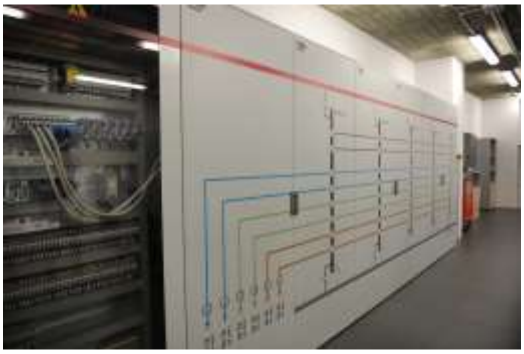
PTFE

Plataforma Tecnológica Ferroviaria Española

Position Paper

Sustainable and smart management of energy in railways

January, 2017



GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

Secretaría Técnica:
Technical Secretariat:

FUNDACIÓN DE LOS FERROCARRILES ESPAÑOLES

TECHNICAL SECRETARIAT
SPANISH RAILWAYS TECHNOLOGICAL PLATFORM
Fundación de los Ferrocarriles Españoles
C/ Santa Isabel, 44 – 28012Madrid
Tel.: (34)911511099
E-mail:
fuepu39@ffe.es
www.ptferroviaria.es

I. Introduction

Some of the most important priorities in the Spanish and European strategic documents of the railway sector refer to aspects such as internationalization, economic elements (efficiency in management, use of infrastructures), but also to energy and environmental priorities, given that our growth pattern, despite its successes, has proven to be deeply unsustainable. In this sense, contributing to the achievement of the objectives that our country has acquired in terms of improving energy efficiency, renewable energies and other low carbon technologies, is a reference framework for the development of R&D in the railway sector. Given its special characteristics, rail is more efficient, energy and environmentally friendly than other transport modes with which it competes, both regarding primary energy consumption, in particular, from non-renewable sources and greenhouse gas emissions (GHG). Equally less harmful are its local emissions, both because of their lower amounts, and because of their offsetting. Also, the social competitive advantage that the railroad has over other modes should be added: it is perceived by society as a sustainable mode. The PTFE survey on public perception of rail transport in Spain highlights, among other results, that the railway is perceived as a transport that contributes to the protection of the environment, especially due to its low atmospheric pollution, visual impact and generation of waste.

For several years, the authorities and railway companies have established as a priority in their strategy the sustainable management of energy, due in large part to the high economic cost, but also to the need of the railway operators to support and promote rail as a "green mode", reinforcing the message that energy consumption can be reduced by intensifying the use of railways to the detriment of other modes. In this sense, energy efficiency through sustainable management in operation, the development of on-board energy storage technology and the regulation and implementation of smart grids, among others, are key challenges that remain valid despite the achievements in recent years.

The main objective of the Spanish Railways Technology Platform (PTFE) is to create the necessary tools to contribute to the improvement of the scientific and technological breakthroughs that allow the competitiveness, internationalization and sustainability of the Railway Sector, applying the guidelines indicated by the Ministry of Economy and Competitiveness, PTFE´s funding and tutelage body. Taking this into account, PTFE has understood that sustainable and smart energy management in the field of research and innovation in the railway sector, is a key factor in favoring competitiveness and ensuring the leadership of the railway industry. In this context, the present document "Position Paper on Sustainable and Smart Energy Management in the Railway Sector" is a document that seeks to capture the pulse of innovation in energy management in infrastructure, in rolling stock and in operation, as well as future trends and applications. This strategic document has been elaborated under the coordination of the Research, Development and Innovation Department of the Engineering and Innovation Division of ADIF, and with the participation of companies, technological centers and research groups from different universities (all of them PTFE entities), and also contains a series of challenges and recommendations to continue consolidating the differentiating and competitive elements of the railroad with respect to the other modes.

II. State of the art. The Spanish case

For a number of years the public administration and railway companies have set the strategic priority of sustainable energy management, particularly with regards to vehicles traction. This is principally due to the high economic cost of this type of energy, which represents some 15% of the fixed costs of rail operations. The promotion of railways as an "ecological mode of transport" is another reason for railway operators to reduce energy consumption, albeit to a lesser extent.

Over the last 10 years in Spain there have been a significant number of projects targeting the reduction of the electric traction energy consumed. As indicated above, the rationale behind many of these energy reduction projects relate to economic factors with the aim of gaining a return on investment. This return is only made possible if the savings made in kilowatts can be converted into savings in euros.

