuracy (important for billing) and safety requirements must be defined.

For the standardisation international standards for road vehicle applications should be amended with respect railway applications instead of the creation of new railway standards due to the following reasons:

- The existing standards are well established with many petrol station manufacturers and their customers,
- Requirements do not have to be re-invented,
- International acceptance procedures and approval processes were considered in the creation of the standard,
- Limited knowledge of railway undertakings, infrastructure managers and industry with respect to hydrogen refuelling technology,
- Higher competence of the working groups.

The following standards with respect to hydrogen refuelling are identified:

- ISO 17268 Gaseous hydrogen land vehicle refuelling connection devices,
- ISO 19880-1 Gaseous hydrogen fuelling stations - Part 1: Gaseous hydrogen fuelling station,
- ISO 19885-x Gaseous hydrogen - Fuelling protocols for hydrogen-fuelled vehicles, Part x: High flow refuelling protocol for rail vehicles,

- SAE 2601-5 High-Flow Prescriptive Fuelling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles
- EuroSpec Specification for alternative traction energy supply and related infrastructure interfaces – Part 2: Hydrogen

The automobile standards should be amended regarding railway applications. Especially the communication between vehicle and infrastructure must be developed and amended to the SAE 2601-5 or ISO 19885. This must be clarified within the project in the next year. Basis for the standardisation of the communication should be the work carried out in the FCH project PRHYDE [21] [22].

In addition to the ISO standards, common European railway refuelling parameters and performance should be defined in the Europec part 2 [8].

In Table 11 all standards to be adopted are listed.

Standard	Objective	Rationale
ISO 17268: 2020 Gaseous hydrogen land vehicle refuelling connection devices	Standardisation of the mechanical interface parameters and performance of hydrogen refuelling for rail vehicles	The standard for automobile application has to be amended by railway applications. This requires the engagement of rail exterts in the standardisation working group.
ISO 19880-1:2020 Gaseous hydrogen fuelling stations - Part 1: Gaseous hydrogen fuelling station	Standardisation of performance, interfaces and components of gaseous hydrogen fuelling stations	The standard for automotive applications (cars, buses and lorries) should be amended for railway application. This requires the engagement of rail exterts in the standardisation working group. It must be clarified whether the railway requirements can be integrated in part 1 or whether a new part just for railway application shall be added.
ISO 19885-1 Gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles - Part 1: Design and development process for fuelling protocols	Standardisation of the communication protocoll between refuelling station and vehicle	The forseen standard for automotive applications (cars, buses and lorries) should be amended by part x for railway application. This requires the engagement of rail exterts in the standardisation working group.
ISO 19885-2 Gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles - Part 2: Definition of communications between the vehicle and dispenser control systems	Standardisation of the communication protocoll between refuelling station and vehicle	The forseen standard for automotive applications (cars, buses and lorries) should be amended by part x for railway application. This requires the engagement of rail exterts in the standardisation working group.
ISO 19885-3 Gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles - Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles	Standardisation of the communication protocoll between refuelling station and vehicle	The forseen standard for automotive applications (cars, buses and lorries) should be amended by part x for railway application. This requires the engagement of rail exterts in the standardisation working group.
SAE J2601 202005 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles	Protocol and process limits for hydrogen fueling of vehicles for 35 and 70 Mpa and fuel temperatures of -40 °C, -30 °C, and -20 °C	It has to be clarified whether the protocoll for light duty vehicles is sufficient for railway application, especially with respect to refuelling time
EuroSpec Specification for alternative traction energy supply and related infrastructure interfaces - **Part 2**: Hydrogen	Review and amendment of the EuroSpec based on the work in Rail4EARTH WP1, WP8 and WP9	Specification of common European interfaces between vehicle and infrastructure with respect to hydrogen refuelling

Table 11: Standards for hydrogen refuelling

Pre-standardisation for Communication between the HRS and Vehicle

A safe communication between refuelling station (HRS) and vehicle is required to allow a fast refuelling, see Figure 7Figure 8. If there is no communication the hydrogen refuelling speed must be limited to prevent an overheating of the hydrogen in the vehicle hydrogen storage system. Three kinds of communication hardware are discussed:

- Wireless,
- By wire,
- Manual input.

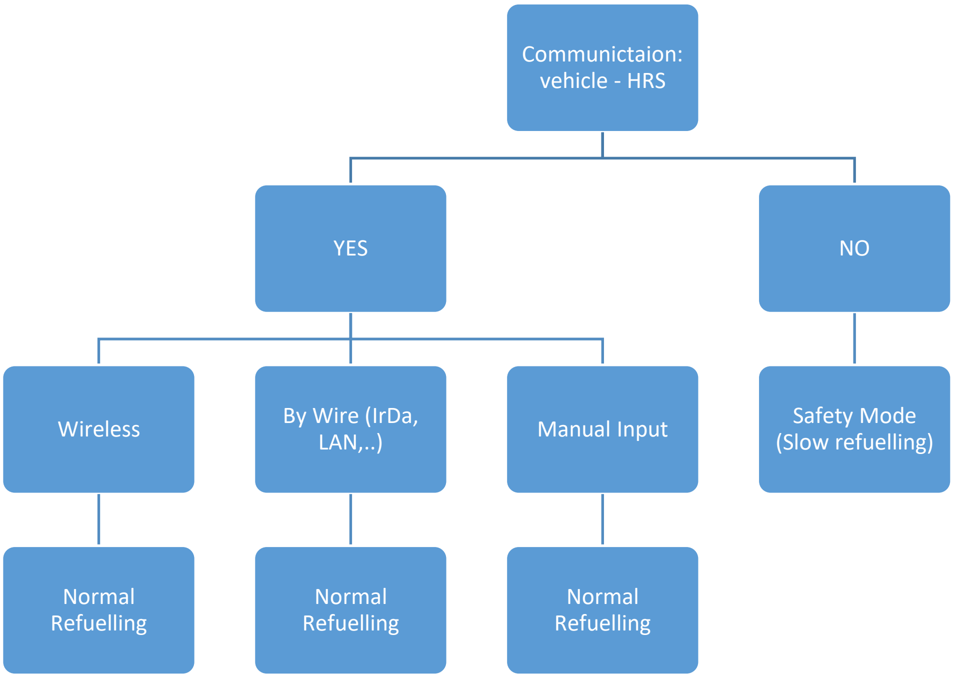


Figure 8: Communication modes and technologies for refuelling of hydrogen vehicles

Parameters of the communication are currently subject to the standardisation process. In this document there are listed some proposed communication parameters:

- Kind of vehicle: the refuelling station knows the type of the CHSS on train,
- Concrete vehicle (No Transponder needed; HRS has only one type of train),
- Initial pressure in CHSS before refuelling (before pressure pulse at start),
- Initial Temperature in the tank of the vehicle,
- Signal “Ready for refuelling” (from vehicle; the parking brake is engaged),
- Signals should be transmitted permanently to ensure safe condition for refuelling,
- Signal: “Refuelling in progress” (from Station),
- Signal: “Connection established” (hose is under pressure),
- Temperature measurements point in tank (85°C may not be exceeded, only safety function),
- Pressure in tank (for each CHS-subsystem in parallel and local position),
- Signal for abort refuelling regarding to safety reasons (must be clarified).

5.4 Pre-Standardisation of Operational Interfaces

Due to the limited battery capacity BEMUs and HMUs several energy functions have to be implemented to control the energy flow and minimise the energy consumption. Important energy functions are:

- Calculation of the BEMU range as a function of the battery capacity
- Lift and drop of pantograph
- Connected or hybrid driver assistant system (C-DAS)
- Pre-conditioning of the train and the ESS
- Control of external energy supply during parking

The energy functions require static and dynamic infrastructure and parameters of the traffic management system (TMS), ETCS and the vehicle disposition (by the RU), see Figure 1. The communication between vehicle and landside should be standardized with respect to the communication channel and the parameters.

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

- Permitted peed profile
- Location of the stations
- Gradient
- Location of the electrified and non-electrified sections
- Overhead line voltage
- Overhead line frequency
- Max. 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
- Max. permitted charging power

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.

5.4.1 Standardised Data Exchange

The standardisation of the interfaces between vehicle and TMS require a standardised data exchange. Here the following most suitable standard is identified:

Standard	Objective	Rationale
IRS-90940:2022, Ed. 2 Digitalisation, Data, Emerging Innovations - Exchange of data - Data exchange with Driver Advisory Systems (DAS) following the SFERA protocol	Definition of energy functions, data exchange, and common interfaces between train and operation / traffic mangement systsem (TMS) to manage the energy-efficient operation of trains with alternative drives	In addition to the DAS interfaces a new chapter in the standard shall be added to describe the new energy fuctions and interfaces for the energy funcions of BEMUs and HMUs.

Table 12: Standard for operational interfaces and data exchange

Some of the parameters mentioned above are already exchanged between train and infrastructure/ TMS today. As a basis for future data exchange the data exchange applied today must be evaluated. This is the focus of the task work in 2024.

5.4.2 Future Data Exchange

For the data exchange of future trains, the following standards for data exchange between train and infrastructure/ TMS were identified:

- UIC SFERA IRS 90940 v2 Data exchange with DAS following the SFERA protocol [12],
- UNISIG ATO-OB / ATO-TS FFFIS Application Layer, Subset-126 of ATO over ETCS [13],
- railML® [14].

IRS 90940:

This document addresses the standardisation of data exchange flows with Driver Advisory Systems (DAS) by proposing the new SFERA protocol. 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.

UNISIG:

The purpose of the UNISIG System Interface Description document is to present the interoperable interface between the two subsystems of the Automatic Train Operation (ATO) system, namely the ATO trackside (ATO-TS) and the ATO on-board (ATO-OB).

railML® (Railway Markup Language):

RailML® is a open-source XML-based data exchange format for data interoperability of railway applications. The development is carried out by the partners involved in the railML.org initiative. Software that uses the railML format must be certified to ensure the quality of the railML interfaces.

The pre-standardisation of the data exchange must be done in collaboration with the flagship projects FP1 and FP2 as well as the system pillar.

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 [15].

Train characteristics	Battery train	Hybrid Hydrogen/Battery train	Hybrid Diesel/Battery train
Type of operation	Mainly Regional Sub-urban	Regional	Mainly Regional Intercity
Maximum speed	160 km/h	160 km/h	160 km/h (Regional) 200 km/h (Intercity)
Type of Energy supply	Battery Electric (panto / 3rd rail)	Mainly H2 + Battery Electric (panto)	Electric Diesel + Battery Battery only*
Range in Catenary Free Operation	80 km (from 40 – 150 km)	800 km (from 400 to > 1000)	>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	Step IV or V

Table 13: 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 to develop 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

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 depending 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 lake of energy might be chaotic if it happens on a non-electrified section by delaying. So, it’s required an accurate range estimation prediction to give more confidence to the operator for using alternative drive locomotives.

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

How to calculate the range in operation?

Today, most of the vehicles are using a simplified range calculation. This simplified range calculation is based on available energy on-board, divided by a fixed consumption factor. Example bellow 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 the 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, we can have a so called "**predictive range estimation**". This new autonomy calculation is based on:

- Energy available inside the traction batteries,
- Route information,
- Simulation model.

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 used 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" we recommend 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.

