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E-LOBSTER

Electric losses balancing through integrated storage and power electronics towards increased synergy between railways and electricity distribution networks

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Smart Management of Railway Networks

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Terms and Abbreviation

Abbreviation	Description
ATO	Automatic Train Operation
CCS	Combined Charging System
CDS	Close Distribution Systems
CDSO	Close Distribution Systems Operator
CER	Community of European Railway
DES	Distributed Energy Sources
DMS	Demand Side Management
DPTS	Driver Practical Training System
DR	Demand Response
DSO	Distribution System Operator
DSR	Demand side response
EMO	Electricity Market Operator
ERRAC	European Rail Research Advisory Council
ESO	Electricity System Operator
ESS	Energy Storage System
EV	Electric vehicles
GGE	Greenhouse gas emissions
GHG	Green-house Gas
HVAC	Heat, Ventilation, an Air Conditioning
ICE	Internal Combustion Engine
ICT	Information and Communications Technologies
IM	Infrastructure Manager
IoT	Internet of things
KPIs	Key Performance Indicators
P2P	Peer-to-Peer
P+R	Park-and-ride
PQ	Power quality
PTC	Positive Train Control
PTO	Public Transport Operator
REM	Railway Energy Management
RES	Renewable energy sources
RSS	Reversible substation
RU	Railway Undertaking
SRN	Smart Railway Network
sSOP	Soft-Open Point
T2G	Train to Grid
T&D	Transmission and distribution
ToU	Time of Use
TSIs	Technical Specifications for Interoperability
TSO	Transmission System Operator
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to grid
GenCom	Generation Company

Executive Summary

The overall scope of the H2020 E-LOBSTER project is to propose an innovative Railway to Grid Management system which, combined with advanced power electronics and storage technologies (the smart Soft Open Point and the electric storage developed in the framework of the project), will be able to reduce electricity losses in both the power distribution and the railway distribution networks. In particular, the system will be able to make the best use of the available energy on both the grids by increasing their mutual synergies and maximizing the consumption of local RES production through electric energy storages and at the same time by creating synergy with charging stations for electric vehicles.

In this public report, the concept of smart management of railway networks is introduced, by justifying its application to manage some of the goals set in this project.

In particular, in the framework of the document special attention is paid to illustrate the motivation for the use of smart management of railway network and the importance of energy efficiency in the European Railway Network. Then a special focus was put on the stakeholder vision and how smart grid savings affect the stakeholders of a railway system.

The report presents an overview of the state of the art of energy smart management in railways and the main case studies and projects as well as an overview on smart grid, Electric Vehicles (EV), charging stations for EVs, V2G concept, electromobility in general and its synergies with railways. Furthermore, special attention is paid to customer behaviour, Demand side management and Demand side response.

In the second part of the document the focus was moved on the implementation of smart management of railway networks towards power losses minimization by focusing then in particular on the E-LOBSTER solutions. In particular, the aspects that are considered most interesting in order to understand the importance and the usefulness of smart management regarding the development of the ELOBSTER project are fully illustrated.

1 Introduction

The main objective of the E-LOBSTER project is to develop and demonstrate up to TRL 6 in relevant environment (a real underground railway in Madrid connected to a local power distribution network with a high penetration of RES) an innovative, economically viable and easily replicable Electric Transport-Grid Inter-Connection System that properly managed will be able to establish mutual synergies between power distribution networks, electrified urban transport networks (metro, trams, light railways etc.) and charging stations for electric vehicles.

In particular, E-LOBSTER is demonstrating tools and technologies, software and hardware to assess the source of losses of both the networks (transport and electricity distribution networks) prioritising techniques for their minimisation via a coordinated control of the power supply for electrified transport and recharge stations for electric cars and towards the maximisation of the local consumption of Renewable Energy Sources (RES) production thanks to the use of Electrical Energy Storage (EES) and advanced power electronics devices.

In its concept, E-LOBSTER project is proposing an innovative Railway to Grid Management system which, combined with advanced power electronics, will be able to reduce electricity losses in both the power distribution and the railway distribution network. The system will be able to make the best use of the available energy on both the grids by increasing their mutual synergies and maximizing the consumption of local RES production through electric energy storages.

This document aims to introduce and develop the concept of smart management of railway networks, by justifying its application to manage some of the goals set in this project. In order to fully cover this issue, the document deals with several aspects of this technology: from the main and basic concepts, to the regulation and the EU policy, the synergies regarding other transport and energy services, how it affects the classic aspects of demand and costumer behaviour, and, finally, a brief mention to future challenges and a case study that sketches an example of smart management application.

The scope of this report is the dissemination of the general concepts and technologies that enable the use of smart management within the context of railway networks. Consequently, it does not tackle a detailed and specific technology, but a general description of the aspects that are considered most interesting in order to understand the importance and the usefulness of smart management regarding the development of the ELOBSTER project.

2 Reasons and motivation for the use of Smart management of railway network

Energy efficiency is one of the main aims regarding worldwide industry. Thus, considering the weight of transport in terms of energy consumption (over 24% of global CO2 emissions in 2016[1]), energy savings in this sector play an important role. In this context, railways are regarded to be the most appropriate mean of transport to achieve the energy consumption reduction goal, due to their own characteristics regarding energy efficiency and low emissions.

As expressed by CER (Community of European Railway and Infrastructure Companies) in its position paper "The Strategy for long-term EU greenhouse gas emissions reductions" issued on the September 2018:

"Energy-efficient low-emission railway is the only mode reducing its emissions and it is the solution to address the current emissions gap compared to the ambition for 60% GHG reduction target by 2050 for transport, as set in the 2011 Transport White Paper "[2]

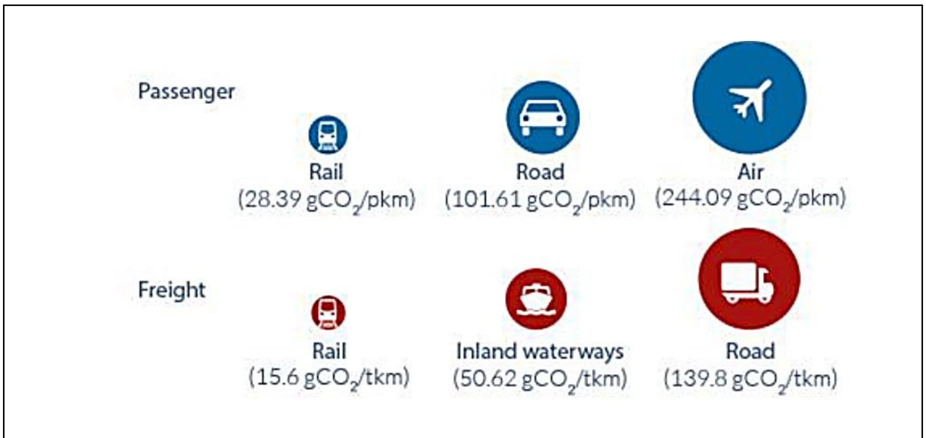

Figure 1 Specific CO2 emissions per transport mode (EEA, 2017)

In terms of the European framework, the goals set by the Transport White Paper of 2011 on energy and emissions, have their reflection in some of the R&D visions and objectives set by the ERRAC (European Rail Research Advisory Council) in its paper "Rail 2030: Research and Innovation priorities" issued in 2019 . In this sense, there is a clear case for the smart management of energy in rail networks in order to achieve full decarbonisation of the rail system:

"Develop smart energy infrastructure: On-board and line-side energy storage technologies and charging technologies will make possible to recover a big amount of the braking energy and will support balancing the flow of energy. Electricity supply using SMART grid technologies coupled with increasing the residence and variety of supply resources (e.g. main grid, local renewable, recovered, etc.) not only for rail traction systems but also for road usage and stations"[3]

[1] IEA (2018). CO2 Emissions from Fuel Combustion 2018 Highlights)
[2] Position paper "The Strategy for long-term EU greenhouse gas emissions reductions", September 2018. CER. Page 1
[3] "Rail 2030: Research and Innovation priorities" ERRAC, 2019.

Having all these into account, there is a clear case for the E-LOBSTER technologies, as it clearly contributes to the development of smart grid energy infrastructure.

2.1 Importance of energy efficiency in the European Railway Network

As it has been underlined in the previous section, the EU transport bodies provide the main policy guidelines in order to reduce energy losses; or, in other words, to increase energy efficiency in transport. Some of them, like the ERRAC, have also set up a path where the smart management of railway networks can actively contribute to the achievement of the energy efficiency goals.

To introduce the importance of energy efficiency in railway networks and its relationship with railway smart management, it is important to provide a clear definition. In this sense, smart management of railway network is:

" [..] *the series of procedures that aim to develop procedures and equipment that promote the reduction of electrical energy losses throughout the different elements of electric railway infrastructure, in addition to the implementation of economic driving plans and new technologies that allow the utilization of electric energy generated by the vehicles ´regenerative braking system*[4] *[…]"*.

Therefore, in order to understand and work on energy efficiency and smart management of railway networks it is important to differentiate between the various parts that define railway network management. These are usually divided into infrastructure (transmission grid, distribution grid and rail grid), operation, and rolling stock (braking energy reinjection and driving strategies).

2.1.1 European vision towards energy efficiency

This section aims to summarise how the European Railway community faces energy efficiency in their networks. Regarding energy efficiency in pure energetic performance terms, EU organisations also have a clear vision to optimise it, obviously apart from the characteristics of railways (specific energy consumption is 6 times lower than road[5]), which is also related to smart grids integration.

Firstly, the EU Commission sets a strong goal towards the transport sector decarbonisation and the role of railways, which is likely to be vital for the future of sustainable transport. The Transport White Paper reinforces this vision with a 60% GHG reduction target by 2050 for transport and sets a path for the energy efficiency of the system.

"*Improving the energy efficiency performance of vehicles across all modes, developing and deploying sustainable fuels and propulsion systems*"[6].

But also identifying an adequate regulatory framework for innovative energy efficiency initiatives:

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[4]PTFE position paper. Sustainable and smart management of energy in railways (2017)

[5] The Strategy for long-term EU greenhouse gas emissions reductions Position Paper Brussels, 28 September 2018 CER

[6] "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system". EU Commission, 2011.

"Identify the necessary regulatory framework conditions through standardisation or regulation: Appropriate standards for CO_2 emissions of vehicles in all modes, where necessary supplemented by requirements on energy efficiency to address all types of propulsion systems;"[7]

Continuing with the analysis referred to energy efficiency, the following is described, which gives a clear vision of the objectives to be reached by railways concerning energy efficiency:

"by 2030, the European railways will reduce their specific final energy consumption from train operations by 30% compared to the base year 1990. By 2050, the European railways will strive towards halving their specific final energy consumption from train operation by 2050 compared to the base year 1990",[8]

Concerning the inclusion of new systems tackling energy efficiency in terms of operation and management, like those that are expected to be part of E-LOBSTER project, the European Rail Research and Advisory Council (ERRAC) has expressed the aim of having a fully decarbonised, silent and eco-friendly rail system by 2030. It is suggested that Horizon Europe (the next European Framework Programme for Research and Innovation) includes a "Holistic energy management approach for railways"[9] to be developed attending three main drivers (digitalization, rolling stock and infrastructure) where:

"The energy consumption of trains in regular operation is influences by many different factors, and therefore complementary technological developments should be undertaken to reduce it."[10]

Finally, and in order to understand the importance of energy efficiency for the rail European stakeholders, ERRAC sets it out as one of its main points inside the challenge "sustainability/security" for 2030.

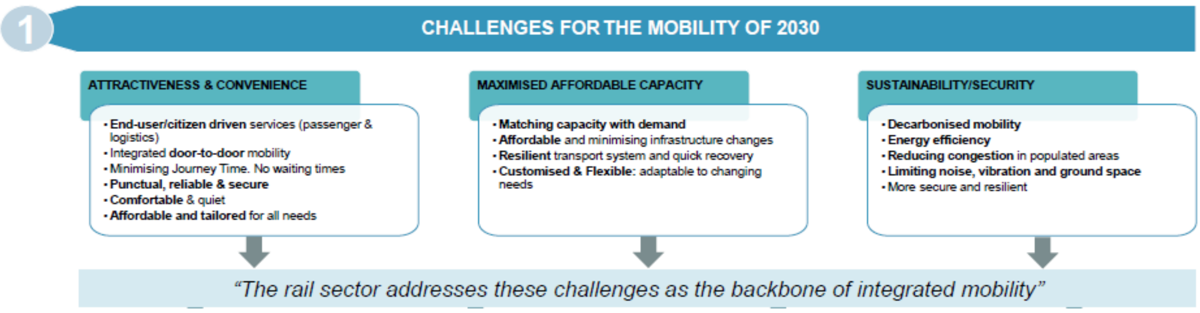

Figure 2 ERRAC Challenges for 2030[11]

[7] "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system". EU Commission, 2011.
[8] CER&UIC (2012). Moving towards sustainable mobility: a strategy for 2030 and beyond for the European railway sector.
[9] "Rail 2030: Research and Innovation priorities" ERRAC, 2019.
[10] "Rail 2030: Research and Innovation priorities" ERRAC, 2019.
[11] "Rail 2030: Research and Innovation priorities" ERRAC, 2019.

2.1.2 Railway stakeholders technical vision on energy efficiency

This section aims to summarise the stakeholders' technical vision considering the key role of railways within the transport sector towards the achievement of the Transport White Paper goals on energy efficiency. Additionally, the effect of energy savings on stakeholders will be studied further in in this deliverable.

The following table sums up the vision of rail stakeholders on energy efficiency, which was gathered by ERRAC, focusing on those characteristics that E-LOBSTER project implementation is supposed to influence.

Table 1. Stakeholders' vision towards energy efficiency [12]

Well to wheel energy efficiency	Effects on energy efficiency in electricity and fuels supply, as well as in use; evolution over time and depending on market penetration, etc
Energy cost in EU	The European railway networks are spending billions of Euros annually on energy and the energy costs have increased significantly over the last few years (more than 10% per year).
Need of energy efficiency improvement	The continued increase in oil prices to a level of 100 $ per barrel underlines the necessity for improved energy efficiency, also because the electricity prices are highly influenced by the prices on coal, crude oil and gas.
Railways and its effects over climate change	Climate change has become a strategic cornerstone for railways. Railways are fortunate to run 80% on electricity in Europe but it is not possible for all industrial electricity consumers to switch to renewable energy sources at once. Therefore, improved energy efficiency is vital when the railways want to achieve their individual CO2 targets.
Energy mix increasing importance	The energy mix in Europe is highly heterogeneous as the percentage of nuclear power, energy from fossil fuels and regenerative energies vary very much from country to country.
Role of innovation towards railway technology and energy efficiency	R&D projects proposing solutions close the market can contribute to the necessary innovation to further optimise the well to wheel energy efficiency for the rail system. It is important to differentiate between research into energy efficiency measures between long distance rail and urban rail.

Regarding the available technologies, the same document refers to the ERRAC Energy Efficiency Roadmap that exposed those technologies that were presumed to be the most promising regarding energy efficiency and low emissions.

Actually, as it may observed, 10 years ago, the roadmap envisaged by 2020 a special focus on smart grid and on the multiplication of energy sources as it is really happening in E-LOBSTER thanks to the innovative technologies that the project is proposing.

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[12] European Rail Research Advisory Council (2011). European Rail Research Advisory Council. Extracted from the Position Paper "Answer to the questionnaire for STTP Stakeholders' Hearing on Rail Transport"

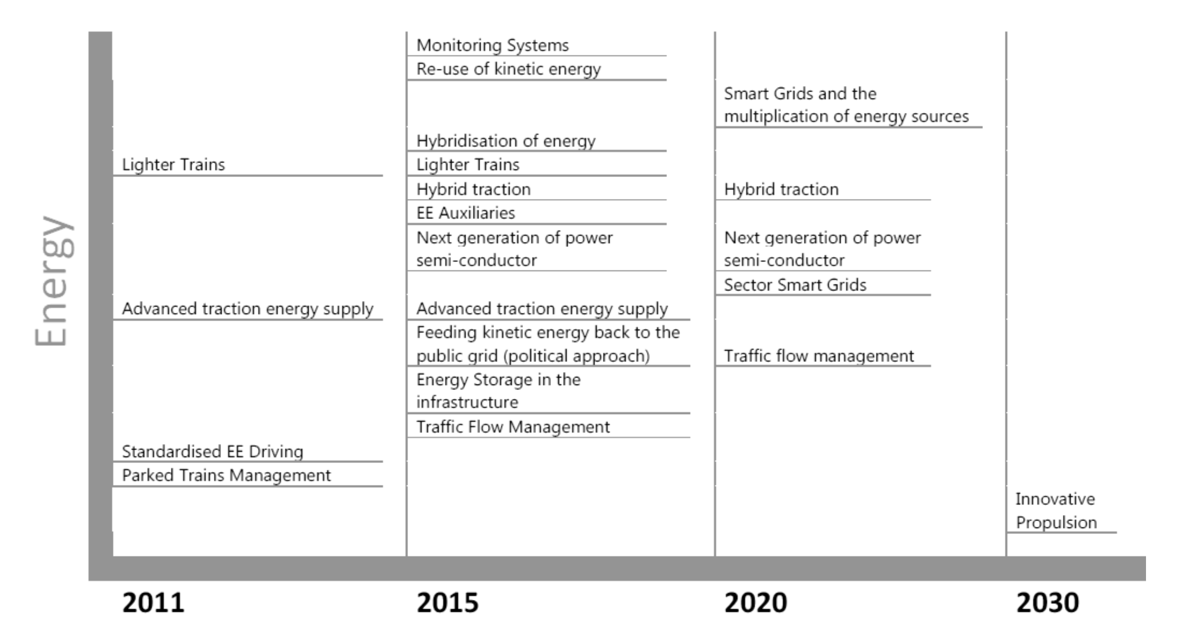

Figure 3. Most promising technologies regarding energy efficiency in railways operation[12]

This first section has introduced the importance of energy efficiency in transport and the role that railways play. There is also a link between the use of new technologies smart grids, new driving and operating techniques (complementary to the E-LOBSTER approach) and the achievement of rail objectives concerning energy efficiency and CO2 emissions.

2.2 How Smart grid savings affect the stakeholders of a railway system

The concept of smart grid is the main column that sustains smart management and the advantages of the first term are shared by the second. Consequently, smart grid potential is to improve energy efficiency, increase the reliability, availability and security of the supply, and reduce customer costs.

This potential is based on the fact that railway system will no longer be a passive load, consuming energy from the grid, but it will be part of a larger smart grid and communicate with "non-railway" systems such as smart buildings, electrical vehicles charging station, distributed energy resources, etc.

These characteristics of smart grids will affect to those facilities where they are installed and, in this case, to those actors that act within the railway network. To be able to study these effects, it is necessary to know who the main stakeholders of a railway system are, by grouping them in the following main categories:

- Railway Operator/Train Operating Company;
- Infrastructure Manager;
- Energy Supplier;
- Grid Owner;
- Electricity Market Operator;
- Customers of the railway service;
- EV owners.

The definition of each category is the following:

- *Railway Operator* means any public or private undertaking licensed according to the "Directive 2012/34/EU of the European Parliament and of the Council," Official Journal of the European Union, European Union, 2012, whose principal business is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction; this also includes undertakings which provide traction only. It may possess the rolling stocks and it is authorized with the access to the railway infrastructure.

- *Infrastructure Manager* means anybody or firm responsible in particular for establishing, managing and maintaining railway infrastructure, including traffic management and control-command and signalling; the functions of the Infrastructure Manager on a network or part of a network may be allocated to different bodies or firms.
- An *Energy Supplier* refers to a party that supplies the customers or the market with electricity and receives profits from the energy trading activities.
- The *Grid Owner* acts as Transmission System Operator (TSO) and Distribution System Operator (DSO). TSO is an entity entrusted with transporting energy in the form of electrical power on a national or regional level, using fixed infrastructure. DSO shall be responsible for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity, for operating, maintaining and developing under economic conditions a secure, reliable and efficient electricity distribution system in its area with due regard for the environment and energy efficiency.
- The *Electricity Market Operator* represents any company in charge of all the operations required for the electricity market operation (receiving the purchasing/selling bids, matching process, billing….). Its role in a wholesale electricity market is to manage the security of the power system in real time and coordinate the supply of and demand for electricity, avoiding fluctuations in frequency or interruptions of supply.