In general these projects have aimed to develop procedures and equipment that promote the reduction of electrical energy loss throughout the different elements of electric railway infrastructure, in addition to the implementation of economic driving [i1] plans and new technologies that allow the utilization of electric energy generated by the vehicles ´regenerative braking system. Specifically, the use of this type of energy has become one of the main ways to manage and utilize the energy from networks with electric traction, above all those with direct current which in turn minimizes the use of rheostat brakes. There are various studies that argue the train´s capability to regenerate between 30% and 40% of the energy consumed, and as such this value is set as an ideal energy reduction target when applying this type of braking system. However, for various reasons, on the majority of the metropolitan lines there are rheostat consumption losses of around 10-12% which limits the real savings obtained by regenerative braking. For this reason there is an increasing use of storage technologies (on land and principally on board) and substation converters used on the network.

It should be highlighted that between 2007 and 2009 a group of Spanish companies and institutions developed the ELECRAIL research project (Systematic analysis of energy consumption on metropolitan, commuter and high speed railway lines, with an energy and economic impact evaluation, including the development of models and parameterized simulators)[2]. The project calculated that in a typical year trains operating on the Spanish network lose 1.200 GWh of energy through braking. Currently just under 50% of this energy is used, the rest of which is wasted: due to some trains not having regenerative braking or due to the impossibility of returning the DC electrical energy from the rail network back to

---

[1] [1]This type of driving, defined as that which allows the maximum utilization of traction energy, seeks to avoid using the brakes as it aims to take advantage of coasting, that is to say using the kinetic energy and momentum of the train to cover a maximum number of kilometers without applying traction.

[2] National research Project ELECRAIL, funded by the Ministry of Public Works through CEDEX

the general network. This project sets the foundations of the subsequent technological development necessary to maximize the utilization of this energy.

In terms of rolling stock, the operators and manufacturers have made important progress optimize energy consumption in their operations. An appropriate management of rolling stock energy is estimated to produce savings of up to 20% of total energy consumption. These energy savings have been achieved through the progressive introduction of more efficient trains over the last few years.

III. Policy and regulation framework

The first European Mandate related to the Smart use of the energy in all areas was the M/441 in 2009, which scope was to find a European Standard to access to a minimum level of functionality in the smart measuring of the energy. Smart Grids were firstly mentioned in this mandate. In 2011 the smart grid mandate M/490 that has as scope the development of standards in the European frame was developed, elaborating many process to reach the interoperability and making easier the implementation of the many levels of smart grid with each of the functionalities in Europe. With all the afore mentioned documents and with referent papers as CEN/CENELEC, the MERLIN project takes the smart grid into a railway scope. It proposed a series of technical recommendations to get a better and standardized management of the energy in the railway systems, analyzing the architecture of the control system.

Taking into account the Spanish regulation, we find the 1110/2007 regulation that allows the unified rules of measurement points of the electric system. Hereinafter the 1011/2009 took a big step in benefit of the smart saving of energy. It allows to pour back into the network the energy that the big consumers with saving and efficient systems do not consume in their installations, as the case of the energy obtained by the regenerative break in the railways. In a political field, many energy efficiency national plans and programs to help establish specific actions that guarantee the fulfillment of the aims proposed by the European Union for the year 2020 have been developed. These plans are development by the IDAE (Instituto para la Diversificación y Ahorro de la Energía by its initials).

Currently there are many adjustments in the market, as the case of the interruptibility service, where the big consumers are remunerated for not consuming in determined period of time when the grid needs more energy than the available. Through the Order IET/2013/2013 and its following modifications the rules to participate in the mechanism to compete for the assignment to this *s*ervice using auctions is developed.

IV. Infrastructure

Railway infrastructure plays and will continue to play a fundamental role in the sustainable and intelligent management of energy for the railway system as a whole. Some studies have concluded that key improvements and future savings in the area of energy will come from the application of measures in the railway field, by virtue of the high level of efficiency already reached through electric traction rolling stock.

In this Infrastructure chapter the discussion should not be limited to those elements that allow the operation of railways with electric traction[3], but should also consider other measures related to the initial design of the platform. In reality, the overall energy consumed by a vehicle on a railway line is highly influenced by the geometric characteristics of the line layout, which highlights the importance of **analyzing and designing energy efficient line layouts** as an additional measure.

Investment in the construction of new lines or the improvement of existing ones is often based on the need to reduce the energy consumption and emissions of the transport system as a whole. In order to do this, railway infrastructure needs to be designed taking into account the energy related perspective and criteria.

