# Final Publishable Summary for 16ENG04 MyRailS
# Metrology for smart energy management in electric railway systems

## Overview

The project aimed to develop the metrological infrastructure for accurate measurement of energy exchange and reliable system monitoring to enable energy efficient management of the European DC and AC railway and DC subway systems. New facilities for the calibration of the whole energy measurement chains under distorted electrical conditions have provided the metrological infrastructure necessary to improve the reliability of energy billing for railway enterprises. Moreover, the methods developed for the calibration of the energy measurement systems directly on-board the trains will save time and money in the periodic verification of their accuracy. The project also focused on the efficiency assessment of new reversible substations, as well as on the assessment of eco-driving performances. New measurement facilities for the accurate determination of the wasted power in DC railway systems have provided not only means for an energy survey of the railway system but also interesting data that can be deployed towards achieving a more sustainable railway and metro transport system.

## Need

Considering the overall annual energy consumption of the European railway system, about 36.5 TWh, and the ambitious target of reducing $CO_2$ railway transport emissions by 50 % by 2030, it is clear that an efficient use of energy in the railway system is required. To this end, accurate and reliable knowledge of the energy absorbed/exchanged between the train and the railway grid that takes harsh on-board measurement conditions into account is essential. In order to establish a single European railway area, the European Commission mandated that energy billings had to be computed on the actual energy consumed by 2019. Consequently, all trains had to be equipped with an energy measurement function (EMF), whose measurement accuracy would be assessed and periodically re-verified in accordance with EN 50463-2. For this, calibration set-ups and procedures which go beyond the well-known procedures developed for pure sinusoidal or continuous regimes were required, to ensure metrological reliability of the EMF under operating conditions.

Efficient use of the infrastructure, as encouraged by the European Union, required new constraints for railway energy supply systems. In this scenario, accurate knowledge of the real-time power quality was a valuable tool to foster the efficiency of the whole railway system by “rewarding” the delivery and absorption of good power quality. Moreover, the saving of energy through eco-driving entailed the application of combined efficient driving strategies to achieve the required running time while minimising energy consumption. The reduction of the absorbed energy had been estimated to be of the order of tens of percent: that was with the same order of magnitude as the uncertainty associated with the on-board energy measurement. There was therefore a need to develop measurement systems able to reduce the on-site absorbed energy uncertainty down to several percent.





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## Objectives

The overall objective of the project was to develop the metrological framework and measurement infrastructure that underpin the adoption of energy efficient technologies in European railway systems. The specific objectives of the project were:

1. To develop a metrological framework for calibration (comprising laboratory and on-board train calibration / measurement set-ups and robust data processing algorithms) to enable high accuracy energy and power quality (PQ) measurements under highly dynamic electrical conditions approaching the uncertainty limits stated in the EN 50463-2:2013-05 with a frequency range from a few hertz up to 5 kHz for AC systems and up to 3 kHz for DC systems. The uncertainty targets for laboratory calibrations are 0.5 % and 0.1 % respectively for AC and DC systems, and 0.4 % for on-board calibration of DC systems. All major European supply systems (25 kV/50 Hz, 15 kV/16.7 Hz, 3 kV/DC, 1.5 kV/DC, 750 V/DC and 600 V/DC) will be considered.
2. To develop a wide-area power quality monitoring architecture. This will include diagnostic studies, system models, numerical simulations, power quality indices definition, measurement system implementation, time-synchronisation, wide-area communication, centralised data collection for quantifying the efficient use of the railway infrastructure and for on-board identification of the PQ events affecting the power exchanged between the supply system and the rolling stock (including high-capacity converter device effects, intermittent sliding-contact arcing and resonance effect).
3. To set up combined measurement-simulation tools to analyse the existing energy-use profiles of DC rolling-stock supplied with traditional unidirectional substations and to quantify the impact of the installation of new reversible substations in terms of energy saving but also in terms of power quality with a target uncertainty of 1 %.
4. To develop accurate measurement systems and procedures for evaluating the energy saving provided by an eco-driving strategy. To reduce the uncertainty of the on-board energy measurement to 1 % to enable assessment of the reliability of an eco-driving forecasting model and to identify and test good practices in on-site estimation of eco-driving benefit.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories), standard developing organisations (EN) and end users (train manufacturers, railway companies).