Each of the above-mentioned categories of stakeholders may be influenced by the adoption of smart grids in the railway system. Each stakeholder will be affected in different ways and may have savings coming from the new system.

With the use of smart grids, optimisation is not only carried out to benefit one single stakeholder, but for the whole system, including all stakeholders involved, trying to “share” energy efficiency gains.

New communication technologies allow to increase the intelligence level of distribution and transmission grid, with the aim to optimize the management of new renewable sources, loads, storage system and the grid. Smart grids technologies interest also the railway system to optimize the recovery of the braking energy of the trains, to integrate local renewable production and storage systems, to ensure high quality train supply and globally to increase the energy efficiency and to reduce the energy cost.

By studying the technologies providing energy losses reduction to the railway system, analysed in the E-LOBSTER public report D1.1 “Measures for energy losses prevention in the traction chain”[13], it is possible to analyse the main impacts of those technologies/measures on the different stakeholders.

In general, the benefits of smart grids include grid loss reduction, enhanced system performance and asset utilisation, integration of renewable energy sources, active demand response and energy efficiency. In adapting smart grids to railways, these advantages should all be realised.

Smart grids have been initially introduced within a context of power stabilisation and further developed with energy saving, increasing renewable energy usage and reducing greenhouse gas emissions. In particular, the smart grid framework in Europe is customer-oriented and the grid is being designed to be flexible, accessible, reliable and economical for customers.

Considering the characteristics of traction loads in railways, it is necessary for a railway smart grid to be:

[13] https://cordis.europa.eu/project/id/774392/results

- Reliable: It should provide quality power to electric trains. The electrical load of trains systems changes depending on the traffic situation and tracks the spatial movement of individual trains.
- Combinable: It should integrate distributed generation sources, including regenerative braking energy, and use these efficiently.
- Accessible and Predictable: It should be not only accessible to monitoring, managing and control systems but should also analyse data and forecast energy consumption.
- Eco-friendly: It should reduce greenhouse gas emissions.
- Economical: The best possible value should be attainable through innovation, efficient energy management and levelling the playing field in terms of competition and regulation.

All these aspects and advantages provided by smart grids may have different implication on the stakeholders of the railway system.

The railway operator will have benefits by having a reliable service, as availability of the service is one of its main objectives. By adopting technologies such as driving style optimisation and timetable scheduling optimisation, the railway operator may have significant improvements, as also shown further on in this deliverable and through the energy consumption figures provided in D1.1.

The infrastructure manager, as responsible of maintaining the railway infrastructure, will have benefits from the use of smart grid systems; infrastructure upgrading methods to reduce energy losses include using of energy storage devices, reversible substation, renewable energy sources. Energy storage devices can be used to store regenerative braking for reuse.

When a new smart Soft-Open Point (sSOP) device is used to interconnect railway electrification and power distribution networks, the benefit is not only the improvement of the regenerative braking energy usage, but also the support to the distribution network from an additional power source. To analyse and optimise the performance of the sSOP, the train operation has to be considered; in the meanwhile, the control strategy of the sSOP should be studied to achieve the best benefit.

The electricity can also flow from the Infrastructure Manager back to the energy supplier, as the regenerated energy flows from trains through railway infrastructure to the supplier or to the electricity market.

Another important impact of the adoption of smart grids in the railway domain is the increased customer participation. Smart grid technologies allow monitoring of the supply network and information exchange, enabling the provision of near real-time data to consumers. The outcome of receiving this information is that consumers can take direct action to reduce their energy consumption. The customer receiving this information is not an individual, but the train operating company. Based upon their electricity use information, railway operator can work towards minimising their consumption and observe the effect of introducing energy-saving measures.

As well as monitoring usage, there is scope to gather information regarding electricity purchasing, which can be used to track the progress towards sustainable sources. Railway operator will also be able to provide this information to their customers, thereby allowing passengers to make travel decisions based on real-time data concerning the environmental impact of services. However, this is most likely to be achieved through variation in passenger pricing, rather than direct access to energy information. It is possible that data could also be used for other purposes, such as remote condition monitoring. Like smart grids, remote condition monitoring uses automated sensor readings to assess the condition of railway assets. This reduces the need for human inspection and can detect faults before failure, improving safety and reliability.

To meet the peak load, the railway power supply system has to take this load uncertainty into account. In some cases, this means that the equipment is over-specified, making it more expensive to replace and maintain. Smart grid technologies would enable monitoring to understand where these problems occur, and therefore where equipment ratings can be reduced and where more sources are needed. This monitoring, coupled with active demand management and the integration of Distributed

Energy Resources would help optimise the performance of the railway power supply system, thus reducing losses and operating costs.

As introduced before, smart grids can provide benefits in attracting customers. This is achieved by improving the performance and reliability of train services: electric trains are faster, quieter and pollutant free (at point of use), and a more reliable supply will incur fewer delays and disruptions for passengers. The energy-saving potential of smart grids may also attract consumers, provided that economic benefits are passed onto the customer by the train operating company.

Smart grids have the potential to save energy by minimising power supply losses and allowing for the integration of renewables and ESSs. Monitoring of supply and demand may also incentivise operators to implement energy saving measures to reduce consumption and create pressure to incorporate renewables into the electricity mix.

Cost benefit is primarily derived from other benefits as more customers will increase revenue, reducing energy consumption will reduce electricity costs and reducing emissions and energy will help the industry to meet government targets, thus avoiding financial reprimands. It is possible that costs may be reduced through local power generation by the rail industry which decreases the reliance on imported fuels, reduces distribution and transmission costs.

2.3 Implications of smart grid implementation in railway infrastructures

Railway is the mode of transport that contributes more to the policies that aim to foster green and sustainable ways of transport. Despite its own characteristics enough to surpass other modes in terms of efficiency, there has been an increasing interest on to increase even more its energy efficiency. To do so, smart management of railway networks arises as the most profitable group of technologies to achieve it. Nevertheless, there are two main challenges regarding smart management of railway networks:

- Firstly, railways are formed by different subsystems: operation, infrastructure and rolling stock, that should perfectly assemble to assure their correct functioning.
- Secondly, and in a similar way, smart management of railway network implies the combination of several technologies, which increases the difficulty of its implementation.

This section deals with the state of the art of smart management of railway networks and splits its analysis into the legal framework regarding the electrical market and its relationship with smart grids and railways, and the overview of the implication of installing smart management systems in railway facilities. The considered technologies within railway field like infrastructure, rolling stock and operation will be further developed in section 4.1.

2.3.1 Legal framework

An overview of the market and legal framework for the electricity market has been performed in the E-LOBSTER project (see Deliverable D3.2 “Report on the existing policy framework” [14]). The review of the existing regulations in the field of energy and railways has been done in order to identify possible market, social and institutional framework implications of the adoption of the E-LOBSTER solution.

In the Railway and Energy sectors, the EU is setting out a “target system” of technical and regulation through the Interoperability Directive (2016/797/EC) and their “Essential Requirements”, with the aim of moving the legal framework from country-by-country legislation and technical standards. The political aim is a single European market where products and services can be freely traded and will also be technically compatible.

[14] https://cordis.europa.eu/project/id/774392/results

In the rail industry, the Technical Specifications for Interoperability (TSIs) set out a common, harmonised, technical specification for that target system to ensure that the "Essential Requirements" of rail interoperability are met in the longer term. These include standards on safety, reliability and availability, health, environmental protection and technical compatibility.

Similarly, the Electricity Directive, (2019/944/EC) sets out a common framework for the market within Europe, but here the focus is on the ability to move electricity around a common electricity network between producer and customer, avoiding local monopolies.

The railway interoperability Directive[15] applies to the entire "Union rail system" and the scope of the TSIs is extended to cover the vehicles and networks not included in the previous trans-European rail system and fully set out in Annex I "Elements of The Union Rail System" of the directive. The Directive (Article 3) specifically does not apply to metros; trams and light rail vehicles, and the infrastructure used exclusively by those vehicles; networks that are functionally separate from the rest of the Union rail system and intended only for the operation of local, urban or suburban passenger services, as well as undertakings operating solely on those networks.

The Electricity Directive states that the internal market for electricity, which has been progressively implemented throughout the Union since 1999, aims, by organising competitive electricity markets across country borders, to deliver real choice for all final customers, citizens or businesses, to deliver new business opportunities, competitive prices, efficient investment signals and higher standards of service, and to contribute to security of supply and sustainability. Efficient use of energy and movement away from carbon-based fuels is also a commission aim.

Relevant to E-LOBSTER, are the proposals in the Directive that consumers should be able to consume, to store and to sell self-generated electricity to the market and to participate in all electricity markets by providing flexibility to the system, for instance through energy storage, such as storage using electric vehicles, through demand response or through energy efficiency schemes.

The directive recognises that legal and commercial barriers exist, including, for example, disproportionate fees for internally consumed electricity, obligations to feed self- generated electricity to the energy system, and administrative burdens, such as the need for consumers who self- generate electricity and sell it to the system to comply with the requirements for suppliers.

It is the aim of the Directive that such obstacles, which prevent consumers from consuming, storing or selling self-generated electricity to the market, should be removed while it should be ensured that such consumers contribute adequately to system costs.

E-LOBSTER represents a new technology development that will facilitate efficient operation of the electricity network by moving energy from one part of a network to another and by including the ability to store or provide electricity depending upon technical or commercial imperatives. It may also be possible to "buy" electricity from one network, store it, and "sell" it to another network.

The Electricity Directive facilitates the aims of E-LOBSTER by making it possible to connect to networks on fair terms. The directive also envisages the concept of "smart metering" which could be a vital part of E-LOBSTER being a practical an economic solution.

Developing standards for railway smart grids is important for ensuring that the technologies delivered are compatible and interoperable with the remainder of the system. However, although compliance with standards is generally considered good practice, industry standards are voluntary. On the other hand, regulations are issued by government and must be met by law. It is expected that any safety critical aspect of the railway smart grids would be governed by regulations and the aspects relating to interoperability would meet published standards. Therefore, standardisation will be

[15] DIRECTIVE (EU) 2016/797 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 May 2016 on the interoperability of the rail system within the European Union (recast) (Text with EEA relevance)

necessary for monitoring and control devices, communications system (including protocols), electromagnetic compatibility, cybersecurity, data collection, storage and sharing.

2.3.2 State of the art of energy smart management in railways

European organisations have made progress regarding smart management of rail electric grids, publishing smart grid standards and policies, which are fundamental to foster its implementation in railway infrastructure facilities. Among these documents, the first European Mandate related to the smart use of the energy in all areas was the M/441 in 2009. Shortly after, in 2011, the smart grid mandate M/490 elaborates several processes to reach interoperability and to make easier the implementation of the many levels of a smart grid with each of the functionalities in Europe. Another regulation, the 1011/2009, took a big step in benefit of the smart saving of energy, allowing to pour back into the network the energy that big consumers that use saving and efficient systems do not consume in their installations, as the case of the energy obtained by the regenerative break in the railways. It is important to notice that over these standards, the national legislation of each country regulates the electrical market. There are also some projects whose goals aim to set the staple of smart grid implementation in the electrical grid, among them, Merlin [16]stands out as an example of European study about the relationship between smart grid and railways.

In terms of railway operation, smart management systems offer new business opportunities and also add new technical and organisational problems to be tackled. Regarding the business side, smart management integration into the system means the expansion of the very same railway system, taking into consideration that new actors come into play (management of EV, renewables, energy storage systems, etc.), and, therefore, the entry of new potential business fields, like energy purchasing and integrated transport systems. On the side of new technical and organisational issues, the creation of timetables and the calculation of headways considering new inputs, like the energy that is recovered from train braking and its reinjection into the grid or into energy storage systems.

These concepts and the state of the art of smart management application to railways will be further developed, as it was said before, in section 4.

[16] EU FP7 Project "MERLIN (2015)". GA - 314125

3 Implementation of smart mobility solutions

As mobility is considered one of the key issues regarding the sustainability of modern cities, the flexibility of transport solutions and a smart integrated approach gain in importance as a key point. However, there are technical, social and economic barriers to its implementation which would also need to be addressed to create a sustainable solution.

Emission levels reduction is a key driver for governments and citizens worldwide. Trends, such as the drive towards cleaner, greener technologies like Electric Vehicles (EVs) and electrification will continue to grow as technologies develop and become more efficient and sustainable. Many cities are looking at delivering car-free centres to reduce emissions, noise and temperature. The ability for people to be able to make choices on where to live and work can be improved through combining transport types, creating a fully integrated network.

In this section, the synergies and possible ways of integration of electrical vehicles (EV) and railways, the different types of EV charging technologies, and the customer behaviour, demand side management and demand side response are studied.

3.1 Levels of integration, means of transport and main challenges

A first step to introduce the topic and the problem that arises related to public transport in population centres is to factorise the issue into subtopics. From this division, it is easier to draw a big picture of how different modes of transport and facilities that coexist in the same space may get synergies from one another. Focusing on the E-LOBSTER project context, railway, tram or metro stations would be the nerve centre of the analysis, and where the study of their connection to other ways of transport and power grids must be evaluated.

This subdivision shows three main fields that become vital to understand the potential of E-LOBSTER regarding mobility in cities: reduction of emissions, multimodality, and increasing of passenger capacity.

As it was developed in section 1, reducing GGE (greenhouse gas emissions) is one of the main policies of EU towards horizon 2020 and 2050. To do so, electrification of transport is a key point to achieve this goal, also introducing renewable energy sources (RES) in order not only to locally solve the problem. Therefore, electric vehicles play a vital role regarding the improvement of ai quality in population centres.

Following on the foregoing, multimodality is another key point to achieve the electrification of transport, combining the advantages of different ways of transport and achieving the best results. For instance, following this model, it is possible to make the most from the high passenger capacity of railways, trams, or metros while EV allow citizens to accomplish the highest flexibility in their movements. Consequently, if establishing synergies between these two ways of transport is achieved in terms of energy savings and, therefore, energy efficiency, transferring power flows between them, through an electrical connection of facilities, then multimodality arises as powerful tool to manage the previous goals.

Finally, the passenger capacity increasing is a concept that links energy sustainability with the principles of urbanism planning. If carrying the same number of passengers is achieved using the fewest number of vehicles, then traffic density is reduced, what is translated into a reduction of total amount of emissions.

3.1.1 Overview of likely relationships between EVs and railways

As it was presented in the previous paragraph, smart mobility solutions in population centres are mainly supported by modes of transport that use electricity as energy source. Therefore, railways and

EV stand out as the main modes to be studied within this section. This introduction deals with the possibilities in terms of energy synergies that come from these two ways of transport in order to reduce the total consumption of energy.

Regarding railway current energy technologies, the use of residual energy that can be recovered from braking may be transferred through the overhead conductor, so that it is possible to directly use or to storage it. This electrical power that may reach up to the order of megawatts is likely to be used as power source of another facility or mode of transport. From this concept, the idea of reuse energy braking from railways sets an important support to EV, whose battery charge is considered one of the main problems regarding the currently available charge points. In a nutshell, there are three aspects to take into consideration, bearing in mind that mostly DC railway facilities are studied:

- **DC network**: typically, regenerated energy is used to feed the auxiliary systems of the train and the surplus is returned to the power supply grid. However, the power supply grid in urban railways is a DC network, which is not always receptive to regenerated energy. To be receptive, other trains have to consume the regenerated energy in the moment of generation, because it cannot be sent to the utility grid. Therefore, it is that this energy is wasted in on-board resistors (rheostats).
- **Reversible substations and energy storage systems**: there are several methods to maximize the use of regenerative energy, such as reversible substations or energy storage systems on the road. Reversible substations improve responsiveness by returning regenerated energy to the electrical grid. On the other hand, energy storage on the road are used to store stocks that exceed the regenerated energy and to supply that energy when trains need it.
- **Space at stations**: EVs are supposed to be charged close to railway facilities, from where the electrical energy comes. The problem that arises from this condition is that parking space are usually not as much accessible as it would be necessary to get maximum benefits.

Regarding EVs, they appear as the keystone to the near-term improvement of the road traffic sustainability. The use of EVs allows improving cities air quality and reducing the noise pollution due to cars as well. However, nowadays there are barriers that limit the adoption of EVs by consumers.

One of the main difficulties for the adoption of electric vehicles by consumers is the scarcity of a suitable charging infrastructure. The use of the railway power supplies to charge electric vehicle batteries could facilitate the deployment of charging infrastructure in cities. It would reduce the cost because of the use of an existing installation. An EV should always have available a charging station within tis displacement range. Therefore, there is a need for a wide charging infrastructure in cities to promote electrical mobility.

Charging infrastructure could be developed for assuming the EV demand or could be shared with other existing installations. In literature, it is possible to find solutions that use the railway power supply grid to feed EV charging points. The use of the railway electrical system for charging EVs would reduce the cost and would facilitate the deployment of EV charging stations in cities.

There are currently several real studies and projects in the field of charging electric vehicles using regenerative rail energy.

3.1.2 State of the art of electromobility and its synergies with railways

This section aims to summarise the two main technologies regarding EV and its implementation in cities considering how their parking is managed: Park-and-Ride and EV stations. Furthermore, several projects of EV stations will be introduced, in order to explain how they have developed the idea of making the most of the interaction between railways and EV, for example, using braking energy of railways to charge EVs and using EVs as ESS.

3.1.2.1 Park-and-ride solution

The popularity of P+R among cities is not without a reason. For example, on the edge of cities and towns, more and more parking facilities pop up with direct access to a public transport service. These so-called park-and-ride (P+R) facilities intercept motorist from travelling into the city, close to their destination, and are popular throughout the United States and Europe[17]. There are four main reasons to be confident of this technology:

- First, it improves accessibility. Most cities suffer from congestion; they are often physically constrained to increase the capacity of the road network and the parking stock in the city centre. P+R increases the number of parking places while avoiding the construction of new car parks in the urban core.
- Second, by encouraging people to take public transport for part of their trips, P+R facilities help to alleviate traffic congestion and other adverse external effects of travel by private car. Any reduction in congestion from the transfer of motorists to P+R frees road space in the city and may induce further visitors that stimulate economic activity.
- Third, opening P+R facilities along existing public transport networks increases public transport ridership and may improve the cost recovery of those services. For example, current fare revenues of urban public transport fall short of the operational costs by 66% in North America[18] and by an average of 48% in Europe[19]. Moreover, increased public transport ridership allows for further improvements in quality of service.
- Finally, as an urban transport policy, P+R is also generally saleable to the public. It widens the choice of transport options, not forcing people out of their cars when using a car is their preferred option. P+R facilities integrate the private car into the public transport system, allowing motorists to evade the low speeds of inner city driving, the inevitable congestion delays, and the high costs of parking in the city, while enjoying the convenience and comfort of their private car for the larger part of the journey outside the city.

Innovation will be required in the transport infrastructure to meet future pressures from increasing carbon emissions, changes in power demand and limited physical space. These will need to be addressed alongside our requirement for more flexible transport options. It is a debate on railways could be successfully integrated and used to charge electric vehicles (EV) batteries at station P+R facilities.

Following on the foregoing, multimodality is another key point to achieve the electrification of transport, combining the advantages of different ways of transport and achieving the best results. For instance, following this model, it is possible to make the most from the high passenger capacity of railways, trams, or metros while EV allow citizens to accomplish the highest flexibility in their movements. Consequently, if establishing synergies between these two ways of transport is achieved in terms of energy savings and, therefore, energy efficiency, transferring power flows between them, through an electrical connection of facilities, then multimodality arises as powerful tool to manage the previous goals.

Finally, the passenger capacity increasing is a concept that links energy sustainability with the principles of urbanism planning. If carrying the same number of passengers is achieved using the fewest number of vehicles, then traffic density is reduced, what is translated into a reduction of total amount of emissions.

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[17] American Association of State Highway and Transportation Officials (AASHTO), 2004. Guide for Park-and-Ride Facilities. http://www.transportation.org/.
[18] Federal Transit Administration, 2008. National transit database. http://www.ntdprogram.gov/ntdprogram/.
[19] UITP (International Association of Public Transport), 2005. Mobility in cities database. Mimeo.

In this section, firstly, a brief introduction of the developed technology is included, secondly, the state of art referring to electromobility and its synergies with railways is analysed.