To achieve this objective it is necessary to base project design decisions on a thorough understanding of energy consumption, as well as the application of robust modeling tools with the end objective of improving the energy efficiency of different types of trains, lines and services.

Thus, part of the energy consumption of a train is linked to the energy needed to overcome the mechanical resistance to progress, where layout plays a fundamental role. Therefore, the energetically efficient design of railway layout should consider aspects such as the harmonization of slopes with speeds and enhancing the use of economical driving advisory systems, whether manual or automatic.

For any given track layout (regardless of its energy efficiency) the **analysis and design of the electrical infrastructure for an optimum utilization of the energy regenerated** is another measure that should be reinforced to enable a sustainable and intelligent management of the energy. This measure will generally be more important for DC fed lines.

In general terms, from an electrical infrastructure perspective, a DC railway line would need to improve its energy efficiency if it presented excessive losses from driving (Joule effect) or from rheostatic braking. As already mentioned, this last source of energy loss is becoming somewhat problematic from the point of view of energy efficiency.

In this respect it is worth making the distinction between those actions without cost (or very low cost), predominantly based on an improved utilization of the elements available in the infrastructure, and those actions that require a greater level of economic investment.

The first ones should be applied to all those elements of the infrastructure to which a simple maneuver would allow a better utilization of the regenerated energy. One example of this is using the regulation of substation transformers in order to operate a line with an open circuit voltage which avoids excessively low voltage on the pantograph but at the same time reduces the loss in rheostatics. Another example is the disconnection of some substations at off peak times in order to reduce the frequency of events in which the presence of an active substation between trains exchanging energy, limits receptivity. Lines with a high density of traffic – normally metro and commuter lines – will benefit most from these types of actions. This is due to the large volume of stops made on these types of lines, which

[3] Mainly Electric Traction substation. Air conctact lines and power conductors

involve frequent accelerations and braking (it has been estimated that between 15% and 30% of the energy consumed is being recuperated).

Reversible power-supply substations and energy storage systems are amongst those measures with a high cost associated. The installation of reversible power-supply substations is currently the favored option, due to their greater level of reliability, life span and cost per MW (provided that the energy returned to the electricity network is remunerated). However, the intense research effort into improving storage technologies suggests that energy storage devices will become a competitive technology in the medium term, especially when one takes into account that these devices have other possible applications beyond energy saving.

It is important to highlight that the cost of reversible converters is not insignificant. Once high rheostat losses on the line have been detected and the need to install a reversible substation is identified it is important to carry out a careful feasibility study to ensure that the rail operators and administrators will receive a return on the investment within a reasonable timescale. In general, terms it is not economically viable to install reversible converters in all of the substations, rather the optimum number and location should be considered. Furthermore, the power of the converters installed will influence the effectiveness to reduce rheostats. It will therefore be necessary to approach the improvement of electrical infrastructure in terms of optimization.

Simulation models are generally applied when dealing with infrastructure improvements. These models should be precise in order to avoid energy saving errors. In addition to precision in the modelling of common elements of electrical infrastructure and rolling stock, other aspects, including the influence of the stochastic variables of traffic in rheostatic losses, are being taken into account within the most recently developed optimizers. With regards to this last point it should be noted that almost all current studies include only a simplified traffic scenario, with fixed stopping times which have proved to be insufficient in representing the complex energy interactions between trains on an urban and metropolitan line.

The optimum utilization of recovered energy on lines fed by single-phase alternating current tends to have a lower strategic impact when you take into account that the return of energy to the company´s network is something that happens as a result of the system´s technical characteristics and not because of using rectifier stations. Nevertheless, in this cases it could be interesting to analyze the impact derived from the use of storage systems in order to improve the quality of the electric supply (for example, reducing excessive voltage drops).

As is to be expected in a chapter on infrastructure, it is also necessary to take into account those **elements that are external to the traction circuit but that also consume energy**, with a view to optimizing their consumption. For example, point heating equipment stands out as one such external element because of its high energy demand. This calls for the development of more efficient systems, not only in terms of its components but its process of connection and disconnection.

In general, the use of low consumption lighting in stations and tunnels, self-sustaining solar powered street lights and the use of LED technology light bulbs in illuminated fixed signs, are all measures that will help to improve the energetic sustainability of the infrastructure.

It should be noted that these types of measures are already being supported by the rail administrators and operators in Spain.