## Progress beyond the state of the art

New facilities developed for the calibration of the EMFs which have the capability to apply traceable distorted power to the device under test provide a considerable improvement in the state of the art evidenced by the application of pure 50 Hz, 16.7 Hz and DC voltage and current signals to EMFs for calibration purposes. Moreover, the new capabilities allow reverification of an EMF's accuracy on board the traction unit. These project outputs are contributing to the revision of the international standard IEC 62888.

An important advancement was made in the comprehension of the transient PQ events affecting the DC railway and metro systems. In particular, thanks to the combination of data collected in-field and modelling activity, the conducted effects triggered by the arc events occurring at pantograph have been analysed and described.

Due to the limited receptivity of the DC supply network during braking, about 20 % - 40 % of the traction energy converted into electrical energy is wasted by braking resistors. Nowadays, new reversible substations (RSS) that allow bidirectional energy exchange between AC and DC railway grids can save a further 11 % to 20 % of the traction energy. The project developed a reliable methodology for the estimation of the RSS benefits in terms of reduction of energy dissipated by braking rheostats and reduction of the supply voltage fluctuation, which are of high significance for railway operators. The new methodology will be proposed to IEC TC 9 WG 50, working on the new IEC 62590 standard, and to IEC TC9 AHG 26, which is drafting a new work item proposal on reversible substations.

Adoption of eco-driving, defined as driving a train as efficiently as possible by maintaining a speed profile designed to reduce economic and environmental costs, necessitated accurate on-board energy measurements for the determination of the optimally energy efficient driving strategy. Uncertainties of tens of percent in the measurements of absorbed energy made them unusable for this purpose. The project developed a measurement setup with calibrated transducers and measurement models able to quantify the energy flows

on board trains (i.e. energy absorbed by traction and auxiliary systems and dissipated by braking rheostats) which allows energy consumption measurements with an uncertainty lower than 1 %.

**Results**

*Development of a metrological framework for calibration (laboratory and on-board) to enable high accuracy energy and power quality measurements under highly dynamic electrical conditions*

New laboratory facilities for EMF calibration under highly distorted conditions for AC EMFs have been developed. The uncertainty associated with energy measurement after a calibration carried out under distorted conditions is 0.5 % for the AC regime. The setups for the energy measurement systems generate 25 kV 50 Hz or 15 kV 16,7 Hz with harmonics up to 5 kHz, with phase-fired current waveforms going up to 500 A and harmonics up to 5 kHz. Progress achieved in the field of material structures, combined with high power wideband amplifiers, made transportable and compact phantom power generation possible.

A new system for the generation of standard DC Power has been developed, which has the capability to generate phantom DC power up to 8 MW with the supply voltage ranging from 1kV to 4 kV and current from 10 A to 2000 A. The system is able to generate both stationary and dynamic electric quantities. Moreover, a superimposed ripple with arbitrary frequency content up to 15 kHz for the voltage and 600 Hz for the current can be generated. The developed reference measuring system allows the determination of generated power with uncertainties ranging from 90 µW/W to 200 µW/W for stationary conditions and up to 1200 µW/W for dynamic generation. This reference system enables the calibration of both the entire measuring chain EMF and the transducer module commonly constituted by a combined voltage-current transducer. The standard generation system, operating in dynamic mode, can reproduce the time behaviour of voltage and current experienced by an EMF during an actual journey. Finally, a setup has been developed to calibrate the Energy Calculation Function, which is a component of EMF that performs calculations of power and energy based on the voltage and current information provided by the voltage (VMF) and current transducer (CMF). The methodologies developed for the calibration of AC and DC EMFs can be employed in the on-board calibration or periodic reverification of such measuring systems.