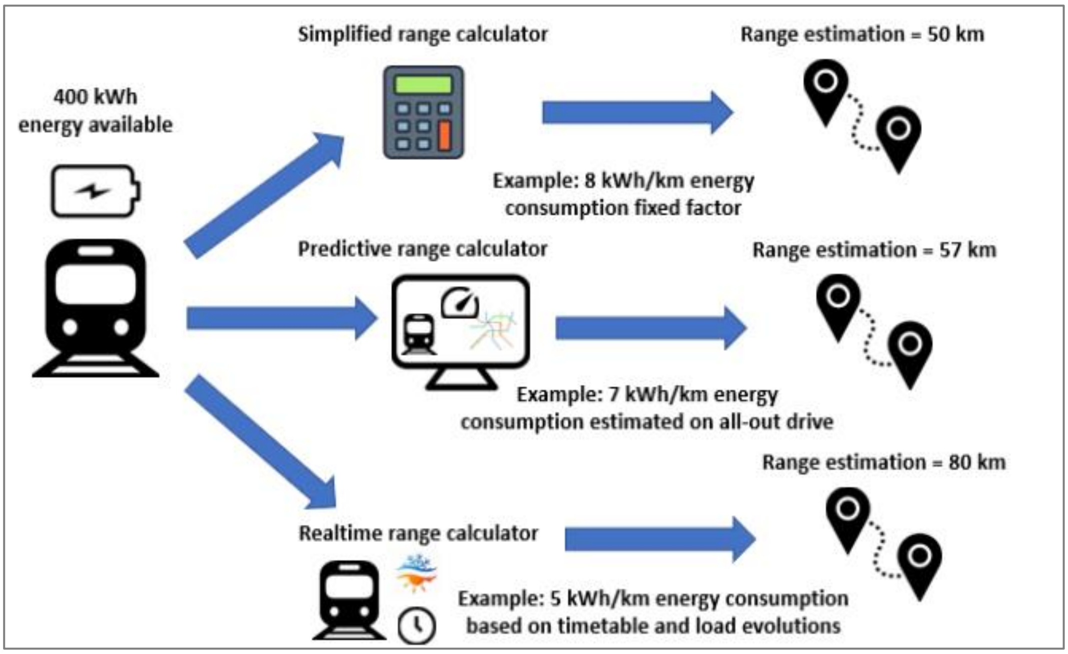


Figure 9 Range calculator methodologies for battery train

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 a smarter operation of the battery train, such as fleet management supervision. These functions are not yet studied and will be part of the work to do for next intermediate deliverable D1.2.

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”). An ESU can be:
    - Lithium-ion battery,
    - Nickel metal hybrid battery,
    - Electric-double layer capacitor,
    - Flywheel.
- 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,
- Inductors,
- Protection devices,
- Cooling systems,
- Etc.

For alternative drive based on hydrogen fuel, the fuel cells are considered in the scope of the “Primary power source” 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 bellows is an extract from the standard and gives a simplified overview of an alternative drive trains:

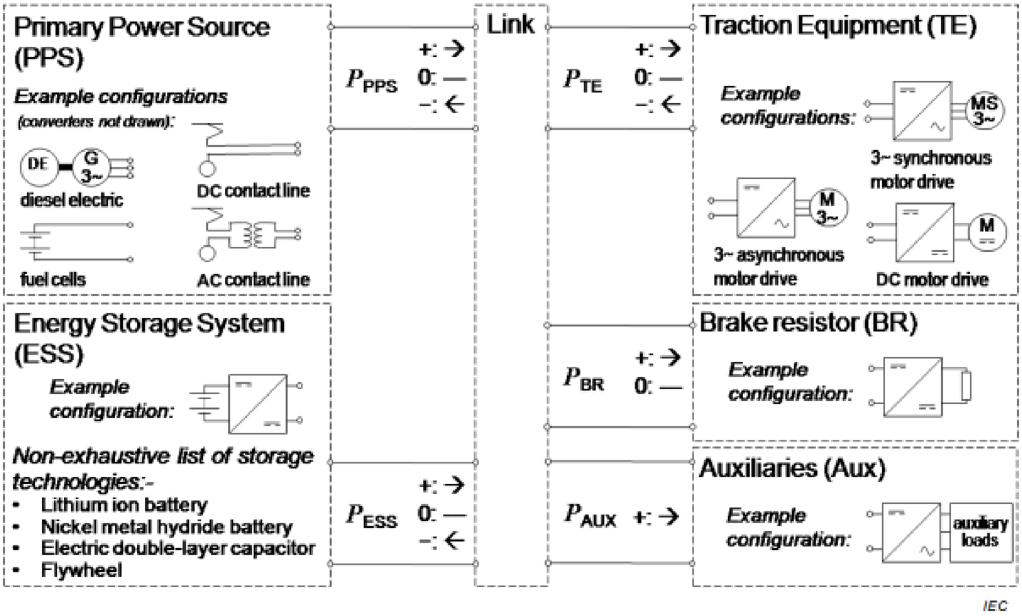


Figure 10: Block diagram of an alternative drive trains according to IEC 62864-1 (source: IEC)

The following components of the ESS shall be standardised with respect to requirements, performance and interfaces (mechanical, electrical and control):

- Battery ESS
- Fuel cell
- Hydrogen storage system HSS
- Power converter

The following standards of 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 maintenability 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 tor 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 characterisics and test methods of electronic power converteres onboard of rolling stock	No adoption with respect to trains with alternative drives required

Table 14: Standards for vehicle components related to alternative drives.

5.5.1 Battery ESS

First of all the scope of battery and ESS shall be clarified. As seen previously, an ESS can be described as defined in the figure bellow:

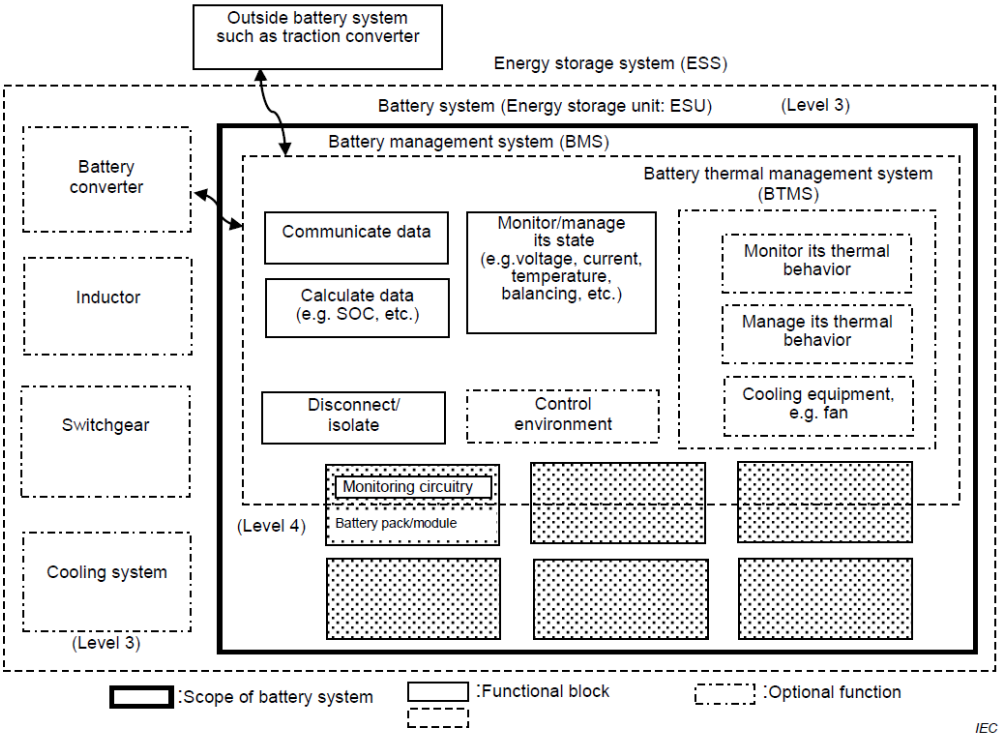


Figure 11: Functional block of battery system (source: IEC)

The following battery/ ESS parameters, requirements, and interfaces should be specified within European standards, if possible:

- Maximum mechanical and weight dimensions,
- Electrical cable connection and connectors,
- Communication and supervision,
- Mechanical interface for cooling and pre-conditioning,
- Environmental conditions (temperature, humidity, vibration, shock …),
- Voltage range

The following standard for battery interfaces was evaluated:

- IEC 62928 Onboard lithium-ion traction batteries

The following additional standards for battery standardisation may be impacted and will be checked in the next period:

- Eurospec Specification for alternative traction power supply and related infrastructure interfaces
- European regulation 2023/1542

General requirements / environmental conditions:

The components of the ESS must be designed to withstand the ambient conditions (mechanical, thermal, environmental) occurring at the installation location and adequate function must be ensured under the given requirements.

- Protection against direct sunlight, rain, dirt, snow, and hail must be provided.
- If the components are installed underfloor, adequate protection against flying ballast, ballast flight, ballast pick-up, against ice plates or chunks of ice must be ensured. If requested by train Customer, ESU on roof should be protected against external aggression as catenary drop, etc.
- A temperature class suitable for the project must be agreed between the customer and supplier in accordance with the expected ambient temperatures and humidity in accordance with EN 50125-1 the equivalent IEC standard is 62498-1
- ESS should be able to be functional with adapted performance out of nominal working temperature until achieve safety limit temperature.
- The permissible temperature range for transport and storage must also be jointly defined.
- The requirements regarding shock and vibration must be selected and tested according to the operating conditions and the installation location of the components in accordance with IEC 61373.
- Fire protection requirements in accordance with EN 45545 must be met.

An Energy storage unit (ESU) is a clearly separated physical equipment with a mechanical enclosure which composed of battery cells, cell blocks, and subsystems.

Some ESUs may not contain certain subsystems (e.g. separated battery management system or battery thermal management system).

According to Figure 11 an energy storage system (ESS) is a physical system which consists of one or more ESUs and the other equipment required to connect to the DC link such as converters, control and monitoring systems, inductors, protection devices, cooling systems, and so on. In most cases, there are separate systems for the traction energy and the on-board power supply. However, it is generally possible for the two systems to support each other or to be combined into one.

Some of the following requirements apply to each ESU and not to the entire ESS.

Safety and protection requirements

The battery management system (BMS) is a subsystem to provide safe operation and optimized performance of the battery system. Each ESU is connected to a BMS that contains at least the following protective functions to ensure safe operation:

- Voltage measurement of Each cell,
- Monitor current in the battery pack,
- Temperature monitoring of representative cells and adjustment of the end-of-charge voltage
- Current limitation (the battery is not able to manage the load but indicate the current limitation,
- Determination of the state of charge (SOC),

- Disconnect or isolate battery packs, battery branches if abnormal operating parameters are detected,
- Optionally: Determination of the "cell health" (ageing, residual capacity, internal resistance, etc.),
- Manage the cells or battery packs/ modules to establish the balance of voltage or SOC.

Optional functions of the management system for the ESS history, authentication and identification can be agreed between the customer and supplier. If necessary, the protective reaction must also be effective when the TCMS is switched off. The vehicle integrator, with the support of the ESS supplier, provides specifications for their use to avoid hazards from the ESS and the ESU during operation and maintenance, even in the event of a fault.

Design and construction requirements

The mechanical size for an ESU is limited to the following dimensions to achieve good manageability in maintenance, during storage and transport and to avoid uneconomical expenses. In individual cases, deviations may be agreed between the customer and the supplier for specific projects if this appears necessary.

- maximum permissible length in the longitudinal direction of the vehicle
- maximum permissible width in the transverse direction of the vehicle
- maximum permissible height of the component
- maximum permissible weight for underframe assembly incl. required lifting gear
- maximum permissible minimum required lifting height for underframe assembly incl. required lifting gear
- maximum permissible weight for roof assembly incl. required lifting gear
- maximum permissible minimum required lifting height for roof assembly incl. required lifting gear

or

- ESU mechanical dimension should allow integration on roof, under the floor or at least into specific area, and respect gauge/envelop of train and infrastructure constrain.
- ESU mechanical dimension should allow transport and warehouse stocking with standard handling tools (forklift, etc.)
- ESU mechanical dimension should allow handling between trains in maintenance warehouse.

The mechanical and electrical interfaces to the vehicle must be planned in such a way that sufficient reserves are available if the ESS/ESU is replaced later.

Mechanical interface for the electrical connections:

Terminal box for the power connections

The terminal box must be designed in such a way that no impermissible pollutants can enter the terminal box from the cells in the event of a fault in the energy storage system.

The vehicle-proof cables are inserted using cable glands.

Terminal strips are provided in the terminal box to allow the cables to be connected using spring terminals or cable lugs.