Finally, it is also necessary to intervene in those elements which have residual energy consumption, even in non-operating situations. This residual consumption is not considered important on an individual level due to the low level of energy consumed, however, when viewed within the entire railway line, the total level of consumption is significant, both from an economic and technical perspective. One of the most representative examples of this is are the existing transformers used in the auto-transformer centres on the lines fed by single-phase alternating current with a 2x25 kV system (the case of high speed lines in Spain). In certain circumstances it could be considered aceptable to disconnect these transformers in order to eliminate their associated residual consumption and in this way improve the utilization of the energy actually consumed by the traction substations.

Identification of current and future challenges and technological developments

Up until now electric railway infrastructure has been based on the concept of a conventional electric network, with unidirectional energy flows and systems of communication without an exchange of information between the different elements. Under normal operating conditions the vehicles receive energy from the traction substation through the electric traction line in contact with the train, constituting a continual process through time. Only in the event of technical faults or limitations to the power demanded will the energy fed to the train be interrupted.

With the aim of optimizing this situation, a considerable number of sector stakeholders (administrators, operators, universities, technology centres and manufacturers) are identifying the advantages of converting the traditional electrical railway network into an **intelligent electrical railway network**, both on direct current and single-phase alternating current lines. Indeed the end of 2015 saw the completion of the European Research Project, MERLIN[4], which defined and established the conceptual framework that should govern on this new type of network.

The overall objective of this intelligent network would be optimizing the management of electrical energy used by the railway system thus improving its operation and energy saving. Conceptually the different components of the electric system would be grouped together in control nodes that would receive and deliver energy to the network. The nodes would be supervised by a central manager programmed with the corresponding algorithms. One interesting possibility relates to the optimization of the cost of the energy given that efficiency does not just depend on reducing energy consumption, but also importation from the electrical network at times when energy production is less efficient (reflected in an increased price). For this reason, according to the specific moment of the electrical market, it could be more beneficial to store the energy, return it to the network, produce part of the electricity within the system, coast, etc.

[4] Project financed by the EU 7th Framework Programme.

The development of this network would require the following technological advances in the infrastructure:

- *Electricity produced by the infrastructure itself, a micro generation of renewable energy close to where it will be consumed (technical buildings, auxiliary facilities, etc.)*

- *Penetration of storage systems* as has been previously indicated these add flexibility to the functioning of the system as a whole. It should be noted that storage systems offer advantages beyond energy savings. They improve the electrical stability of the system smoothing out the substation charge curve or for example providing power to the train at points on the line where subvoltage problems are experienced. This greater level of penetration with rail will also allow the development of new technologies differentiated from the traditional devices (batteries, supercapacitor and flywheels) as is the case with flow batteries which, due to their greater level of capacity, can be very effective for electric railway infrastructure.

As a first step towards building a future intelligent network, electric rail infrastructure should be able to experience improvements in the short and medium term with regards to the **energy management of medium and low voltage**. Currently the remote control centers for traction energy are responsible for centralizing the information coming from the field elements in order to guarantee the operation of the line under safe and efficient conditions. This information is usually limited by the topological situation on the network at the time but it is insufficient if it is being used to incorporate efficiency and energy quality objectives, objective that should be considered by operators in any case. For this reason it would be necessary to provide the facilities with additional devices that collect information that, together with the topological description of the network at all times, allow the analysis of the bond of each configuration from the point of view of efficiency and energy quality.

As previously mentioned, the design of **new line layouts** (or improvements to existing ones) should incorporate energy related factors that have not yet been taken into consideration. In order to achieve this it is necessary to develop the existing knowledge of energy consumption of different types of train on each line section as this will allow understanding of the problem and to adapt the existing models to meet these specific needs. This presents various challenges, such as defining and developing efficiency indicators to evaluate the level of efficiency of each section of line which unleashes the potential to improve and reduce the operating vehicle´s consumption.

Attention should be placed on the technological development of **new elements and schemes of connection** that allow an improved efficiency due to a reduction in electrical and consumption losses. It is worth noting the work carried out to develop superconductor cables for use on direct current lines. With regards to new forms of connection, the development of a double feed system to the catenary that carries direct current to a voltage of 3 kV (system 2 x 3000 V) should be explored, taking into account the improvements to power electronics that equip the required converters. In the case of lines powered by single-phase alternating current at an industrial frequency, the current trend [5] is towards developing new layouts of the electric traction substations connected to the three phase

[5] In 2015 the Project IN2Rail (funded by the H2020 Program of the EU) was launched, in which, amongst many other things, research on new design of these types of substations is being developed.

network with a parallel connection to the overhead line and lower phase rotations in operation. This new connection would allow a reduction in the demand for power from the supply networks and therefore the connection of this type of railway to lines with lower short-circuit power.

