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Position paper

Innovation in energy management: contribution of railways to sustainable mobility

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ACRONYMS AND DEFINITIONS

AC. Alternating Current (facility).

DC. Direct Current (facility).

DAS (Driver Advisory System). System that allows the exchange of information between the railway system and the driver to optimise train driving, obtaining, among other things, energy savings.

DCS (Data Collector System). Computer application that facilitates the data collection process, allowing the acquisition of structured and specific information in a systematic manner, and subsequently being able to perform data analysis on the information.

DMU. Diesel Multiple Unit (formed by several carriages).

EMS. On-board Energy Measurement System.

EMU. Electric Multiple Unit (formed by several carriages).

ESS. Electrical Storage Systems.

EU. European Union.

EU-Rail JU. Europe's Rail Joint Undertaking. European partnership on rail research and innovation (successor of Shift2Rail Joint Undertaking).

External Network. AC power line (three-phase) that feeds the traction power substation.

FACTS (Flexible AC Transmission Systems). Static devices that are controlled by computerised control systems coupled with high-power electronics. They can be used to compensate for imbalances, that is, as load compensators when used with special control algorithms. They can also be used to dynamically support voltage drops on the Transmission Line and reduce harmonics from rolling stock.

IEA. International Energy Agency.

LNG (Liquefied Natural Gas). Natural gas in liquid phase at a temperature of -160ºC, which is why it is considered a cryogenic liquid. It is stored and transported in highly insulated containers to maintain its liquid state. The advantage of the liquid state is its smaller volume, since for each litre of LNG, approximately 570 litres of gaseous natural gas are obtained at room temperature. It is made up of 95% methane (CH_4) and contains tiny amounts of ethane, propane, butane, nitrogen and carbon dioxide. It is an odourless, colourless fuel that is non-toxic and non-corrosive.

RFIG. General Interest Rail Network.

SSEE. Electrical Traction Substation

Transmission Line. DC or AC electrical line (single-phase) through which the energy demanded by the train from the traction electrical substation is transmitted.

TPS *(Traction Power System).* Part of the railway electrical system that integrates the Transmission Line and the electrical traction substations.

UIC. International Union of Railways.

I. INTRODUCTION

In November 2016, the Spanish Railways Technological Platform (PTFE) published the first version of the position paper on *Sustainable and intelligent energy management in the railway sector* As indicated at the time, the PTFE understood that sustainable and intelligent energy management in the field of research and innovation in the railway sector would be a key factor in favouring competitiveness and ensuring the leadership of the railway industry.

The present document is an update of the previous one, given that the sector continues to establish this issue as a strategic priority due, in large part, to the economic cost but also to the need for railway administrators and operators to continue promoting and strengthening rail transport as “sustainable transport”.

This document was created at the end of 2021, which was the European Year of Rail. This decision was adopted by the Council of the European Union in December 2020, in line with EU efforts to promote sustainable modes of transport such as rail, and with its commitment to achieve climate neutrality by 2050 through the *European Green Deal*.

Although transport accounts for around 25% of greenhouse gas emissions in the EU, rail is only responsible for 0.4% of these emissions. It is the only means of transport that has substantially reduced its emissions since 1990, which justifies its fundamental role in sustainable mobility.

This is mainly because the railway is heavily electrified. Whilst other modes of transport are stilltrying to migrate towards electrification, the railway had already done so by the end of the 19th century, in what was considered the first technological revolution of this mode of transport[1]. Electrification is undoubtedly the way to continue reducing its emissions.

However, de-carbonisation does not imply *total electrification*, and evolution to other complementary solutions must also be considered. In Spain, approximately 20% of current rail traffic continues to be diesel, so other alternatives must be found for those lines where electrification is not the best solution. With this background, and in an environment of energy transition, the railway energy future is going to be hybrid, that is, it will combine renewable electricity and gas solutions, promoting the development of new associated technologies.

The IEA, in an update of its *Energy Technology Perspectives* report, advanced that the state of maturity of the technologies on which it depends to achieve the total de-carbonisation of the economy in 2050 is extremely low (between 2 and 20% depending on the segment of activity). For this reason, it emphasised the need to combine the acceleration of development and innovation projects with effective solutions in terms of energy efficiency.

In this new context, this position paper on *Innovation in energy management: contribution of railways to sustainable mobility*, re-analyses the role of innovation in energy management in infrastructure, rolling stock and operation, as well as future trends and applications. The document, once again coordinated by ADIF's Research, Development and Innovation Area, with the participation of companies, technology centres and research groups from different universities, all members of the PTFE, has been validated by the majority of national,

[1] To reinforce this fact, and to increase awareness, the main milestones in the use of electrical energy on railways are included in the final Annex of this document.

regional and metropolitan railway operators and administrators, and identifies new challenges and recommendations in this context, while analysing the achievement and status put forward in the first document.

It is important to note that innovative approaches and technologies will be promoted in the new Europe's Rail Joint Undertaking technology initiative in its FA 4 programme.

II. GENERAL ANALYSIS OF THE SITUATION IN SPAIN

Spain is currently immersed in a period of energy transition with established and binding decarbonisation objectives for the economy for 2030 and 2050 that affect all sectors, and therefore transport. In this process, the public sector will play an essential role in designing policies and mechanisms to address the challenges to be faced in the coming decades.

During the last five years, the technological activity in the field of energy on the railway sector has been especially important, both in terms of the development of technological projects as well as on the application of effective solutions for energy efficiency. In relation to the projects, technological initiatives of significant importance and impact for the sector have been developed (and continue to be developed). Specifically, since November 2016, more than fifteen projects have taken place with the participation of different national agents, evidencing the extensive activity of the sector in this field.

Regarding energy efficiency initiatives and solutions, all railway administrators and operators have new plans (or updates of previous ones) for energy efficiency at company level. In the case of electricity consumption, considering that more than 70% of this consumption is used for traction electricity, the implementation of saving measures in this area has been, and continues to be, very effective.

DC RAILWAY SERVICES

Focusing the analysis on DC electrical infrastructure, the most widely used in the Spanish railway, highlights the penetration of energy recovery technology in electrical traction substations. Companies such as ADIF, Metro de Madrid or TMB continue to install this technology in their networks.

On the other hand, operators have continued to evolve and implement energy optimisation modules in their ATO systems. Thus, for example, FGC will implement an ATO system with an efficient driving module in 2023.

In general, the promotion of a culture of energy efficiency within the driving staff through the training of drivers and the preparation and distribution of manuals of good practices to carry out efficient driving, are other positive actions.

One aspect of significance refers to the progressive use of electric traction by freight operators. It is worth mentioning here the FGC initiative which, from mid-2022, will begin to change its diesel locomotives for the transport of goods for dual electric and diesel traction locomotives, with savings of 70% in emissions. Additionally, some private operators have begun to introduce electric locomotives with the latest technology.

AC RAILWAY SERVICES

An independent area of analysis would be that of railway services that use AC systems, such as high-speed. These are very efficient services from an energy point of view (use higher electrical voltage and electrical regeneration without the need to specify energy recuperators in the traction substations). However, they are responsible for 45% of the General Interest Rail Network (RFIG)'s total traction electricity consumption, which is why during the last five years, important initiatives have also continued to be developed with the aim of reducing their consumption. Among others, ADIF Alta Velocidad continues to count on the *double* catenary power supply system, of the 2 x 25 kV type, more efficient than the simple single-phase 1 x 25 kV system. On the other hand, this type of network will be the first to experience the benefits associated with the transformation of the *conventional* electrical system to *intelligent* ones (during 2022 a pilot test is planned for a specific path of this AC network).