New services for the calibration of EMF even under distorted electrical conditions have been activated for AC 50 Hz and 16.7 Hz and DC railway systems providing the metrological framework defined in the first project objective. The calibration facilities for the on-board reverification of AC EMF have been developed. The DC calibration facilities for laboratory application can also be used for on-board reverifications. The objective was achieved.

*Development of a wide-area power quality monitoring architecture*

In total, five measurements campaigns were conducted both on board locomotives and in supply substations utilising characterised measurement systems. Two of the campaigns were performed on board DC locomotives operating in regular commuter services in the north of Italy and one was performed on board a train operating on Metro de Madrid lines. Two campaigns were performed in supply substations: one in an AC substation supplying the high-speed line between Milan and Bologna and the other supplying the DC line between Bologna and Rimini. Additionally, large amounts of data were collected from the field and other data on AC railway systems were made available by project partners. Such valuable data served as the foundation for the development and testing of algorithms for power quality analyses on both DC and AC railway systems.

For DC railway systems, thanks to the high sample frequency (50 kHz) used to acquire data, a rich collection of transient events affecting the quality of the power exchanged between train and supply system was obtained. Moreover, two methodologies for the detection of arc events, a consequence of detachments between an overhead contact line and a pantograph, were developed. The methods exploit the conducted effects triggered by the arc event on the voltage and current observed at pantograph. One of these methodologies has been submitted for a patent and it has been used to detect such phenomena from the acquired data. A dataset collected from arc events has been published. Thanks to the synchronised measurements performed both in a substation and on board a train supplied by the monitored substation, it was possible to observe the same phenomenon (arc event) from both locations.

For AC railway systems, long term monitoring of a substation supplying a 2x25 kV – 50 Hz system was conducted. Four electrical quantities were monitored, specifically, the current absorbed by the feeder and the catenary, and the feeder and catenary voltages. The data were acquired at 20.48 kHz. The RMS values and the harmonic contents of the electrical quantities were aggregated over 200 ms and broadcasted via an internet connection. The feed system was found to be very stable. In 95 % of the cases, the RMS value of the catenary voltage was between 25.69 kV and 26.47 kV and feeder voltage was between 25.73 kV and 26.48 kV. The

total harmonic distortion (THD) parameter, for both voltages, varied between 1 % and 7.4 % with an average value of 2.3 %. A set of data related to 2x25 KV – 50 Hz and 15 kV – 16.7 Hz acquired at pantograph and made available by project partners was analysed. Considering the typical sequence of train motion of acceleration – coasting – braking, the voltage THD is always lower than 8 %, while the THD of the current reaches 20 %. The 11$^{th}$ harmonic is the most important for both voltage and current during the traction and braking stage, while it is almost zero during the coasting stage. The amplitude of the 17$^{th}$ harmonic follows the RMS behaviour of the current. It was demonstrated that such harmonics, in particular for the 11$^{th}$ and 17$^{th}$, carried power of hundreds of watts.

The experience gathered in-field has allowed identification of the electrical quantities to be monitored both on-board and in substation for PQ purposes and provided a possible solution for a stand-alone system able to collect data. Circuital approaches supporting the comprehension of the effects produced by PQ phenomena have been provided, in particular for DC systems. Optimized algorithms for the detection and the quantification of PQ events are now available for uptake by the railway communities. Finally, a possible architecture for wide monitoring of PQ events has been recommended to the CENELEC TC9X Committee, in fulfilment of the project objective.

*Setting up combined measurement-simulation tools to quantify the impact of reversible substations in terms of energy saving and power quality with a target uncertainty of 1 %*

The energy dissipated by on-board braking rheostats represents the energy to be potentially saved by the introduction of reversible substations in the railway electric supply system. A measurement setup with an accurate measurement model to quantify such energy has been developed and applied to railway and metro traction units. A model has been developed to quantify and correct both the errors introduced by the simplified measurement model and the distortions introduced by the limited bandwidth of the current sensors implied in the detection of the chopped current. Two approaches for the characterization of the current sensors have been proposed: one in the time domain and the other in the frequency domain. The proposed measurement infrastructure allows the estimation of the braking rheostat energy with an overall uncertainty lower than 1 %. The methodology has been applied to several journeys in order to demonstrate the potential impact of new supply architecture (RSS and/or storage systems). The variability of such wasted energy was found to depend not only on train weight, line slope, number of stops or line receptivity, but also on the driver's style. For example, on a single journey between Bardonecchia and Turin on a descending mountain line, the dissipated energy that could be recovered was 580 kWh. Whereas on the flat line between Rimini and Bologna, the energy dissipated by the braking rheostats was about 200 kWh over a consumption of 1.8 MWh.