The availability of a large amount of information regarding the electrical behaviour of the system, as has occurred elsewhere, will most probably stimulate the appearance of new value added systems associated to this information. The development of these types of measures should consider cloud storage as well as large scale data analysis tools which are being successfully used in other technical areas and for the optimization of processes (**BIG DATA).**

V. Rolling stock

Despite the fact that the rolling stock currently supplied by the railway industry is characterized by its high level of energy efficiency, especially that employing electric traction, there are continued efforts to further improve the technology.

In terms of electric traction, the development in power electronics experienced over the last few years has undoubtedly led to improvements in the energy efficiency of vehicles. In this way, the three phase asynchronous motor has taken over the slip ring motor and even the synchronous motor, not only due to its robustness and simplicity but also in terms of its efficiency. However, it would appear that the asynchronous traction engine can be surpassed in efficiency by a synchronous vehicle with permanent magnets, a type of motor already being used in some operating trains. This engine, in the same way as the asynchronous motor, has no exposed low voltage element in its interior nor switches nor elements of contact friction, offering all the advantages of the asynchronous motor with reduced maintenance costs yet superior performance. The performance value of these permanent-magnet motors, varies between 97.2% and 97.6%, exceeding even that of power transformers.

The Pulse-Width Modulation (PWM) inverter with insulated-gate bipolar transistors (IGBT) controlled with microprocessors, has taken over the other types of inverters due to its improved features including its reduced weight and volume. The Service Entrance Power Converter differs according to the type of electric traction. In the case of catenaries powered by alternating current, the 4QS converter is used because of its improved features and regenerative braking system. In the case of direct current catenaries it has been possible to eliminate the entrance chopper switch, being directly connected to the PWM inverter through a filter switch, which now makes the traction chain more straight forward (direct inverter).

In addition to the improvements experienced in the components of the traction chain, this type of material has been positively influenced by the **development of on board energy storage technologies** (mainly technology-based batteries and supercapacitors). The availability of an onboard system capable of absorbing the power regenerated by the train during braking phases allows, in general, to significantly reduce losses by sending regenerated power to rheostats. This energy is used directly instead of trying to reintroduce it in the catenary, thus avoiding the consequent increase in the voltage at pantograph. However, although this technology can reduce power transmission losses in the network, it is necessary to weigh the extent to which this affects the increases the train mass derived from the installation of on-board storage systems.

A rigorous study of optimization of these equipment should not be carried out by analyzing an isolated train. Interactions with other trains in the system and the traction power substations will allow to obtain lighter designs of the storage systems that result in a better performance in energy efficiency globally. Therefore, to maximize the beneficial impact of these devices on the system, it is necessary not only to optimize the strategy of energy management of the storage systems, their power and storage capacity, but also adequately model the rest of elements in the electric infrastructure including operational aspects such as traffic, which may have a considerable influence on the results. A complete optimizer will make use of all these elements to obtain the globally optimal solution in terms of energy savings.

Apparently there is no optimal management for all scenarios. For each case the optimal control will have to be designed and further research on the characteristics of each technology will have to be performed in order to increase their lifecycle. Due to the characteristics of each technology, hybridization is a priority, combining rapid (supercapacitors or flywheels for example) and slow response technologies (batteries or fuel cells) with their different characteristics. The scenarios considered are mainly two: Scenarios with catenary where the goal is to reduce consumption peaks and scenarios without catenary where the target of the storage system is to cover 100% of the power demanded by the train constantly (traction and auxiliary).

Additional to braking energy recovery systems such as storage systems, today other energy-saving technologies are developed in the rolling stock such as efficient driving systems, energy consumption planning systems, ancillary consumption management systems and intelligent climate control systems. In any case, it must be regarded that the pattern of energy consumption should be the basis of any initiative to reduce energy consumption, so it is essential the implementation of energy measurement systems in rail vehicles.