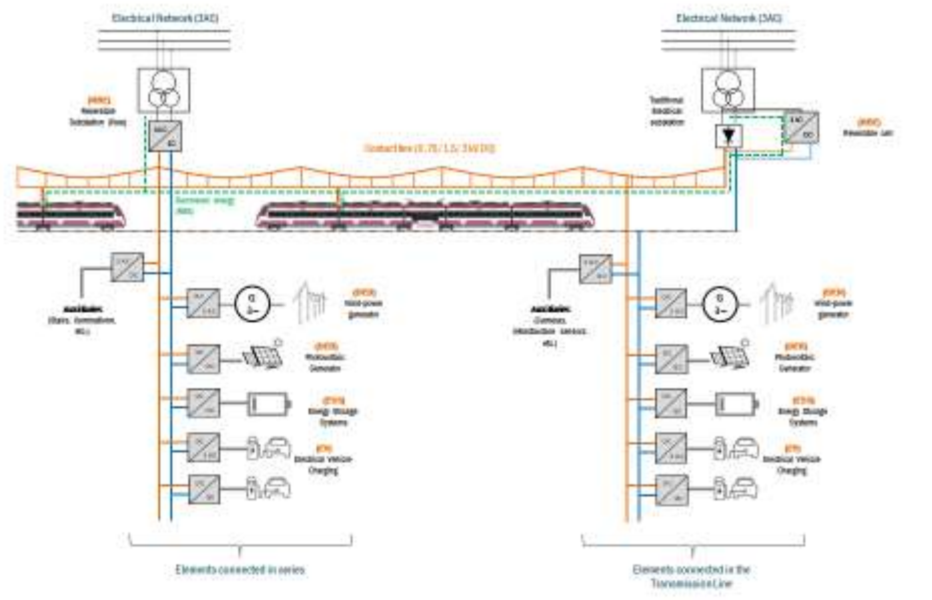
In the same way, railway operators are also developing different lines of work: Renfe continues to implement automatic efficient driving equipment, as well as the development of associated applications, in the EMUs S102, S112, S130 and S730.

TECHNOLOGICAL PROJECTS: ORIENTATION TOWARDS NEW INTELLIGENT ELECTRICAL NETWORKS

Since 2016, R&D&i projects developed in the field of electrification systems have been remarkably diverse, especially the European collaborative projects such as In2Rail, In2Stempo and E-LOBSTER, all of which are related to the implementation of new *intelligent* assets in the railway electrical network and/or integration in equally *intelligent* networks. These projects have continued to lay the foundations for the development of more efficient railway electrical networks, which demonstrates the commitment of the sector to continue innovating and improving the railway electrical infrastructure.

The main functions to be developed by this type of network are the following:

- Improve and make the management of electricity flows in the railway system more flexible.
- Improve the operation and maintenance of electrical infrastructure assets, maximizing the possibilities of remote management and minimizing the overall cost of operation and maintenance.
- Obtain a more autonomous and dynamic response from the network. With information management, it is possible to act on the devices and improve the response and protection of the infrastructure against failures or the coordination of distributed energy resources to avoid power supply failures, increasing the safety and reliability of the railway electrical system.
- Broadenunderstanding of the wide variety of consumption points in a network as complex as the railway traction network.
- Control power flows considering the possible introduction of delocalised electricity generators based on renewable sources.
- Help future decision-making on strategic approaches related to electricity, such as the possible evolution towards a self-consumption model in certain locations and the redefinition of the electricity supply model (energy storage systems, etc. may be considered).



General representation of an intelligent railway electrical network.

OTHER ENERGY VECTORS

Electricity will continue to be the main energy vector of Spanish rail transport. That said, which other energy vectors will also be used in the future? In view of the different initiatives launched by the operators and the industry, these vectors would be Hydrogen, LNG and zero footprint fuels.

Indeed, as indicated above, around 20% of current rail traffic in Spain continues to be developed with diesel traction, so the introduction of new vectors that decarbonise this traffic is a process that has already begun.

In the case of Hydrogen, the initiatives launched since 2020 are diverse, with the main objective the development of a new generation of vehicles with this type of traction. An example is the European collaborative project FCH2RAIL in which a new hybrid electric/hydrogen train modality will be developed starting from an EMU 463 belonging to Renfe.

In fact, the main Spanish manufacturers of rolling stock are already developing technological projects in this area.

LNG has also been involved in different projects in recent years, highlighting the transformation of an EMU 2600, also belonging to Renfe, in the RaiLNG project.

Renfe has been running a Fleet Renewal Plan since 2019, with the main objective to reduce the average age of its railway fleet. Specifically, the Cercanías and Media Distancia services - which account for more than 80% of the company's public service - count on railway material that is more than 30 years old, making it essential to act. This rejuvenation of rolling stock is partly linked to having trains with better characteristics in terms of energy consumption and environmental impact. Specifically, there will be a commitment to trains with dual technology (electric and hydrogen and batteries) for the Cercanías and Media Distancia services.

GENERATION WITH RENEWABLE ENERGY. SELF-CONSUMPTION

In Spain there is currently a clear commitment to the promotion of renewable energy generation to contribute to the reduction of greenhouse gas emissions targets. In this sense, the integration of renewable energies into the energy consumption of the transport sector is also a priority.

Different administrators and rail operators are conducting studies and analysis to plan and introduce distributed generation based on photovoltaic solar energy, and subsequently self-consuming from it. This approach, which has normally been promoted in the field of construction (for example, passenger stations or auxiliary areas such as car parks), is also being oriented towards the energy consumption of trains.

III. POLICY AND REGULATORY FRAMEWORK

Since the first edition of the position paper on *Sustainable and smart management of energy in railways*, the legislative and regulatory framework has grown in general terms, in relation to the use of alternative fuels to diesel.

As seen above, although the Spanish railway sector has undertaken significant efforts in terms of electrification, it must continue to advance in the field of decarbonisation of lines and rolling stock dependent on diesel.

In the field of electrification, at Spanish national level, the *Royal Decree 1011/2009* [2] continues to be applied by the sector as the main incentive for the discharge of the energy generated in the regenerative braking of trains into the external network. In the field of smart grids, little progress has been made in legal and regulatory terms since 2016. It should even be considered that non-rail electricity networks, which are the most advanced in this area, do not still have an effective regulatory and governance framework with the aim of encouraging an innovative design of the energy market and greater interaction with the end user. In railway terms, it is essential that new technological projects help develop this framework for railways.

NEW ENERGY VECTORS

In relation to the main political and regulatory actions during this time, some are highlighted below in chronological order, closely aligned with the use of new energy vectors:

- In December 2019, the so-called *European Green Deal* was approved, setting ambitious targets for reducing greenhouse gas emissions, improving energy efficiency and the penetration of renewable energies by 2030.

[2] Royal Decree 1011/2009, June 19th, which regulates the Supplier Switching Office (and according to its twelfth additional provision regarding discharges to the electricity network for consumers who implement saving and efficiency systems).

- In July 2020, the *European Hydrogen Strategy* was published to provide a roadmap for the deployment of hydrogen at EU level. Following this, in October 2020, the *Ministry for Ecological Transition and Demographic Challenge* launched the *Hydrogen Roadmap*, positioning renewable hydrogen as part of the solution to achieve climate neutrality by 2050 and develop innovative industrial value chains in Spain. This Roadmap forecasts that by 2030 there will be hydrogen-powered trains on at least two non-electrified commercial lines.

- In September 2020, the *Ministry for Transport, Mobility and Urban Agenda* approved the *Strategy for Safe, Sustainable and Connected Mobility 2030* to respond to the new challenges that arise in mobility and transport to contribute to the decarbonisation of the economy. It should be noted that this strategy already expressly indicates the need to use Hydrogen and LNG on the railway.

- In November 2020, at the proposal of the Ministry for the Ecological Transition and the Demographic Challenge, the *Long-Term Decarboniszation Strategy 2050* (ELP 2050) was approved in Spain, which is aimed at achieving climate neutrality in 2050. It establishes that the decarbonisation of the transport sector will come hand in hand with the intensification of energy efficiency measures, together with the substitution of fossil fuels for other products with low or zero net carbon emissions. In 2030, because of the measures provided at the *Integrated National Energy and Climate Plan* (such as the change in mobility models and the increase of electrification), a 28% share of renewable energy in transport is expected, as well as a 30% reduction in greenhouse gas emissions between 2021 and 2030. On the way to climate neutrality in this sector, from 2030, progress must be made in energy efficiency measures, electrification, promotion of liquid fuels and renewable gases, digitisation and integrated urban planning.