3.1.2.2 Electrical Vehicle (EV) – station solution

This technology is derived from the concept of having a parking area that is equipped with charging facilities. The idea is to use the energy that comes from train braking to supply these facilities. To introduce this concept, several studies and projects that have been developed are presented down below.

a. Modelling and Simulation of Electric Vehicle Fast Charging Stations Driven by High Speed Railway Systems

One of previously mentioned studies is "Modelling and Simulation of Electric Vehicle Fast Charging Stations Driven by High Speed Railway Systems" [20], in which the connection of charging stations to high-speed power supply is proposed. High-speed rail lines support high loads and are generally located near highways. Therefore, this connection allows the installation of charging stations in service areas that address the problem of finding suitable energy sources.

In this study, a detailed investigation of the modelling and simulation of a 2x25 kV system to feed the railway is presented. A model was developed and implemented using the SimPower systems tool, using MATLAB/Simulink to simulate the railway system itself. This model allows to simulate battery charging process and the railway system as a whole following two successive steps. The results showed that the concept analysed could work in an actual situation.

The results obtained from these simulations revealed that the energy quality of the railway system plays a vital role in order not to compromise the functioning of the system due to the high-power charging infrastructures. This means that it is not possible to achieve the same refuelling rate of traditional cars because of the charging time is much greater than a traditional car refuelling one. Consequently, high-speed railway systems are not able to provide the extra power that larger charging-facility needs. Nevertheless, the disadvantage of the system is that the power provided by the train is limited, so that the charging stations must limit the charging power, even though, under some circumstances, the system is able to supply the power demanded. This does not mean that the system is not feasible, but it just set a limit in its power limit, being a proper solution due to its easy and economical installation.

b. Ferrolinera 3.0

The Spanish railway infrastructure manager (ADIF) led a project called Ferrolinera 3.0. This project aimed to develop, use and validate an innovative system that is able to charge EVs using clean energy from regenerative train braking in high speed and metro networks.

The concept of Ferrolineras consisted of installing a network of charging points connected to the railway network, from where the energy is taken and used for them. Furthermore, the project included the installation of a photovoltaic system as an additional source of energy, which would serve as a power reinforcement, if necessary, for the end user.

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[20] Brenna. M, Longo. M, Yaïci. W. (2017). Modelling and Simulation of Electric Vehicle Fast Charging Stations Driven by High Speed Railway Systems. Extracted from www.mdpi.com/journal/energies

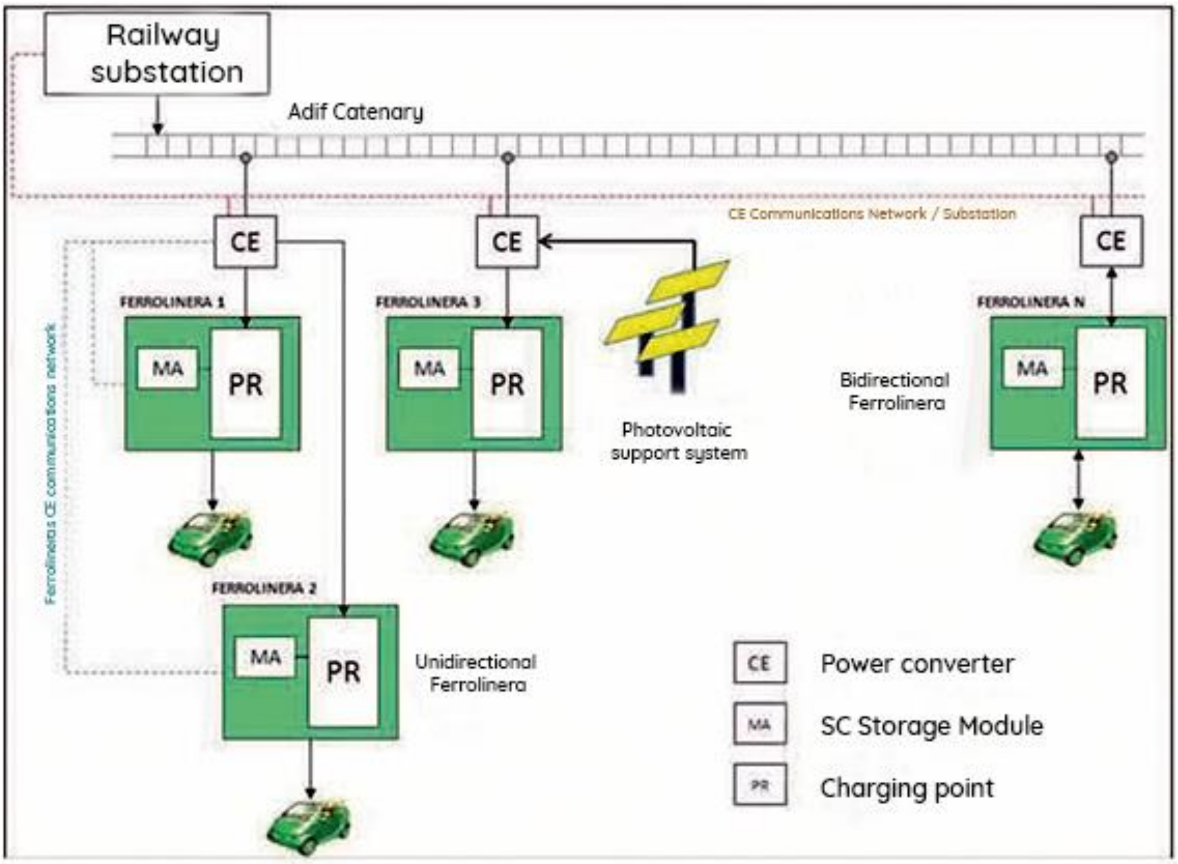

Figure 4 Overview of the proyect Ferrolinera 3.0 (ADIF)

This diagram considers different Ferrolineras distributed through the system, realistically reflecting how the system works:

- ✓ There is a railway catenary, which is powered by a traction substation.
- ✓ Each connecting point to the catenary feeds a power converter (ACDC converter in a DC catenary or in a AC single-phase transformer).
- ✓ The inverter is connected to the *Ferrolinera*, where a storage module MA focuses the energy from the electric braking of trains. This module was developed with supercapacitors and batteries as ESS.
- ✓ PR is the charging point that is close to the storage system.
- ✓ There may be a support photovoltaic system that feeds the Ferrolinera through an appropriate CE.
- ✓ There are also bi-directional Ferrolineras, i.e., those vehicle batteries that can contribute to the power of the electric rail system if they are demanded to do so.
- ✓ There is a communications network that connects all CE computers with the management team of the substation, emitting instructions of operation, which are based on the load curve of the substation, to each CE. Although it is not indicated in the scheme, this system is also connected to the corresponding planning and traffic control system
- ✓ In addition, for those CE that feed several Ferrolineras, also internal communications network exists, which regulates the operation of each one of them according to the CE control set point

A pilot was carried out in two different locations: the ADIF energy laboratory, which was recently built for carrying out tests with different experimental technologies that might be used in the railway electrical traction system, and the Malaga Metro, whose viability is tested.

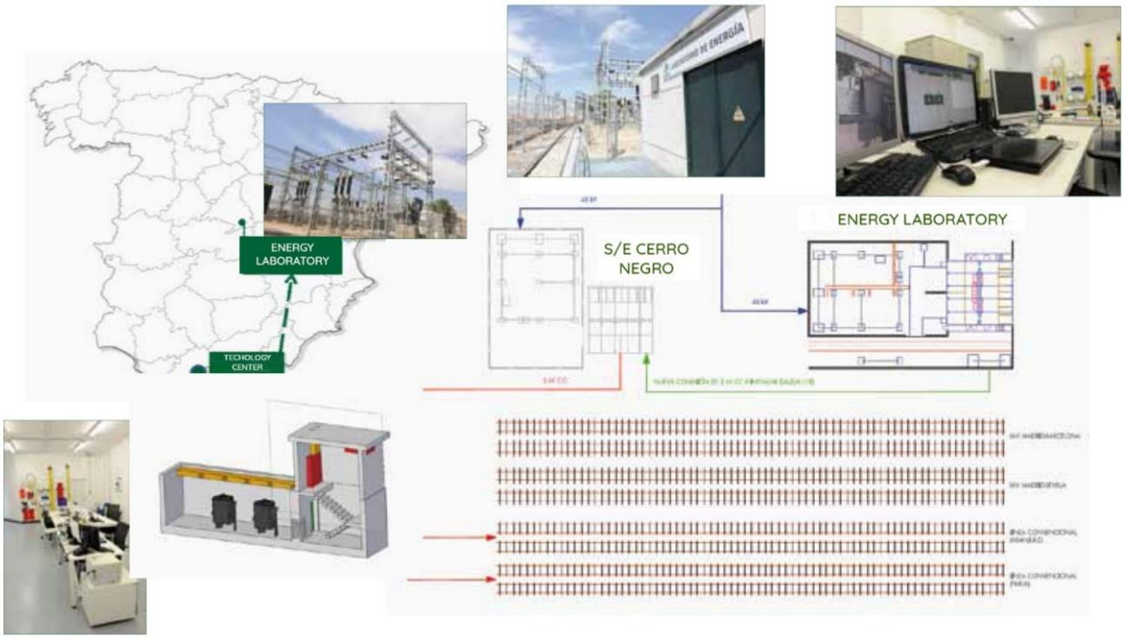

Figure 5 Location of testing facilities (ADIF)

c. Train2Car

Another project carried out in urban railways is the Train2Car project. This project was run by Metro de Madrid and consisted of the development of an EV charging point connected to the network of an urban railway as an energy supply, through an innovative and smart management of DC grid and other electrical devices (traction substations, fixed accumulators, batteries ...), in order to the make the most of the train energy to charge the EVs.

To this end, a prototype of a smart management energy system was developed in Metro de Madrid, at the station of Sainz de Baranda.

Figure 6 Sainz de Baranda station charging point (Metro de Madrid)

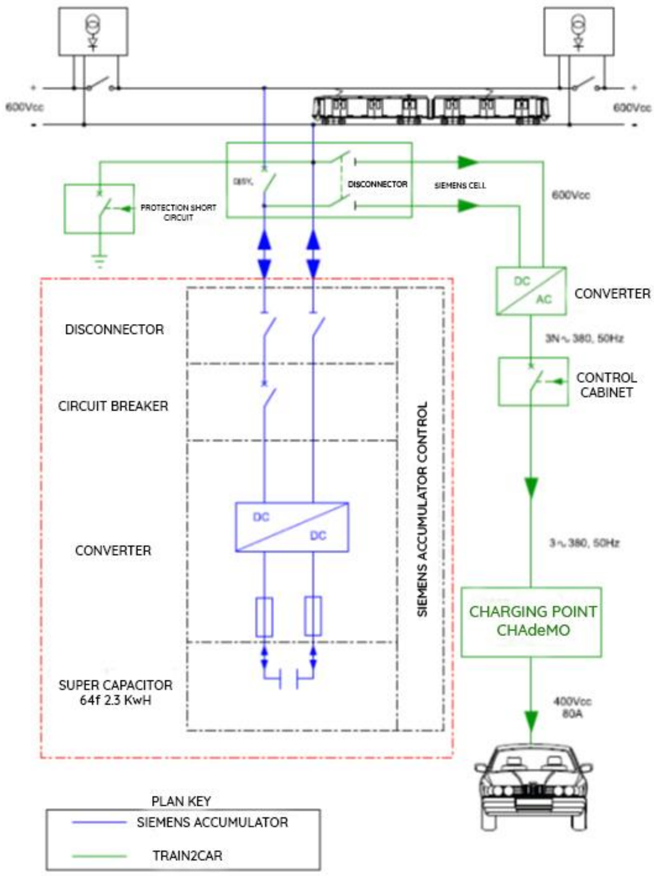

Figure 7 Operating diagram (Metro de Madrid)

To maximize system efficiency, Train2Car takes into account and manages the characteristics of all the built-in components, from supply needs for the metro network based on train traffic and hours, to the load demanded by electric cars.

The energy for charging EVs is not obtained directly from the metro network, but comes from accumulators that are used to store the energy generated by braking trains, returning it as traction energy when the vehicle starts moving.

The EVs' charging point installed by Siemens are manufactured by the GH Group company, based in Valencia. The charging point supplies 50 kW of power and uses the CHAdeMO fast and safe charging protocol, compatible with most commercial electric cars.

Currently this charging point is still available, in which EV users can charge their vehicle for free and with a charging time of between 20-25 minutes.

d. Eliptic Project

One of the most important projects at European level on this topic is the Eliptic project, which is part of Horizon 2020 Framework Programme. The main objective of ELIPTIC is the optimization of the public electric transport infrastructure and energy savings, which leads to the reduction of fossil fuel consumption and improves air quality.

Eliptic is based on the analysis of several concepts in 11 cities (Barcelona, Bremen, Brussels, Eberswalde, Gdynia, Lanciano, Leipzig, London, Oberhausen, Szeged and Warsaw). These projects do not directly analyse the scope of EV charging through the use of regenerative energy from the train or tram braking, but rather analyse it separately. On one hand they deal with the optimization of braking train energy and, on the other hand, with the use of this energy that comes from the metro and tram network in EV charging. In addition, ELIPTIC also investigates the use of energy for charging of e-buses and / or plug-in hybrid buses.

Apart from Eliptic, those projects that cope with the optimization of energy recovery in braking are:

- ✓ Recuperation of braking energy from trams: Refurbishment of a flywheel energy storage system (Bremen, DE)

  Currently, Bremen has 119 trams of the public transport operator (BSAG). All of them are able to recuperate electrical energy while braking and to feed it back into the power grids. However, this energy is only possible to use if at the same time other trams are locally available, speeding up, and, thus, consuming the energy generated from other vehicles braking.

  This use of energy can only be carried out in the city centre, as the demand is greater. However, in the outskirts, the braking energy available cannot be used due to the much lower traffic density. Due to this problem, the BSAG decided to implement a flywheel storage system to use the recovered energy

  The system is formed by several components like coolers, vacuum pumps, inverters, circuit breakers, emergency braking resistors and electronic system control. It is designed to store a minimum of 2 kWh. This is sufficient to collect the energy of a single braking of a tram as it is in use.

  The technology concept in Bremen is still at a stage of research and development, whereby it is not yet ready for fully commercial application.

- ✓ Optimised braking energy recovery in light rail network (Brussels, BE)

  The Use Case consisted of a study of feasibility that aims to evaluate the opportunity of installing braking energy recovery systems in Brussels Tram Network.

Three types of braking energy recovery technologies have been studied in three tram lines to provide insights of the potential of these technologies in the tram network.

The three analysed technologies were reversible sub-stations, on-board energy storage systems with batteries or super capacitors and stationary energy storage systems with batteries or super capacitors located as close as possible to the main breaking / accelerating area.

The conclusion of the study was that the energy efficiency could be increased (avg.: amount of used recuperated braking energy by 3%), while the reversible substations might become partly obsolete due to improved energy storage solutions (e.g. batteries, supercapacitors, flywheels) installed on-board or at trackside. Due to problems of available space for its installation, high cost and little profit, Brussels will not implement the technology.

Regarding the use of energy from the metro and / or tram network in EV charging, the projects developed at Eliptic are:

✓ Use of tram network sub-station for (re)charging e-vehicles (Leipzig, DE)

This study describes the requirements and possibilities of how to support e-mobility in case of multi-purpose use of infrastructure. It is based on the verification of contemporary legal regulations, focusing on recharging of electric / e-buses using the tram energy thanks to the tram infrastructure.

Within this study, external experts took into consideration those German legislation and standards that deal with the support or restriction for the use of tram power network to recharge electric vehicles. The review of these regulations for the use of vehicles electrical supply within the framework of transport companies or third parties was also reviewed at German level[21].

✓ Fast-charging stations for e-cars powered by the tram network (Oberhausen, DE)

The energy supplier Energieversorgung Oberhausen AG (EVO) decided to demonstrate how fast charging stations for cars and LEVs can be implemented with a relatively efficient cost in cities where DC tram infrastructure already exists, and, thus, what enhances the rapid introduction of electric vehicles.

Since November 2017, at the Oberhausen-Sterkrade train station such fast-charging stations (in total three) were put into operation. The electricity is taken from the 750 V DC tram catenary and transformed to supply fast-charging stations powered with 50 kW, usable by cars and LEVs. The special feature of this technical solution is that batteries are considered to be loaded significantly faster than using a conventional technology.

These days, fast-charging stations are still operational, so users can recharge their vehicle for free.

[21] Leipzig Final Use Case Report - Thoralf Knote, Fraunhofer Andreas Böttcher, LVB - programme under grant agreement No 636012 - 15/06/2018

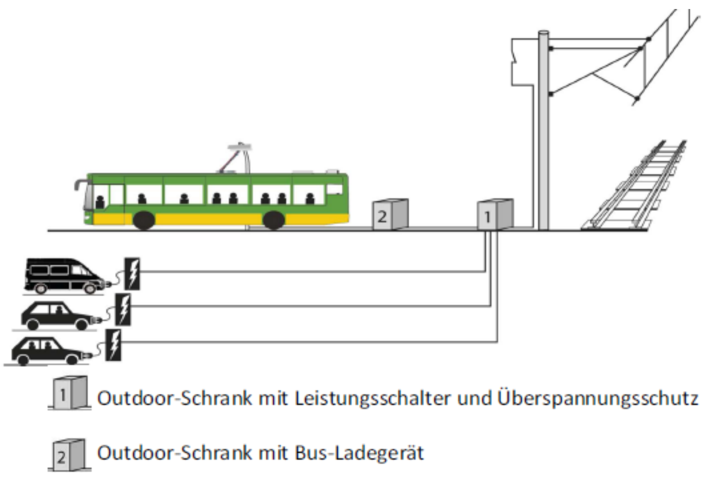

Figure 8: Schematic Sketch of Fast-charging for e-Vehicles from the Tram Catenary at the Train Station Sterkrade (Eliptic proyect)

✓ Use of metro/tram infrastructure for recharging e-cars (municipal fleet and private e-cars) (Barcelona, ES)

The objective of this project is to analyse the operational and legal viability of electric vehicle chargers, focusing on obtaining energy from the railway network.

Considering this goal, connection opportunities offered by the railway electrical network were analysed, identifying time slots and points where the EV chargers could be deployed.

The main results obtained from this analysis are divided into four groups:

- Demand analysis report

  Due to the increase on EVs in the city of Barcelona, around 331 charging points are to be needed by 2020, which makes necessary to analyse several alternatives to obtain energy.

- Infrastructure design and installation report

  The recommended distance between the railway network and the EV chargers should not be more than 300 meters long, and that the recommended connection is AC 420V in the substation transformers bars.

- Operational model definition report

  The consumption on the average car railway lines have been studied in the operational model definition report

  It is observed that the Railway Operator only uses the total power contracted during peak hours. from 8:00 am to 10:00 am, and during night-time, from 00:00 am to 5:00am, the railway services are not operating during weekdays.

  The excess of energy of the railway service during the rest of time could be perfectly used for the implementation of the double connection Eliptic charging points inside the car park

  So, the power usage during daytime could be a combination of the excess of energy previously mentioned and other sources, and during night-time, the charging system could completely benefit from the railway electrical network.

- Legal report

  The Spanish law decrees and regulations have been considered (study from 2018), and they seem to be likely to become more permissive regarding this topic. Currently, the most likely scenarios to be approved are those where there is only one charging manager (PTO to car park manager) and the end user is related to the public administration.

✓ Use of metro sub-station for (re)charging TfL fleet vehicles (e-cars & e-vans) and zero-emission capable taxis (London, UK)

In London, an analysis was run in order to analyse the use of metro substations for charging both electric vehicles and urban buses. For this, the Lillie Bridge deposit was chosen to serve as the location for the demonstration.

For the demonstration, three double-headed 7kW chargers were procured with the intention of delivering a twofold proof of concept. Firstly, EV charging infrastructure could draw current from the London Underground grid without any adverse effect, neither in the power network nor in underground rail operations. Secondly, the charging equipment could operate effectively and reliably while connected to the highly reliable, although potentially low-quality supply in terms of voltage stability (due to DC traction current), network.

A testing and acceptance programme of electrical power quality monitoring was designed and approved to first install the charging infrastructure and connect it to the London Underground AC grid in a switch room at Lillie Bridge, following a baseline monitoring period to move on to EV charging. Testing was undertaken at various levels, from a single vehicle trickle charging an almost full battery to 6 vehicles charging a heavily depleted battery at maximum current draw. All tests were delivered with no adverse harmonic or voltage deviations recorded.