As an alternative to the terminal box for the power connections, contact can also be made directly to the ESU using freely available sockets directly on the ESU, provided these are sufficient for the ambient conditions.

Equipment into this terminal box could be identified and listed into an update of IEC 62928.

Concerning electrical connection of the ESU:

- An electrical connector is used to connect the electrical output/input to the other part of the energy storage system. The typical voltage applied on the connector is high, between 500 and 1000 V DC,
- ESU should have connectors to easily replace it for maintenance,
- ESU connectors should not allow access to voltage connection even unplugged.

Mechanical interface for cooling / heating connections:

The battery thermal management system (BTMS) is an optional subsystem to maintain the temperature of battery pack/module to achieve the defined performance and lifetime, according to the specified operational pattern.

If the subsystem for cooling or heating is not part of the ESU, a connection to the cooling / heating subsystem must be established via flanges, threads, or quick-release couplings. Components must be used that are sufficient for the ambient conditions, are freely available and comply with a current standard at least at one interface per connection so that they can be replaced with a successor model later.

ESU cooling interface should be with cooling plug system easy to plug and unplug without tools for maintenance and replacement of ESU. ESU cooling disconnection should be done without leakage of cooling liquid.

Communication and supervision

Data and network connections from the vehicle control system to the ESS and between the ESUs shall be made via the Ethernet train backbone (ETB) or CAN. This must be clarified in the project during the next year.

The electrical signal connections, including cable-based data and network connections, ensure safe operation of the ESS in the overall rail system and the self-protection of the ESS and the ESU. As a rule, communication takes place via data or network connections between the ESS and the supplying and consuming energy supply system.

Safety lines are required to report a critical state (e. g. fire alarm) of the ESU to the vehicle's control system.

Data from the ESU should be available on request or live. This has to be updated during the IEC 62928 revision.

List of data will allow to:

- Improve predictive diagnostic and maintenance plan of ESU.
- Adapt modelling aging tools of train fleet according to usage and location,
- Improve second life process (ESU passport link to European regulation 2023/1542),
- Fleet energy management.

The ESS should be able to be wake up and do preconditioning /recharge, initialised from an external supervisor or the internal TCMS (as example).

Voltage (ESU scope):

Decarbonisation of the mobility sector widen the usage of lithium-ion batteries. These batteries are changing the maintenance of the vehicle, especially compared to mechanical combustion engine technology. The impact on the maintenance is important, with potential risks due to the characteristics of the batteries. Voltage used is particularly a key factor to consider for electrical safety of maintenance staff. Based on the state of the art on ESU and modules applied in railway, we can observe:

- For ESU, a voltage in the range of 300 to 900 V DC,
- For modules, a voltage in the range of 25 to 150 V DC,

Therefore, technical discussions are ongoing to define a potential standardise voltage range for battery to minimize the electrical risk for maintenance staff.

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.

Discussion is still open. The date for approval is expected in 2024, and publication in 2025.

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 hydrogen storage 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.

Discussion is still open. The date for approval is expected in 2024, and publication in 2025.

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 BMUs).

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.

5.2 Next Steps

The next steps for the task 1.1 standardisation are:

- Identification of contact persons for the standardisation bodies,
- Continuation of the pre-standardisation work for each interface group,
- Identification of the infrastructure, operational and TMS parameters based on the development of the energy functions in task 1.2 and 5.3,
- Contact with FP1 and the system pillar with respect to the pre-standardisation of infrastructure, operational and TMS parameters,
- Evaluation of the input for the standardisation bodies.

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, we will see more details later in this document. So, we propose to start by a state of the art of energy management functions. To do this activity, we will have a look first on previous studies on this topic, such as Shift2Rail PINTA3 WP3 report [6]. Also, in a common activity with RAIL4EARTh WP5, we will collaborate 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 (VEMS[1]) 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 [6], the energy management strategies (for traction) was classified in 3 categories:

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

The figure bellow shows the main differentiation of these strategies:

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

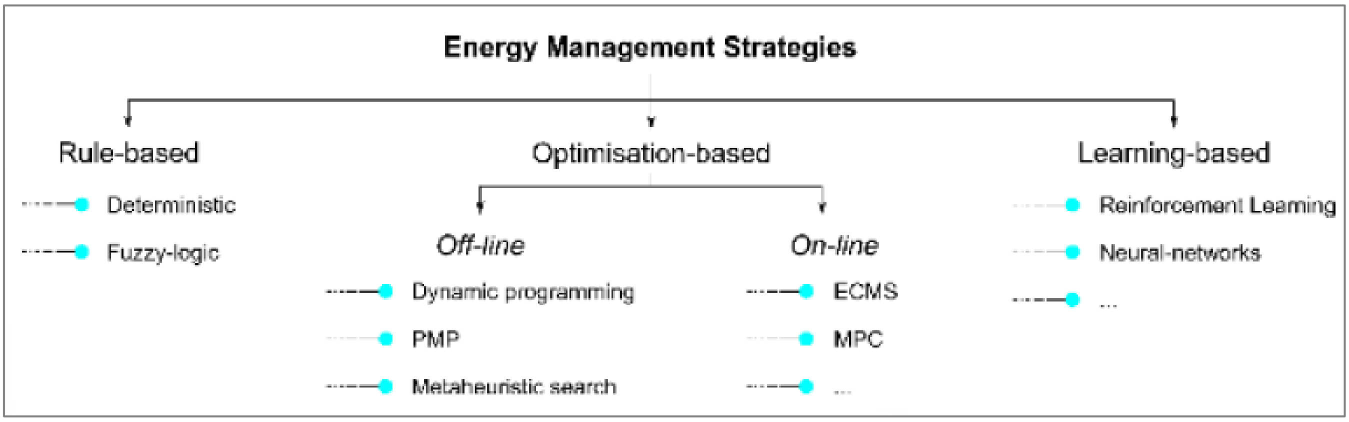

Figure 12: Classification of Energy Management Strategies according to S2R PINTA3 WP3

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(ΔPFC 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(ΔPFC 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 ΔPFC 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.

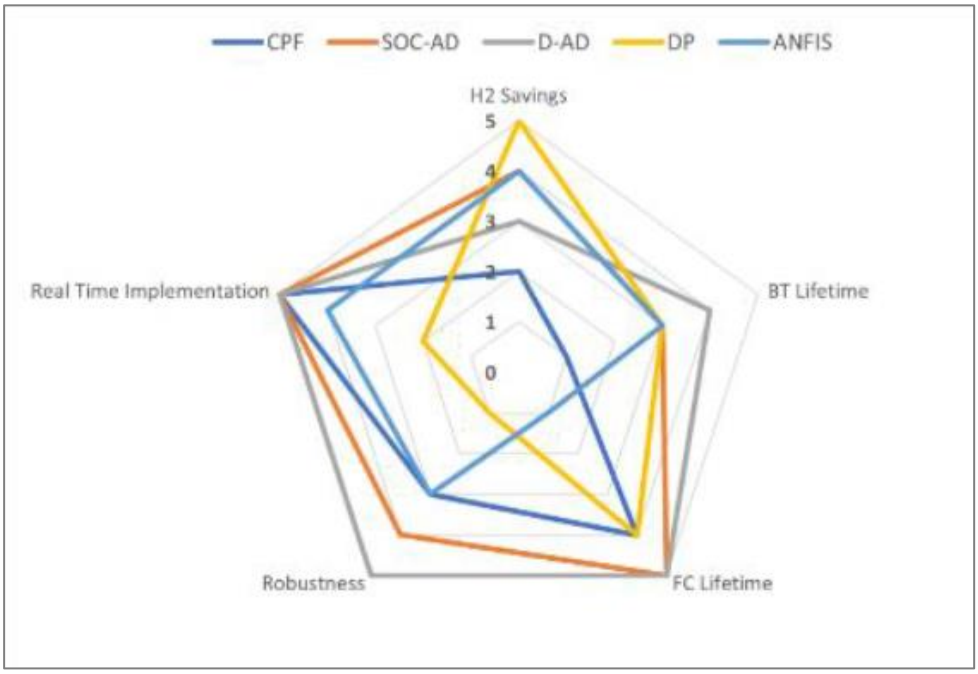

Figure 13: Comparison results of energy management strategies for traction hybrid hydrogen/battery train

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

As explained before, we collaborate 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:

Energy management functions listed in WP1 & WP5:
Long stop eco parking (Energy-saving configuration UIC612-1)
Pre-conditioning of the train (for passengers)
Short stop eco parking (Stand-by configuration UIC612-1)
ESS pre-conditioning
Auxiliary optimization
Hybrid DAS
ESS power assistance
Optimized Regenerative Braking
Peak Shaving
HVAC
BEMU Charging
External Energy Supply
Lift and Drop of Pantograph

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

Detailed descriptions of these functions are given in the Deliverable D5.1 [1]. The next steps in the studies will be the identification of the interfaces for each energy management functions and try to specify standardised definition and parameters. This work will be done in the next period.

6.1.3 Energy Management Functions in Infrastructure (on-ground)

Energy management functions can be also on the infrastructure side. For example, “stop & start substation” is an energy function developed to manage efficiently the energy. According to train traffic, when trains run, substation is active to deliver energy to the trains. However, when there’s no train in service on the area, substation is switch off. This enables to save energy by avoiding no-load power supply. Study is ongoing with infrastructure managers members to make a 1st list of these energy functions. A potential collaboration with RAIL4EARTH WP10 on energy management functions, will be checked as well.
This work will be done during the next period until deliverable D1.2.

6.2 Optimization of Charging Process for Battery Trains

Battery train performance is strongly linked with the charging capacity. 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 by 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. There's one special case in railway for heavy rail battery locomotive, with special charging plug. WABTEC "FLXdrive" battery locomotive is equipped with a 480V AC 3ph plug. 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 [16]. 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.
- **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. 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.

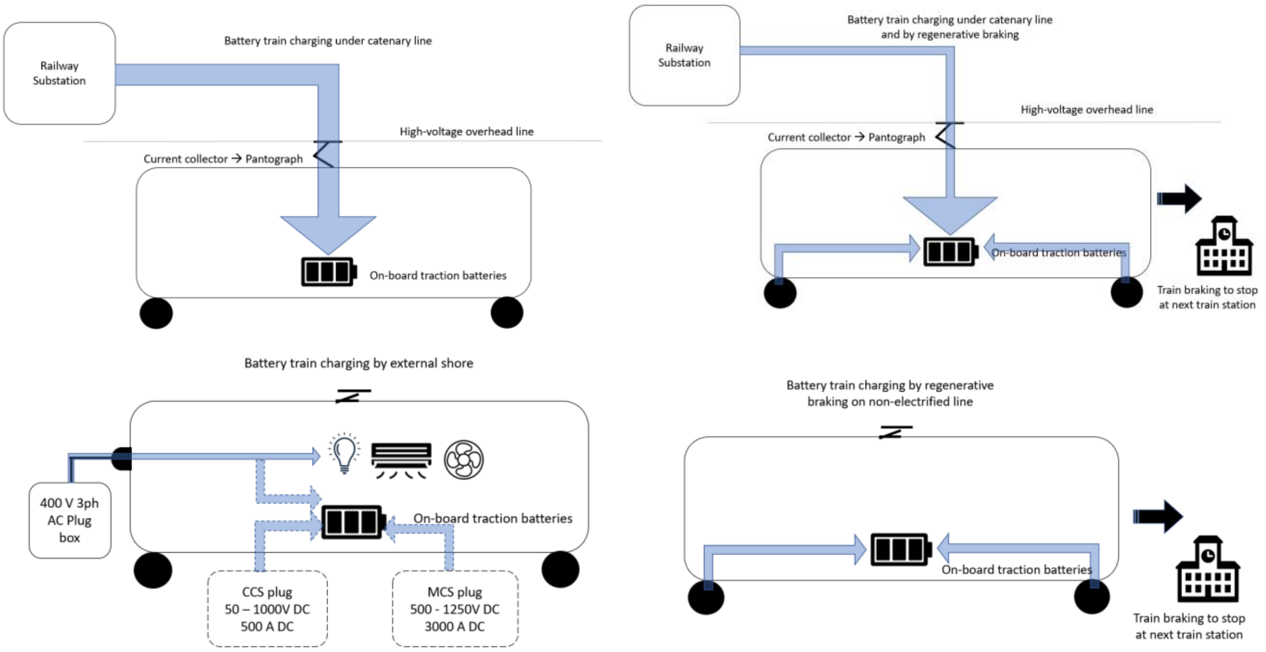

Figure 14: Simplified diagram of recharging options for battery train

Figure 15: On the left, battery locomotive charging plug in Stockton (USA), on the right, charging plug connect to the battery locomotive.