The impact of RSS was analysed through measurements obtained on a traction unit in service along line 10B of Metro de Madrid. The line is supplied by 5 substations, one of which is equipped with an inverter module that allows extra energy to flow from DC to the upstream AC grid. Measurements continuously performed for some weeks on a metro train showed that an average of 10 % of the energy absorbed was dissipated by the braking rheostats. Statistical analysis was performed on a large number of braking events occurring over a long-time interval with different supply conditions (RSS on and off) and variations in the number of circulating trains. The analysis revealed that in case of high traffic, the ratio between the dissipated energy and the braking electric energy had average values of 10 % and 8 %, without and with the RSS, respectively. These values became 22 % and 16 % in low traffic conditions, giving evidence of the higher impact of RSS when few trains are in service. Although RSS are in an experimental stage and the amount of energy sent back to the main grid is limited by the law in force, the results of this comparison show that the adoption of RSS has potential to considerably improve overall efficiency, in particular when the number of trains is low. The algorithm for the voltage level analysis gave evidence of a small improvement in voltage stability introduced by the RSS: a reduction of the mean value (from 1690 V to 1682 V) and of the 95th percentile value (from 1771 V to 1767 V). In practice, the presence of the RSS limits the occurrences of voltage level over 1700 V. The objective was achieved.

*Development of accurate measurement systems and procedures for evaluating the energy saving provided by an eco-driving strategy*

Two test cases were considered for the measurement of the energy savings provided by an eco-driving strategy. For the metro test case, Metro de Madrid line 10B between Marqués de Valdavia and Hospital Infanta Sofía with 4 inter-stations, and with a class 9000 (length: 55 m, weight: 136 *t*, supplied in DC at 1500 V) rolling stock was selected. For each station, the test cases were characterised by information on the infrastructure, the train and the Automatic Train Operation system (ATO). With this information, the 4 inter-stations were modelled and simulated, and a reference driving style (with the ATO) was selected to calculate the expected

energy consumption and running time. After that, an optimisation algorithm was executed to design the eco-driving strategy taking into account the specific characteristics of the ATO equipment on board the trains operating on line 10B. Simulations estimated energy savings of about 33 % with an 26 second increase in travel time. The reliability of the simulations was proved by measurements performed during eco-driving of the actual reduction in energy consumption, which was 33 % with an increase in travel time of 22 seconds.

For the railway test case, a test train without ATO weighing 361 Mg and operating regionally on the DC railway line between Rimini and Bologna in Italy was selected. The journey consisted of stops at 8 inter-stations on a line characterised by a low plan-altimetric gradient. The eco-driving strategy, implemented manually, took the following approach: to reach the maximum allowed speed then to nullify the traction effort, letting the train move forward by inertia, and to reengage the traction when the train's speed fell below a certain threshold until the maximum speed was again attained. This approach provided an energy saving of 38 %, corresponding to approximately 954 kWh, with a travel time increase of 5 seconds.

The described project activities have provided means and methods to perform measurements of energy flow on-board trains with an accuracy lower than 1 %, thus meeting the project objective. The new methods have been applied to real test cases allowing a comparison between the eco-driving energy saving provided by models and estimated in-field. A detailed sensitivity analysis on the quantities affecting the estimated energy saving provided by the eco-driving has been carried out.