- In July 2021, the proposal for a Regulation of the European Parliament and of the Council on the implementation of infrastructures for alternative fuels was presented and the Directive 2014/94/EU of the European Parliament and the Council was repealed. In this regard, it is worth highlighting the ambitious objectives set for 2030 and 2050 in terms of electric recharging points and hydrogen refuelling. The approval of said Regulation will mean its immediate entry into force, without the need for national transposition.

SELF-CONSUMPTION

In April 2019, the Spanish Government approved the Royal Decree 244/2019, which regulates the administrative, technical and economic conditions for self-consumption of electricity in Spain. This rule completes the regulatory framework promoted by the Royal Decree-Law 15/2018, which repealed the so-called sun tax, and provides certainty and security for users.

Among the main regulatory novelties included in Royal Decree 244/2019, a new definition of self-consumption it is stated as the consumption by one or several consumers of electrical energy from generation facilities close to those of consumption and associated with them. It is established that self-consumed energy of renewable origin, cogeneration or waste, will be exempt from all types of charges and tolls.

Two modes of self-consumption are defined: *self-consumption without surpluses*, which at no time can discharge energy into the network. These installations are exempt from the need to obtain access and connection permits for the generation installations, and to register the installation with a very simplified administrative procedure.

The other modality is *self-consumption with surpluses*, in which discharges can be made to the distribution and transport networks (generation with discharge to the network), and which therefore would require processing access and connection permits.

IV. GENERAL TECHNICAL CONSIDERATIONS

One of the objectives of this document is the identification of challenges facing railway administrators and operators responsible for better energy management. According to the procedure in the original document, the different challenges will be grouped according to their scope of application: *Infrastructure, Rolling Stock* and *Use and Operation.*

Specifically, meeting the different challenges may yield improvements in one or several directions:

- *Electric energy saving*
- *Decarbonisation*
- *Efficiency in operation*

Due to their strategic importance for end users, whether these challenges can be associated with direct *economic investment* and their approximate impact is also stated:

- € *No or low economic investment (less than 10 k€)*
- € € *Average economic investment (between 10 and 500 k€)*
- € € € *High economic investment (greater than 500 k€)*

The challenges are also classified according to the technical implications associated with their implementation. In this sense, there will be challenges of a *passive nature*, that is, those that are not based on complex solutions at equipment level (for example, an efficient design of the electrical network based on *good practices*). The challenges of an *active nature* will be those whose application involves the use of technical equipment that fulfils a predetermined function based on a control logic (for example, the operation of an Electronic Power Converter to enable the injection of braking energy into the network). Specifically, a difference is underlined between technical equipment of a *purely electrical* nature and equipment of a *digital* nature:

- *Passive nature (does not imply the use of new equipment)*
- *Active nature (new electrical equipment)*
- *Active nature (new digital equipment)*

Finally, it is important to bear in mind that many of the challenges are interrelated.

V. INFRASTRUCTURE

As stated in 2016, railway infrastructure has a primary role in the energy management of the railway system, and a large part of the expected energy savings must come from the measures adopted in it.

The identified challenges are outlined in the following table.

Challenge	Description	Identified in 2016	Progress since 2016 (*)
R.1	Efficient design of the railway electrical network	Yes	Yes
R.2	Design of the railway layout considering energy consumption aspects	Yes	No
R.3	Promote the active use of electricity generated by the braking of trains (in DC systems)	Yes	Yes
R.4	Introduce (land) storage of external electrical energy	No	-
R.5	Optimise the connection of the AC railway electrical system with external networks	No	-
R.6	Promote predictive maintenance of the railway electrical network assets	No	-
R.7	Introducing the railways electric Smart Grid	Yes	Yes
R.8	Boosting superconductor link technologies	No	-
R.9	Optimise the rlectrical feeding of auxiliary installations.	Yes	No
R.10	Promote the development of efficient (ground) power electronics	No	-

Table 1. Summary of the identified challenges in Infrastructure
(*): According to the opinion of those involved in the editorial team of this document.

R.1. Efficient design of the railway electrical network

Investment:	Nature:	Improvement:
€		

Related to:

R.18

The areas of work in this field continue to be diverse and focus on the efficient design of electrical infrastructure with an emphasis on *good practices* and not on the acquisition of specific technology. Among others, these are:

- Use of adequate reinforcement sections to enable an efficient distribution of traction current.
- Project parallel installations between Transmission Lines.
- Analysis of the reactive energy of the facilities in the project.
- Adoption of efficient technical teams.
- Position of Neutral Zones for electrical phase separation in flat areas (in AC systems).
- Efficient operation of the railway Electrical grid (R.18), design of a network topology that allows optimum use of regenerated energy based on different exploitation scenarios (in DC systems).
- Use of the highest supply voltages, through receivers connected to the transport network and internal Medium Voltage networks, guaranteeing a better quality of supply, a better electricity price and a greater capacity to take advantage of all the energy regenerated by the recuperators of traction in DC systems.

In principle, these areas of work should not be complex for the different users. On the contrary, it is worth highlighting two lines of action that, as they are specific to the corresponding engineering projects, would have a significant impact on the functionality and characteristics of the network. Namely, the increase in the nominal electrical voltage of the Transmission Line and the evolution to single-phase alternating current traction systems instead of direct current (referring to the RFIG). In fact, the latter has already being implemented in recent years, not only in newly built infrastructures, but also in the existing infrastructures that are electrified. The advantages of using this current are greater than its main disadvantage (generating disturbances on the external network and on nearby railway facilities).

R.2. Design of the railway layout considering energy consumption aspects

Investment:	Nature:	Improvement:
€		

An efficient layout design in terms of energy consumption is understood as a homogeneous speed profile.

The homogeneity of the speed profile reduces the use of the brake to decelerate on the line, limiting it to stops. In many cases, it implies that speed is less than the maximum possible speed and can lead to a significant reduction in the average speed of the trip.

To achieve this homogeneous speed profile with a minimum reduction in average speed, it is recommended:

- To avoid specific speed limits.
- Gradient at stations is elevated, to minimise the necessary braking on approach.
- Gradient at stations is horizontal to reduce starting power.
- Slopes are harmonised with the speed allowed by the sections.

R.3. Promote the active use of electricity generated by the braking of trains (in DC systems)		
Investment: € € €	Nature:	Improvement:
Related to: **R.7 R.8 R.10**		

The active use of regenerated energy from braking on direct current lines will continue to be a strategic aspect for railway companies, both in terms of the installation of electronic power converters to inject the energy surplus into the network (reversible cells) and the installation of grounded storage systems.

The technology is becoming standard, although it is necessary to continue optimising it as more knowledge is available at the operation phase.

Royal Decree 1011/2009 continues to represent a fundamental tool for the implementation of reversible cells, as it represents a direct economic incentive for users. It should be noted that the operating experience has confirmed that the savings produced are particularly important, with values that can exceed 50% of the total energy consumed by the substation, providing a return on investment in a few years.

On the other hand, the implementation of grounded storage systems has been scarce, although this is expected to change as a result of the gradual introduction of new smart grids. Currently, this solution is considered more expensive than the use of reversible cells, although it also has other technical advantages associated with the improvement of energy flows in the network, such as:

- The minimisation of problems caused by undervoltage.
- The continuity of the electricity supply in the event of a fault from the substation (for example, for a train leaving a tunnel or arriving at a nearby station).
- Limitation of disturbances coming from the installation.
- Improving the quality of energy distribution.

In any case, it is necessary to update, at sector level, the technical and economic characteristics of the different storage technologies, identifying which ones would be the most efficient for the current needs of railway companies. These technologies must be aimed at improving energy capacity as well as the cost ratio per unit of energy for each charge/discharge cycle.