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 schema is applied:

- On a 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.

A prioritization is defined to determine how much power can be transferred into the battery. Currently, the charging of the 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:

$$PchargESS = Plinemax - Ptraction - Pauxiliary$$

- PchargESS: Charging power for the Energy Storage System (ESS),
- Plinemax: Maximum power from the infrastructure line,
- Ptraction: Power requested by the traction system of the rolling stock,
- Pauxiliary: 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, Ptraction 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 Plinemax, Ptraction and Pauxiliary, 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 SoC / SoE at the maximum. This strategy makes sure that the traction batteries may be reused with highest available energy in a shorter time. The figure bellow shows an example of this type of strategy on a line with a first section non-electrified, and then a long-electrified section until the terminus. The electrified section is on 1.5 kV DC.

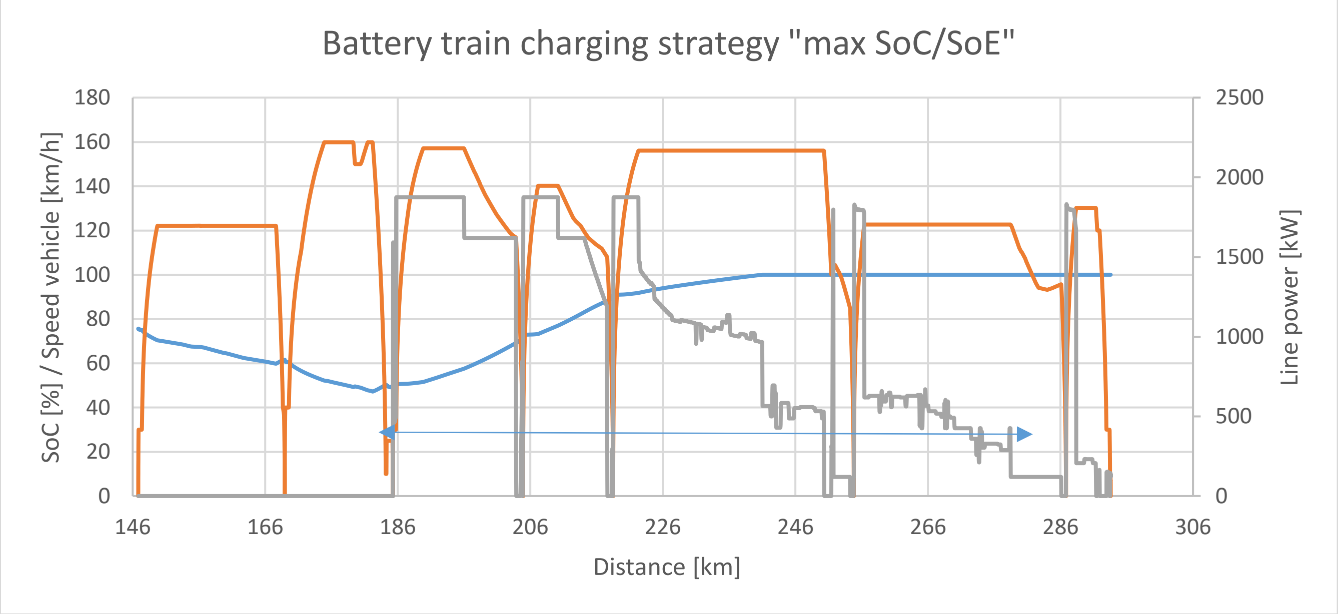

Figure 16: Example of battery train charging strategy for max SoC/SoE

After using the traction batterie on the non-electrified section, the battery train start to charge immediately when the pantograph is rise on the electrified line. The strategy request 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 train decelerating, the line power is reduced due to regenerative power produced by the traction motors. The regenerative braking power is used first to recharge the traction batteries to avoid consuming energy on the catenary line. The SoC reached his maximum at kilometer 242, around 50 km before the end of the line. So, an important margin for this case gives possibilities to use other kind of charging optimization strategies. We will look at different charging strategy perspectives, such as infrastructure or lifetime of the batteries, in the next parts.

6.2.2 Optimization of the Battery Train Charging from Infrastructure Side

From 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 phenomena can be quite hazardous. As different trains are requesting maximum power from

the infrastructure line, an unbalancing may happen, when a train start 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.

6.2.3 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

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 temperature is increasing. So, improving the control strategy of the charging with a prioritization on cycling and temperature reduction shall be developed.
This strategy will be studied in the next period.

6.2.4 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.
This strategy will be studied in the next period.

6.3 Preconditioning of Vehicle and ESS

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” [1]. 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 [17].

Existing battery cells typically used in road EVs have an allowed temperature range from approx. -40 ºC to 60 ºC, but in order to maximize their life, capacity, and overall performance the suggested operating temperatures range is between 10 ºC and 35 ºC. To achieve this, Battery Thermal Management System (BTMS) are used, which manage 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 [18] 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 the vehicle [19]. For intercity services in Sweden, the estimations of auxiliary energy usage vary between 19% in summer and 30% in winter [17]. Independently of the technical systems proposed for vehicle environment preheating, the operational cycles including parking, idling, and stabling 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 affects 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 in intermediate operative stops allows for extra net energy that would not need to be utilized from the OESS, 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 a 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

This section has no inputs to share at this time and will be developed in the next period. A definition of auto adaptative train energy consumptions functions will be given, followed by a description of these functions.

6.5 Optimization of Energy Management at Railway System Level

6.5.1 Methodology Approach

Objective of this subtask is to compare different strategies to optimize energy, cost, and operation at rail system level, for alternative drive trains on several use cases and scenarios. This study will be based on simulation tool to modelized the railway system. By railway system, we mean to consider rolling stock side, infrastructure side and finally operational side.
We need to define criterion for the comparison of use cases and scenarios. These criterions should give comprehensive information for the evaluation. According to the results, classification may be realized to prioritize strategy.

6.1.1.1 Criterions Definition

As the vision for this study is system, we proposed to define criterion based on the 3 parts of rail system: rolling stock, operation, and infrastructure.

6.1.1.1.1 Operation Criteria

From operational perspective, we propose the definition of 5 criterion 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,
- Timetable compliance → For every use case and scenario, we need to evaluate if timetable is respecting along the route,
- Daily profile compliance (based on shuttle service) → Daily profile compliance for a shuttle service means to check if alternative drive trains can keep going consecutive operation on a dedicated route (shuttle). This might be affected by short turnaround time duration or vehicle performance’s reduction,
- Daily profile compliance (based on other services) → Daily profile compliance for other services indicate to analyse if alternative drive trains can continue the operation on various lines (other services). This might be affected by short turnaround time duration or vehicle performance’s reduction, or by the characteristics of the route.
- Maximum duration of service stop → This criteria is linked with the minimum State of Charge observed during the load cycle. At this minimum point, we can estimate the maximum time to spend at standstill due to a service stop. To calculate this duration, we use 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, we can conclude on the time to allow for supplying auxiliary loads during abnormal operation stop.

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
UC1 – FR / BEMU 1st gen & No additional infra	All-out/Scheduled/Eco	Yes/No	Yes/No	Yes/No	XX min
UC1 – FR / BEMU 1st gen & Additional infra 1	All-out/Scheduled/Eco	Yes/No	Yes/No	Yes/No	XX min
UC1 – FR / BEMU 1st gen & Additional infra 2	All-out/Scheduled/Eco	Yes/No	Yes/No	Yes/No	XX min
…	All-out/Scheduled/Eco	Yes/No	Yes/No	Yes/No	XX min

Table 17: Operational criterion list

6.1.1.1.2 Rolling stock criteria

From vehicle perspective, we propose the definition of 4 criterion on:

- Vehicle ESS lower SoC → Representing the lowest State of Charge during the operation simulated. This value is important to determine if the SoC stays in the limits defined for nominal usage. Furthermore, it's also giving the energy margin to compensate potential events with extra energy consumption required,
- Vehicle ESS DoD → Expressing the Deep of Discharge of the batteries during the load profile. The DoD is calculated in %, when 100% DoD means we used the equivalent of 100% of SoC. It is also the equivalent of one full cycle (100 -> 0%) of discharge. DoD is a factor impacting the batterie's ageing. So, reduced DoD will increase the batteries life and avoid the need of sub
- Vehicle ESS SoC end cycle → The value of batterie's SoC at the end of the load cycle is important to evaluate the gap between SoC at departure and at the end. SoC recovery is key to avoid high charging when train stop at the final station. High charging might required high charging power (in case of limited time to spend) or high charging time (when timetable allows longer duration for turnaround time),
- 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,,
- Vehicle energy consumption on Catenary Free Operation (CFO) → Calculation of energy consumption on non-electrified only.

Use Case	Vehicle / Type of train	Vehicle Lower SoC	Vehicle DoD	Vehicle SoC End Cycle	Vehicle Energy Management functions	Vehicle Energy consumption CFO
UC1 – FR / BEMU 1st gen & No additional infra	1st gen BEMU	XX%	XX%	XX%	Yes/no	XX kWh
UC1 – FR / BEMU 1st gen & Additional infra 1	1st gen BEMU	XX%	XX%	XX%	Yes/no	XX kWh
UC1 – FR / BEMU 1st gen & Additional infra 2	1st gen BEMU	XX%	XX%	XX%	Yes/no	XX kWh
…	1st gen BEMU	XX%	XX%	XX%	Yes/no	XX kWh

Table 18: Rolling stock criterion list

6.1.1.1.3 Infrastructure criteria

From infrastructure perspective, we propose the definition of 4 criterion on:

- New infrastructure substation → This criterion is related if a new charging infrastructure is needed,
- New infrastructure electrification length → Distance of added electrification length
- New infrastructure total cost → Total estimated cost of new infrastructure, ,
- New infrastructure energy management function → Considering potential energy management function on infrastructure side to reduce the energy consumption (e.g. stop & start of substation).

Use Case	Infrastructure New Substation	Infrastructure New Electrification length (km)	Infrastructure New Electrification Total Cost (M€)	Infrastructure New Energy management function
UC1 – FR / BEMU 1st gen & No additional infra	-	-	-	-
UC1 – FR / BEMU 1st gen & Additional infra 1	Number	Distance value	Estimated cost	Yes/no
UC1 – FR / BEMU 1st gen & Additional infra 2	Number	Distance value	Estimated cost	Yes/no
…	…	…	…	…

Table 19: Infrastructure criterion list

To calculate the cost of additional infrastructure, we look on the estimation of infrastructure electrification cost. According to previous publications, such as Verband der Elektrotechnik, Elektronik Informationstechnik e. V. (VDE) report in 2020 [20] or thesis on new electrification with DC medium voltage in 2019 [23], electrification cost is estimated between 1 and 3 M€ / km.

6.5.2 Simulation Tool

6.5.2.1 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 capacity 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.

