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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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Table of Contents

Terms and abbreviations

The table below lists (alphabetically) the terms and abbreviations used in this document.

Term	Description
Non-technical losses	Power losses that are incurred due to administrative gaps, metering errors and theft.
Technical losses	Power losses incurred due to supplying the energy required to make the distribution system operate.

Abbreviation	Description
AC	Alternating Current
AEW	Aerial Earth Wires
BEV	Battery Electric Vehicle; an EV which is fully electric
BT	Booster Transformers
CB	Circuit Breaker
DC	Direct Current
DG	Distributed Generation
DSO	Distribution System Operator
DN	Distribution Network
EMI	Electromagnetic Interference
EV	Electric Vehicles
HV	High Voltage
ICT	Information and Communication Technology
LV	Low Voltage
MV	Medium Voltage
NOPs	Normal Open Points
NPS	Negative Phase Sequence
Ofgem	(UK) Office for Gas and Electricity market
PF	Power factor
RC	Return Conductors
RR	Running rails
sSOP	Smart Soft Open Point
TL	Technical Losses

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 will demonstrate tools and technologies, software and hardware to monitor in real time the source of losses of both the networks (Transport and distribution networks (DN)) 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 this context, the scope of this document is to provide an overview of the most suitable technologies for electricity losses reduction in the Power Distribution Network and Electrified Railway Systems. Actually, this deliverable provides an assessment of technologies and methodologies for maximize mutual benefit synergies between the two grids with a particular focus on losses reduction and state of the art practices.

The following paragraphs introduces briefly the different power losses categories by detailing then the main contents of this deliverable.

1.1 Power losses categories

The power losses can be split into categories as shown in Figure 1-1. Known technical losses are split into fixed and variable losses. Fixed losses are independent on the power flow: for example, the energy used by transformers to create magnetic field that is directly related to the applied voltage rather than the current. Variable power losses are those that are dependent on the power flow over the transmission medium. No matter how the network design is optimised, there could be a technical limitation on how close the generation can be to the consumption and hence there is a further portion of variable losses that is unavoidable. There are, however, avoidable losses that can be completely eliminated by using a good engineering design that reflects the unpredicted power flows due to intermittent power generation and unpredicted consumption.

The E-LOBSTER project focuses on methodologies to reduce or even eliminate the avoidable variable losses.

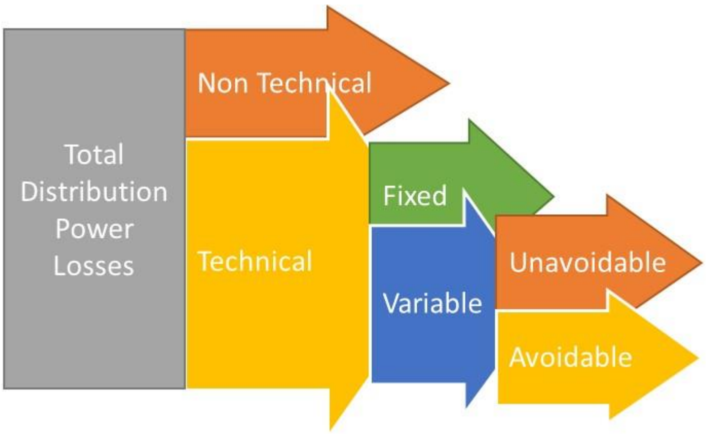


Figure 1-1. Power losses categories. Note that the figure is not drawn to scale. The proportion of the losses highly varies from one network area to another.

1.2 Scope

This report describes the structure and characteristics of railway electrification networks and power distribution networks with the aim of identifying the conditions for their optimal operations. On the basis of these requirements, the analysis focuses on the impact on the overall network energy consumption and the power losses of the installation of a new smart Soft-Open Point (sSOP) device (one of the main enabling technologies proposed by E-LOBSTER) interconnecting railway electrification and power distribution networks. This includes the characterisation of the individual sub-systems, i.e. power converters and energy storage, their control and the connection schemes.