The experience of use on the ground, although low, identifies that electrochemical storage is the most interesting at this time compared to purely mechanical storage. Thus, lithium ion batteries are being improved, and batteries that use titanium are also being developed. On the other hand, there is ongoing work to optimise redox flow batteries.

It should be noted that one of the energy storage systems that is proposed for the future is the use of green hydrogen. In the production stage, it could be obtained from renewable electricity, preferably solar and wind energy, through electrolysis, and therefore it would be another of the storage elements necessary to improve management of the electric grid.

R.4. Introduce (land) storage of external electrical energy

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.7 R.9 R.10 R.20

This refers to the storage of electrical energy generated by external renewable energy sources (R.2 refers to the exclusive storage of electrical energy generated by braking). It is necessary to introduce the use of renewable energy sources for power supply, not only for auxiliary installations or railway buildings, but also for trains.

In any case, electricity from other networks could also be accumulated in cheaper tariff periods so that they can be used as auxiliary or emergency supply sources, or as support at times of maximum energy demand.

This challenge is especially important for the development of the challenges related to smart grids (R.6) and of self-consumption by the railway managers and operators (R.20).

R.5. Optimise the connection of the AC railway electrical system with external networks

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.7 R.10

The expansion of single-phase alternating current railways with industrial frequency is promoting the development of new connection schemes that allow their use to be compatible with the electrical power networks, producing a minimum effect on them.

Traditionally, the development of large high-speed axes has been associated with the construction of the necessary supply networks (normally related to energy transport). But sometimes it is not possible to deploy this infrastructure, so networks with lower technical features are used, that can be more affected when connecting with the railway. It must be considered that, in any case, different conventional RFIG corridors will migrate to alternating current systems in the future, being able to take advantage of existing external networks (distribution in these cases). This approach should be seen as a sustainable energy management measure.

The use of FACTS in alternating current electrical substations could be a necessary requirement, migrating to new traction equipment that would allow control of imbalances on the external network as well as the voltage value on the Transmission Line. This considers the use of an external electrical network with low short-circuit power. In the same way, it is expected that energy consumption can be reduced, as demonstrated in the European R&D project In2Rail.

R.6. Promote predictive maintenance of the railway electrical network assets

Investment:	Nature:	Improvement:
€ €		

Related to:

R.7

The maintenance normally applied to the railway infrastructure is periodic and preventive. The purpose of this maintenance is to anticipate failure by repairing or replacing the elements of an installation, respecting service lifetime, which will be defined by the manufacturer's criteria. For this, continuous monitoring of the elements of the installation is carried out based on the documentation provided by the manufacturer. In this way, the parts are replaced without waiting for their end of life or breakdown, and maintenance is carried out during hours that do not affect the operation of the railway line.

Alternately, best performance can be achieved with predictive or condition-based maintenance. This is based on the use of tools that acquire information on the deterioration of the elements and provide a knowledge base that enables assessment of risk of failure and development of strategies to decide when to carry out the intervention or delay it, if applicable. It is a monitored process in which the objective is to have the maximum amount of data that helps the railway manager to determine the moment at which a fault will occur and thus determine the opportune moment to act.

The application of this type of maintenance to the electrical assets of the infrastructure may result in an improvement in operations, making them more sustainable.

R.7. Introducing the railway electric Smart Grid

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.3 R.4 R.5 R.6 R.10

This type of network fosters the development that best combines the railway electrical system and new digital techniques to implement a more efficient network, not only from the point of view of electricity consumption but also of operation. In 2016 this challenge was already specifically identified and, since then, progress has been made in this area thanks to the completion of various projects such as In2Rail, In2Stempo and E-LOBSTER.

This new railway electricity network can be seen as a grouping of the rest of the aforementioned technologies (reversible cells, storage systems, renewable energy sources, etc.), forming nodes. Considering that others could be added (to have a greater number of functionalities), in any case a control discipline must oversee execution and regulation of the appropriate actions.

The challenge is therefore that the railway electricity network is transformed in the coming years into an energy concentrator or *energy HUB* incorporating *distributed generation nodes (DER), nodes that efficiently use the regenerative braking energy of trains (RBE), nodes of energy storage on land (ESS) and nodes associated with charging infrastructures for electric vehicles (EV)* among others (see diagram below).

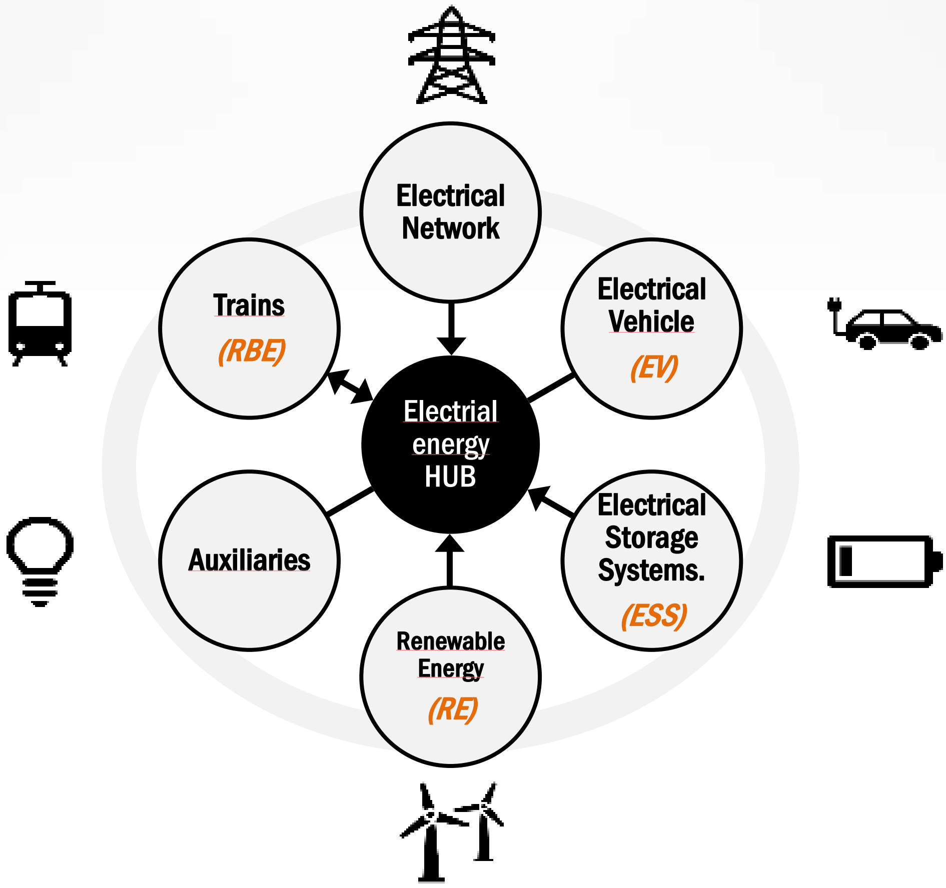
To date, some railway administrators have developed different initiatives and/or projects at the level of these nodes independently (reversible cell projects, RBE), underlining the necessity to promote new projects that integrate them all together.

The train should be able to become a mobile node of the system and can be integrated into the aforementioned HUB. Specifically, the connectivity of the train with the electrical infrastructure is a challenge to be addressed. The advanced management of a fleet of trains is making it possible to know the status of each vehicle, its consumption, and its operating conditions. This information, processed by means of precise and detailed algorithms, would make it possible to identify points for improvement and define new energy optimisation criteria.

The evolution of current simulation techniques will enable knowledge of the infrastructure for a given use, with the ability to adjust both the operation and the configuration of the infrastructure based on joint energy efficiency. The individual consumption of the vehicle may not be optimal while the collective consumption of the system represents the optimum. The synchronisation of the tension of the Transmission Line together with the circulation schedules and the instants of acceleration and braking of the vehicle, will allow for the optimisation of the entire system.