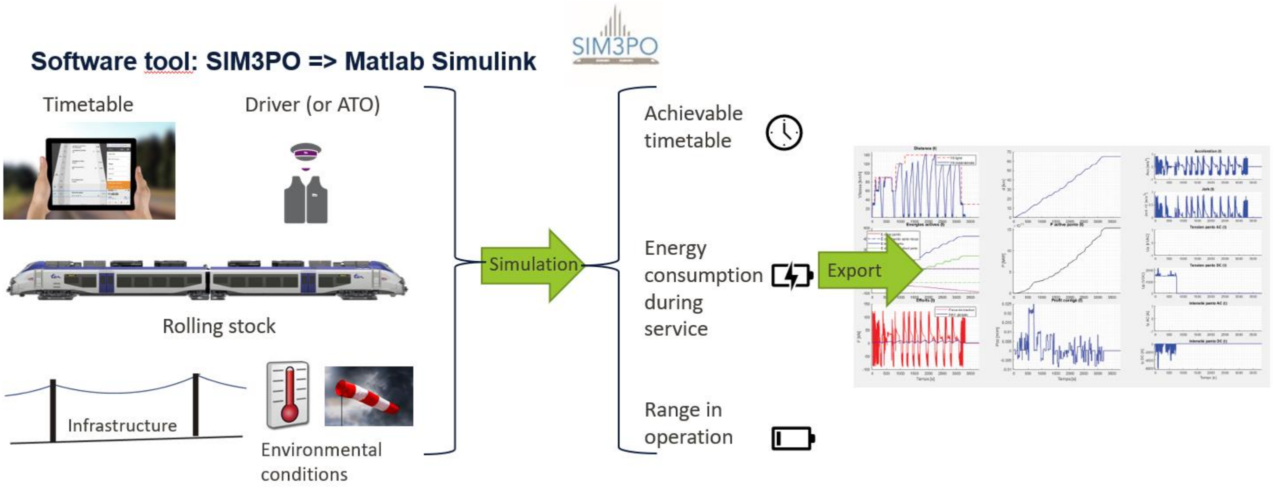

Figure 17: Simplified scheme of SIM3PO simulation tool.

SIM3PO simulation tool is also based on a modular architecture. The setting for each component is established on an object approach and also an libraries (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 18: Libraries for rolling stock in SIM3PO tool

6.5.2.2 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.

6.5.3 Use Cases and Scenarios

In this chapter, we will present the definition of use cases and scenarios for the optimization of energy at system level.
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 in each use case to observe a specific condition. For each scenario, we need to evaluate the impacts from operational, infrastructure and rolling stock perspectives. All scenarios and associated impacts will be impacts evaluated according to the methodology defined. The global analysis of all scenarios will bring information on much there are influencing the criterions defined in the methodology to compare the optimization at system level.

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. Other kind of railway lines will be studies in the next period.
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.

6.5.4 Analysis and Comparison of the Results

6.5.4.1.0 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 20: Distance between stations on France UC1

As we can see 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).

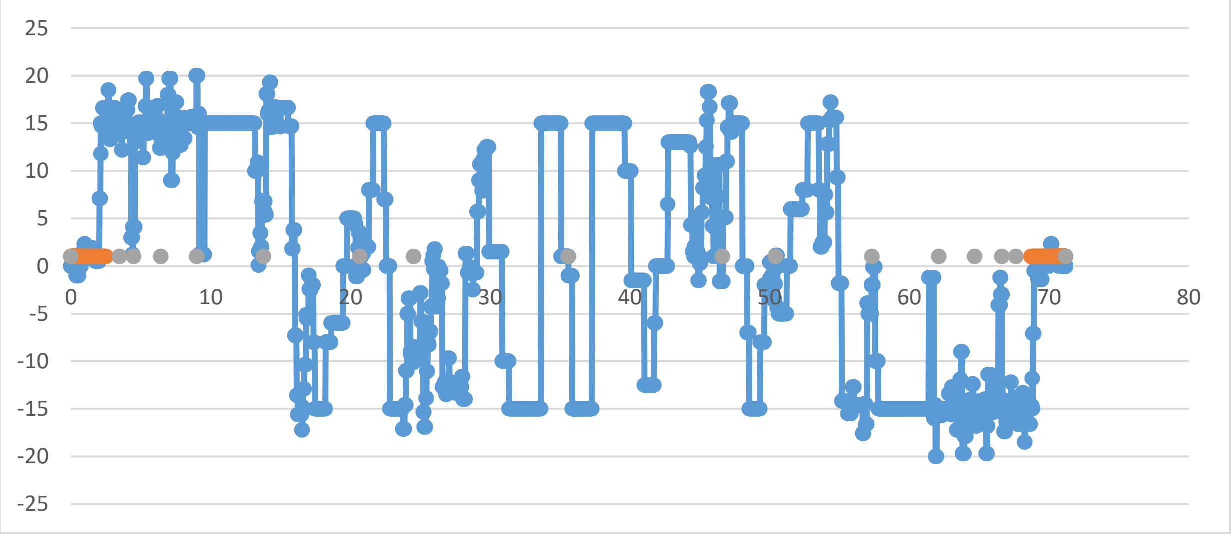

Figure 19: Uphill/Downhill line profile characteristics, including electrification and stations.

6.5.4.1.1 Scenario 1 “1st Generation Battery Train in Operation”

This first scenario will be focused on a 1st generation of battery train. By 1st generation, we are talking about BEMU based on mass production battery technology and so available on the market. For this example, the lithium-ion battery technology used is NMC. 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
Battery technology	NMC
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 21: Characteristics of 1st gen BEMU for regional operation in France

6.5.4.1.2 Operational impact: All-out driving analysis

We will start first by the analysis based on all-out driving style condition. 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.

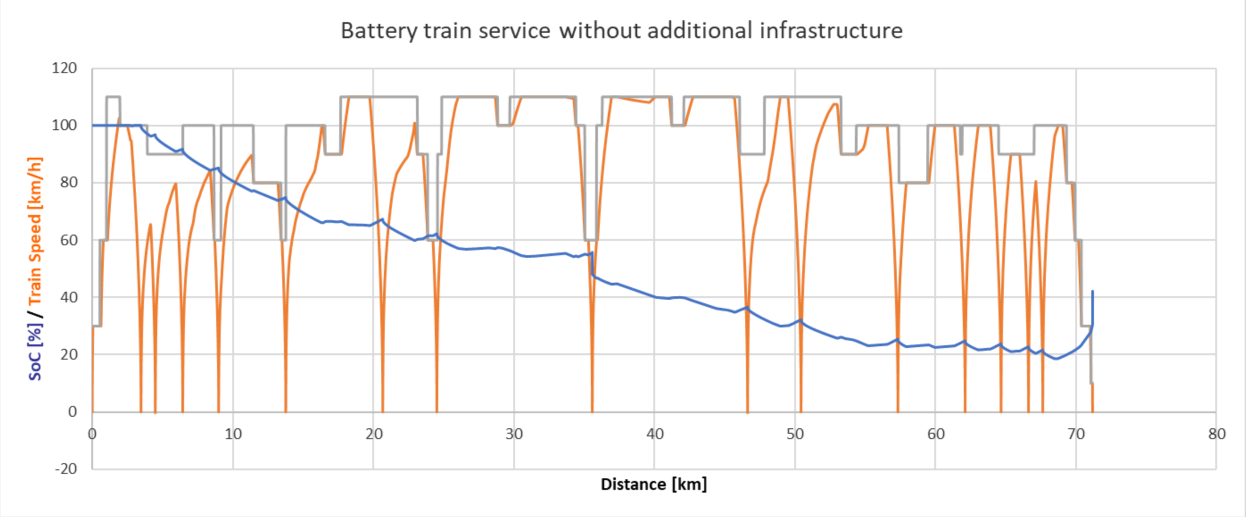

Figure 20: 1st gen regional battery train service in all-out driving, without additional infrastructure

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, we considered an assumption of signalling display on-ground to inform the train driver about the end of the electrified sections. 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. We can conclude about 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 1st gen & No additional infra	All-out	Yes	No	-	51	1st gen BEMU	19%	-110%	42%	No	739,2	-	-	-	No

Table 22: France UC1 - S1 - Comparative criterion synthesis for All-out driving impact

Now we will evaluate the effect on the SoC by changing the driving style from all-out to scheduled.

6.5.4.1.3 Operational Impact: Scheduled Driving Analysis

Now we will observe 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.

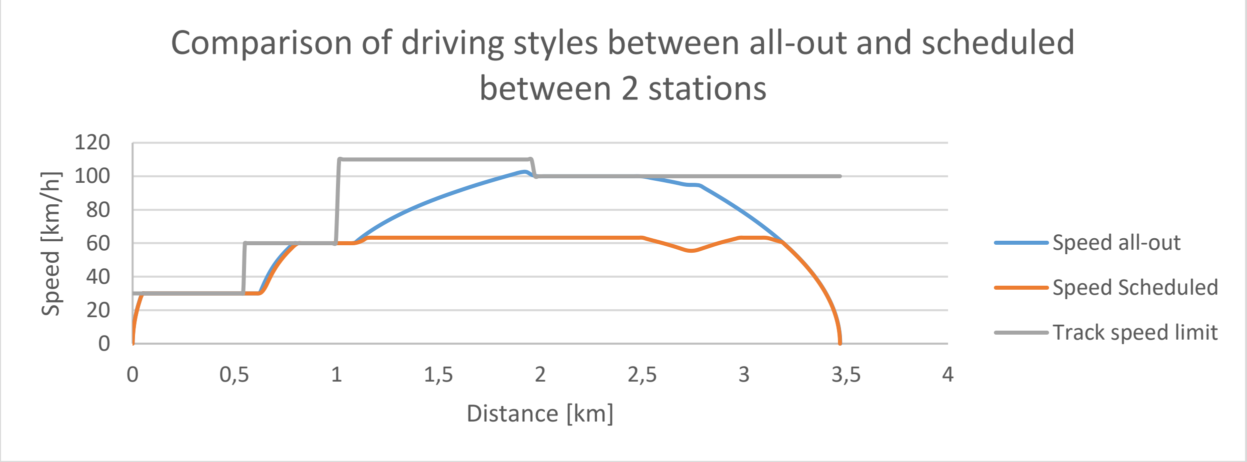

Figure 21:Comparison of driving styles between all-tout and scheduled driving on the line between station A and B

This lower average speed gives a smaller amount of energy consumption of the train. The figure bellows shows the effect of this optimisation strategy of driving between 2 stations (A and B) with a reduction of the average speed of -15%.
We will analyse the results on the full cycle. 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.

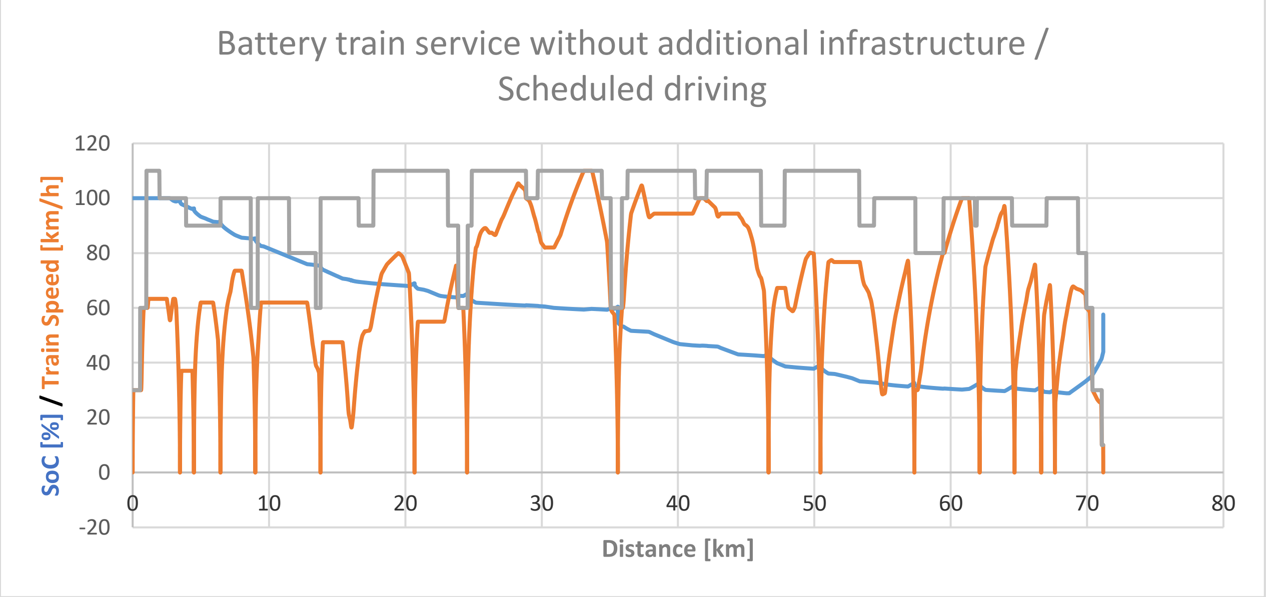

Figure 22: 1st gen regional battery train service in scheduled driving, without additional infrastructure