The main technical features of the most suitable technologies for the practical demonstration of E-LOBSTER and the impact on the whole system losses are qualitatively analysed in this report.

The subsystems are classified in terms of electrical requirements for the connection to railway and distribution networks (AC or DC, nominal voltage, nominal frequency) and capability of interconnection (continuous and peak power, power factor, energy stored).

1.3 Purpose of the deliverable

The purpose of this deliverable is to analyse the state of the art and to identify new cost-effective solutions for electrical losses reduction for the interconnected transport and electricity networks through providing an overview of:

- Current practices of infrastructure operators
- Emerging technologies and subsystems introduced by equipment manufactures
- Reported R&D experiences through various EU demonstration projects
- Regulations that may potentially limit or facilitate innovative solutions

In particular, in Chapter 2 an analysis of energy losses in the Electricity Distribution Networks as well as a study on the emerging solutions and technologies to reduce losses were carried out.
In Chapter 3, the losses in the Rail Electrification Networks was investigated as well as potential technologies for their reductions. Chapter 4 deals with Energy storage solutions and their losses. Chapter 5 investigated distribution and rail networks interconnections by proposing 3 potential configurations to be studied in the framework of E-LOBSTER by taking into account its enabling technologies. Chapter 6 provides an overview of the initial system requirements whereas Chapter 7 describes the technology challenges and risks measures. Chapter 8 reports the conclusions.
A first release of this deliverable was prepared at November 2018 (M6 of the project). This version represents the updated second release completed at May 2019 (M12 of the project).

2 Electricity Distribution Networks

This chapter reviews the main topologies and characteristics of power distribution networks. This chapter will also take a detailed look into the impact of each technology on the losses in addition to the main business case/growth drivers for the DSO to adopt inter-sector subsystems/shared assets as an introduction to the next chapter.

2.1 The evolution of the distribution network – an overview

2.1.1 Electricity distribution structure

Electricity distribution networks transport electricity from the national transmission systems through to industrial, commercial and domestic users at various stages. Typical voltage levels of the distribution system are 132kV, 33kV, 11kV and 400/230V. From the losses point of view, the bulk of the power losses occur in the 11kV and 400/230V LV networks. A typical part of the LV network is shown in Figure 2-1.

The backbone infrastructure of these networks was built in the 1950s and 1960s in most of the developed countries. In radial distribution grids, the voltage drops along the line dependently on the variation in power flow resulting in variable losses. As part of the grid codes, maximum and minimum operating voltages are normally regulated using transformer taps. Additionally, typical urban network configuration contains Normally Open Points (NOPs) that allow network reconfiguration by which the power flow and hence the losses can be optimised.

There have been however big changes since 2010 in Europe owing to the integration of renewable energy in response to the Regulator incentives in the form of Feed-in-Tariffs[1]. The introduction of renewables in the form of Distributed Generation (DG) has changed the way the power flows through the LV network, see Figure 2-2, especially at times when the generation at low voltage circuit exceeds its demand. To overcome such situations, DSOs have started to analyse their networks to check where new DG connections will require network reinforcement.

A promising technology to address this problem is based on Soft Open Points (SOPs). SOPs are modular ac/ac back-to-back power converters to connect together the bus bars of NOPs in a flexible way. The SOP connection can be controlled, so that the two bus bars can operate independently or interconnected in order to dynamically minimize the system losses.