Advanced connectivity allows the infrastructure to detect the knowledge and be able to optimise the expected consumption of the rolling stock, while the vehicle can know the needs of the infrastructure and update its operation. The driving assistance systems will enable the prediction of the operation of rolling stock, train-infrastructure communication and driving schemes according to a global optimisation.

Finally, it should be considered that cybersecurity is a key aspect in the development of these new railway electricity networks due to the large amount of information generated, recorded and processed for decision-making and actions.



R.8. Boosting superconductor link technologies

Investment:	Nature:	Improvement:
To be analysed		

Related to:

R.3

A technology that is beginning to be implemented in direct current systems is the use of superconducting auxiliary cables, and there are already experiences of this use in Japan. As superconducting cables have low electrical resistance, considerable energy savings can be achieved, while voltage stability can be increased. This is an advantage in direct current systems since the voltage drops significantly as the distance from the substation increases.

This solution could help improve the electrical energy regeneration process if there is not a train consuming near another that is slowing down. It would be possible to increase the energy recovered with regenerative braking, including the energy returned to the external network in traction substations equipped with reversible cells.

R.9. Optimise the electrical feeding of auxiliary installations.		
Investment: € €	Nature:	Improvement:
Related to: **R.4**		

These auxiliary installations, which are of a diverse nature, are limited to the case of isolated geographical locations where there is no direct power supply to external networks or where it does exist, it is not continuous over time (in this case it is usually switched with another type of system based on conventional generator sets).

The objective is to strategically migrate to sustainable generation systems based on other energy vectors such as hydrogen fuel cells or conventional batteries. It should be noted that the use of zero footprint fuels (produced with water and CO2) in conventional generator sets would also be an option to explore.

On the other hand, this challenge identifies another area referring to the use of the concept of Energy Harvesting or extraction of Ambient Energy, especially in the case of reduced electrical consumption (in the case, for example, of new sensors distributed along the track). Thus, it should be analysed whether the use of the noise and vibration produced by the train is a feasible option as a source of energy for this type of device.

Triboelectric nanogenerators have recently been developed that can harvest sound and low-frequency vibrations. In any case, the economic viability of these new systems must be analysed considering their subsequent maintenance.

It is also worth noting the existence of pilot projects based on the recovery of wind energy in tunnels, through wind turbines or the use of geothermal energy, and the air conditioning of traction substations through the groundwater captured in the pump wells (solutions with interest in underground operations).

R.10. Promote the development of efficient (ground) power electronics

Investment:	Nature:	Improvement:
To be analysed		

Related to:

R.3 R.4 R.5 R.7

While power electronics have traditionally been used in rolling stock, their use in ground infrastructure has been more limited. The introduction of new operating approaches and electrical connections (to which the previously introduced challenges refer) has changed this trend and the use of this new equipment has been essential for the last few years.

Unlike what happens with on-board equipment, in the field of ground infrastructure, the requirements associated with mechanical aspects (space and vibrations, among others), are less important, although there are other new requirements that are currently not fully explored. A particularly important aspect refers to compliance with all the standards associated with the generation of disturbances in the railway system, on the Control, Command and Signalling installations, since it will be common practice to be able to connect this equipment in locations other than the electrical substations of traction, with the connection to the running rail being compulsory.

Modelling techniques (digital twin) in Medium Voltage networks will help to guarantee a decent quality of electrical service when, increasingly, new systems based on generation and power electronics are being incorporated.

On the other hand, semiconductors have been based throughout history on silicon as the basic element. Silicon carbide has been replacing silicon for a few years, especially for blocking voltages above 500 V. Silicon carbide components have much lower losses than silicon-based power semiconductors. In addition, higher blocking voltages and higher operating temperatures dominate. Somehow, the use of this new material has made it possible to find the ideal component that allows the blocking of high voltages (in the open state), high currents (in the conduction state) and low power losses to be combined in the same element.

VI. ROLLING STOCK

Electric traction rolling stock is highly optimised, as already stated in the 2016 document. In any case, improvement in this area will be represented by the new energy vectors.

Identified challenges are laid out in the following table:

Challenge	Description	Identified in 2016	Advances since 2016 (*)
R.11	Promote on board electrical energy storage	Yes	Yes
R.12	Boost traction with hydrogen in a fuel cell	No	-
R.13	Promote traction with LNG	Yes	Yes
R.14	Boost traction with zero footprint fuels	No	-
R.15	Implement on board measurement systems	Yes	Yes
R.16	Promote development of efficient (on board) power electronics	No	-

Table 2. Abstract of the challenges identified in Rolling stock
(*): Under general criteria of entities participating in the document.

R.11. Promote the on board electrical energy storage

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.16

On board storage of energy on the vehicle continues to be presented as one of the main improvements in the energy management of the railway system. Like applications on the ground, technologies are numerous and continue to be developed, with electrochemical storage being the most used and best placed for the coming years. The aim is to optimise the duration of the charge and the number of life cycles of the battery. Lithium and titanium batteries are a significant improvement over lithium ion batteries.

While ground infrastructure storage has a clear positive effect on the electrical stability of the system, in the case of rolling stock it can bring definite improvements in safety, for example, moving the train in the event of a supply fault. This functionality has already been used in urban rolling stock, in some cases also for the transition of the vehicle through areas that do not have a transmission line.

It is of special interest to review the solution implemented in the EMU N700S of the Japanese railway (JR Central), in service since the summer of 2020. This train is the first high-speed train equipped with this technology, which allows it to self-propel in case of interrupted transmission line current. The system is fitted to four of the sixteen cars on the train and is based on lithium-ion batteries.

On the other hand, it should also be noted that among the EU-Rail JU initiatives is the development of a new generation of vehicles powered specifically by batteries (BEMUS) that, at specific points along the route, would be charged in the same way as electric road vehicles.

R.12. Boosting traction with hydrogen in a fuel cell

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.16

The use of hydrogen as an energy vector in new railway traction can help meet environmental objectives on those lines where electrification is not an economically viable alternative. Although it is a technology that has been known for several decades, its commercial application in the railway can still be considered immature or incipient from a technological point of view, since there is not much experience in its use. We cannot ignore the fact that large industrial suppliers are betting heavily on this technology since its use is strongly backed by EU policies and economic aid.

The use of hydrogen has great advantages. On the one hand, the vehicle would be free of emissions, both in the generation process if obtained through renewable energy sources (green Hydrogen) and in the combustion process. On the other hand, it enables coverage of areas greater than 100 kilometres, which is the current limit for recharging batteries. Another advantage is the reduction of noise emitted by the vehicle, important both for users and for inhabitants of areas near the railway line.

However, the use of hydrogen has several disadvantages. Amongst them is the lack of security of supply, understood as the availability of energy resources and the flexibility of the supply chain to meet the expected demand (both in terms of quantity and quality). Safety of use can also be regarded as a disadvantage. Safety implies management of the risks associated with the handling of fuel during transport, refuelling and its use. In this sense, it is necessary to conduct further technical analysis related to the use of rolling stock in confined areas such as tunnels and underground stations.

Hydrogen on board the train can be stored as pressurised gas, in liquid form or stored through other organic liquids. Whilst in the aviation sector, important analysis has been carried out regarding the use of stored hydrogen (liquid hydrogen is recommended due to the reduction in the necessary volume and also the reduction in weight compared to storage in gaseous form), in the railway sector, gases at a pressure of 350 bars are being chosen, since the treatment of liquid hydrogen requires cryonisation at -257ºC with the cost and technical difficulties that this entails. It is necessary to continue analysis and find indicators to increase knowledge and experience in the different options.

The use of other hydrogen-carrying molecules to produce it on board -allowing high energy densities to feed fuel cells- is showing that bioethanol and renewable ammonia (liquefied under pressure) can be a great alternative. Both compounds are liquid fuels and therefore have a high energy density.

It must be acknowledged that the use of hydrogen in rail is strongly supported by the EU and mandatory in the EU in the coming years in different countries. Most countries in the European Union have launched their prototype projects, homologation tests or commercial projects for the use of hydrogen with a fuel cell in passenger or manoeuvring vehicles (and to a lesser extent line locomotives).