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 1st gen & No additional infra	Scheduled	Yes	No	-	78	1st gen BEMU	29%	-73%	58%	No	490,56	-	-	-	No

Table 23: France UC1 - S1 - Comparative criterion synthesis for Scheduled driving impact

6.5.4.1.4 Operational Impact: Turnaround Time and Journey 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.

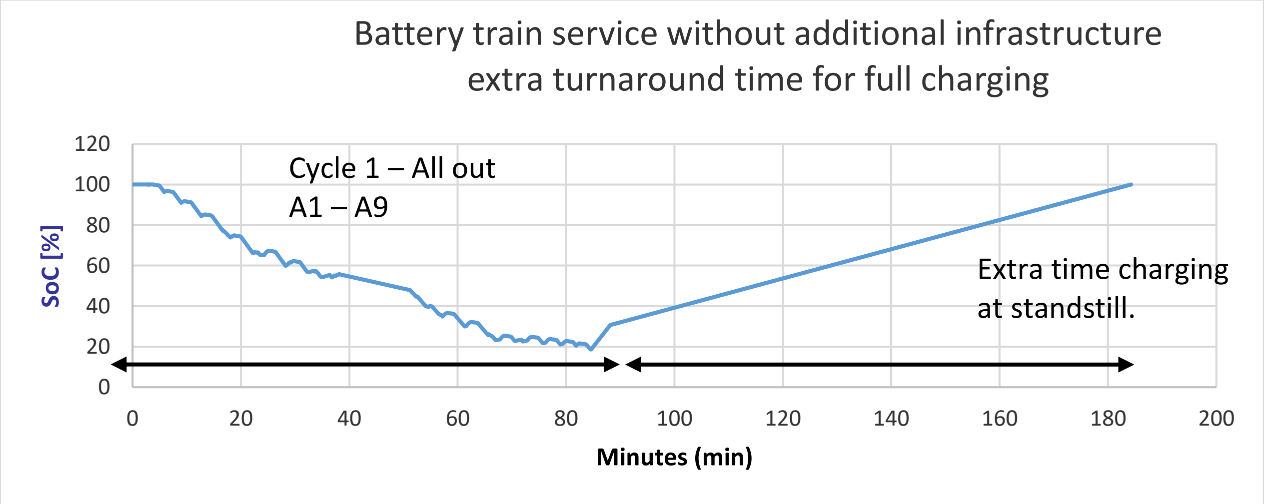

Figure 23: Evolution of SoC based on time duration of the cycle in all-out drive, with extra time for charging.

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 1st gen & No additional infra & Extra time charging	All-out	Yes	Yes	-	51	1st gen BEMU	19%	-110%	100%	No	739,2	-	-	-	No

Table 24: France UC1 - S1 - Comparative criterion synthesis for Extra time charge & All-out driving impact

This constraint is linked to shuttle service journey profile of the battery trains. Whereas other types of journey profiles can be selected. In this scenario, we will observe 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.

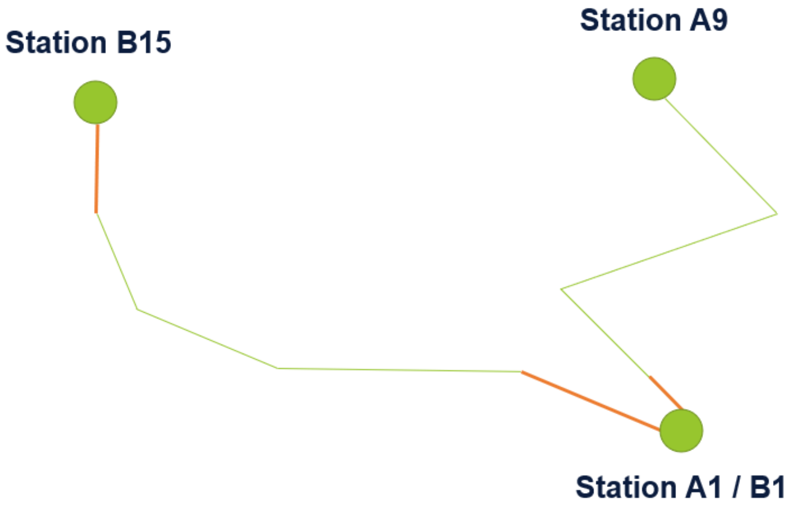

Figure 24: Simplified map of the 2 lines of France uphill/downhill line regional train service

We simulated 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). We will 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 journey profile.

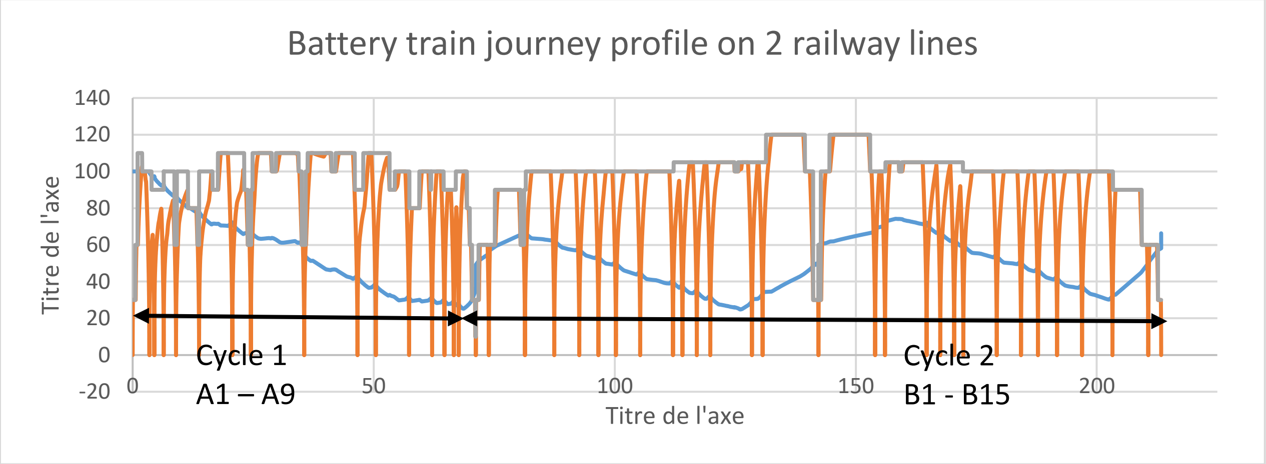

Figure 25: Journey profile simulation of 1st gen BEMU in all-out drive

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 journey 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, we can comply the journey profile with 1st gen BEMU.

France Use Case 1	**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 25: France UC1 - S1 - Comparative criterion synthesis for Journey profile & All-out driving impact

6.5.4.1.5 Operational Impact: Service Stop Due to Event on the Line

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:

- Fatalities,
- Flooding,
- Unaccompanied luggage,
- Dead leaf and lack of adhesion,
- Fraud,
- Exceptional attendance,
- Radio alert,
- Crew member delay or missing,
- Animals along the track,
- Extreme weather,
- Fire along the track,
- Overheald line incident,
- Railway crossing,
- Rail break,
- Signalling,
- Infrastructure maintenance activities,
- Illness on-board,
- Strike,
- Traffic regulation (e.g. delay due to another train).

From few minutes' duration, we can find an 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.

We took the assumption of 3 different duration of service stops: 30 min, 60 min and 120 min. According to previous simulations, we look at the results 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 26: Evolution of SoC per station along the uphill/downhill scenario for the 1st gen battery train

So, we added an extra energy consumption at standstill in station A2↓ to simulate the effect of stop duration on the energy consumption. We first start with the case of 30 min duration. During the stop, auxiliary loads kept the same value. Therefore, this is representing an energy consumption of:

$Ec = Paux \times \Delta t$ with $Paux = 150\ kW$ & $\Delta t = 0{,}5\ h$; $Ec = 150 \times 0{,}5 = 75\ kWh$

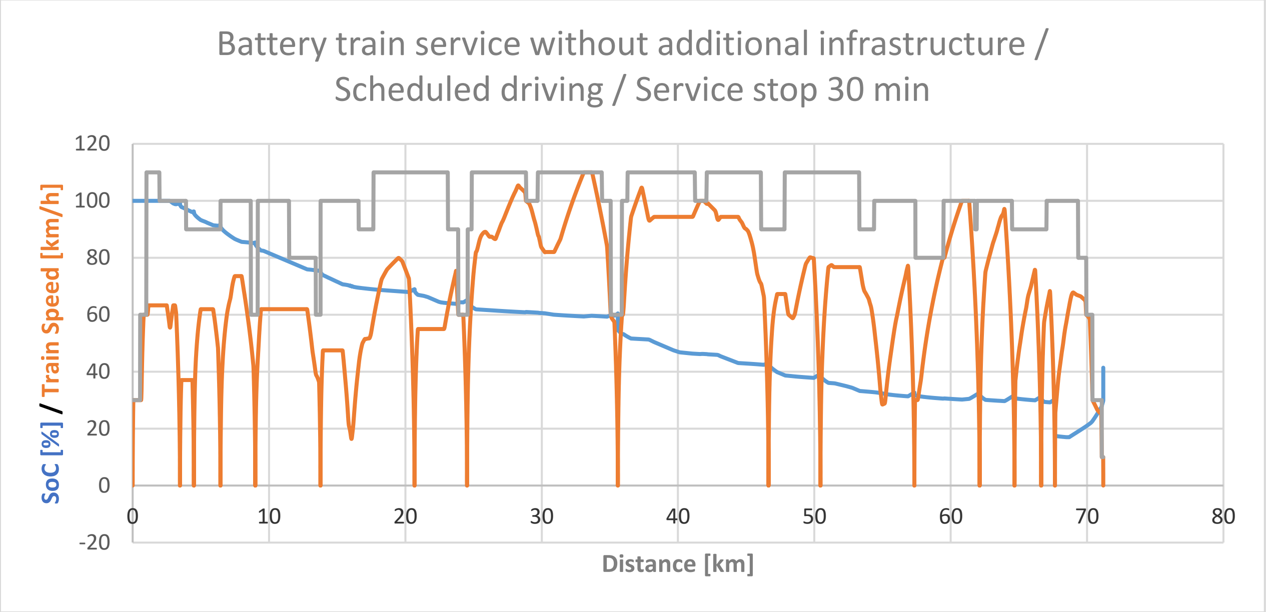

Figure 26: 1st gen battery in scheduled driving on the uphill/downhill line without additional infrastructure, with a stop of 30 min during the trip

The SoC reduced by 12% and reached 18% (30% - 12%) after the extra stop duration of 30 min. With 18% of SoC available, the 1st gen battery train shall run around 1 km on battery mode to join the electrified section and lift the pantograph. At the end of the cycle, including the charging time during the turnaround in station A1, the SoC is 41%.

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 1st gen & No additional infra & Service stop 30 min	Scheduled	Yes	No	Yes	60	1st gen BEMU	18%	-98%	41%	No	658,56	-	-	-	No

Table 27: France UC1 - S1 - Comparative criterion synthesis for Service stop 30 min & All-out driving impact

We apply the same method 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.