**Impact**

As of the end of the project, 42 articles were published in peer reviewed journals, 35 presentations of project activities were made at 17 international and 3 national conferences. In addition, the system developed during the project for the calibration of DC EMFs directly on-board was presented at a key Italian railway exhibition, the EXPO Ferroviaria. The project has also been promoted through various media outlets; 30 articles were published in the popular press, 3 press releases were issued, clips and videos were made available on RaiTV, YouTube, and dedicated pages were created on ResearchGate, Facebook and Youtube, which provide more information on the MyRailS. The dissemination has been supported by the production of 47 small videos describing not only the project activities but also the results and their importance for stakeholders.

The project webpage, found at http://myrails.it/, has drawn more than 170,000 visitors since July 2019. The Facebook page on MyRailS to which 47 videos and several posts have been uploaded has accumulated more than 1200 followers. The posts and videos have reached an audience of thousands.

Furthermore, the final workshop "Metrology and measurements for an efficient electric railway system," devoted to the dissemination of the project results among the stakeholders and held in January 2021, met with considerable success. It was organised in collaboration with CIFI (Collegio degli Ingenegri Ferroviari Italiani), the Italian organisation for railway engineering. There were more than 250 registrations from many European countries as well as Japan and China. The workshop was broadcasted live on YouTube (https://www.youtube.com/watch?v=KAgsV1t-oFE); and more than 800 views were counted.

*Impact on industrial and other user communities*

New metrological services for the calibration of AC and DC EMF were established. The services allow the calibration of EMF both under pure AC and DC signals and in the presences of distortions for the AC and ripple for the DC. Testing of commercial DC and AC EMFs made available by stakeholders (HaslerRail and Mors Smitt) have been performed. These tests have been carried out by applying real voltage – current waveforms recorded in-field. The calibration system for railway EMFs is also of interest to manufacturers of combined voltage-current transducers for AC electric distribution grids, as well as to producers of smart terminations for MV cables that embed both voltage and current transducers. As their production has risen, new testing and calibration services capable of characterising these devices under real working conditions has become an emerging need.

The methods developed for the detection of arc events in DC railway systems will serve both infrastructure managers and railway companies. This tool deployed in conjunction with a widespread data collecting system could allow predictive maintenance of sliding contacts. In this framework, there is also considerable interest from manufacturers of EMFs drawn to the idea of embedding a new arc detection functionality in the EMF. With this, the number of arc events and their position in the railway network could be broadcasted by exploiting the ground data collection system already in use for energy billing. A database collecting the time-behaviour of the electric quantities at pantograph has been made freely available. Based on the experience gained through on-board measurements, the project has prepared a good practice guide for on-board energy flux

estimation. The best practices defined in these guides will enable eco-driving energy saving assessments which will permit optimisation of ATO, improve the design of DC railway supply systems involving new RSS, and support better financial decision-making. It is worth noting that the participation of industrial partners in the project helped to align the project with industrial needs. The links now established between railway industry partners and international and European railway consortia (UIC and CER) will guarantee notable uptake and exploitation of project output.

*Impact on the metrological and scientific communities*

The project outputs contributed to new calibration methods related to AC and DC compact electronic transducers supplied under actual harsh railway conditions. The information gathered will help the realisation of a harmonised calibration procedure, a reliable measurement model and a robust uncertainty budget. New/extended sensor calibration capabilities adapted to harsh non-sinusoidal conditions were developed and a guideline document for the whole energy meter chain calibration was made available to end users and the metrological community. The development of standard DC power for MV DC grids has triggered a process for the addition of DC power as a new quantity in the BIPM Key Comparison Database. In addition, the definition of PQ events and related metrics will have a significant scientific impact on the academic community dealing with the study of new LV and MV DC power transmission/distribution grids and relevant harmonic distortion.