R.13. Promote traction with LNG

Investment:	Nature:	Improvement:
€ € €		

Related to:

R.16

The enhancement of other energy vectors such as LNG should not be ignored. This fuel has already been studied in Spain in different research projects on diesel rolling stock. The results have been very satisfactory.

LNG has great advantages of use compared to other alternative fuels. In this sense, although the emissions are not zero as is the case with the use of hydrogen, its technological maturity, its security of supply and its security of use are greater in comparison.

In economic terms, the use of LNG as a new energy vector for railway traction is also more advantageous. Thus, the investment associated with both the supply and refuelling chain and the adaptation of the traction chain is less in all cases. Likewise, the cost of raw materials is also lower.

Finally, the ability of each operator's existing vehicles to adapt competitively to LNG, is greater than for the use of hydrogen.

R.14. Boost traction with zero footprint fuels		
Investment:	Nature:	Improvement:
Related to: **R.16**		
The use of zero-footprint fuels produced with water and CO2 as the only raw materials which can be used in any current vehicle without the need to change infrastructure, should also be analysed.		

R.15. Implant on board measurement systems		
Investment:	Nature:	Improvement:
Related to:		
A challenge that must continue to be explored is the use of on-board metering equipment that makes it possible to control the traction consumption of vehicles, always as an action prior to the energy management of those consumptions (the system would be complemented by sending the information to a measurement concentrator). This equipment will also allow the operator to invoice based on a real measurement. For the specific case of diesel traction vehicles, the installation of flowmeters and automatic and optimal measurement of diesel consumption is also considered.		

R.16. Promote the development of efficient (on board) power electronics

Investment:	Nature:	Improvement:
€ €		

Related to:

R.11 R.12 R.13 R.14

Unlike the ground application, on-board power electronics are very well researched. In any case, it is widely accepted that the use of silicon carbide in on-board equipment would have greater advantages than in ground equipment. In recent projects, significant reductions in energy consumption have been verified due to lower energy losses, lower thermal dissipation needs and lower volumes and weights.

The challenge must also effect the evolution and optimisation of electronic control strategies, allowing rolling stock to operate at its most efficient point. To this end, work is proposed on techniques for identifying and applying the maximum performance operating point, optimising the distribution of effort applied by the different traction equipment.

VII. USE AND OPERATION

As indicated in the first document, the implementation of actions in the infrastructure and rolling stock that optimise the energy management of the system must accompany actions that allow this material to operate efficiently on that infrastructure. The identified challenges are outlined in the following table.

Challenge	Description	Identified in 2016	Advances since 2016 (*)
R.17	Purchase of "Green" electrical energy	No	-
R.18	Efficient operation of the railway Electrical grid	Yes	Yes
R.19	Efficient operation of Rolling Stock	Yes	Yes
R.20	Promotion of self-consumption	No	-
R.21	Promotion of the digitisation of mobility	No	-

Table 3. Abstract of the challenges identified in the areas of use and operation.
(**): To the general criteria of the entities participating in the document.

R.17. Purchase of "Green" electrical energy		
Investment: *NP*	Nature:	Improvement:
Related to:		

There is no particular energy mix for the railway electricity network, as it is the same as the electricity demand of the corresponding country. In Spain there is a very distributed mix, without apreponderance of a specific technology although it has a high percentage of renewable energy generation.

However, the purchase of "green" electrical energy by the railway companies is a positive challenge for greater decarbonisation of the railway (in indirect terms). The consumption of "green" electrical energy means the electricity company guarantees that, with the money paid by that user, 100% of the energy consumed is produced by renewable sources.

A good measure to promote the purchase of green energy would be the aggregate purchase of energy (joint purchase between different railway operators).

R.18. Efficient operation of the railway electrical grid		
Investment: €	Nature:	Improvement:
Related to: **R.1 R.19**		

The efficient operation of the different elements of the railway electricity network is a challenge that must be met, considering that it does not imply higher costs for infrastructure managers. As already indicated in the 2016 document, the future implementation of state-of-the-art electrical networks (intelligent) will help to operate the network efficiently. In this sense, the sensorisation of all the electrical loads of the system would allow the adoption of optimal operating instructions, providing data that can be used for the development of algorithms that help vehicles to operate efficiently (in line with the challenge R .19).

In the meantime, operating strategies must be identified that enable progress on this issue. An example of action that has been conducted in recent years is based on the convenience of operating alternating current traction substations with a single transformer. The purpose of this measure is to cancel the vacuum losses of one of the two traction transformers of the substation, leaving it out of service. The increase in load losses that the transformer that remains in service will have (and that must assume the entire load associated with the substation) are lower than the no-load losses that are avoided by disconnecting the other transformer. Thus, through the disconnection of a transformer for a year, consumption (due to vacuum losses) of between 0.70 and 0.53 MWh/year has been avoided.

An operational topology that promotes the generation of electrical braking energy and its use by other trains is another action that can be carried out.

R.19. Efficiently operate the Rolling Stock

Investment:	Nature:	Improvement:
€ €		

Related to:

R.18

It is essential to continue promoting the development and application of efficient operating strategies for rolling stock, to maximise the potential savings associated with the specific challenges of the infrastructure and the material itself. As is well known, the main energy saving strategy associated with vehicle operation is economical driving.

Some technological developments continue to focus on advising on manual driving as an aid to reduce consumption. These are the driving assistance systems or DAS. These systems receive a target time that they must meet according to the schedule and calculate the driving that the train driver must carry out on the route. These systems must allow recalculation in real time to be able to adapt in case of delay or change in the schedule.

On the other hand, there are the developments associated with the integration of this type of strategies on the ATO/ATP systems. Bearing in mind that metropolitan services are a reference in this type of development, the initiatives aimed at implementing these techniques in the ERTMS interoperable system are of special importance, in interurban or commuter lines.

In addition to driving, energy efficiency can be improved from centralised traffic control and planning systems. Specifically, schedules can be designed according to criteria based on service quality as well as efficiency. Energy savings in the design of schedules and their online recalculation can be achieved through an efficient distribution of time margins along the route (so that they can be used through economical driving), through the synchronisation of train starts and stops nearby (to improve the use of regenerated energy), or to reduce the power peaks demanded in the substation.

In a more operational way, railway operators can continue to reduce the energy consumption of vehicles during parking, enhancing their automatic disconnection or optimising energy consumption for pre-conditioning.

R.20. Promote self-consumption		
Investment: € € €	Nature:	Improvement:
Related to: **R.4**		

The implementation of new distributed generation facilities based on renewable energies to promote self-consumption are an action of great strategic interest for railway administrators and operators, reducing in any case energy consumption from external networks.

Self-consumption can have a broad dimension, not only at the level of the electrical supply of buildings and installations, but also of the traction loads themselves.

R.21. Promote the digitisation of mobility		
Investment: € € €	Nature:	Improvement:
Related to:		

Mobility as a service is already considered the international standard for the future of mobility solutions. The aim is for users to have a unified service experience, in a completely transparent way on their door-to-door journey, whether in public or private mode.

The development of digital applications that offer comprehensive mobility solutions to all users, allowing them to plan their trips from the moment they leave their homes until they reach their destination, reserving all the necessary additional services during the journey and at the destination, is a challenge for operators to consider. These are applications that, among other functionalities, involve customers and raise awareness in reducing their carbon footprint, not only on the train journey, but throughout their entire trip.

The combination of and cooperation between sustainable modes of transport indirectly provides an improvement in energy management, both from the point of view of energy saving and from the point of view of not using polluting energy sources, which results in better air quality and the reduction of greenhouse gas emissions.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Railways must continue aim for improvement in the field of sustainable and intelligent energy management. Since 2016, the year in which this position paper was first published, there has been progress in some of the challenges and recommendations identified at that time.

Although electrification is already a reality in the railway sector, services that use diesel, and for which electrification may not be the best technical solution, still have to be optimised.