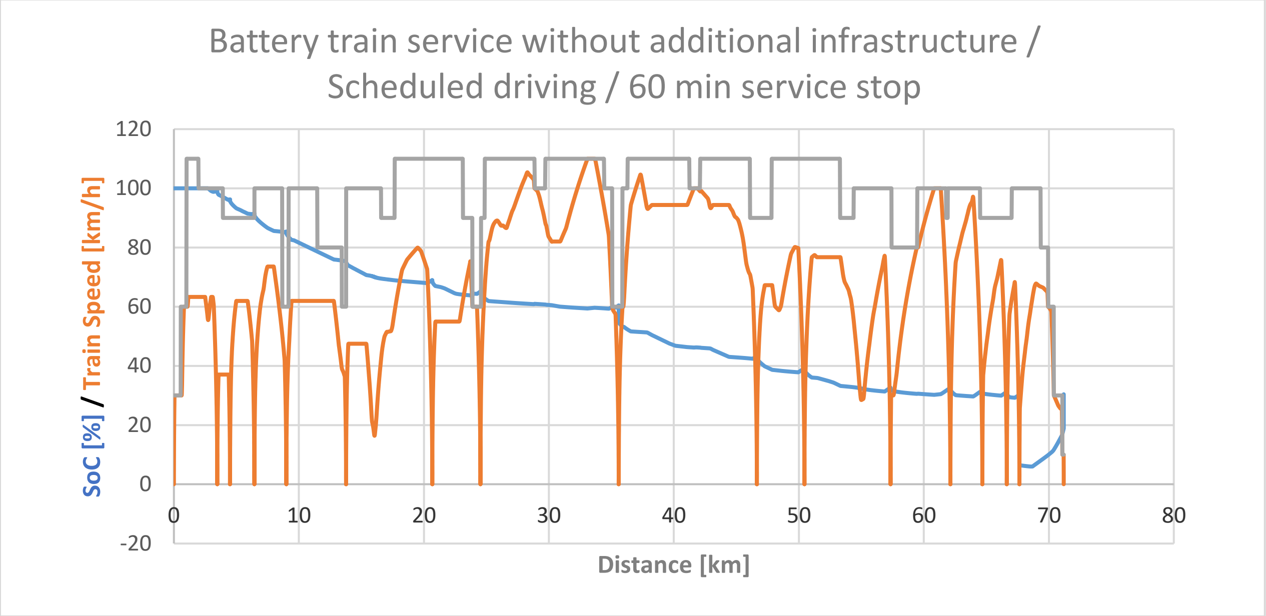

Figure 27: 1st gen battery in scheduled driving on the uphill/downhill line without additional infrastructure, with a stop of 60 min during the trip

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

6.5.4.1.6 Operational impact: Driver's Actions Mistake for Switching Between Electrified and Non-electrified Sections, and Vice-Versa

For battery trains, it is key to use efficiently the electrified sections to recharge the batteries. Depending on the characteristics of the line, transition from/to catenary to non-electrified mode may happen several times. So, it might be a source of potential mistake by the train driver to forgot to raise or lower the pantograph at the defined location. According to pr:TS 50729 standard “Interface requirements between charging infrastructure with dedicated contact line sections and electric traction units with onboard electric traction energy storages and current collectors” [4], a risk analysis is important to avoid:

- Drawing an electric arc while leaving electrified section,
- Mechanical interference with current collector head and fading contact line,
- Hitting obstacles like bridges and tunnels,
- Raising too late the current collector in electrified section,
- Damaging/overheating the contact line.

To manage these risks, following mitigations can be used:

- Protection signalling (possibly automatic),
- Neutral section connected to return circuit,
- Vertical fading of contact wire and automatic lowering of pantograph at a certain level.

So, we will evaluate the effect of such mistake by considering the train departure in battery mode from departure station A1. Consequently, the energy is consuming from the beginning of the service and SoC starts to decrease. On the return, there’s not a second mistake and so the pantograph is lift correctly at 2,5 km until the terminus station A1.

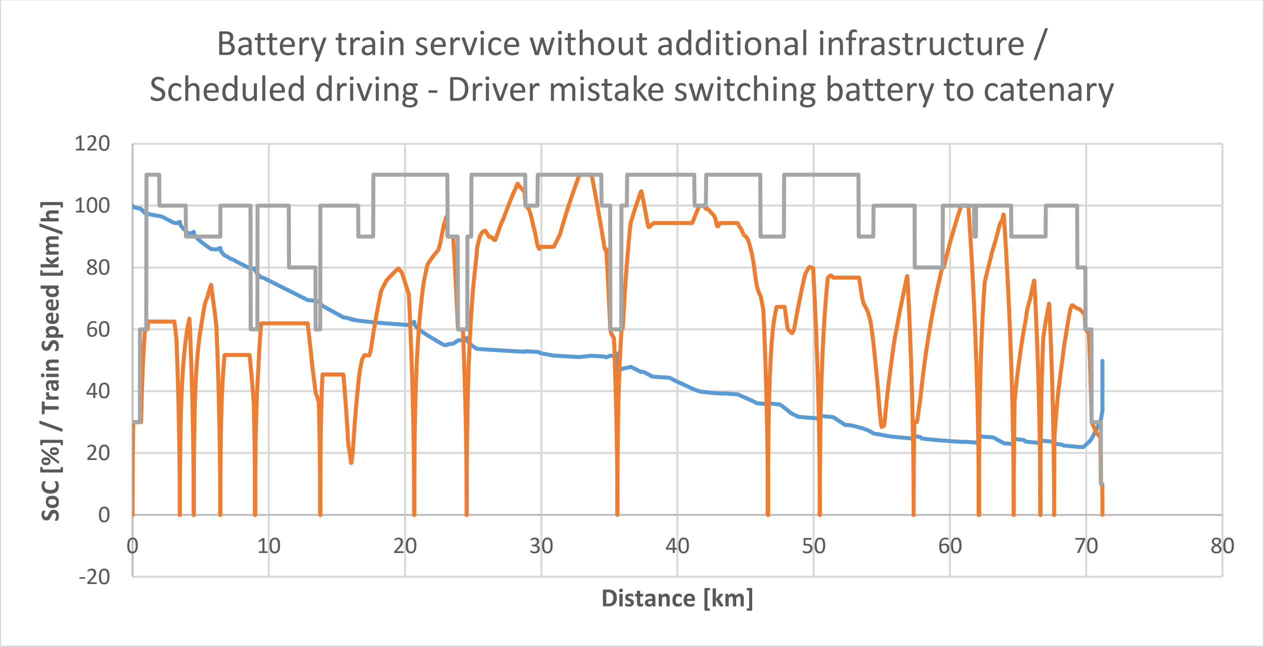

Figure 28: Battery train without additional infra, driver mistake when switching battery to catenary mode.

The SoC drops of -48% when arriving in station A9. Thus create an additional loss of SoC of 8% compared to normal use of the electrified section at the starting point of the line. Therefore, minimum SoC value also decreasing to 22%.

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 1st gen & No additional infra & Driver mistake lift panto	Scheduled	Yes	No	No	60	1st gen BEMU	22%	-96%	50%	No	645,12	-	-	-	No

Table 29: France UC1 - S1 - Comparative criterion synthesis for Service mistake lift panto & Scheduled driving impact.

6.5.4.1.7 Infrastructure impact: Additional Charging Infrastructure – Case 1 – Charging Station

In this section, we will study the impact of an additional charging infrastructure on the line. The first case we 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. 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 BEMU keeps as it is and will be evaluated with both all-out and scheduled driving style.

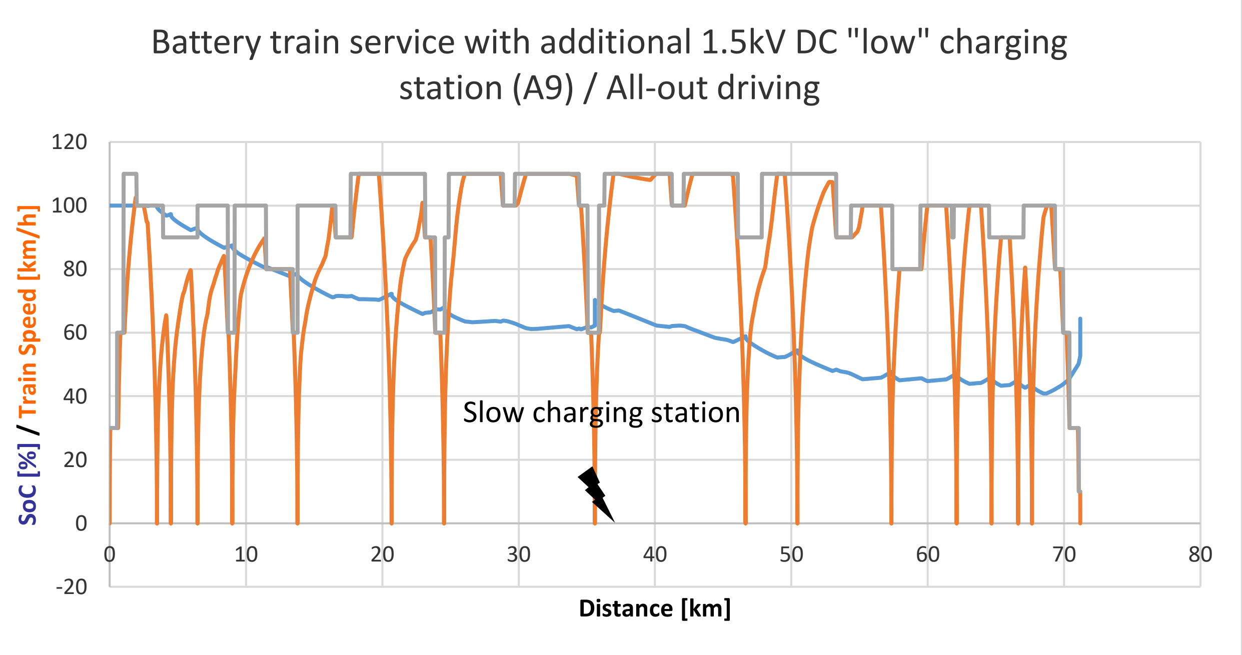

Figure 29: 1st gen BEMU on UC1 with additional charging station & all-out driving

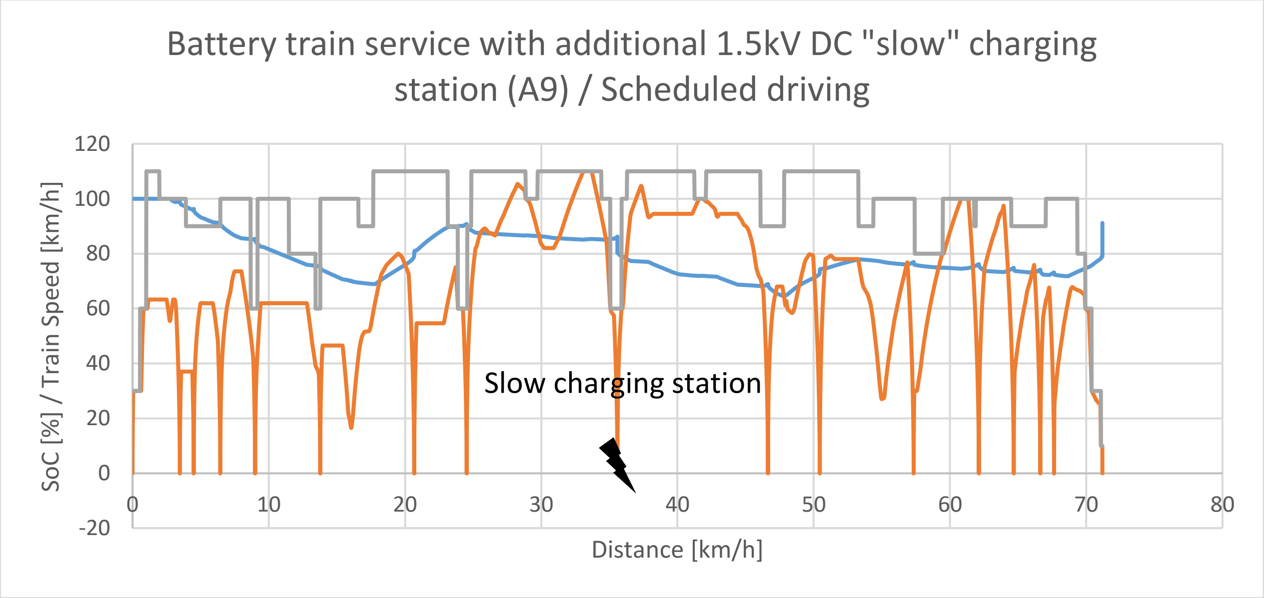

Figure 30: 1st gen BEMU on UC1 with additional charging station & scheduled driving

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 1st 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 1st gen & Additional charging station slow charge	Scheduled	Yes	No	Yes	185	1st gen BEMU	65%	-73%	91%	No	490,56	-	-	-	No

Table 30: France UC1 - S1 - Comparative criterion synthesis for additional charging slow station & All-out / Scheduled driving impact

As we can observe, the influence of the additional charging station in station A9 is significantly impacting the vehicle criterion, 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. Concerning the DoD, positive impact is noted in all-out drive only. For the SoC at the end of the scenario, the additional charging infrastructure improved considerably the results, with +22% in all-out drive and +33% in scheduled drive. In scheduled drive, we almost achieved same SoC between beginning and end of the scenario (91% at the end so minus 9%).