The data logging in onboard equipment sets out certain challenges as the need to develop a methodology for recording and transmitting data between the vehicle and the control center to analyze, process, treat and properly filter the amount of information obtained. In addition, designs must be made taking into account possible technological evolution of communication systems. This idea seeks to address the need to define a homogenous and commonly acceptable method to attribute to each train, in each service and infrastructure, their energy consumption and associated CO2 emissions in the case of diesel traction rolling stock. Currently different European standards regulate how to conduct this process and specify the power metering equipment that vehicles must install in order to know their consumption and enable the billing operations of the various rail operators based on the actual consumption of trains.

Identification of current and future challenges and technological developments

The challenges are oriented to both the development of technologies and methodologies to maximize energy efficiency and therefore fuel consumption per kilometer, and the use of technologies to supply the required energy with minimal CO2 emissions. Several major fields of activity are raised in this scenario, in which the introduction of alternative fuels in the field of diesel traction must be underlined.

In fact, these alternative fuels to diesel refer to those containing higher energy density while allowing a reduction of pollutant emissions of diesel engines, typically particles. In the midterm the design and adaptation of methodologies for the use of Liquefied Natural Gas (LNG) or bioethanol is raised. A long-term approach, aim at fuels such as hydrogen and methane mixtures second generation biofuels.

The use of LNG in vehicles with diesel traction is an opportunity to improve energy efficiency by reducing emissions of CO2 / km and the impact of emissions of nitrogen oxides (NOx), particulates and unburned into the atmosphere. Currently it should be noted the existence of technological projects in this area highlighting the LNG project in which a real pilot with this type of fuel on a test vehicle develops. The project consists of verifying the technical, legal and economic feasibility of railway traction with LNG in the Spanish rail network, to conclude on the possibility of extending this new solution traction commercial area in Spain.

The application of LNG in rail vehicles can also be associated with the adaptation of existing engines, in two specific action lines. With a lower degree of intervention on the engine, there is work being developed on adaptations based on indirect injection of gas into the intake manifold with premixed type processes of combustion, animated by a first stroke diesel combustion. Also, with more substantial adaptations, direct injection processes in the combustion chamber with the diesel with diffusion diesel combustion processes are studied most appropriate to prevent gas short circuits in two-stroke engines. Both types of approaches are being analyzed from the approach of substitution of gas for obtainable oil, emissions, fuel economy and reliability in operation.

The use of fuel cells for this type of traction is another challenge currently being evaluated. Countries like Germany and Japan have significant implementation plans in this area. The improvements in the efficiency of use, the disappearance of pollutant emissions in service and the orientation towards electric traction of these technologies provide an important range of applications in the railway sector.

As the most significant technological project, this technology has been used for the transformation of a tramway vehicle in Spain, which has finally led to the first experience of railway vehicle in Europe that uses a propulsion system based on hybridised fuel cell batteries and supercapacitors. The vehicle developed is a rolling stock test facility to assess the behavior of different hybridizations of fuel cells with batteries, supercapacitors or both systems simultaneously. The system has been designed to comply with current regulations, especially those related to hydrogen and the rail sector. The management strategy is based on ultracapacitors controlling the bus voltage, battery support ultracapacitors in the power peaks (acceleration and braking) and fuel cells, operating in quasi-stationary mode, are responsible for maintaining the load of the batteries and provide all the energy needed by the tram. Overall, the project aims, through testing on this vehicle, to collect information on the behavior, maintenance needs, consumption, performance, autonomy, efficiency, improvement areas, etc. for optimizing the design and operation of future infrastructures.

Different industry stakeholders agree that another field of action or challenge in the chapter of Rolling Stock lies in **predictive maintenance oriented to energy management**. This raises a new variable in the decision map of maintenance protocols, introducing energy efficiency of the system as a technical economic and environmental variable in deciding the timing and type of action required in the maintenance of a unit. Learning algorithms fed by telemonitorizied signals that allow the isolation of the influence of the state of maintenance of the systems with their energy consumption. The development of intelligent predictive maintenance systems which also consider consumption and energy efficiency, will allow the development of new methodologies, decision trees and auxiliary equipment.

As previously discussed, onboard storage will continue to be strengthened, so that the development of new technologies such as rechargeable high energy density batteries based on novel chemical developments (metal air) and new hybrid systems.

VI. Operation

The implementation of actions on the infrastructure and rolling stock aiming at the optimization of the energy management of the system must be accompanied by actions to operate efficiently this material on the infrastructure.

In this sense, **driver advisory systems (DAS)** are becoming more common because of their potential of energy savings, especially in long distance routes with few stops. By solely fitting to the commercial time and not arriving before to stations can assume great energy savings. Also, if efficient driving strategies are applied during the journey, savings can sum up to 20% of the total consumption.