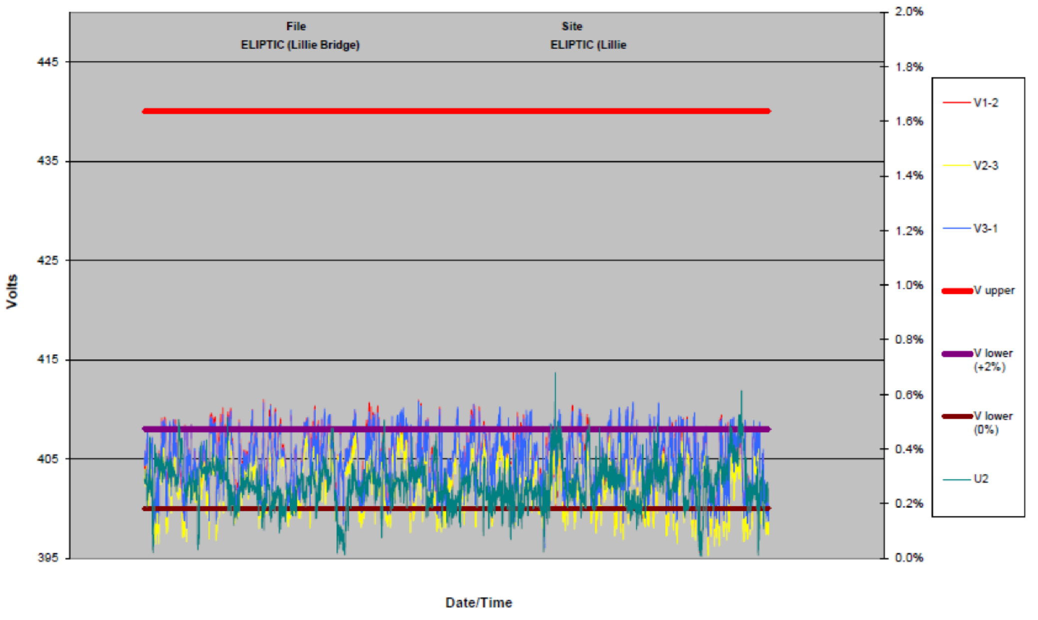

Figure 9: Voltage Monitoring Lillie Bridge EV Test(Eliptic proyect)

As a result of the test, charging infrastructure connected to LU grid had been accepted considering long term use and those vehicles that collectively use charge points reduce tailpipe CO_2 emissions of the TfL support fleet by more than 13 tonnes per year.

This project showed that EV charging using London Underground grid, experienced no detrimental effects, neither in the AC grid nor in Underground train operations. As a result, discussions are taking place around replicating the ELIPTIC solution at a MW scale deployment of electric bus recharging.

3.2 Electric Vehicles, charging stations and V2G concept

EU transmission and distribution (T&D) networks are already operating close to, or beyond, their rated capacity and struggling more frequently to maintain supply due to demands beyond original design specifications. Therefore, to satisfy EV fleets at any reasonable volume and maintain electrical power quality, additional power sources will be required on the network at a rate to match the market growth of more electric vehicles. However, the EVs also are potential on serving the electric grid as independent distributed energy source. It has been revealed by some studies [22]that most vehicles are parked almost 95% of their time. In this case, they can remain connected to grid and be ready to deliver the energy stored in their batteries under the concept of vehicle to grid (V2G).

The EV charging industry seems to be caught at a crossroads currently with regards to standardisation of charging plugs and connectors. The two main types of charging connectors available are the Combined Charging System (CCS) and CHAdeMO. Both types of plugs have found favour with different vehicle manufacturers. CCS is the preferred type of European and US manufacturers such as BMW, Volkswagen, GM and Ford. On the other hand, Japanese manufacturers such as Nissan, Mitsubishi and Subaru tend to prefer the CHAdeMO type as illustrated in Figure 10.

Figure 10 CCS Combo 1&2 Connectors (Left) & CHAdeMO connector (right)

CHAdeMO is typically used for DC charging of EVs, while CCS, as a combined system, can provide both AC and DC charging. The problem for consumers and charge point providers is that the two systems are wholly incompatible. Because of this incompatibility, network operators are currently installing both standards at most public charging stations to cater for all users. This increases the complexity and the cost of the infrastructure. A single standard charger type would be best for all involved. Regarding Ireland & the UK, the European Union has been trying to address this through regulation over recent years.

IEC 62196-1:2014 is the relevant European standard which lays out the general requirements applicable to plugs, socket-outlets, vehicle connectors and vehicle inlets for charging of electric

[22] Shoup, Donald. (1997). The High Cost of Free Parking. Journal of Planning Education and Research. 17. 3-20.

vehicles. Since the release of this standard in 2014, it has been a requirement in Europe for all AC public charging stations to incorporate a Type 2 connector, which is compatible with the CCS system. This would indicate that the CCS standard for charging connectors will most likely prevail in Europe. Only time will tell whether it can win out over CHAdeMO, but it still has a long way to go before this issue is settled.

3.2.1 Charger types

Network operators, through their own market research and procurement practices have decided on the type of network they operate and the chargers which operate on it. At a high level, chargers are typically broken into categories based on the speed of recharging they offer – slow, fast and rapid – although as technology advances, ultra-fast chargers are now becoming viable. Regarding the charge speed, there are other factors which come into play depending on the type of car being charged and the charging connector used for example. This section will provide a brief outline and discuss the range of equipment which is currently or will soon be available to consumers on these networks. To put all this information into some context, Figure 11 provides a useful visual indication of the number of driving miles added per minute of charging, depending on the charger 'type' or output.

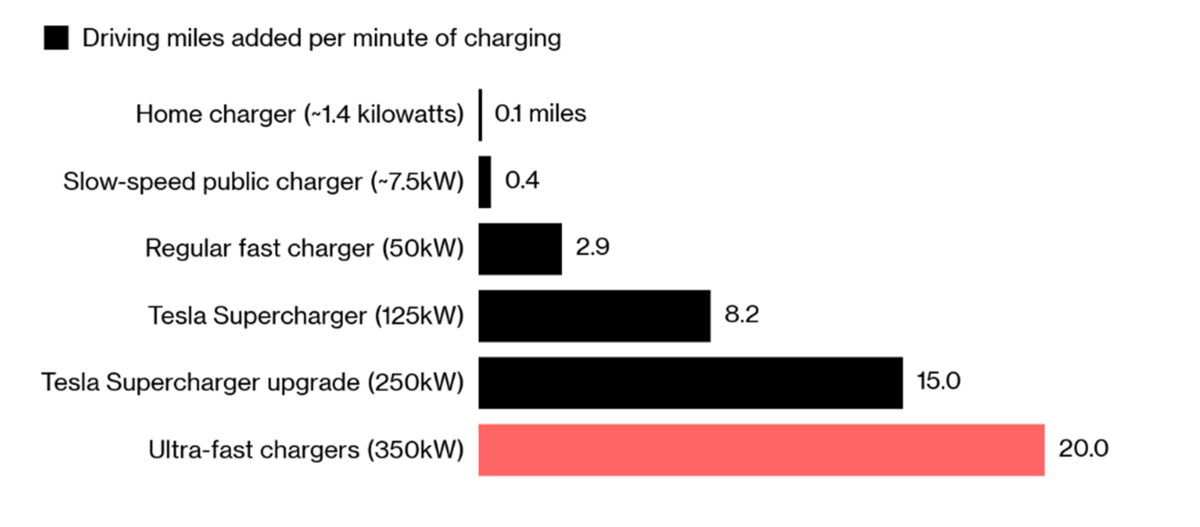

Figure 11 Driving miles added per minutes of Charging[23]

When a driver stops to recharge, it is very beneficial for them to know how much range they will add to their vehicle during their stop. This is an idea that drivers of ICE vehicles are already very comfortable with and are aware that in a matter of minutes, they can be on the road again with maximum range. Although this is beginning to become a possibility for EVs with ultra-fast charging becoming available, it is most certainly not yet widespread. The development of public infrastructure must now focus on installing networks of ultra-fast chargers at strategic locations. EVs will only be able to compete with ICE vehicles when similar range can be added to a battery within a matter of minutes – single digits would be ideal.

[23] Governors Wind & Solar Energy Coalition, "News," 12 May 2019. [Online]. Available: https://governorswindenergycoalition.org/fastest-electric-car-chargers-are-waitingfor-batteries-to-catch-up/.

3.2.1.1 Slow Chargers

Slow chargers are those that typically provide a charging output of around 3 kW. For most cars on the road today, that would mean a full charge could take around 12 hours, and as battery capacities are increasing in newer models, this means some may take even longer.

These charge points are typically 'untethered', meaning that the user needs their own cable and/or adaptor to connect to the unit. During the initial rollout of infrastructure in Ireland and the UK, slow chargers such as these would have been common. However, they are now becoming largely redundant in the public charging market. There is an exception to this though, as some city councils are beginning to convert street lighting lampposts into slow charger units as shown in Figure 12, which are particularly useful in built up areas where users do not have a drive to park their car for a charge overnight[24]. This technology allows them to charge overnight while parked on the street. It also keeps disruption due to construction to a minimum as it retrofits the units on existing infrastructure.

Figure 12 Slow Charger (Public or Home)

3.2.1.2 Fast Charger

Fast chargers are those that typically provide a charging output of somewhere between 7 kW and 22 kW. At the full charge output, most cars on the market today could be charged fully in approximately 2 to 3 hours on a fast charger unit. They are usually a 'tethered' unit – meaning a cable is permanently attached and the user's vehicle must be compatible with the connector type supplied. Type 2 connectors, as required by IEC 62196, would be the typical connector provided at these units – allowing almost all cars to utilise them, some using an adaptor.

3.2.1.3 Rapid Charger

Rapid chargers are those that typically provide a charging output of 43 kW and above, up to 120 kW on the Tesla Supercharger network. They can allow for an 80% charge of an EV battery in around 30 minutes, sometimes even as quickly as 20 minutes. These are the new standard in the current rollout

[24] EA Technology Limited, "My Electric Avenue: Summary Report," EA Technology Limited, Cheshire, 2016.

of charging infrastructure and in many sites, they are replacing the older slow and fast charger points installed previously. They are typically a 'tethered' unit with a cable attached as shown in Fig.13. Many of these chargers offer CHAdeMO (DC charging) and CCS type connectors for rapid charging[25]. Tesla tend to utilise a modified Type 2 connector at their sites.

Figure 13 Rapid Charger

3.2.1.4 Ultra-Fast Chargers

Ultra-Fast chargers are relatively new to the market and are those that provide a charging output of around 350 kW shown in Figure 13 These are most useful for recharging regular passenger vehicles at a very high speed or for charging larger vehicles such as buses or trucks. They are likely to become a gamechanger in the EV charging market, as they can offer an 80% charge in a matter of minutes. This will bring the duration spent charging an EV very close to that of refuelling an ICE vehicle. For many people, this may be the advancement needed in technology to encourage them to make the switch to electric driving[26]. Due to their high-power output, they are not suitable for every site. Many charge network operators are trialling ultra-fast chargers currently, so it seems that it will not be long before these chargers become the new standard.

[25] ESB EV Solutions, "Coventry," 21 July 2019. [Online]. https://www.esbevsolutions.co.uk/coventry.
[26] Green Car Congress, "News," 11 July 2018. [Online]. https://www.greencarcongress.com/2018/07/20180711-tritium.html.

Figure 14 Ultra-Fast Chargers

3.2.2 Chargers by Location

The types of chargers installed can vary depending on the location of the site. Whether it is a motorway services station, a public street or workplace car park or even a home. The slow chargers are becoming redundant in the public space, they still have a use elsewhere. In many homes and business, it is not feasible to provide fast or rapid charging due to the power demand required. Many people’s vehicles are parked for long periods of time in these locations, typically greater than 8 hours – during the working day or overnight – this makes conditions more favourable for a slower charger unit.

The opposite would be true of a public space in a petrol station forecourt. Users tend to stop for short period only and require a high level of recharge in this short window as shown in fig. 15. There may also be a high demand on the unit, so it is important to get customers in and out quickly. It is more feasible for these sites to have a large import capacity compared to a home or small business, which allows the installation of multiple charging units – anywhere from slow chargers right up to ultra-fast chargers.

Therefore, it can be seen how diversity in the network is required to suit the needs of the user at that particular location. The network is not likely to become one providing a blanket of ultra-fast chargers any time soon. It will most likely be defined by the driving habits of the users and will evolve accordingly over time.

Figure 15 UK's largest public rapid charging hub (Milton Keynes)[27]

3.3 Customer behaviour, Demand side management and Demand side response

The aim of an electrical generation and distribution system is to provide energy in a perfect equilibrium of power requested by users and generated power. However, the requested power is not steady, and it changes significantly during the day. The typical energy demand is very low during the night due to reduced amount of ongoing activities and has few peaks during the day with the higher one in the first part of the morning, mostly driven by the beginning of the users' activities.

Below Figure 16 depicts an example of actual energy demand data in the Italian national grid. Red line is the predicted demand, blue line is the actual recorded demand.

[27] BP UK, "Press releases and latest news," https://www.bp.com/en_gb/united-kingdom/home/news/press-releases/uks-largestpublic-rapid-charging-hub-inaugurated-in-milton-keynes.html.

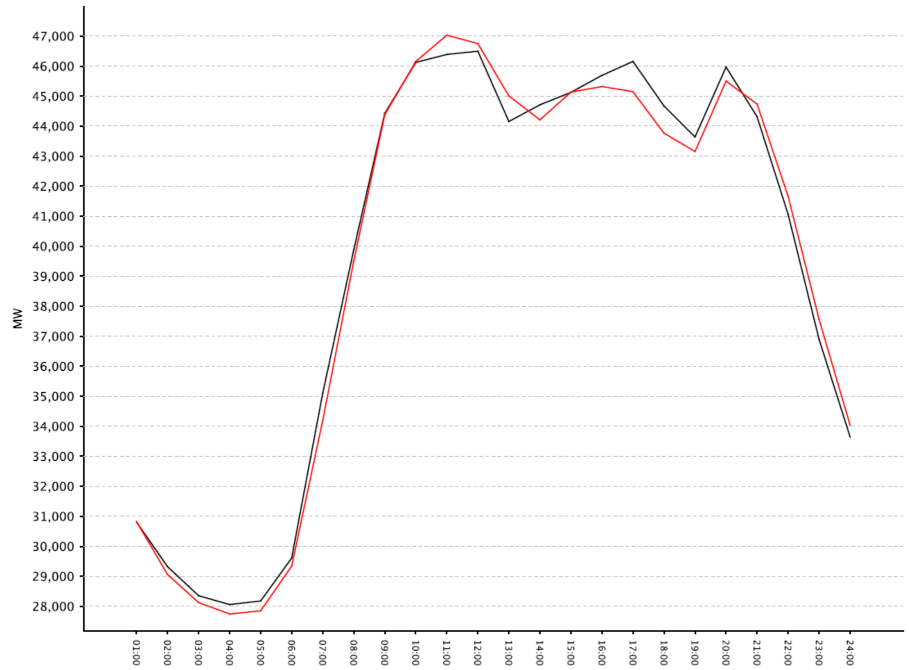

Figure 16 Example of Actual Operating Data about Energy Demand (Red line is the predicted demand, blue line is the actual recorded demand). Source: Italian TSO Terna, September 2019

Energy supply and demand must be balanced on a second-by-second basis, and this is achieved by using several response and reserve services that allow the grid to respond quickly to any unexpected changes in supply or demand and maintain continuity of service.

The Transmission System Operator (TSO) continuously obtains data about system status and implements the proper corrective actions in order to keep energy demand and generation balanced:

- On planning phase: developing energy supply plan on the basis of foreseen energy demand and energy generation capability. This allows to set up generation levels, grid configuration and reserve services.
- On real time control phase: analysing the current status of the system in order to adjust the energy generation and adjust grid confirmation if needed in order to optimize the distribution service or recovering any disruptions.
- On operating data analysis phase: analysing statistics of actual operating data and production and transmission system in order to obtain useful data for optimizing the system.

The energy demand is not the only issue for TSOs. Management of the great difference between peak and off-peak demand during daily curve is also challenging.

Once the topic has been introduced, this section will deal with the EV integration and grid challenges (time of use tariffs, V2G and smart metering/chargers), the implications of smart grid installation towards demand side management and demand side response, and, finally, a brief review of the opinion provided by the E-LOBSTER project stakeholders.

3.3.1 EV integration and Grid Challenges

The outlook and future projections for the electric vehicle industry is very positive. There are many reasons for this. One of which would be the United Nations Framework Convention on Climate Change (UNFCCC) vision. In 2016, many nations signed the Paris Agreement with the aim of limiting the impact of global warming. As of July 2019, 185 of the 197 parties to the convention have ratified the agreement. As the transport sector produces a significant portion of the emissions in most developed countries and much technology already exists which can help to reduce these emissions, more and more countries are looking at electric vehicles and associated charging infrastructure as a way to achieve the aims of the Paris Agreement.

The existing infrastructure for EVs was originally developed in response to meet the needs of early adopters of electric vehicles and was a viable means of investing in 'green energy' technologies. EVs are now becoming more commonplace and the needs which must be served by the infrastructure are rapidly changing – requiring higher power, faster charging units. Infrastructure is also being clearly shaped and influenced by government policies as much as it is by technical problems such as grid capacity and power flow issues. Lessons have been learned in all these areas since the first modern electric vehicles took to our roads and these have raised their own questions.

In order to build on the successes to date and further develop the infrastructure networks to a point where it can meet the demands of a fully electric fleet of vehicles on our roads, it has been shown that the electricity grid must also evolve and become more flexible in its approach to power distribution.

If consumers are to switch to electric vehicles as anticipated, it would be fair to expect that the distribution network will encounter a wide range of problems stemming from the increased demand on the network. This may even become more pronounced depending on consumer habits – for example, if many people plug in their vehicles during the existing network peak upon arrival home from work in the evenings. The typical approach by utilities to increased demand on their network would be to upgrade infrastructure such as transformers, underground cables or overhead lines. However, this will likely be unfeasible due to the large cost and workload involved due to a large and rapid increase in electric vehicles on our roads. The utilities may simply be unable to keep up. These are some of the reasons that many utilities are beginning to look at deploying new technologies to customers' homes and businesses.

A smart solution needs to be found to this problem. With the ongoing advancement in communication technologies and the internet of things (IoT), many innovative solutions are being proposed which may prevent the typical problems associated with a large increase in demand across the entire network. Utilities need to achieve some method of demand diversity in order to prevent these problems. The following solutions are some of the most likely to be implemented in the coming years.

3.3.1.1 Time of Use Tariffs / Demand Side Response

Time of Use (ToU) tariffs are a method of demand side response (DSR) which have been around for a long time, up until recently there were typically used by utilities for night rate tariffs and storage heating supplies, with the aim of 'flattening' the daily demand curve.

Encouraging consumers to use electricity at night by offering cheaper rates during the demand 'trough', this can have the effect of easing the daily demand 'peak'. This idea could again gain in popularity as a method of achieving the diversity needed to manage the power flows on local feeders, by encouraging users to charge vehicles at off-peak times.

3.3.1.2 Vehicle to Grid (V2G)

Vehicle-to-Grid, commonly referred to as V2G, is another method of demand side response. It operates on the principle that the battery of an electric vehicle is used as a bidirectional device, not only consuming power as a load but also exporting power back to the grid when required.

By reversing the direction of the power flow, from the vehicle to the grid, the batteries could essentially be used to provide an ancillary service to the grid, such as frequency response. This is an ancillary service which is designed to maintain system frequency and stability during a sudden change in supply or demand on the grid. It is typically provided by larger scale batteries or flywheels, with the providers of the service receiving a payment from the grid for the service availability. The ultimate goal of V2G technology would be for it to advance to a place where it could compete in the ancillary services market. For this to happen, the number of EV's on the road needs to increase dramatically and customers need to be aware of and willing to participate in providing such a service.

There are companies currently looking at providing such a service, who are involved in energy aggregation. This would involve them signing up customers, who drive EVs and are willing to partake in providing the service in return for payment. They may however need to sign up to a set of terms and conditions with the aggregator such as ensuring their vehicle is connected to the grid for a certain number of hours a day, or at certain times. They may also be required to accept a pre-agreed minimum charge capacity. For example, where the aggregator has control over 20% of the battery capacity to provide grid services, the customers battery charge level could then be as low as 80% when unplugged depending on the interaction with the V2G charger. Battery technologies may need to adapt to ensure the batteries being installed in vehicles for use with V2G are suitable for the increased charge and discharge cycles which this may inflict on the cells.