6.5.4.1.8 Infrastructure impact: Additional charging infrastructure – case 2 – Partial electrification

In this section, we will study the impact of another type of additional infrastructure with a partial electrification zone (also called “electrification island). In this scenario, the objective is to define an optimal electrification length of the current non-electrified line. Different approaches may be considered to select the most appropriate area to electrify. First, the objective is to avoid complex environments to build substation and install catenary. Such environments are typically tunnels or bridges. Electrify these environments will increase the cost of electrification. Based on previous table about distances between stations on the line, we added the list of complex environments along the line.

Station	Distance between station	Environmental infrastructure conditions
A1	0	
A2	3,5	Bridge
A3	1	
A4	2	Bridges
A5	2,6	Bridges
A6	4,8	Bridges & Tunnels
A7	6,9	
A8	3,9	
A9	11,1	Bridges & Tunnels

Table 31: Distance between stations & complex environmental conditions on France UC1

Therefore, a selection of a catenary island zone of 5 km between station A7 and A8 was decided for the test. As there’s no complex environmental conditions in this area, the cost for electrification should be reduced. In this scenario, the train driver will need to lift and drop the pantograph on this new catenary zone. This might be a potential risk to forget this action and so, it would be highly recommended to install an automatic lift/drop function on the vehicle. Thanks to the catenary island, the BEMU can recharge his traction batteries, while also supplying the traction system and auxiliary loads from the overhead line. So, it’s providing benefits by reducing the energy needs to deliver from the traction batteries. As the previous scenario, we will check the performance with both types of driving styles.

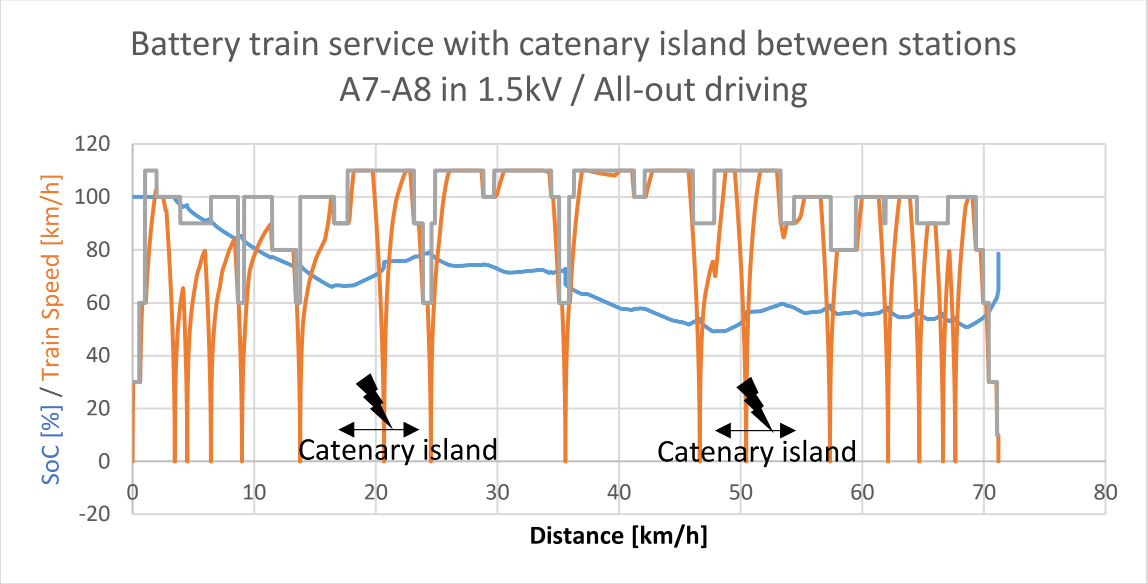

Figure 31: 1st gen BEMU on UC1 with additional catenary island & all-out driving

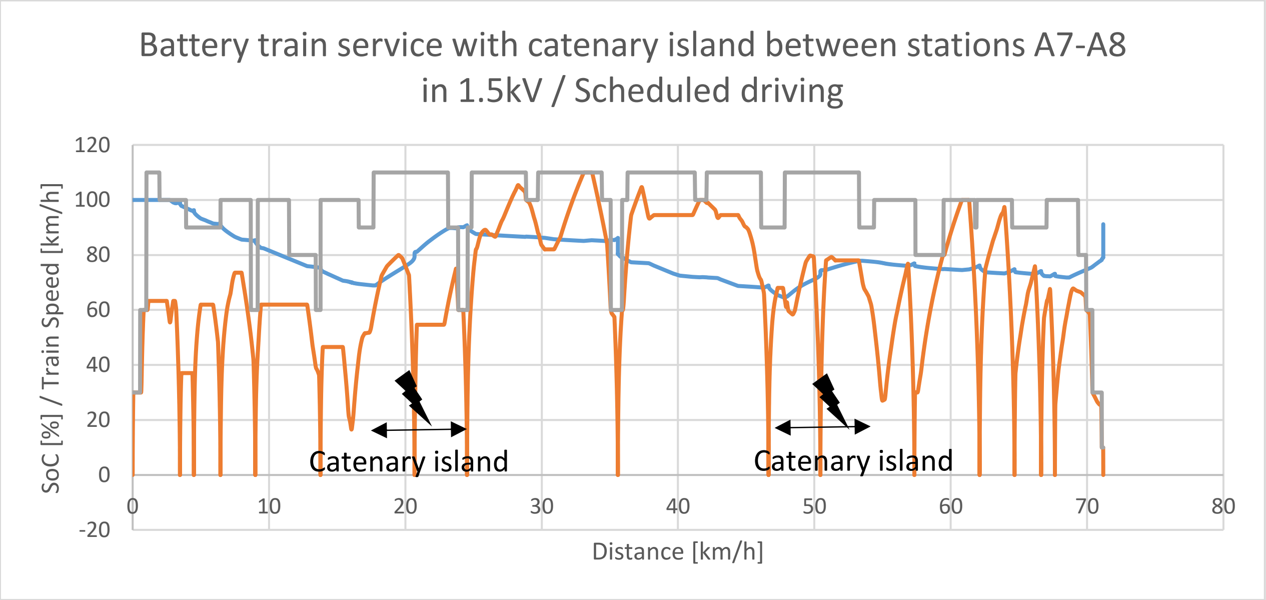

Figure 32: 1st gen BEMU on UC1 with additional catenary island & scheduled driving

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 1st gen & Addtional catenary island 1.5kV DC	All-out	Yes	No	Yes	153	1st gen BEMU	57%	-81%	82%	No	544,32	-	-	-	No
UC1 – FR / BEMU 1st gen & Addtional catenary island 1.5kV DC	Scheduled	Yes	Yes	Yes	185	1st gen BEMU	69%	-67%	100%	No	450,24	-	-	-	No

Table 32: France UC1 - S1 - Comparative criterion synthesis for additional catenary island 1.5kV DC & All-out / Scheduled driving impact

As we can see, the impact of this new catenary island on the line is improving the performance of vehicle and operational criterion. In scheduled driving, the parameters are slightly better than the previous scenario with low charging infrastructure. Main change is about SoC at the end of scenario with for the first time, the maximum SoC value is reached. So, it gives a positive result for operational point of view in case of shuttle service on this route. Additionally, interesting improvements in all-out drive is also observed on vehicle side for SoC lower value (+16% compared to charging station scenario) and DoD (-12% versus charging station result). These improvements in all-out drive condition is giving more robustness in operation in case of delay.

6.5.4.1.9 Future Works on Scenarios Analysis

In the next period, additional scenarios will be analyzed to enlarge the scope of influence and improved the comparability to look for an optimization at system level. Next scenarios studies will focus on:

- Infrastructure charging current limitation,
- Infrastructure resilience against failure events,
- Rolling stock auxiliary loads consumption,
- Rolling stock traction batteries ageing,
- Rolling stock traction batteries failure,
- Etc.

As explained previously, new use cases and scenarios will be discussed and reported according to the methodology defined. Additional criterion may be also added to improve the comparability.

7 Impacts on KPIs

Based on the progress of WP1, we can estimate the impact on each KPI as followed:

- Physical energy consumption (train, infrastructure, station):
  - Subtask 1.2.2 on “Optimization of energy management at railway system level” shows first results based one use case in France for regional operation. The methodology defined will help to evaluate the impact in terms of energy consumption for each scenario (e.g. driving styles, additional charging infrastructure, etc.).
- Physical CO2 equivalent emissions:
  - 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:
  - 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 criterion on operation, rolling stock and infrastructure. The first use case ongoing analysis shows already results on cost savings. Depending on the prioritization of the criterion, 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,

8 Conclusions

This document is the first intermediate Report mainly used to report progress on WP1 activities in 16 months.

For task 1.1, scope of pre-standardization of alternative drives is large, to cover interfaces at vehicle level for ESS, and at system level with interfaces between rolling stock and infrastructure, also between rolling stock and operation. A working procedure has been created to describe the process from the definition of interfaces and the requirements to achieve the pre-standardisation.

For interfaces between train and infrastructure, needs for BEMU train to have fast charging system have been identified and evaluated in terms of impacts. List of parameters has been established to be shared between vehicle and infrastructure for the management of the charging. Finally, a first list of standards to update or create has been initiated to integrate these evolutions. Similar approach was done for parking energy supply and hydrogen refuelling.

For interfaces between train and operation, preliminary list of parameters to communicate has been created. Furthermore, problematic about range calculation in operation is explained, and potentials options in range calculation were analysed. Additional functions related to operation of alternative drive trains have not yet been discussed and will be developed in the next period of WP1.

For interfaces on vehicle components for alternative drive trains, list of interfaces was defined. Based on these interfaces, preliminary requirements have been established to standardise. For fuel cell, hydrogen storage and converters, analysis of existing standards was reported. This work will continue the next period to propose improvements on these standards.

Generally, at task 1.1 level, works on next period will focus on the identification of contact persons and evaluation of inputs for standardisation bodies, continuation of pre-standardisation activities, contacts with other FPs and SP.

For task 1.2, scope of this task is partially concerning pre-standardisation, for energy management functions, but also concerning studies for optimisation of energy efficiency 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 with current works in RAIL4EARTH WP5 was created. The state of the art mainly concerned rolling stock side and will consider infrastructure side with works to do on the next period. Charging process for BEMU was analysed and different strategies to optimize the charging will be further developed on the next period. Preconditioning and auto adaptative train energy consumption functions will be also worked on the next period.

For the optimisation of energy consumption at system level, a 1st methodology was created. Based on use cases and associated scenarios, a list of criterions to compare the performance on operational level, infrastructure level and rolling stock was built. A 1st use case and scenario was analysed and new ones will be added on the next period until deliverable D1.2 in M36.

Generally, at task 1.2 level, works on next period will focus on the standardisation of energy management functions, description of preconditioning and auto adaptative train energy consumption functions. Studies will continue for the optimisation of energy consumption at system level with additional use cases and scenarios. Contacts with other FPs and SP will be done as well.

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10 Appendices