In recent years, off-line driving advisory systems are very common. Systems are based on profiles calculated by efficient prediction profile tools and stored on the train to show the driver the necessary instructions. In addition to the optimum profile calculated faster and slower profiles are usually calculated to cope with delays and advances. However, these precalculated profiles do not usually take into account situations of schedule changes or train degraded states, this is, they cannot recalculate profiles depending on environmental conditions.

Due to this particular reason, systems with on board dynamic calculation and connected with the traffic system engine are becoming more extended. So, the system and the train can now know the new arrival times, so the system can consider a more efficient driving profile. The architecture of these systems is known. They count with the embarked calculation engine, with a database containing all the parameters describing the boundary conditions and a system of communication with the ground, in order to know updates on times and track speeds in order to update the database. The user interface will be in charge of creating the driving instructions from the profiles calculated by the engine.

It should be underlined that Spain has been a pioneer in the development of various research projects focused on assessing the impact of the economic leadership in energy consumption associated with the operation of high-speed trains. It has been demonstrated that high-speed lines are suitable for the implementation of this type of driving with a broad savings potential due to the fact that these lines are usually exclusively dedicated with few disturbances and margins of regularity that can be leveraged to reduce consumption. It is key to note the punctuality requirements of the operator to ensure the recovery of delays in an efficient manner.

Also, projects tackling efficient driving in commuter and subway lines are being implemented. Specifically subway lines equipped with CBTC have developed new optimization models able to leverage communication and continuous train control and is awaiting the transfer of such models of efficient control to the CBTC lines in service, and also waiting for manufacturers of ATO equipment to incorporate the features of the most appropriate driving regulations.

Identification of current and future challenges and technological developments

As in the infrastructure chapter, the **development of smart rail power grid** also represents a major technological challenge in the operation chapter. This new network will have to consider integrating the rail power system with control systems and traffic planning, having to develop applications that can establish efficient instructions for the operation of trains depending on the different characteristics of the electrical system (eg , state of the traction substations of a particular line). Optimizing energy efficiency will not only be carried out under the planned conditions of operation, but also to unexpected situations. For example, it will be possible to recalculate the driving strategy of a train when there has been an unplanned stop, or even foresee that this stop will occur and modify the driving strategy to save energy.

A strategy should be enhanced by managers and train operators is the **optimal design of schedules** from a viewpoint of energy efficiency. Thus, in DC fed lines designing efficient schedules can help improve the use of energy regenerated in the braking, matching them with traction from other trains that can consume this energy. This type of strategy is especially useful in subway and commuter lines, with frequent braking and starts, and must be taken into account when assessing other strategies of regenerated energy recovery such as those indicated in the infrastructure chapter.

As it has just been indicated, in metropolitan lines automatic driving is widespread, which has facilitated the implementation of automatic regulation centralized systems and efficient driving systems optimized depending on the characteristics of the ATO equipment and the type of exploitation. On the other hands, lines equipped with **ETCS signaling systems**, usually high speed lines in Spain, these driving strategies are hardly used. Projects that seek to exploit the communication lines that provide these systems to develop efficient ATO systems are being developed.

Unlike metropolitan systems, the ATO equipment in long-distance lines have to update the driving strategies of the lines between stations to accommodate delays or unforeseen situations, using real time computational algorithms that can run on the train or in the control center. The purpose of these algorithms is to meet business hours minimizing consumption.

In this line of work, UNISIG ERTMS Users Group have specified the requirements of a new interoperable ATO system (AoE (ATO over ERTMS)), with the aim of it being part of the technical specifications for interoperability. This ATO aims to improve the operation of trains, both regularity of traffic (by controlling trains automatically from a central location) and the energy efficiency of automatic driving (shipped implementing algorithms that minimize consumption). The system consists of the track subsystem (ATO-TS) and the onboard (ATO-OB). ATO-TS is connected to the traffic management system (TMS), calculates the delays of trains, and sends the ATO-OB of each train (through the RBC or beacons) the following timing points to be observed by the train ie, what time the train has to pass the following benchmarks (either stations or intermediate step). When there are issues that require recalculating the departure of trains, schedules, or even the route, the real-time ATO-TS recalculates the timing points and sends them to the trains. The ATO-OB's main objective is to drive the train efficiently to meet timing points sent by the ground system. It optimizes real-time driving with lower power that fits journey times imposed to the following timing points.