3.3.1.3 Smart Metering & Smart Chargers

As mentioned, communication technologies and IoT are making huge advancements in recent times. People's homes and businesses are smarter and more connected now than ever before. 'Big data' is also becoming an increasingly common tool. Combining consumer data around electricity usage trends is something that can provide utilities with a clearer picture of customer habits, particularly around the charging of electric vehicles as they become more common. Smart Meters and Smart Charging devices are beginning to be rolled out by many utilities as a method of harnessing this data and providing services to consumers tailored to their usage pattern.

Smart meters may have many different functions built in, such as the implementation of a ToU tariff, as mentioned previously. The devices could be installed with the functionality of changing the unit price of electricity (in either real time or predetermined) depending on local demand on the distribution network. This can have the benefit of discouraging people from charging their EVs at peak demand times to ease the demand on the local network. The built-in communication technology can provide updates or notifications to consumers regarding tariff changes, to allow them to decide whether to leave the load connected or to reduce their demand. Used in conjunction with a smart charger - discussed in further detail below – the increase in unit price above a pre-set threshold could signal the smart charger to disconnect the EV until such a time that an acceptable unit price is available once again.

Smart Chargers may also have many different functions built-in, such as the implementation of V2G as mentioned previously. Smart chargers can be provided with an in-built bidirectional charger, which can be used to provide power flow back to the grid from the EV battery. Another useful function of smart chargers could be their ability to provide load balancing. This is extremely useful in installations with a limited electrical import capacity. This may become prevalent in charging stations providing multiple charging units. For example, a three-phase 50 kW charger will draw approximately 70 Amps from the supply. There are many sites, such as workplaces, which may only provide a 100 Amp supply but multiple 50 kW chargers. This could prove problematic where multiple EVs attempt to charge simultaneously, exceeding the capacity and tripping out the main circuit. By using smart chargers, they can be set to balance the load in real time so that main supply is never exceeded. In the case of four EVs charging simultaneously, they could each be limited to 25 Amps each. Obviously, this reduces the speed of charging but maintains the security of supply.

3.3.2 Implications of smart grid installation towards demand side management and demand side response

The goal of this section is to draft how the implementation of E-LOBSTER as an interface between train and distribution grid affects demand side management and response. As background knowledge, MERLIN project[28], which tackles the issue of smart grid implementation and synergies between railways and electrical distribution grid, arises as the most similar study and it is likely to serve as a source of data regarding the behaviour of the electrical market towards smart grid use.

The following paragraphs will try to briefly outline the behaviour of electrical market and its response when new agents, in this case E-LOBSTER device and its implications, come into play.

Firstly, the definition of the characters that play an important role within the energy market and its relation regarding railway systems are the following:

- Electricity Market Operator (EMO): company that operates an organized electricity market.
- Electricity System Operator (ESO): companies in charge of balancing the generation and the demand.
- Transmission System Operator (TSO): companies operating a transmission grid.
- Distribution System Operators (DSO): companies in charge of operating the distribution grids, which supply electrical energy to every costumer with the required quality.
- Close Distribution Systems (CDS): systems which distribute electricity within small areas (small industrial, commercial or shared services zones) that do not supply energy to household customers and which fulfil the following conditions: (i) integrated operations and production process, (ii) energy distributed to the owner and the operator of the system and (iii) other industrial, commercial and shared services.
- Trading companies: responsible for producing the energy that has been committed in each power plant.
- Infrastructure Manager (IM): any body or firm responsible for establishing, managing and maintaining railway infrastructure, including traffic management and control-command and signalling. An IM must also provide ancillary services to RUs, such as traction current.
- Railway Undertaking (RU): any public or private undertaking licensed whose main business is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction.

Establishing a smart grid is supposed to enable a proper controllability of the interactions between these actors and fosters every element to become reactive. Therefore, the electrical system is no longer the only one considered to play a reactive role.

[28] https://cordis.europa.eu/project/id/314125

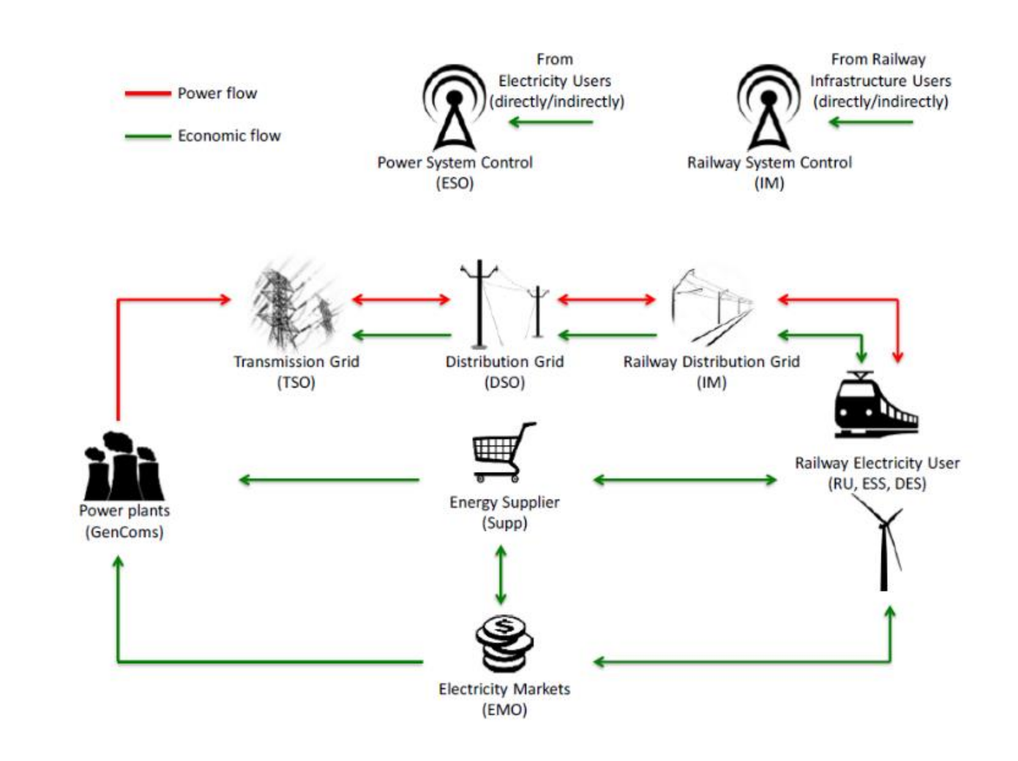

Figure 17 Power and economic flow of Energy Market[29]

With the aim of presenting how the interaction between the energy system actors may change with the introduction of the E-LOBSTER device into the system, the traditional and the most likely new interaction of the different actors with the energy are described.

3.3.2.1 Traditional interaction between the different electrical energy markets

The traditional point of view of electrical interactions sets railway facilities as merely consumers of electrical services or loads. These interactions may be split into the following:

a. **Interaction with the energy market**: Every consumer can freely choose their energy supplier and the energy can be purchased by two different kinds of mechanism:
    - Contractual agreements (non-organized market) with a Generation Company (GenCom) or with any other supplier (retail or wholesale) or even the IM. In order to mitigate the risks, supply contracts incorporate a risk premium (which is normally lower when agreed prices are indexed to market prices).
    - Direct purchase in organized markets. As the production of every power plant at each hour has to be established in advance (power plants may require several hours or even a few days, depending on the generation technology and the previous operating conditions, to start up), a multi-timescale scheme is commonly used in operation and, consequently, in organized markets (where acquisition of the energy is done in different moments, with different time horizons).

However, the direct purchase in organized markets may be very challenging in practice because of the uncertainty in the estimation of prices (final prices are not known when the bids are submitted)

[29] EU FP7 Project “MERLIN (2015)”. GA - 314125

and in the estimation of the energy demand (the real consumption/generation is only known in real time, when it is measured and, in fact, varies every day).
As deviations from the expected consumption/generation profile are normally penalized in the electricity market, in the scenario in Spain set out by the MERLIN project, a 50% reduction of the risk premium charged by an existing energy supplier thanks to the improved predictability achieved by a smart Railway Energy Management (REM) system could led to overall estimated savings of 1.84%.

b. **Interaction with the public grid**: most of the energy used in railways is produced in power plants external to the railway and crosses different intermediate grids before reaching the railway infrastructure. As a user of the electrical system, each railway agent has to pay:
   - A toll to the intermediate grid operators, include two terms: (i) a term proportional to the supplied energy and (ii) a term proportional to the supplied power.
   - A fee to the ESO for the different operation costs, which is normally proportional to the consumed energy.

From an electrical point of view, these power peaks also have a negative impact in the distribution grids. An appropriate integration with the electrical system would be beneficial for both systems, but it is not feasible without using smart grid technologies. the implementation of a system such as a smart REM system can lead to an average reduction of 15% of the power peaks. the electricity bill can be reduced a 5.54% thanks to this reduction in the power peaks[30].

c. **Interaction with the railway electrical grids**: According to the Directive 2009/72 and reinforced by the Directive 2019/944, the railway power system can be considered as a CDS and, therefore, the IM would act as a CDSO. According to Directive 2009/72, the IM must allow the Third-Party Access, provided that the established technical requirements are met. The Directive 2019/944, which updates D 2009/72 and D 2012/34, also points out the necessity of fostering the use of EV in terms of reducing the greenhouse gas emissions and the use of the ESS in order to enable the use of new sources of energy.

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One of the most important goals of railways smart grids is to achieve a more efficient utilization of the available resources, not only of the energy but also of the installed capacity of the infrastructure. To allow a proper optimization of the operation, the train power profiles must be predictable for all the trains and their allocated power at each substation should not be exceeded.

3.3.2.2 New interaction within the different electrical energy markets

On the other hand, the new interactions that the introduction of E-LOBSTER and smart grids in railway facilities will cause the development of several architectures and information exchanges structures that allow new ways of interaction between the involved agents (IM, RU, EMO, TSO, DSO, etc. Some of the services are, namely:

- Railway system operation services, provided by a REM.
- Execution of the control actions performed by the trains, ESSs, DESs, etc.
- Energy procurement services: provided by an algorithm.

Some interesting potential services to be investigated with respect to E-LOBSTER could be the following:

- **Electrical railway system operation systems**: These services aim to optimise the energy flows (trains consumption/regeneration, infrastructure consumption, ESS charge/discharge, DES production, etc.). The entity supplying this operation control services (normally the IM) should be paid for providing these services, either by means of a fixed

[30] EU FP7 Project "MERLIN (2015)". GA - 314125

term (that should be established in the network statement) or using a distribution mechanism of the achieved savings. In some on-field tests carried out in Malaga in the MERLIN project, these savings have been estimated in 101k€/yr-9.64% (energy minimization under traffic congestion situation), 108k€/yr-10.28% (power peak minimization) and 126k€/yr-11.97% (combined energy and power peak minimization).

- **Execution of control actions**: These services consist in executing the instructions received from a REM to enhance the operation (for example, to reduce power peaks, to reduce losses, etc.) and are provided to all the agents involved in the operation (RUs, IMs, etc.). The agents that follow these instructions should be paid according to a distribution mechanism of the achieved savings.
- **Energy procurement services**: In order to minimize the volatility of energy prices, a practical solution is to manage a portfolio of supply alternatives, combining long term contracts and participation in the spot markets.

To minimize the uncertainty in the volume of energy, one has to be able to minimize the deviations by operating the system (giving instructions to the trains and to the infrastructure). Secondly, the management of the portfolio of supply alternatives has to minimize the exposure to the deviations. For this second approach, an algorithm can determine the way of combining contracts and the participation in the spot market in order to minimize the impact of the deviations.

This service can be provided by the IM (or, alternatively by a third party retailer) and should be paid for, either by means of a fixed term (that should be established in the network statement) or using a distribution mechanism of the achieved savings, which might be higher than 50%.

The following considerations regarding smart grids and its implementation are the following:

- The adoption of smart grid technologies has achieved savings of 11% of the total energy consumption under traffic congestion situation and 15% of the power.
- The optimization of the energy procurement is advisable, not only because of the average energy price reduction it can achieved, but also because of the risk management strategies that can be followed to reduce the exposure to the volatilities of spot market prices and the energy demand.
- To allow a proper optimization of the operation, the train power profiles must be predictable for all the trains (those equipped with smart grid technologies and those which are not) and their allocated power at each substation (which is dynamic) should not be exceeded (unless the control system authorize it.
- In order to provide the appropriate economic signals, a mechanism for distributing the economic savings that can be achieved by the smart grid has to be detailed, including both the “mark-up” to be paid to the IM and the payments to the RUs.

3.3.3 Stakeholders’ behaviour, comments, and positions expressed by E-LOBSTER PTOs

Furthermore, the stakeholders’ point of view is also an interesting input regarding the behaviour of demand side response and management. In the E-LOBSTER workshop involving the PTO (Public Transport Operators) agents that took place in Madrid on the 20th of November 2019, several concepts were revealed as starting points. Among other the three main ideas were electrical power flow between the grid and the railway net, energy storage systems regarding their application to E-LOBSTER project, and energy losses and their relationship with converters and inverters.

Regarding the demand side, the stance of stakeholders was that some of the new opportunities that smart management technologies enable are to be further developed to have an impact on energy consuming. This point refers to the action of selling the energy that comes from train braking that should be further investigated by taking into account the current evolution of the regulatory scenario as well as the limited extension of the use of smart grid technologies, which means a high price for this energy.

Furthermore, the future role of IM and rail operators, planning the headway, timetables and frequencies in order not to cause peak or valley times regarding energy, will hoist smart management technologies to a place where it would be essential. In addition, the concept of synergies within smart cities, will also allow to widen the business, linking EV fleets and parking, railways, and energy distribution.

In conclusion, the implementation of railway smart management with the help of E-LOBSTER controller may allow to achieve the following:

- Novel reversible power supply with dynamic regulation for all DC transport systems. It is the technology that enables full reuse of the kinetic energy recovered by the train in braking phases.
    - Recovered energy during braking mode (after exchanges between trains)
- Greatly improve traction network sizing (equipment, civil works and urban real estate)
    - Due to its recovery of the braking energy, rheostatic heat dissipation is reduced. This implies less tunnel and in-station ventilation.
    - Less HVAC energy, hence reduced energy bills.
    - Increase the distance between substations, hence less sub-stations required.
- Greatly improve energy performance and consumption
    - Very low current harmonics levels.
    - Unity power factor (Cos phi = 1).
- Environmental Benefits
    - Energy recovery solution:
- Limits the energy consumed, hence Lower CO2 emissions.
- Lower Heat emissions.
- Lower Energy Costs
    - Braking energy is re-injected back into the industrial network or sold back to the energy provider allowing considerable saving.
    - Train rheostatic converters and resistors can be eliminated, thereby reducing the train’s weight leading to further energy savings.

4 Implementation of smart management of railway networks towards power losses minimization

As it has been introduced along the previous sections, the implementation of smart management technologies in railway networks will mean advantages worthy of consideration. Beyond energy savings that these kinds of systems allow to achieve, new opportunities of business are enabled. With regard to the latter, the purchase of energy and the entry of new actors, like EV, open a new business framework that was not previously considered.

This section aims to set the current framework and future challenges of the use of smart management systems in railway network, and some case studies where energy losses are analysed.

4.1 Overview of smart management of railway networks

Smart management of railway networks has already been subject of study and several projects have settled indications about its implementation in existing facilities. These studies and projects essentially focus on how it might be possible to reduce energy losses in railway traction, which represents around 15% of the total amount of energy that is consumed in this type of facilities and which is the main source of power demand. The main idea is based on translating power savings into economic savings, that can be achieved if the total power balance, power demanded versus power offered, tends to be zero.

The origin of the very concept of railway smart management might come from the opportunity that regenerative braking offers. There are several studies that argue the train´s capability of energy regeneration is between 30% and 40% of the energy consumed. For several reasons, on most of the metropolitan lines there are rheostat consumption losses of around 10-12%, which limits the real savings obtained by regenerative braking. Some projects argue that Spanish railway network losses per year around 1200 GWh through rheostat braking, which means only less than 50% of this energy is used. Thus, an appropriate management of rolling stock energy is estimated to produce savings of up to 20% of total energy consumption, which in a typical year, trains operating on the Spanish network lose 1.200 GWh of energy through[31] braking. 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.

This section aims to tackle the results of installing smart management technology in railway networks and to analyse some examples of studies and projects that have been carried out, considering three main aspects: infrastructure, rolling stock and operation.

4.1.1 Infrastructure role within smart management of railways network

Given that smart management technologies are mainly supported by smart grids and considering that those are installed within the power grid, infrastructure elements are regarded to play a rather important role regarding energy efficiency. This section aims to review the main losses in

[31] ElecRail Spanish national Project. Centro de Estudios y experimentación de Obras Públicas (Ministerio de Fomento), número de proyecto PT-2007-038-20IAPM. http://www.investigacion-ffe.es/elecrail_publicaciones.asp

infrastructures, which were analysed in previous E-LOBSTER deliverables, the way this issue may be tackled, and how smart grid could be integrated in railway facilities.

Therefore, considering that train traction energy represents around 15% of fixed operation costs[32], it becomes vital to try to optimise this in order to improve the total energy efficiency of the facility. Here is where implementation of smart technologies, which allow to manage the power flow, like smart grids, can make a difference in terms of energy and economic savings.

Consequently, if the point is to analyse the effect of smart grids implantation regarding energy efficiency, then it is also necessary to take into account the main sources of energy losses in DC railway facility:

1. Energy losses that occur on the feeder cables of the substation and track sectioning cabins and on the return-cables depend on length of feeder/return cables, cross-section of conductors/cables, material of which conductors or cables are made, and the value of the current that flows through them.
2. Energy losses in the internal resistance of the substation depend on the external characteristics of the substation and the ratings of the set: short-circuit power on the AC busbars of the substation, off-load voltage of the rectifier, number of active rectifier sets, rated power of the transformer, short-circuit voltage of the transformer, expressed as a percentage, rated voltage of the set, rated current of the set, voltage drop on a single diode of the set, and number of diodes in a branch in the case of a series connection.
3. Energy losses occurring on distribution network due to harmonics and power factor.
4. Other non-technical losses due to the lack of power consumption metering

After enumerating the main energy losses, it is important to highlight that the implementation of smart technologies will not completely avoid these losses, but it will generate the possibility that the total energy balance could be nearly neutral. Hence, the actions that are introduced in order to increase the energy efficiency, or reduce losses are the following.

- Regulating substation transformers to operate a line that possess an open circuit voltage allows to avoid excessively low voltage on the pantograph and, at the same time, reduce the loss in rheostatic braking.
- Disconnecting some substations at off peak times to reduce the frequency of events in which the presence of an active substation between trains exchanging energy, limits receptivity. Metro and commuter lines, for instance, with a high density of traffic are likely to benefit most from these types of actions due to the large volume of stops made, which involve frequent accelerations and braking.
- Reversible power-supply substations is currently the favoured option, due to the greater level of reliability, life span and cost per mega Watt, only if the energy returned to the electricity network is remunerated, which is not something currently approved in the Spanish electrical legislation (E-LOBSTER public report D3.2 to be consulted for further information of other countries).[33]
- Energy storage devices are another option that is likely to become a competitive technology in the medium term. They allow to match the power offer and demand and, thence, the introduction of renewable energies in the rail grid. Energy storage can be integrated at different levels of the electricity system with an amount of savings estimated between 15% and 30% of the energy consumed.:
    - Generation level: Arbitrage, balancing and reserve power, etc.
    - Transmission level: frequency control rtc.
    - Distribution level: voltage control, capacity support, etc.

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[32] PTFE (January, 2017). Sustainable and smart management of energy in railways

[33] D3.2 “Report on the existing policy framework” https://cordis.europa.eu/project/id/774392/results

- Customer level: peak shaving, time of use cost management, etc.