The organisations and companies that have drafted this document have identified the following general recommendations:

1. The energy factor should be included in the design of railway routes.

2. The continued promotion of electrical energy metering and billing systems on board rolling stock.

3. The continued promotion of the development of the railway electrical networks of the future (intelligent networks).

4. The continued promotion of the development of new storage technologies alongside a relative reduction in cost.

5. The promotion of regenerated electrical energy in braking processes for uses other than traction, considering it as an additional source of energy.

6. The development of technological projects in the field of superconductivity applied to railways.

7. The development of ATO projects on ERTMS:

    a. It is necessary to deepen the development of on-board driving algorithms and ground traffic regulation models, to improve the efficiency in the operation of the ATO system over ERTMS.

    b. In ground ATO systems, it is necessary to develop algorithms for the design of schedules, both in planning and in real time, to improve efficiency. These schedules have an impact on the power peaks measured in substations, on the use of regenerated energy and on the margins available for economical driving. Therefore, it is necessary to coordinate the operation of traffic with the control of smart networks and thus optimise the use of energy in the railway network, which can incorporate interactions with other points of consumption such as power stations and electric vehicles.

8. The continued promotion of the development of new traction based on hydrogen and biofuels.

9. The promotion of joint initiatives and think tanks for the use of hydrogen in the railway, involving the entire supply chain.

10. A stronger regulatory framework in the following areas:

a. Smart electrical networks applied to the railway.
b. Use of hydrogen in the railway.

11. Coordination between all agents in the sector is essential to avoid duplicating efforts and developing lines of work that have already commenced.

12. Specialisation in this subject should be promoted in some university technical careers.

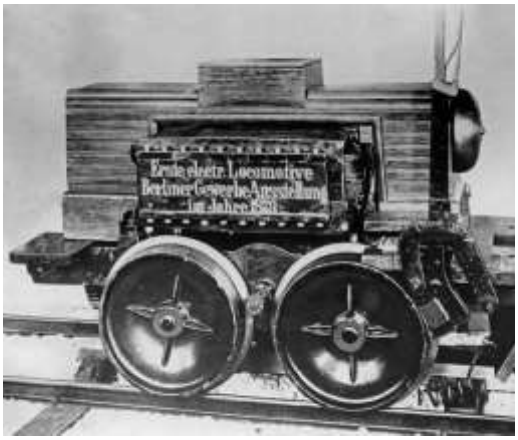
13. The promotion of harmonised life cycle analysis and eco-design tools, especially when the study of modern technologies such as hydrogen is encouraged.

ANNEX

Main milestones in the use of electrical energy in railways

Worldwide

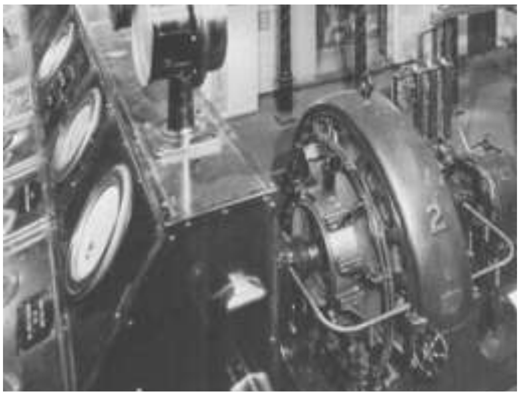
1879. Electric traction is born in Berlin, with an electric tractor from W. Siemens.



Siemens

1888. First network of urban electric trams in Richmond, Virginia, United States.

1890. First electric subway in London with direct current. Until approximately 1927, all the direct current electrifications will make use of rotary machines for the direct generation of direct current, as the rectification process as such, did not exist.



London Transport Museum

1895. First electrification of a main railway line: Tunnel of the "B&O" company in Baltimore, Maryland, United States.

1895. First network of urban electric trams in Kyoto, Japan.

1898. First electrification of a line in Europe with 1,435 mm gauge, between Burgdorf and Thun, in Switzerland, with three-phase alternating current.

1900. Electrification of the Austerlitz-Orsay line, in Paris, at 600 V direct current (DC).

1902. First Italian electrification with triphasic current: *La Valtellina* line.

1903. First speed record above 200 km/h in Germany, between the Berlin-Marienfeld and Zossen stations, with two three-phase railcars.

Siemens

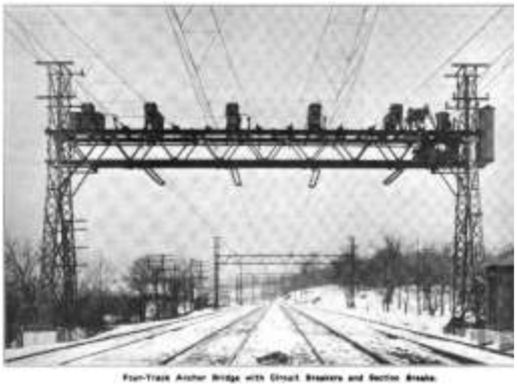
1905. Oerlikon company tests between Seebach and Wettingen stations, Switzerland, at 15,000 V and 16,7 Hz in alternating current (AC)

1906. Electrification in Switzerland of the Simplon tunnel, then the longest in the world, with triphasic traction, carried out by the Brown-Boveri company.

1906. Electrification of the Grand Central Terminal, in New York, at 660 V in DC, promoted by the General Electric company.

1906. Start of operation on the Japanese Ochanomizu-Nakano line, at 600 V DC.

1907. Electrification of the New Haven (NH) railway at 11,000 V and 25 Hz in AC, by the Westinghouse company. NH becomes the world's busiest railway with electric traction in the 1920s.



Wikiwand

1912. The Swiss company BLS inaugurates the Lötschberg tunnel, electrified at 15,000 V and 16.7 Hz in AC.

1915. Electrification at 3,000 V DC of the Milwaukee Road transcontinental line in Montana, United States.

American Rail

1917. Electrification at 1,500 V in DC of the British line Shildon-Newport. Great Britain begins to promote direct current electrification in other countries.

1920. Electrification of the San Gotardo tunnel, in Switzerland, at 15,000 V and 16.7 Hz in AC.

1922. In France, the Midi inaugurates the first French line electrified at 1,500 V in DC, which had been chosen as the unified system in France in 1920.

1925. First 1,500 V DC electrification in India, on the Bombay-Kurla line.

1928. First electrification at 3,000 V DC in Italy, a system that will gradually replace three-phase electrifications in the north of the country until 1976.

1935. Completion of the electrification of the line between Washington and New York, in the United States, by the Pennsylvania company, which becomes the main operation with electric traction in the world before the Second World War.

1951. The French railway company SNCF announces the success of its trials with the new electrification system at 25,000 V and 50 Hz in AC, which will become the most widely used in the world.

1954. The Valenciennes-Thionville line is the first French electrification at 25,000 V and 50 Hz in AC, in a *simple single-phase configuration* (1x25 kV).

SNCF

1955. World speed record in France with the BB-9004 locomotive (331 km/h) under a 1,500 V DC system.

SNCF – CAV – Lucien Delille

1964. Inauguration in Japan of the Tokaido Shinkansen, the world's first high-speed line (210 km/h) with a 25,000 V and 60 Hz AC system, in *Booster* configuration.

Internet Archive

1965. In the mid-1960s, the beginning of the ***first period of the application of power electronics in traction*** can be placed, still conserving the direct current motor. This traction revolution began with the application of the silicon diode, and then, during the 1970s, with that of the thyristor. Silicon diodes make it possible to definitively strengthen the development of electric traction at 25,000 V and 50 Hz in AC, diesel traction with three-phase/continuous electric transmission, and the replacement of mercury rectifiers in traction substations (this technology had been established since 1927 regarding the use of rotating machines for the direct generation of direct current). The first experimental application of the silicon diode is recorded in the last BB-12000 locomotives of the SNCF, in 1960.