*Impact on relevant standards*

The project consortium promoted the MyRailS results within the standardisation community and provided input to specific technical committees (CENELEC/IEC TC 9X, CENELEC/IEC TC 38 [WG 47 and WG 55]) on the subject of on-board energy measurements. The project was presented at the CEI CT 38 (the Italian standardisation technical committee on instrument transformers) during their periodic general assembly and at the annual meeting of the Sub-committee Power and Energy of the EURAMET TC-EM. Moreover, the project was introduced to IEC TC 9. The experience gathered through development of the calibration facilities for EMFs and the uncertainty budget estimation was made available to the maintenance group of the IEC 62888 standard “Energy measurement on board trains”. The coordinator, as an expert member of this technical committee, collected the contributions provided by some partners and proposed a new version of Annex C of IEC 62888-2 introducing a more rigorous metrological approach in estimation of the uncertainty associated with the power measurements performed by the AC EMFs. The proposal is under discussion. The project activities on reversible substations and monitoring of the voltage fluctuations were shared with IEC TC 9 and CENELEC TC 9X. As a consequence, the committees prepared a priority research topic, “Specifications for non-conventional DC substation and performance assessment of non-conventional subs,” which became the basis for the selected research topic (SRT), “Metrology support for enhanced energy efficiency in DC railway systems,” in the 2021 Normative call of the European Partnership on Metrology under Horizon Europe.

*Longer-term economic, social and environmental impacts*

At the outset of the project, it was the practice for many rail operators to charge for a train’s energy consumption based on a simple estimation. However, an error of 5 % on 36.5 TWh of energy used on European railways each year would equate to around 110M €. Accurate billing of energy consumption between rail network operators is essential for interoperability and is an important financial incentive. To that end, agreed and mutually accepted calibration tools, procedures and guidelines for the on-board energy measurement systems can increase mutual confidence in billing, fostering interoperability with reference to the rail ‘energy’ subsystem in the EU. To further improve energy efficiency, reliable tools for continuous monitoring of power quality events can be used to regulate energy billing, which will consider the electromagnetic impact of the user’s (the railway company’s) trains on the supply system and vice-versa.

In addition, it has been estimated that, for a single-track suburban line (30 km) with an annual traction consumption of 6 GWh, reversible substations can produce a saving of about 1.4 GWh (23 % of the traction consumption). The reduction of the energy dissipated by on-board braking rheostats will give a valuable contribution to solving the issue of tube temperature increase, which is detected by many underground network managers. A decrease of such temperature will consequently improve the energy efficiency of the traction units. Overall, by increasing the interoperability and integration of railway networks along with increased passenger confidence in the railway as a means of transport, the EU objectives of tripling the existing high-speed rail network by 2030 and moving the majority of medium distance passengers by rail by 2050 can be fulfilled.

In terms of environmental impact, train eco-driving techniques will improve PQ and can have a significant impact on the energy consumed for trains operating over the same route with the same stopping patterns.

Coupled with the financial incentive enabled by a billing infrastructure, this should lead to significant energy saving and resultant reductions in emissions. By using accurate energy data and an optimised driving technique, the potential considering all the EU25 train drivers is estimated to be a yearly $CO_2$ emission reduction of 2.4 Mt. Moreover, the development of an integrated and energy efficient railway infrastructure at European level, as fostered by the output of this project, will support the shift from medium distance road freight to rail freight green corridors.

Both social and environmental impact will be achieved, through widespread PQ monitoring system and data processing architecture which will prevent malfunctioning of railway electrical equipment thus ensuring greater confidence in the use of the electric public transport. This will also produce a reduction in car-use and have a positive impact on pollution-related health and environment problems, as well as, on the reduction of road congestion and the number of accidents, leading to an improvement in quality of life indexes.

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|---|---|---|
| Project start date and duration: | | 01 September 2017, 41 months |
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| Internal Funded Partners:<br>1 INRIM, Italy<br>2 CMI, Czech Republic<br>3 FFII, Spain<br>4 LNE, France<br>5 NPL, United Kingdom<br>6 VSL, Netherlands | External Funded Partners:<br>7 Comillas, Spain<br>8 HRI, Italy<br>9 MM, Spain<br>10 R.F.I., Italy<br>11 Railenium, France<br>12 STRATH, United Kingdom<br>13 SUN, Italy<br>14 Trenitalia, Italy | Unfunded Partners:<br>15 ASTM, Switzerland<br>16 METAS, Switzerland |
| RMG: - | | |