- The use of reversible converters is mandatory to install these types of technologies, being its cost significant, which means that it is not viable to install reversible converters in all of the substations. In spite of doing this, the option that should be considered is to find the optimum number and location.
- Power factor correction in order to increase in the reactive power transported by the distribution network to supply the load requirements. Individual load compensation method is typically achieved with static capacitors applied to the system on linear or no-linear loads. This method eliminates the need for switching the capacitors because they are on when the motor is on and off when the motor is off and avoids having the capacitance on the system while the motor is not presenting the inductive reactance.
- Voltage regulation to achieve a constant power load, as the voltage at the load bus is reduced the current required by the load increases, which increases the current flow in the distribution lines and increases the power losses ($P_{loss} = Z_{cable} \cdot I^2$). Thus, the voltage control technology can be implemented at the system level by optimising position of tap changing transformers.
- The distribution networks that are equipped with automatic voltage control schemes (AVC), which measures the local voltage and compares this with a target voltage, allow the tap ratio of the transformer to achieve the target voltage. An AVC may have line drop compensation, using line current and impedance to calculate the voltage drop at the end of the line.
- Harmonic compensation in order to avoid those harmonics injected by the non-linear equipment that causes harmonic currents to flow in other loads, such as fixed impedance heating demands/constant load demand and motors. Because of the additional harmonics in the line, the rms value of the current increases, which results in an increase in the copper losses and thus heating. The extent of the overall sensitivity of losses depends upon the extent of the harmonics and also the composition of the demand.
  a. Passive filter: passive filters are made up of inductors and capacitors, which are tuned to block or absorb particular harmonic content.
  b. Active harmonic filter: active harmonic filters are designed using power electronics such that the device either provides variable harmonic impedance to absorb some or all the harmonic currents or else provides harmonic current of opposite polarity to cancel the harmonic current. These active filters are expensive compare to the passive filters[2].
- The use of smart meters for the assessment of electricity consumption is essential as it affect the volume of non-technical losses in mainly two ways:
  a. It helps to reduce metering errors and to have more accurate measurement of electricity consumption. Therefore, the estimation or calculation of non-technical losses is likely to be more exact.
  b. Real time reading of energy consumption and an establishment of dynamic tariffs might help to reduce the gap between peak demand and the available power at any given time, what helps ESS in its duty.

4.1.2 Rolling stock role within smart management of railways

The aim of this section is to point out those key points regarding rolling stock where the application of smart management may make a difference in terms of energy efficiency, or at least where smart technologies shall be used to contribute to energy losses reduction.

According to literature data[34], 70–90% of the total energy consumption in urban rail is due to rolling stock operation, which comprises traction, signalling, HVAC, etc. The remaining part is used in stations and other infrastructure within the system. Furthermore, and focusing on rolling stock, a high percentage of the traction energy is dissipated during braking phases[8], hence, the energy saving potential offered by the use of regenerative braking, which has been estimated by Spanish Manager of Railway Infrastructures (ADIF) up to 20% of the total energy consumed[35], has an important relevance in particular with respect to E-LOBSTER. On the other hand, the auxiliary equipment of the rolling stock may account for about 20% of its total energy consumption.

The expected increase in the use of regenerative braking as well as renewable energy generation in urban rail systems will result in the need for optimised management of energy flows within the network. In this framework, the application of the smart grid concept, originally developed for electric networks with distributed power generation is gaining growing attention[36]. This approach enables efficient management of all the energy sources in the network by taking into account the actual demand. Actually, in this context, the power from renewable sources, from regenerative braking or from the public grid can be either used to match the demanded power of the system, or stored for later use shaving peak consumptions, determining in this way relevant cost savings[37].

Furthermore, ancillary systems in railways are other part where smart management of energy implementation could improve their efficiency. Within these, apart from converters, transformers, rectifiers, etc. the HVAC systems might need from smart management technologies in order to increase the efficiency due to the large amount of date that would be necessary to reach a conclusion about reducing energy losses., which account for up 30% of the overall traction energy demand.

4.1.3 Railway operation within smart management of railways

Finally, this section aims to introduce smart management into operation and how it affects to railway and DSO stakeholders.

Apart from the technical discussion about the introduction of smart management in railway networks, the opinion and thoughts of stakeholders (administrators, operators, universities, technology centres and manufacturers) about the topic is an important subject to consider. Besides the discussion that was tackled in different E-LOBSTER deliverables, and with the aim of not repeating the same ideas about the concept of the very same sSOP of E-LOBSTER, the aim of the stakeholders is that the idea of increasing energy efficiency is not only about reducing energy losses, but also recovering as much energy from the facility as possible. That is why energy storage systems increase their importance within the project as a method to be able to exploit all the energy that cannot be injected into the grid. Therefore, the challenges that arise in this project considering smart infrastructure may be summarised:

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

[34] González-Gil A, Palacin R, Batty P, Powell JP. “A systems approach to reduce urban rail energy consumption”. Energy Conversion and Management 2014, 80, 509-524.
[35]Lafoz Pastor, M., García-Tabarés Rodríguez, L., Vázquez Vélez, C. Flywheels Store to Save Improving railway efficiency with energy storage. IEEE Electrification Magazine (December 2013)
[36] C. Chéron, M. Walter, J. Sandor, E. Wiebe, ERRAC – European railway energy roadmap: towards 2030, In: 9th World Congress on Railway Research – WCRR 2011, Lille, France; 2011.
[37] A.E. Díez, I.C. Díez, J.A. Lopera, A. Bohorquez, E. Velandia, A. Albarracin, M. Restrepo, Trolleybuses in smart grids as effective strategy to reduce greenhouse emissions, In: IEEE International Electric Vehicle Conference – IEVC 2012, Greenville, USA; 2012.

- Penetration of storage systems, as has been previously indicated, adds 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 sub-voltage problems are experienced.

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 several challenges, such as defining and developing efficiency indicators to evaluate the level of efficiency of each section of line.

Flexibility, which is also a way to reach higher energy efficiency, in a context including a significant penetrations of autonomous wind and solar generation, could be provided by four sources[29]: flexible generation, interconnection, demand side response and electricity storage, as follows.

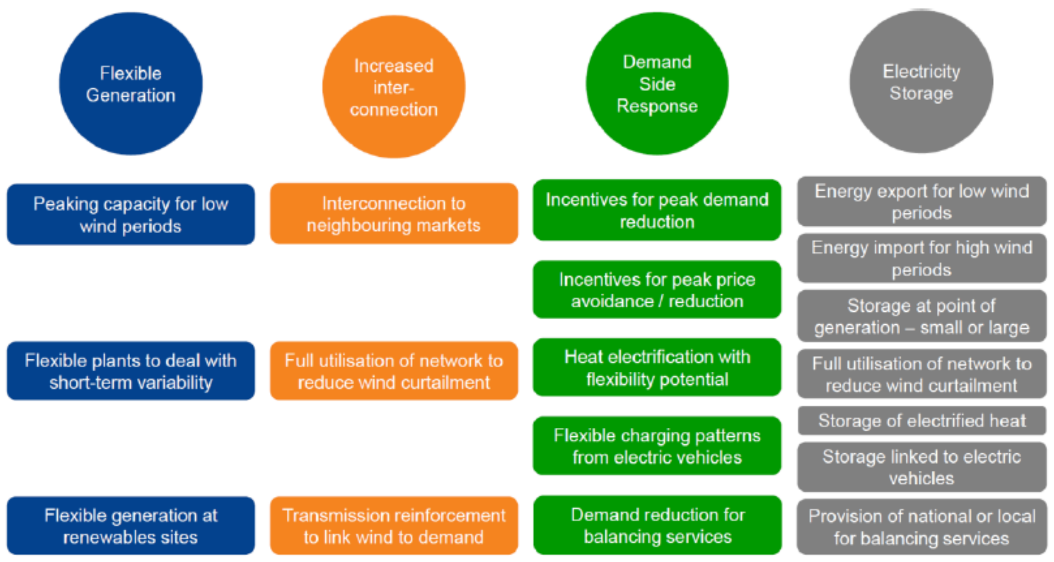

Figure 18 sources of flexibility[38]

Smart grids use innovative products and services together with intelligent monitoring, control, communication and self-healing technologies in order to:

- Better facilitate the connection and operation of generators of all sizes and technologies.
- Allow electricity consumers to play a part in optimizing the operation of the system.
- Provide consumers with greater information and options for choice of supply.
- Significantly reduce the environmental impact of the whole electricity supply system.
- Maintain or even improve the existing high levels of system reliability, quality and security of supply.
- Maintain and improve the existing services efficiently.
- Foster market integration towards a European integrated market.

[38] Smarter Network Storage-LCNF-Interim-Report-Regulatory Legal Framework, 2015

4.1.4 Current situation and examples of smart management of railway networks

Currently, several studies and projects aim to improve energy efficiency of railway facilities. To do so, they are focused on building a worldwide network of smart grids.

Among these projects and studies some of the most relevant ones are the following.

Big Data on Rails: The Siemens RailFusion platform

The Siemens RailFusion platform is the next generation of remote monitoring and smart asset management. RailFusion controls, meters, and analyses data at specific points placed at the railway infrastructure, including onboard and trackside elements such as road crossings and end-of-train detectors.

This system is designed to translate big data into smart management of railway infrastructure, intuitively monitoring an analysing, and improving system operations and safety.

This smart management works thanks to a cloud-based system that enables smart-decision making. This functioning includes:

- Enabling devices that are placed on rail infrastructure to communicate with one another to remotely determine the status and performance of maintenance activities, road crossings, and locomotive operation.
- Accessing to live information about the occupation of the crossing in order to address first responders to the quickest and most available route, saving time in an emergency case.
- Identifying faulty device's behaviour, like the false occupation of a crossing, and offering remote control to authorized operators, allowing them to manage the traffic situation.
- Analysing patterns along the trackside based on historical data, so that operations concerning trackside can be performed with higher efficiency and reliability.
- Offering operators of all skill levels an easy-to-use platform to manage complex rail infrastructure.

Operators are provided with insights of the activity along the entire railway infrastructure due to the system remotely monitors and captures data from both Siemens and third-party devices located at the infrastructure.

Using the captured data, the software can identify tendencies to help railroads to improve their planned operations, adapting them to their needs, and fixing issues.

RailFusion can interact with any device or system located along the rail infrastructure, including Positive Train Control (PTC). The software will offer operators the ability to monitor the state of a PTC network and the equipment, providing services for the control system. The information gathered by the RailFusion system is securely transmitted in real-time and stored in a Siemens data centre where the analytics and reporting will be performed.

The software is currently being piloted in North America.

- **MyRailS (EURAMET)**

The project aims to develop an infrastructure for accurate measurement of energy exchange and reliable system monitoring, which supports the implementation of an energy efficient management of the European DC and AC railway and DC metro system. The project also focuses on the characterisation of the railway subsystem as a producer-consumer, with a view of its integration within a wide smart grid, as well as on the assessment of eco-driving performances.

The main objective of the project is to develop the measurement framework and infrastructure that support the adoption of efficient energy technologies in European railway systems.

The specific objectives of the project are:

- To develop a metering 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.
- To develop a wide-area of power quality monitoring architecture.
- To set up combined measurement-simulation tools to quantify the impact of the installation of new reversible substations (RSSs) in terms of energy saving and power quality.
- To develop accurate metering systems and procedures for evaluating the energy savings provided by an eco-driving strategy.
- To facilitate the take up of the technology and metering infrastructure developed in the project.

- **A strategy for utilization of regenerative energy in urban railway system by application of smart train scheduling and wayside energy storage system (Japan)**[39]

Nowadays, electrical railway systems are considered as an efficient and environmentally-friendly solution for transportation system. Therefore, the management of multiple energy sources is an important issue for railway planning and operation. The arrival of modern railway technologies has allowed the implementation of regenerative braking systems, which can recover considerable energy from braking operation. The management of regenerative energy becomes vital considering the enhancement of railway operation. This research presents a strategy to use regenerative energy in urban railway system by adjusting train operating schedule and employing energy storage system placed at trackside. Optimizing train schedule aims to increase the degree of regenerative energy usage, and the use of super capacitor as temporary energy storage will make possible the surplus of regenerative energy. By integrating appropriate train scheduling and energy storage systems, energy management can be more flexible and effective, leading to an improvement of energy-saving operation.

On the other hand, optimizing train schedule is sensitive to traffic condition. By integrating a suitable scenario of storing and recycling, thanks to the application of Energy Storage System (ESS), energy management is supposed to be more stable and effective in different traffic conditions. The Bangkok Rapid Transit System was selected as a practical example of application of timetable and ESS to improve energy-saving operation.

Numerical case studies were performed to express the effect of ESS and the fitting of timetable to network receptivity of regenerative energy and energy saving rate. From preliminary estimation of the amount of regenerative energy produced, it resulted feasible to be effectively used for high traffic condition. However, network receptivity drastically decreases in moderate and low traffic condition.

The application of adjusting timetable and installing ESS are supposed to improve energy-saving operation. By performing sensitivity analysis, the suitable location and capacity for installing an ESS can be decided.

Finally, the integrated design approach provides examples of smart timetable and suitable ESS capacity to achieve energy-saving operation in difference traffic scenarios. When the proposed integrated design is applied, the energy saving can be improved up to 3.6 % compared with nominal operation without ESS.

[39] Warayut Kampeerawat, Takafumi Koseki. Strategy for utilization of regenerative energy in urban railway system by application of smart train scheduling and wayside energy storage system. AEDCEE, 25 - 26 May 2017, Bangkok, Thailand

- **Smart Railway Network (SRN) Project (India)**

Smart Railway Network (SRN) project envisages "On Line" operation of the existing Train Indicators at various stations and also the provision of Passenger Information System as Video Display Units, placed at the station entrances to indicate running train information to the commuters.

The SRN system primarily provides "ONLINE‟ display of movements of all trains with Train Numbers/Rake numbers on video monitors, as well as overview indication panel, located in the control room.

Through this system, the optimization of services allows consequent savings in energy and time, since knowing the exact position of the train and the time of arrival at the station enables better management of railway traffic is carried out.

- **Train to Grid (T2G)**

Korea Railroad conducted a research on the use of Train to Grid (T2G) in the Reduction of Electricity Prices.

This research introduces the T2G system using the wireless railway vehicles with a large-capacity energy storage system (ESS) and proposes a method for the reduction of electricity prices using a T2G system, which allows to reduce both demand and energy charges.

The method is designed to decrease the peak power and the hourly power consumption. An algorithm that determines the number of railways to be charged or discharged, based on the time-of-use price change, is also proposed.

With the aim of testing this method, the simulations are performed using real data on the Korean urban railroad Line No. 2, 3, and 4. Besides, to verify the superiority of the method, the simulation results are compared with the conventional electricity prices. The total electricity prices per month are decreased by 0.75% for Line No. 2, by 0.74% for Line No. 2, and by 0.74% for Line No. 4.

It presents that both demand and energy charges are slightly decreased. These results come from the characteristics of wireless railway vehicles that use high-speed charging. The ESSs can only be utilized for power demand distribution, while the wireless railway vehicles are mainly for transportation without being employed solely for power demand distribution.

Additionally, this paper did not address the power supplies by regenerative braking, one of the most prominent characteristics of wireless railway vehicles. Therefore, it is concluded that as the size of utilized power is inconsiderable, the electricity prices are presented to be decreased slightly.

By applying both the T2G system and the regenerative energy, more effective energy reduction can be achieved. The scheme using both the T2G system and the regenerative energy are expected to be studied in the future.

4.2 Future challenges in the smart management of smart railway networks

Railways have an enormous potential in the implementation of smart management, considering their advantages of being permanently connected to the electricity grid and interacting with it.

Trains can exploit these advantages of permanent connection that certainly will exempt them from losses due to recharge time and the inconvenience of moving heavy energy storage systems. Moreover, railways can dynamically and intelligently interact with smart grids, returning power to the grid when it is most needed or storing it when there is a surplus and even offering (with adequate remuneration) in the case of an imbalance in the power-frequency of the system.

This chapter describes some possible challenges facing when implementing smart grids in railway systems. Challenges of smart management development can be identified from the technical point of view, but also more in general they can be related to instructional and regulatory framework, social environment, etc....

Several challenges need to be considered for the development and introduction of a railway smart grid. Most of the technologies suitable for railway smart grids are already being used in other sectors, but the unique socio-political and technological environment of rail makes their implementation even more challenging.

4.2.1 Instructional and regulatory framework

The development of smart grids, especially in the railway domain, requires a legal and regulatory basis that sets the right incentives and clearly defines the roles of different power system actors, the interactions between them and enables a smooth communication between all its components.

Developing standards for railway smart grids is important for ensuring that the technologies delivered are compatible and interoperable with the remainder of the system. It is expected that any safety critical aspect of the railway smart grids would be governed by regulations and the aspects relating to interoperability would meet published standards. Therefore, standardisation will be necessary for monitoring and control devices, communications system (including protocols), electromagnetic compatibility, cybersecurity, data collection, storage and sharing.

In the scope of the project, an analysis of the gaps in standardisation of railway applications is ongoing and proposals for new standards, policies, and legislative measures to cover these gaps and unlock the existing barriers are expected to be suggested.

4.2.2 Technical challenges

Considering the possible technical challenges generated by the instruction of smart management of railway systems, i.e. use of smart grids inside the railway domain, the following main items can be identified: nature of the traction demand, optimisation of train driving, complexity, interfacing new equipment, communications (efficiency and reliability), security and cybersecurity, electromagnetic compatibility, distributed generation, data management. Some of the above mentioned, such as cybersecurity, information sharing, require not only technical solutions but also good planning and management.

4.2.2.1 Nature of the traction demand

One of the most important drivers and challenges of railway smart grids implementation is the nature of the traction demand. There are a wide range of railway traction power supply systems existing across the world. These systems operate at different voltages, use different transmission methods and require different conversion equipment. RTPSS are either powered by DC or AC supplies. Typically, intra-city rail services are powered by DC via third rail or OLE (overhead line equipment), whereas inter-city and HSR (high speed railway) are powered by AC supplies exclusively using OLE. Although 25kV 50 or 60Hz AC is considered as the world standard for main line railways and HSR, at least two other AC systems exist, 11 kV 25Hz and 15 kV 16 2/3 Hz. These are non-standard legacy systems, which were developed at low frequency to deal with the limitations of early traction motors. Although these issues have since been overcome, such systems are unlikely to be replaced because of the expense and disruption of changing the railway and, in some cases, power supply infrastructure. For example, in Austria, Switzerland and parts of Germany, there are dedicated plants which supply power at 16 2/3 Hz via a single-phase power distribution network for the railway.

Other than the exceptions mentioned above, in most cases both DC and AC supplies for rail are taken from the public power supply network, which provides a high voltage AC supply in the order of magnitude of hundreds of kilovolts. In a DC network, three-phase duplicated input transformers step down this voltage to tens of kilovolts AC for input to substations along the line. Within the substation, this voltage is reduced again before being rectified to the correct DC voltage for the third rail or OLE.

In an AC network, no intermediary transformer is required. Instead, the substations feed directly from the grid and reduce this voltage to 25 kV for OLE, using a single phase. To balance the load on the grid, different substations draw from different phases.

4.2.2.2 Optimisation of train driving complexity

Optimizing the train driving in a short time is a major challenge the railway smart grids have to address. In general, the main objective of the smart train driving can be different: minimizing the energy consumption, adapting the train consumption to the capacity of the infrastructure in a specific area, and reducing the cost of the electricity.
These goals are usually tackled with the use of Automatic Train Operation (ATO) systems which are rather widespread in the railway network. This kind of systems helps the driver to make the most efficient decisions in order to reduce the energy devotes to traction, improving the timetable and, therefore, the use of the available rolling stock.

4.2.2.3 Interfacing new equipment

One of the first issues to overcome is achieving monitoring and controllability capability for the wide range of devices used in railway power supplies, which operate using different voltages, currents, current types (AC or DC) and software. There is typically a limited set of controllable devices including switches, transformer tap changes and converters, although further controllability is expected in the future. Although railway power systems generally already have integrated supervisory control and data acquisition (SCADA) systems that allow for surveillance, data collection and control, they are not necessarily useful for RSGs (Rail Supply Groups). Traditional SCADA systems evolved over time without standard specifications, leading to a number of different architectures that are proprietary in nature. Realising the need for interoperability, rail is now moving towards distributed and networked SCADA systems with standardised protocols, but many legacy systems are still in service. For older systems, interfacing sensors and communications to meet smart grid requirements may prove challenging, particularly when hardware replacements or software reconfiguration tools are obsolete and expertise and know how is lacking. Rather than designing bespoke smart grid interfaces for each different types of equipment though this may be feasible if there are a large number of each standard component – it may be necessary to completely renew current systems with smart grid interoperability in mind. This would require standardisation across systems and the assurance that these would not become obsolete in 5–10 years' time. With new systems that are currently being installed, it may be possible to use the in-built monitoring capabilities for smart grid purposes. As well as SCADA for example, the European Railway Traffic Management System (ERTMS) has been designed with monitoring capability for faults and failures, speed monitoring, communications monitoring for the Global Systems for Mobile communications – Railway (GSM-R) and health monitoring of the system with remote access for technicians.