1970. In the case of direct current, fast thyristors allow the chopper to be developed in Japan.

1979. The five prototype electric locomotives of the E 120 series of the state company DB appear in Germany, with asynchronous motors, and which were the pioneers of three-phase traction in Europe. In 1987, the reception of 60 E 120 locomotives begins in Germany. Previously, in Japan, three-phase traction had already been applied in various train units.

DB

1981. Inauguration in France of the first part of the new Paris-Lyon high-speed line, which is really the beginning of High Speed in Europe. The system used is 25,000 V and 50 Hz in AC, in *HV* configuration (2x25 kV).

SNCF

SNCF

1985. The beginning of the ***second period of the application of power electronics in traction*** can be placed in the mid-1980s, replacing the direct current traction motor with the three-phase, asynchronous or synchronous motor. The development of the GTO thyristor and the microprocessor allowed the definitive introduction of three-phase traction until the year 2000. As of this year, IGBT transistors displace GTOs.

1988. The SNCF begins to accept *Sybic* locomotives, which have three-phase synchronous traction and are bicurrent 25,000 V and 50 Hz in AC/1,500 V in DC.

1988. Speed record in Germany with the experimental train 401 (407 km/h) on the high-speed line between Hannover and Wurzburg.

1989. SNCF receives the TGV Atlantic trains, the first TGVs with three-phase synchronous motors.

1990. World speed record in France with the TGV Atlantic 325 branch (515.3 km/h).

1993. First application in the world of the new IGBT transistors in the Tokyo Subway.

1996. Speed record in Japan with the experimental train 300X (443 km/h) in the Tokaido Shinkansen.

2002. The first Technical Specification for Interoperability (TSI) for the *Energy subsystem* of high-speed lines is published.

2007. World speed record in France, on April 3rd, with the experimental branch V150 (574.8 km/h). This record has not currently been broken. This train uses permanent magnet motors for the first time, with a higher efficiency than the conventional three-phase motor.

RFF

2008. After the world speed record of 2007, the French multinational Alstom presents a new high-speed train model, called AGV, equipped with permanent magnet traction motors.

Alstom

2009. This year is the year in which railway administrations and operators from many countries begin to promote the development of projects aimed at recovering the electrical braking energy of trains in DC networks. Of note are the projects in the field of energy storage and the return of that energy to the external network, both solutions that require innovative power electronic equipment.

2010. On December 3, a CRH 380A train reaches 486 km/h in China, between the cities of Zaozhuang and Bengbu. The main distinguishing feature of these tests is that they use a commercial train, not a prototype, without any type of modification in the traction chain.

2015. The Japan Research Institute of Technology (RTRI) tests superconducting cables in an aerial electrification system for a direct current passenger line. It is verified that with this type of cable considerable energy savings can be obtained as well as improvements in voltage stability. Until this moment, no real tests had ever been carried out on a line.

2015. The European research project MERLIN (*Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimisation approach*) concludes, and can be considered as the starting point for the development of future projects and new systems for *intelligent* management of electrical energy of the railway. This project was developed under the VII Framework Program for Research of the EC.

2018. Within the H2020 Research Framework Program of the EC, the European research project IN2RAIL (*Intelligent Railway*) concludes. In it, the conception and development of new alternating current traction substations based on STATCOM equipment is studied, allowing them to regulate all power flows in the system. Additionally, progress is being made in the development and standardisation of a railway network with integrated consumption management. This project gave rise to the current *In2Stempo project*, which is expected to end in 2022 and which proposes the practical application of prototypes of previous developments. This project is developed in the framework of the Shift2Rail Joint Undertaking.

In Spain

1911. First Spanish electrification, between Gérgal and Santa Fe, with triphasic current, inspired by that of the Simplon tunnel.

Ralf Reinhold/El Ferrocarril en Andalucía

1946. On January 25, the General Plan for the Electrification of the *normal* gauge lines that constitute the National Network of Spanish Railways is approved. In general terms, the use of 3,000 V DC in this network is standardised and the use of mercury rectifiers in substations is normalised.

1967. RENFE starts receiving the 7900 locomotives, the first Japanese locomotives in Europe. They are universal locomotives with a single-engine and bi-reducer bogie, a technology that will dominate Spanish electric traction until 1985.

RENFE

1982. RENFE receives the 251 series locomotives, which marks the first major application of the chopper in Spain.

JCMA

1987. Speed record in Spain with the prototype of the tilting electric train 443-001 (*Platanito*), reaching 206 km/h under a 3,000 V DC system.


RENFE

1989. RENFE begins the reception of the twenty electric trains that constitute the third batch of the 448 series, and that will constitute the last electric traction material with a direct current motor used by the company.

1992. Inauguration of the first high-speed line in Spain, between Madrid and Seville, with the new series 100 trains (AVE trains), equipped with three-phase synchronous motors. That same year, the reception of the 252 locomotives begins, with asynchronous triphasic traction, which have marked an important milestone in the European development of triphasic traction. At the infrastructure level, a 25,000 V and 50 Hz AC system is used, in a *simple single-phase configuration* (1x25 kV).

RENFE

1993. Speed record in Spain with the AVE 100-015 train (357 km/h) on the Madrid-Seville high-speed line.

1998. Metro de Madrid puts into service the first line with electrification at 1,500 V with DC. This is Line 8. As of this moment, Metro de Madrid will begin to implement this system on the rest of the wide gauge lines.

2001. Speed record in Spain with the prototype of the 102 series (359 km/h) on the Madrid-Seville high-speed line.

2003. Inauguration of the second high-speed line in Spain between Madrid and Lérida (future Madrid-Barcelona line). The system used is 25,000 V and 50 Hz, in HV configuration (2x25 kV), the first time it has been used in the Spanish railway network.


JCMA

2005. Start of commercial operation in Spain with the new 102 series trains. They use IGBT transistors. Previously, the prototype used for its approval was one of the most significant applications worldwide of this type of semiconductor. With this prototype, a speed record was set in Spain in 2002 (362 km/h) on the Madrid-Barcelona high-speed line (Zaragoza-Lérida route), during its construction phase.

José C. Martínez

RENFE

2005. New speed record in Spain with a series 102 train (367 km/h) on the Madrid-Lérida high-speed line.

2006. Speed record in Spain with a series 103 train (402 km/h) on the Madrid-Barcelona high-speed line, Alcolea del Pinar-Las Inviernas route.

JCMA

2008. After several years of work, the Railway Infrastructure Administrator, ADIF, completes the development of a storage plant for the braking energy of trains in 3,000 V DC networks, based on the use of flywheels. The plant was developed in the vicinity of the Madrid-Atocha station.

ADIF

2009. Royal Decree 1011/2009 is published, of June 19, which regulates, among other aspects, discharge into the electricity grid for those consumers who implement energy saving and efficiency systems. In this way, in those moments in which the electrical energy saved cannot be consumed in the installation itself, the energy can be poured into the network, fulfilling a series of previous requirements. This Decree promotes from then on the implementation of this type of system by railway managers and operators, mainly inverters or power inverters in direct current electrical substations.

2010. Bilbao Metro installs the first power inverter in Spain at the Ripa substation (Bilbao), in a 1,500 V DC system. It enables recoveryand reuse of 8% of the energy of the trains.

2011. ADIF patents a procedure for charging electric vehicles from the railway power grid, additionally developing all the associated technology. The system is popularly known as *Ferrolinera.*

2013. Metro de Madrid implements the efficient driving of metropolitan trains with ATO, starting on Line 3.

2014. ADIF implements a power inverter in the La Comba substation (Málaga), in a 3,000 V DC system, constituting at that time the first inverter in the world at that voltage using IGBT semiconductors. Years later, this development has been extended to other traction substations distributed throughout the Spanish network.

2016. The Spanish Railways Technological Platform, PTFE, publishes the first version of the Position Paper on *sustainable and intelligent energy management in the railway field.*

2021. ADIF puts into service a fast charging station for electric vehicles powered from an AC transmission line. It is also developing an experimental facility at the Madrid-Atocha station to test electronic power converters from the DC transmission line and also to power electric vehicles.

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