The challenge is to develop algorithms implementing both the ATO-TS and the ATO-OB for calculating optimal passing times and for calculating efficient driving that meets imposed times.

The market now aims to integrate the entire fleet of a rail system with a ground system that optimizes the operation of the fleet with reduced consumption at peak power in substations, but always respecting the commercial schedule.

VII. CONCLUSIONS AND GENERAL RECOMMENDATIONS

A current and future challenge of railways should be the continuous improvement in the field of sustainable and intelligent energy management. While other modes are improving energy efficiency, there is still a significant gap in favor of rail compared to road and air. Still, the railway should not neglect their competitive advantage and must continue to innovate, both from a technological and management of processes point of view, in order to reduce energy consumption in traction and in other uses.

Agencies and companies who drafted this document identified the following general recommendations:

1. Encourage the inclusion of the energy sector in the design of railway lines (eg additional score in the technical assessments subject to public tender).

2. Promote the implementation of onboard energy measurement and billing systems. Infrastructure managers must be prepared for this scenario. It is important to underline that this action is already covered and described in the Technical Specification for Interoperability of the Rolling Stock Subsystem. Continuar desarrollando nuevos modelos de gestión de energía y herramientas de predicción de consumo de energía (redes neuronales, algoritmos genéticos, etc.).

3. Continue promoting and encouraging, from the different public administrations, the return of the regenerated energy to the public grid from the rail systems equipped with DC systems, as this will favor the implementation of more reversible substations, allowing the development of a more sustainable electric rail system.

4. Continue developing new models of energy management and prediction tools of energy consumption (neural networks, genetic algorithms, etc.).

5. Develop a regulatory framework that defines thresholds for the quality levels of electric power to be supplied to the train and to the supply points of high voltage substations in high-speed lines. The proliferation of new electronic equipment is affecting the quality of energy causing a distortion in its waveform which causes effects such as heating equipment and distribution transformers, while cause supply disruptions affecting the production conditions. It should be noted that an important set of standards, internationally accepted regarding the identification of parameters that define the quality of energy and how to measure it, in order to standardize them, have been developed up to date. We have also developed various intelligent electronic devices that measure certain parameters of the energy wave and calculate the quality of it with a more than acceptable precision. Public administrations that regulate the development of the electricity sector, meanwhile, have also defined the limits to be met by suppliers of electricity to ensure the quality of supply received by the end energy customer. However, as indicated the railway sector has no regulatory framework of the quality of energy yet.

6. Incorporate BIG DATA techniques to optimize rail electrical system. Aspects such as topologies currently employed and power currently used in the contracting parameters

of electric supply and even the use of redundant elements in order to guarantee continuity of service can be reconsidered once the analysis of currently "running" existing power lines is performed.

7. Develop the legal framework for the future operation of smart grids (eg regarding the rail network that may have other uses such as allowing third parties to use it to pour the energy they produce, etc.).

8. Specific training in terms of efficient driving strategies to train drivers.

9. Develop an implementation plan in the Spanish rail network of LNG, including a legal framework, non-existent to date, to use is as fuel in rail.

10. Continue promoting the development of R + D + i in the area of sustainable and intelligent energy management of the rail system, with support from national and regional administrations. In order to develop this kind of measures, coordination between all actors it is essential to avoid duplicating efforts and develop lines of work already undertaken and should have a continuos view of all developments. It is important to note here that in the international sphere, and more specifically in Europe, the program of railway research Shift2Rail does not empower in a remarkable way sustainable and intelligent energy management (so for example, in any case new technological developments on DC rail systems are planned).

11. Promote basic research into new storage technologies both for on board and on ground.

Scientific - Technical Coordination:

José Conrado Martínez

Document produced by:

Alberto Montes
Gonzalo García

Alfonso Horrillo

Amador Robles

Carlos Tobajas
Antonio Gómez
Antonio Berrios

Antonio Fernández
Paloma Cucala
Ramón Rodríguez
Álvaro López

Alberto García
Daniel Briceño

Eduardo Pilo

Enrique Vila

Félix Marín

Juan Manuel Martín

Ricardo Insa
Pablo Salvador Zuriaga
Ignacio Villalba

Ruth Arregui

Sergio González-Cachón
Angel Bobes

Coordination and Technical Secretariat:

Angeles Táuler, Mª Mar Sacristán, Eduardo Prieto, Aida Herranz, Sarah Whalley