4.2.2.4 Developing communications (efficiency and reliability)

The communication links within the smart grid are essential for achieving its functionality. They must be bi-directional, allowing individual components to report their condition to the management system, and for the management system to take control and perform any necessary actions. They are required to provide a guaranteed quality of service, transmit in 'real-time,' have sufficient bandwidth for future connections, be scalable, and be secure from cyber-security threats. A number of communications systems, such as wireless, optical and wireline, have previously been used in smart grids and for most applications, the choice of technology largely depends on the network requirements (amount of data, sampling rates, etc.) and the distribution of elements in terms of distance.

One of the difficulties for railway communication is ensuring reliable and consistent connections with equipment on-board trains, whilst these trains are moving across the network and through a range of environments. By necessity these communication systems have to be wireless, which means that tunnels, deep-cuttings and remote areas can create problems. There are a number of radio-based technologies currently deployed, with GSM-R representing one of the newest technologies for connecting drivers and signallers. GSM-R is used as part of the ERTMS, complies with the technical specification for interoperability (TSI) and is already deployed in Europe, Asia and Africa. This system is standardising the industry and has already unified a number of legacy communications systems. Its viability for RSG depends on the availability and latency of the system, though in theory, it could be used to interface train data to a wider RSG communications system that uses other technologies. If GSM-R is not used, it would still provide a valuable case study for the development of a system that overcomes the problems created by moving trains.

4.2.2.5 Security and cybersecurity

Security, and more specifically cyber-security, is a challenging issue since the on-going smart grid systems facing increasing vulnerabilities as more and more automation, remote monitoring/controlling and supervision entities are interconnected.

The main goal is to be secure from cybersecurity threats when interfacing smart grid equipment with rail systems security vulnerabilities; this issue should be evaluated and properly mitigated. The fact that SCADA and railway energy management systems are now being interconnected and integrated with external systems creates new possibilities and threats in cybersecurity. Cybersecurity in smart grids is important for ensuring the confidentiality and fidelity of information and the availability of power supply assets. Cyber-attacks could lead to power outages and infrastructure damage, compromise safety, affect operations and maintenance or impact the energy market. Given the importance of cybersecurity for both smart grids and railways, it is essential that railway smart grids are protected and secure from threats targeting the power supply, railway or both. Therefore, when interfacing smart grid equipment with rail systems security vulnerabilities should be evaluated and mitigated. Cybersecurity standards should be developed that build upon current railway and smart grid best practice.

4.2.2.6 Electromagnetic compatibility

The EU electromagnetic compatibility (EMC) directive requires that ‘‘Manufacturers of equipment intended to be connected to networks should construct such equipment in a way that prevents networks from suffering unacceptable degradation of service when used under normal operating conditions’’. Any smart grid equipment installed must therefore take EMC into account and ensure that its performance will not cause electromagnetic interference that could have an adverse effect on the network. Failure to reasonably control electromagnetic interferences in the railway smart grids could compromise safety.

The railway electromagnetic environment is generally considered severe and generates problems not present in other sectors. Transient electromagnetic fields can be produced by train movements, and ground leakage current is a common problem, where current that should return through the rails is transmitted through the ground. Rolling stock electromagnetic emissions can also disturb wireless communications in a number of frequency bands. Therefore, for railway smart grids standardisation and measures to deal with specific railway electromagnetic interferences issues shall be taken into account.

4.2.2.7 Distributed generation

The railway specific technical difficulties related to distributed generation are not solely due to the differences in power supplies and distribution above introduced; even when powered using the same type of supply, the demand varies depending on the service or route sections, is subject to large fluctuations due to daily peaks, and experiences smaller fluctuations due to driving style, delays, loading and regenerative-braking exchange. Due to all these factors, the power requirement at each substation differs. This kind of systems approach would need to be taken for the implementation of smart grid to determine the number, sizing, location and type of distributed energy resources (solar, wind, etc.) to integrate into the railway power supply system, with the added complexity of considering the current power supplied by existing technologies (including trains), the likely future demand, and the limitations of the environment.

4.2.2.8 Data management

Another important challenge in smart grids is relevant to data management and data processing; in order to manage the generation, distribution, transmission and consumption of energy, data must be collected from multiple assets and used to make decisions in real time. The scale and complexity of the data for applications of smart grid makes it difficult to deal with in terms of transportation, storage, and transformation to useful outputs. These issues are complicated by the rail environment because the railway smart grids would need to access and analyse data that belong to multiple stakeholders from both the railway and power sectors; moreover, open data coming from different sources (e.g. arrival and departure times, delays, etc.) are usually in different formats, and this makes it difficult their utilisation.

4.3 Smart management of railway networks case studies with power losses analysis

4.3.1 Driving strategies

The train speed profile is determined by train driving controls, which is a key factor influencing the traction energy consumption. An example of three speed profiles with different driving styles is given in Figure 19. Speed profile 1 accelerates to a highest speed with a longer coasting pattern, while speed profile 2 accelerates to a medium speed with a shorter coasting pattern. Speed profile 3 accelerates to a lowest speed and remains this speed until braking. There is a large amount of literature studying the impact on energy consumption of different driving controls. Compared with flat-out driving, driving with coasting controls can reduce the energy consumption by about 30% with a 5% increase in journey time.

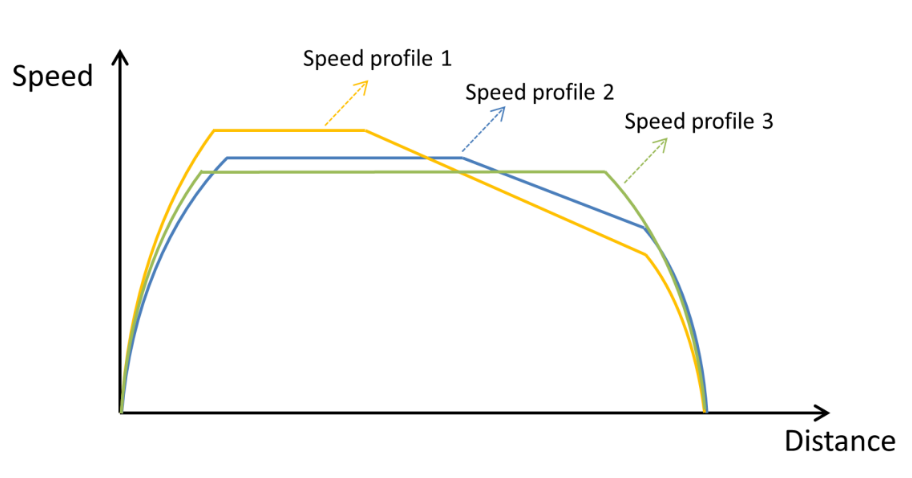

Figure 19 Examples of various speed profiles

An applicable driving solution for reducing traction energy consumption was employed in Edinburgh Tram[40]. The theoretical optimal driving strategies are produced by train simulation using an enhanced Brute Force searching algorithm. In order to achieve the application of energy-efficient strategies, a DPTS (Driver Practical Training System) was developed and coasting signage was tested by Edinburgh Tram. Compared with normal driving, driving with the DPTS reduced the traction energy consumption by around 15%, where the timetable is the same. Driving with coasting signage is easy to install and simple for human drivers to practice. The field test indicates that the traction energy of driving with coasting signage is reduced by around 10%, where a shorter journey time is achieved. From the field test, it can be concluded that with practice the driver can improve the energy saving performance.

4.3.2 Timetable scheduling

In modern railway systems with regenerative braking implemented, motoring trains collect electricity from substations and trains in regenerative braking. When the train is braking, motors transform mechanical energy available at the drive shaft into electrical energy. Then, the electrical energy is transferred back to the network system to power other trains in traction. For normal regenerative braking, all the regenerating energy can be transferred into the transmission network to power other trains. However, as regenerative braking can increase the voltage of a train, a high regen voltage will occur when there are not enough motoring trains absorbing the regenerative energy in the power network. In case of a high voltage hazard, some braking energy is prevented from transferring into contact lines. This part of the braking energy is wasted in the on-board braking rheostat as heat until the network voltage is below the safe value. Based on a DC 1500 V metro line in Korea, the reused regenerative braking energy was calculated based on the measurement of catenary

[40] Z. Tian, N. Zhao, S. Hillmansen, C. Roberts, T. Dowens, and C. Kerr, "SmartDrive: Traction Energy Optimization and Applications in Rail Systems," IEEE Transactions on Intelligent Transportation Systems (Early Access), DOI: 10.1109/TITS.2019.2897279, 2019.

voltage and current, where around 21-39% of traction energy was reused due to regenerated braking[41]. Therefore, it is essential to analyse and improve the amount of usable regenerative energy in railways.

The current strategies for improving regenerative braking energy in urban rails include timetable and trajectory optimisation as well as the implementation of energy storage systems (ESS) and reversible substations[42]. Optimising braking trajectory and timetable can improve the efficiency of using regenerative energy. The Bellman-Ford algorithm was implemented in the optimisation of braking speed trajectory. The regenerative braking energy then increased by 17.23%[43]. The usage of regenerative braking energy can be improved by synchronising the braking phase with the accelerating phase of trains running in the same power network[44]. Figure illustrate the power synchronisation of two trains.

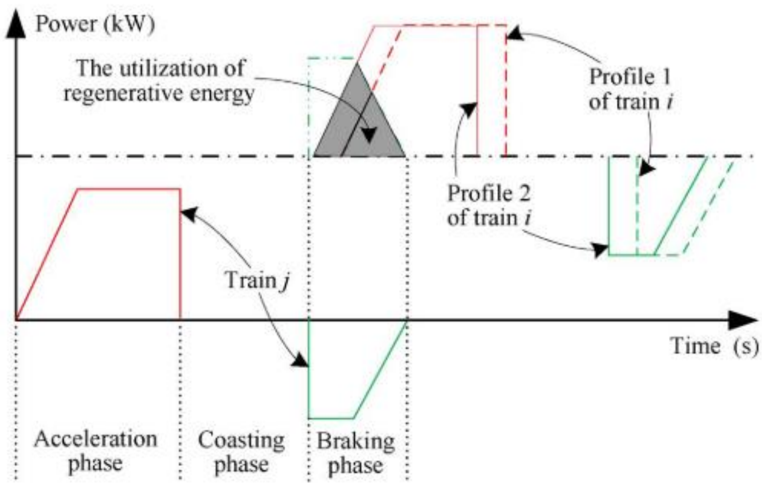

Figure 20 Illustration of power-time profiles of two trains [45]

Table2 shows the system energy consumption for three different operating regimes: the current ATO operation; the best identified by minimising the traction energy; and the best found by minimising the substation energy. The current Automatic Train Operation (ATO) system energy consumption is

[41] B. Chang-han, J. Dong-uk, K. Yong-gi, C. Se-ky, and M. Jai-kyun, "Calculation of regenerative energy in DC 1500V electric railway substations," in 2007 7th Internatonal Conference on Power Electronics, 2007, pp. 801-805.
[42] A. González-Gil, R. Palacin, and P. Batty, "Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy," Energy Conversion and Management, vol. 75, pp. 374-388, 2013.
[43] S. Lu, P. Weston, S. Hillmansen, H. B. Gooi, and C. Roberts, "Increasing the Regenerative Braking Energy for Railway Vehicles," IEEE Transactions on Intelligent Transportation Systems, vol. 15, pp. 2506-2515, 2014.
[44] A. Nasri, M. F. Moghadam, and H. Mokhtari, "Timetable optimization for maximum usage of regenerative energy of braking in electrical railway systems," in SPEEDAM 2010, 2010, pp. 1218-1221.
[45] X. Yang, X. Li, B. Ning, and T. Tang, "A Survey on Energy-Efficient Train Operation for Urban Rail Transit," IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 1, pp. 2-13, 2016.

calculated using a power network simulator using the speed profiles measured by the ATO system. The Traction optimisation column in **Table2** shows the energy consumption of the system under the traction optimisation but keeping the original timetable. The interstation journey times, and dwell times are fixed and only one coasting point is used in each interstation journey. The results show that both traction energy and substation energy can be reduced by 29.9%. With traction optimisation alone, the regenerative efficiency (regenerative energy divided by braking energy) is almost the same as with ATO at 80.6% and 82.1%, respectively. The significant traction energy saving is probably because the motion simulator applies a perfect optimal speed trajectory which is not achieved in real world. Using substation energy optimisation, the traction energy consumption and braking energy is almost the same with the traction energy optimisation results, but the substation energy is reduced by an additional 10%. This is mainly caused by the higher regenerative efficiency which reaches 95.5%.

Table2 Optimisation results comparison[46]

	Current ATO operation	Driving style optimisation	Driving and timetable optimisation
Cycle running time [s]	4281	4281	4248
Substation energy per headway [kWh]	331.28	232.21	203.37
Substation loss per headway [kWh)	12.38	6.41	4.55
Transmission loss per headway [kWh]	26.26	16.60	16.18
Traction energy per headway [kWh]	525.94	372.52	375.12
Braking energy per headway [kWh]	289.51	199.04	201.57
Regenerative energy per headway [kWh]	233.30	163.32	192.48
Efficiency	80.6%	82.1%	95.5%

4.3.3 Infrastructure upgrading

Infrastructure upgrading methods to reducing energy losses including using energy storage devices, reversible substation, renewable energy sources. Energy storage devices can be used to store regenerative braking for reuse. Using energy storage systems not only increases the efficiency of the usage of regenerative braking energy, but also reduces the peak load demand for busy traffic. The energy storage devices include batteries, flywheels, electric double layer capacitors and hybrid energy storage devices. The capacity and locations of way-side energy storage devices can be optimised to minimise the energy losses. In reversible DC fed systems with inverting substations, the regenerative braking energy can be converted and fed back to AC networks, which increases the network receptivity.

The energy consumption of a typical metro network without and with reversible substations has been studied[47].The substation energy consumption results with different timetables in a non-inverting system are shown in Figure 21. When the headway decreases, the regeneration efficiency increases

[46] Z. Tian, P. Weston, N. Zhao, S. Hillmansen, C. Roberts, and L. Chen, "System energy optimisation strategies for metros with regeneration," Transportation Research Part C: Emerging Technologies, vol. 75, pp. 120-135, 2017.

[47] Z. Tian, G. Zhang, N. Zhao, S. Hillmansen, P. Tricoli, and C. Roberts, "Energy Evaluation for DC Railway Systems with Inverting Substations," in 2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), 2018, pp. 1-6.

and leads to a low substation consumption. The minimum energy consumption is 10.3 kWh/train-km, while the maximum is 20.6 kWh/train-km. Around 50% of energy can be saved with the highest receptivity.

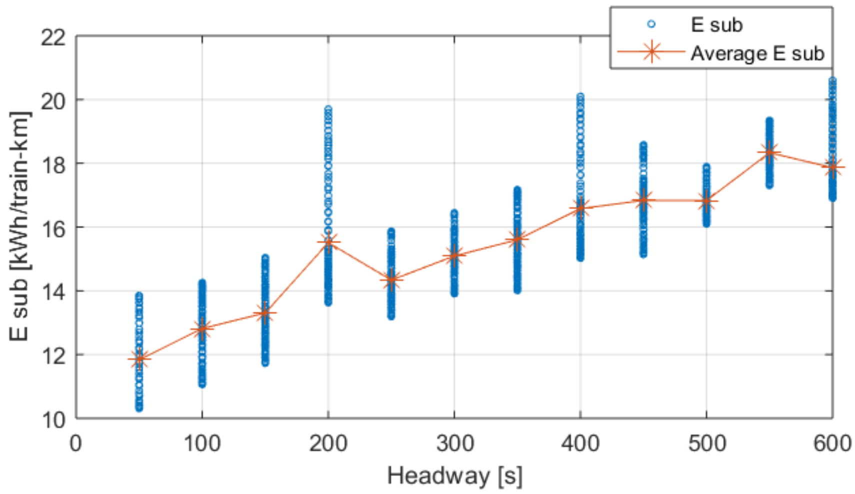

Figure 21 Substation energy consumption of a non-inverting system

The substation energy consumption results in an inverting system are shown in Figure . Although the regeneration efficiency is 100% for an inverting system, the substation energy consumption varies with different timetables. The minimum substation is 10.3 kWh/train-km, which occurs at a headway of 50 s. The maximum substation is 11.2 kWh/train-km, which occurs at a headway of 600 s. The difference between substation energy consumption is mainly because of the difference in transmission losses. The different ratio is not large, which is around 8.7%.

Compared with the energy consumption of the non-inverting system, the percentage of energy saved using inverting substations is shown in Figure . The energy saving by inverting substations rises with the increase of headway. The saving ratio at a headway of 50 s is between 0 and 0.23, with an average of 0.1. The saving ratio at a headway of 600 s increase to an average of 0.38. By using the inverting substations, the global substation energy consumption could be reduced by around 10-40%.

When a new smart Soft-Open Point (sSOP) device is used to interconnect railway electrification and power distribution networks, the benefit is not only the improvement of the regenerative braking energy usage, but also to support the distribution network from an additional power source. To analyse and optimise the performance of the sSOP, the train operation has to be considered. in the meanwhile, the control strategy of the sSOP should be studied to achieve the best benefit.

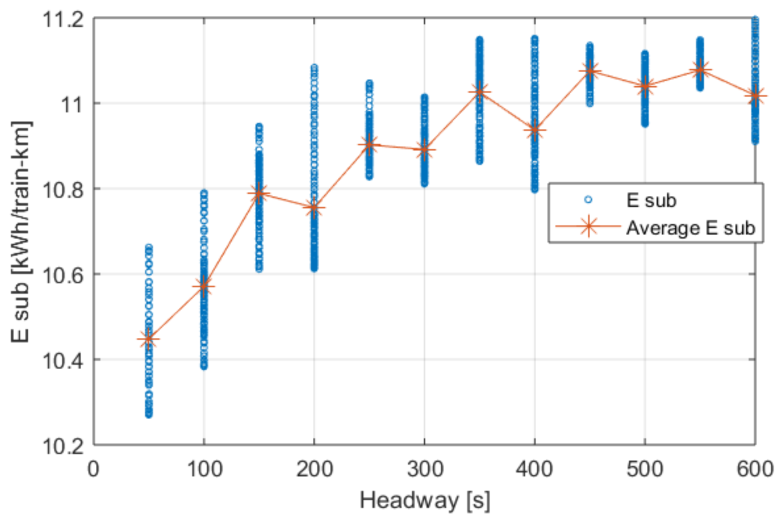

Figure 22 Substation energy consumption of an inverting system

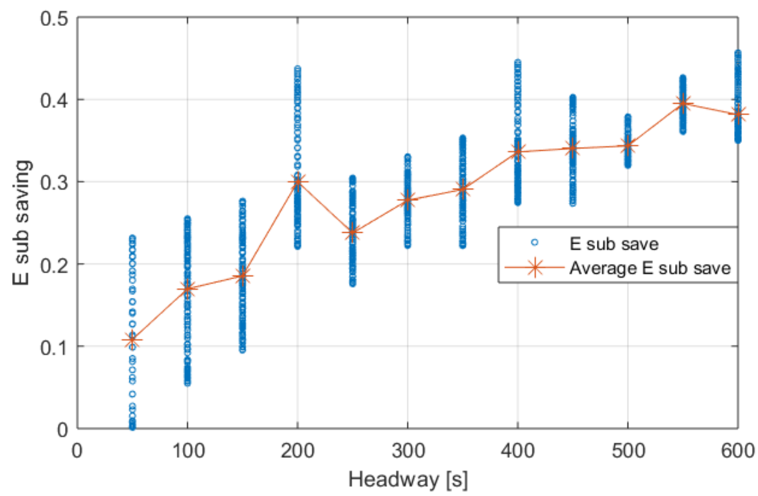

Figure 23 Substation energy saving with inverting substations

4.4 Impact of consumer behaviour on smart management of networks

As already anticipated in Section 3.3, Demand Response (DR) and Demand Side Management (DMS) refer to changes of consumer demand for energy and energy pattern use in general, through various methods such as financial incentives and behavioural change. Today it is widely recognised that Demand Response is a crucial resource for achieving an efficient and sustainable electricity system at a reasonable cost, and estimation suggests that a very small percentage of the overall potential Demand Response in Europe is currently used.

One of the main problems is that it requires active consumer participation and for this reason incentives and encouragement are needed in order to positively influence users. Other constraints are related to proper development of specific regulations, development of feasible commercial aggregation applications and lack of detail metering and communication infrastructure supporting Demand Response.

In order to solve these issues, in Europe there are currently several ongoing projects funded by the European Commission under the Horizon 2020 Programme, and part of the BRIDGE initiative clustering the H2020 smart grid and energy storage projects. Some of the most interesting project related to Demand Response and Demand Side Management are reported below.

1) SMILE (SMart IsLand Energy systems) [48]

The aim of SMILE (Smart Islands Energy Systems) project is to develop smart grid solutions in three large-scale pilot projects, developing and testing different combinations of technological solutions. The project pilots are located in three different islands (Madeira in Portugal, Orkney Islands in UK, Samsø in Denmark), in order to work on topographically similar locations but with different policies, regulations and energy markets. Besides, different combinations of technological solutions have been analysed according to local needs and conditions and the existing local infrastructures.

Nine different solutions have been developed, involving and integrating various technologies such as different kind of batteries, power to heat, power to fuel, EVs, electricity stored on boats, predictive algorithms, and demand side management by exploiting aggregator platforms. Each of the demonstrators brings a specific set of challenges, technology options and, most importantly, energy market conditions, effectively representing most of the EU energy markets. This allows to offer excellent demonstration of settings delivering solutions with maximum impact in terms of replicability.

Particular attention has been focused on the identification of the most appropriate Demand Response strategy for each pilot project, helping the improvement of the overall flexibility of the energy system. [49]

The studies are based on the analysis of each island in terms of grid characteristics (such as type of generation facilities, presence of renewable, characteristics of loads) and its issues and constraints. The market, regulatory and legal context has then been analysed in order to help understanding which further constraints for the possible Demand Response solutions or the possible opportunities. Consequently, a proposal of the more suitable Demand Response strategy was identified for each island.

2) P2P-SmartTest (Peer to Peer Smart Energy Distribution Networks) [50]

The main aim of P2P-SmartTest is to demonstrate how advanced Information and Communications Technologies (ICT) can improve the performance of an electricity distribution system. In this project a Peer-to-Peer (P2P) approach is considered for implementing solutions about optimization of the resources in the network such as Distributed Energy Resources and their integration with a flexible demand side management.

In particular [51] the researches performed in the project are based on the microgrid concept, which is a set of interconnected and distributed loads and energy resources that may operate independently

[48] https://cordis.europa.eu/project/id/731249
[49] Deliverable D5.1 - Most Appropriate DR Services for each Pilot, from https://cordis.europa.eu/project/id/731249/results
[50] https://cordis.europa.eu/project/id/646469
[51] Integration of Demand Side Management and DER for P2P Energy Trading, P2P-SMARTEST-WP4-D4.2, from https://cordis.europa.eu/project/id/646469/results

of the main distribution grid. New figures are defined for the management of the microgrids: the Microgrid Trader, which manages the commercial operation of the microgrid and P2P Aggregator, which allow exploit several potential benefits with respect to a traditional one.

In addition to the management of individual customer, the P2P Aggregator manages the portfolio of Microgrids optimizing not only the resources inside the individual Microgrids but integrating the management with the other microgrids in the cell.

Thanks to this optimization a greater number of individual resources can emerge with less cost in the overall energy market. Moreover, the more remand resources participate in this model, the more effective it is, involving parties from industry, commercial and residential field. Residential players are statistically smaller in terms of power load/capability, but greater in number if compared to the industrial and commercial ones. For this reason, they can provide greater reliability as well as able to provide a faster response when needed.

The project activities highlighted that the greater advantage is the big value that can be obtained by Demand Response systems participating in the balancing market.

P2P-SmartTest project aims to propose a solution to integrate DR in the Balancing market in a feasible way, since today in Europe such applications are not common. Proposed solution, for example, foresees to model and schedule smart home appliances for residential application, or plan the loads as much as possible for the industrial application.

3) inteGRIDy (integrated Smart GRID Cross-Functional Solutions for Optimized Synergetic Energy Distribution, Utilization Storage Technologies) [52]

The main aim of inteGRIDy project is to integrate innovative technologies, solutions and mechanisms in a scalable framework of replicable solutions, involving several stakeholders on both generation and consumption sides. The objective is to facilitate optimal and flexible operation of the distribution grid improving stability of the grid, coordination of distributed load and resources, energy storage solutions and increasing share of renewable energy.

This is achieved by the development of the inteGRIDy framework and its application to ten pilots located in different places around Europe.

InteGRIDy project is based on four pillars:

- Demand Response.
- Smartening the Distribution Grid.
- Energy Storage.
- Smart Integration of grid users from Transport.

Specific functionalities [53] have been developed in order to cover the main aspects of the Demand Response and Demand Side Management. These functionalities involve:

- Users' energy consumption pattern evaluation;
- Evaluation of the amount of flexibility in the energy demand and supply;
- Proposal of the more adequate demand response strategy to each problem or scenario, ensuring benefits to both, grid consumers and operators;
- Delivery of the relevant information to the upper layer in order to calculate optimal operations of the demand response strategy according to specific objectives.

[52] https://cordis.europa.eu/project/id/731268
[53] D1.5 - inteGRIDy Architecture & Functional/Technical Specifications, from https://cordis.europa.eu/project/id/731268/results

The aforementioned functionalities have been successfully applicated on several of the ten inteGRIDy pilots demonstrating the importance of the Demand Response / Demand Side Management solution for a smart grid management

4) ELSA Energy Local Storage Advanced system [54]

The main aim of ELSA project is to study an innovative solution for integrating low-cost second-life Li-ion batteries and other direct and indirect storage options, like decentralized storage systems for distribution grids. The objective is to integrate storage technologies and relevant related energy management systems in order to manage control local loads, generation and single or aggregated storage resources, including demand response.

The project includes six test pilots in various European locations considering different configurations of storage technologies.

Each of the six test pilots have tested various services with the aim to evaluate service performance on different test condition [55]. Five energy services, referred to as use cases, are evaluated based on some KPIs. The following energy services are evaluated: peak shaving, energy purchase time shifting (energy arbitrage) and three Demand Response (DR) services: auto-consumption, cost-minimization and flexibility, as explained below:

- Auto-consumption DR service: minimization of energy consumed from the electric utility over a pre-defined time horizon, e.g. by using renewable energy or locally stored energy.
- Cost-minimization DR service: the electric utility varies the energy cost to deal with a variation of price on the market for instance. It acts on the building energy demand profile in order to consume during the period when the energy is cheaper, reducing the total energy cost over the DR event.
- Flexibility DR Service: takes advantage of all the flexible resources including the storage in order to reduce the amount of building energy demand from the grid

The experiments performed on six test pilots provides good results.

- KPIs, including the ones for the DR services, were close to their target values.
- In some specific cases KPIs seemed to not achieve the target values but that seemed connected to the real condition experimentation.

[54] https://cordis.europa.eu/project/id/646125

[55] D6.3 Results of service evaluation, from https://cordis.europa.eu/project/id/646125/results

5 Case study of railway-grid interconnection model including energy storage system along with renewable energy sources

This section demonstrates a case study for railway-grid interconnected model through the sSOP and the ESS in which the smart integrated management system will be introduced in order to explore new roles for the transport networks in the energy market for enhancing the energy efficiencies at the system level.

5.1 System model

An example of rail-grid interconnected system can be demonstrated in figure 24, in which the railway network is connected to the distribution network through two different contacting routes. Actually, this part presents the main E-LOBSTER concepts developed by exploiting the project enabling technologies. The first route is through the conventional approach in which the DSO, feeding the traction demands, is connected to the railway network through 45kV/15kV transformers and transformers/rectifier traction substations (in red tracks). On the other hand, in order to investigate the possible approaches to merge the railway transport network into the energy markets, another connection is developed in figure 24, in which the DC rail line is connected to other LV distribution network through the sSOP converters along with the energy storage system (ESS) (in purple tracks). This new route will get benefit of the available braking power generated from the trains connected to this DC rail. The utilized sSOP between the two networks will consists of three converters as follows:

1- DC/DC Rail converter: which is responsible for delivering the available braking power to the distribution network and /or to the ESS system.
2- DC/DC ESS converter: which is responsible for charging/discharging the ESS dependant on the availability of the braking power at the railway network as well as the states of the distribution network (either acts as power source or sink).
3- Inverter: which is responsible to send or receive power to/from the distribution network according to the network states (either acts as power source or sink).

The renewable energy sources (RES) can be introduced in this system through a connection with the LV distribution network as illustrated in figure 24, accordingly, based on the power balance between the loads and sources in this network, it can be acted either as power sink or source with respect the sSOP operation.

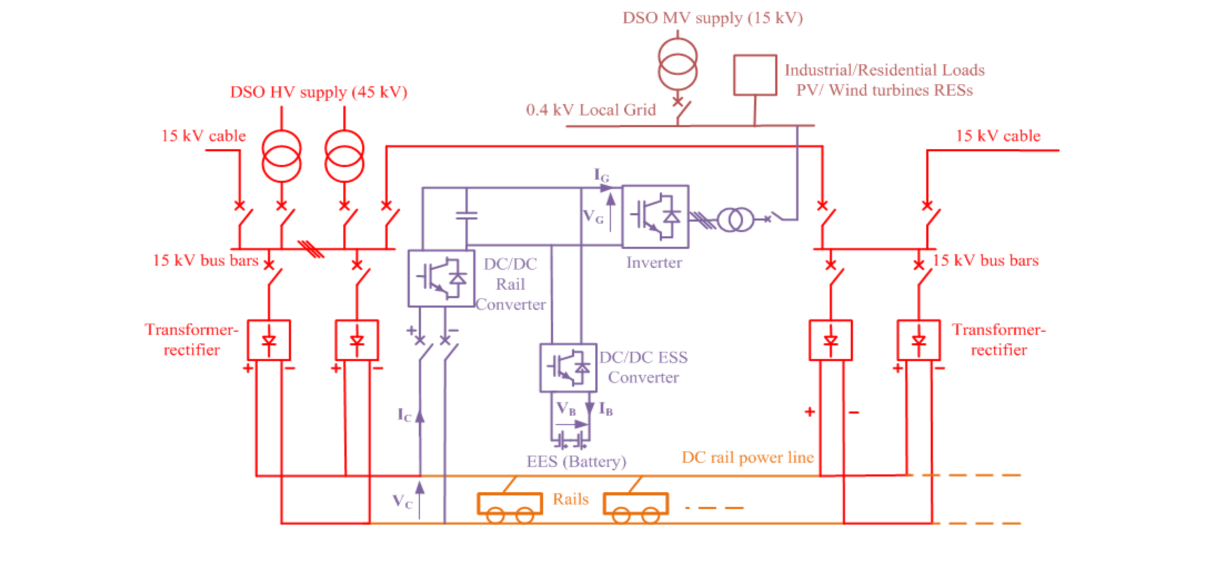

Figure 24 Rail-Grid interconnected model through the sSOP and the ESS

5.2 Control management approach

The flow chart of the control management approach for the proposed example under study is demonstrated in figure 25, in which the I/O data are indicated as follows:

- P_{Gmax}: Maximum power input to the LV distribution network (grid) determined by the grid provider regulations
- $P_{Con\text{-}rating}$: Converters' rating of the sSOP
- $P_{B\text{-}Ch.rated}$, $P_{B\text{-}Dis.rated}$: rated charging and discharging power of the ESS
- $P_{Braking|SOP}$: Braking power (input to the sSOP) and estimated by the sSOP according the measurement of the input voltage of its rail converter
- P_L: Estimated input power value to the grid assessed according to the grid status (grid acts as a power sink)
- P_S: Estimated Output power value from the grid assessed according to the grid status (grid acts as power source)
- P_G*: Power Command to the inverter of the sSOP
- P_B*: Power Command to the ESS converter of the sSOP

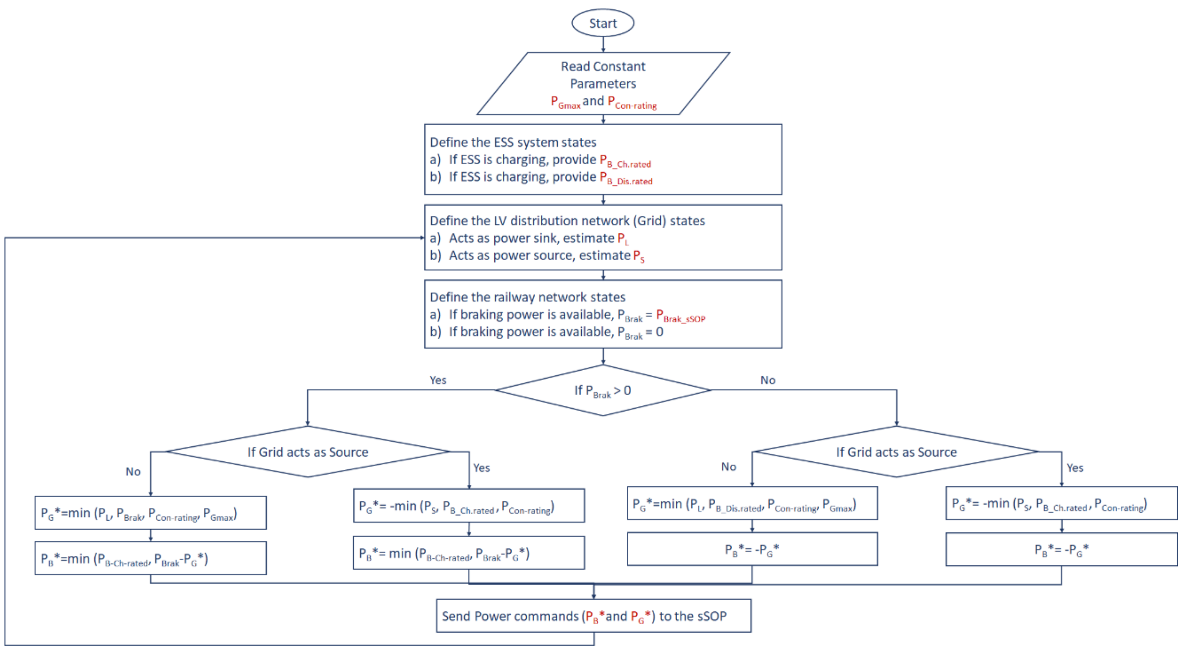

Figure 25 The demonstrated control management approach is described in the following subsections

5.2.1 Functions of the control management

For the proposed interconnected railway-grid scheme, the following control functions could be achieved:

1. Available braking power from the railway traction network could support both the grid (when the grid is highly loaded) as well as charge the ESS; This is labelled as scenario A.
2. Available braking power from the railway traction network as well as the grid (when there is an excess of power from RES) could both be used to charge the ESS; this will be scenario B.
3. ESS could only support the grid (when the grid is highly loaded) and there is no available braking power from the railway network; this will be scenario C.

4. Grid could only charge the ESS (when there is an excess of power from the RES) and there is no available braking power from the railway network; this will be scenario D.

Consequently, there are two control governing constrains which are established for the power flow control management between the two networks as follows:

I. DC railway substation does not support the ESS or the grid network.
II. ESS and the grid do not support supplying the railway network.

These two constrains are fundamentally implemented since the main objectives of the sSOP are to maximize the mutual losses reduction in the railway and local grid networks. Accordingly, the proposed control strategies mainly investigate the benefits of the utilization of the available power from the regenerative braking of the rails to feed the ESS, the grid, or both. Primarily, this regenerative braking power of the rails is wasted in the braking resistance of the rails unless it is utilized by the other rails in the railway network. Additionally, the DC railway substation is supplied from a medium voltage AC network which is sufficiently capable to supply the railway network with three time its nominal ratings [56-57] within defined period of time. Therefore, the considerable advantage of supplying the railway network from the ESS or the grid becomes less relevant. This also becomes more sensible particularly with the high consumed power by the railway network during their acceleration operation periods, which can reach up to range of several MWs, which in turn requires similarly MWs transferred power from the grid or the ESS to make significant contribution in feeding the railway network. However, this is not applicable for the low voltage grid as well as it requires a relatively large storage battery capacity to satisfy these ratings.

5.2.2 Control approach of Scenario (A)

In this scenario, the grid acts as a power sink, in which it can receive any available power from sSOP up to the grid maximum power constrain (P_{Gmax}) determined by the regulations of the provider of the grid. As a result, if there is an available regenerative braking power from the railway network, this power could be used to supply the grid up to P_{Gmax} as well as to charge the ESS up to its rated charging power $P_{B\text{-}Ch.rated}$. Certainly, other factors can limit the injected powers into the grid such as the rated power of sSOP converter as well as the actual required power by the grid (P_L) which could be less than P_{Gmax}.

5.2.3 Control approach of Scenario (B)

In this second scenario, the grid acts as a power source (with excess of power (P_S) from RES) during the availability of braking power from the railway network. Therefore, the ESS can be charged from both supplies up to its $P_{B\text{-}Ch.rated}$.

[56] R. J. Hill, "*Electric railway traction. Part 3. Traction power supplies*," in Power Engineering Journal, vol. 8, no. 6, pp. 275-286, Dec. 1994.

[57] *Railway applications— Supply voltages of traction systems*, BS-EN 50163,2007.

5.2.4 Control approach of Scenario (C)

In this scenario, there is no available braking power from the railway network and the grid acts as power sink. Consequently, the ESS will support the grid to either the minimum of the following; its rated discharging power $P_{B\text{-}Dis.rated}$, P_{Gmax}, P_L, or sSOP converter rating.

5.2.5 Control approach of Scenario (D)

In this last scenario, the grid acts as a power source and there is no availability of braking power from the railway network. Accordingly, the grid will be used to charge the ESS up to the minimum of the following: $P_{B\text{-}Ch.rated}$, P_{Gmax}, P_S, or sSOP converter rating.

6 Conclusions

This pubic deliverable focused on the use of smart management of railway network and the importance of energy efficiency in the European Railway Network. In particular, the document presented an overview of the state of the art of energy smart management in railways and the main case studies and projects as well as an overview on smart grid, Electric Vehicles (EV), charging stations for EVs, V2G concept, electromobility and its synergies with railways.

In the framework of Smart Grids, customer behaviour, Demand side management and Demand side response were analysed too.

Then the implementation of smart management of railway networks towards power losses minimization was investigated by focusing in particular on the E-LOBSTER solutions. In particular, the aspects that are considered most interesting in order to understand the importance and the usefulness of smart management regarding the development of the ELOBSTER project were fully illustrated.

The conclusions of this document are based on three main foundations that support the future development and application of smart management technologies for railway networks.

Firstly, the vision of European railways an energy organisations towards fostering the implementation of smart grids and smart technologies with the aim of reducing energy losses and, therefore, strengthening the role of railways as the future backbone of transport, which will allow to cope with environmental and massive transport issues. This will allow to foster the development of this kind of technology which will help railway undertakings and other related stakeholders obtain market benefits in the future. On the other hand, and apart from the advantages that smart management provides, it is necessary to develop new standards and regulations that establish a framework where new ways of energy and railway management might be developed.

Secondly, apart from the clear advantages in terms of railway energy management, new concepts of urban mobility and the interest in synergies building also arise thanks to the opportunities that smart technologies put into place. Therefore, and as it has been developed throughout this document, the figure of EVs is regarded to be the perfect partner for railway transport in terms of sustainable urban mobility, enabling the use of railway regenerative braking as a possible energy source for the EV charging, and the use of EVs as a possible additional energy storage system.

On the other hand, the effects on customer demand and energy network behaviour due to the implementation of these new system also have been subject of study, using the conclusions that come from other similar studies, like MERLIN, that allow to foresee how these new systems will affect the traditional demand behaviour and functioning of the electric network.

Finally, the effects of the implementation of smart management leads to an increase of savings in terms of energy losses. As it may be observed throughout the study, energy losses are noticeably decreased because of the use of these technologies in the different systems of the railway network (infrastructure, rolling stock, and operation). Of course, these advantages in terms of energy efficiency are linked to new regulatory and technical challenges that force to create new standards and to consider issues that did not exist previously.

To sum up, the implementation of smart management in railway networks lead to interesting results either considering the arise of synergies with other transport services and energy systems or the increase of energy efficiency thanks to the decrease of energy losses and the recovery of otherwise wasted energy.