[1] A. Pyrgoua, A. Kylili, P. A. Fokaides, The future of the Feed-in Tariff (FiT) scheme in Europe: The case of photovoltaics, Energy Policy, vol. 95, August 2016, Pages 94-102

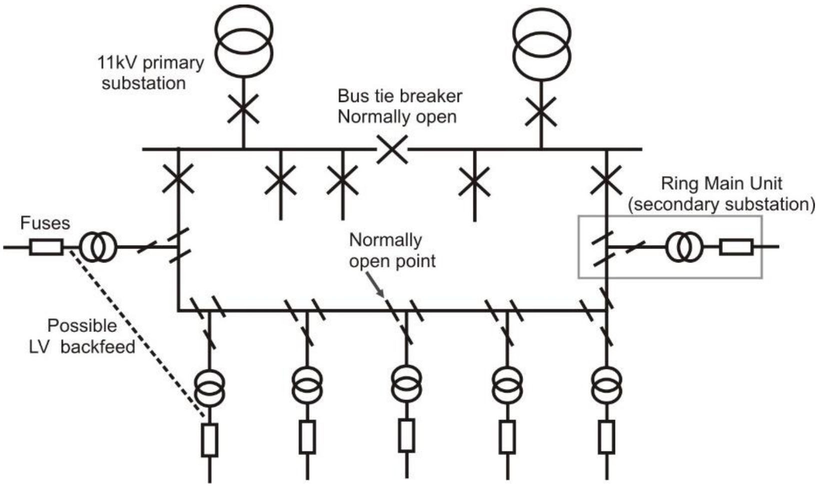


Figure 2-1. Typical LV network distribution system.

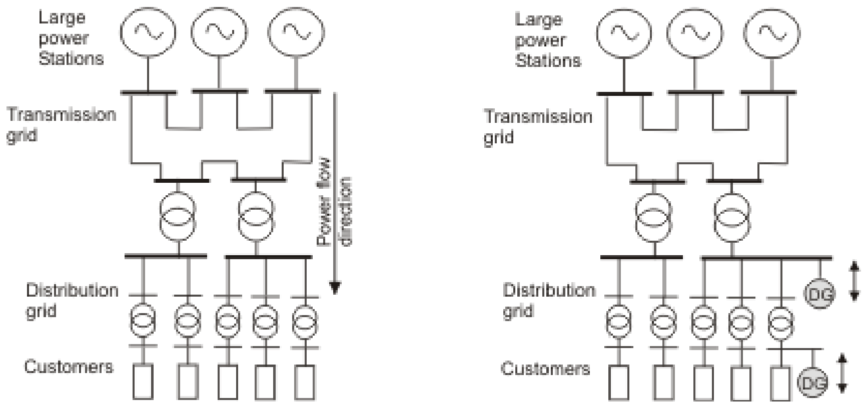


Figure 2-2. Simplified system diagram to show locations with possible reverse power flows (right) as compared to conventional unidirectional power flow network (left).

2.1.2 Planning and operation

In broad terms the DSO conventional roles are to:

- Manage the physical operation of their distribution network;
- Invest in the infrastructure by reinforcing, replacing, or renewing the equipment to ensure power is supplied within statutory tolerances;
- Connect new consumers and generators to the network as appropriate; and
- Promote competition in electricity supply.

Based on some modelling of scenarios[2], it is estimated that there will be an increase of up to 100% in the maximum ramping requirements for balancing production and consumption over a one-hour time horizon in 2030 relative to the current situation. This is primarily driven by the increased renewable energy capacity. This requires the system operator to plan a larger volume of ramping capability of the synchronised generators or other dispatchable demand/supply resource in the system within the respective time frame to meet the demand-supply balancing challenge. Meeting the increased ramping requirements by fossil-based generation is expensive due to: (a) efficiency losses as

[2] A Roadmap for Flexibility Services to 2030, A report to the committee on climate change by PÖYRY and Imperial College, May 2017.

some plants will be required to run part-loaded; (b) increased number of engine start-ups; and c) increase in CO_2 emissions driven by efficiency losses.

It is hence evident that the methods based on the balancing of power flows are the most critical for distribution efficiency view point, and introducing efficient technologies for balancing services need to be part of the planning and operation processes of DSOs.

2.1.3 Regulations

There are some recent regional regulations that directly or indirectly impact distribution losses.

2.1.3.1 Losses specific controls by the regulator

Over the recent years, DSOs have been encouraged by the regulators to reduce losses on their network in exchange of economic incentives. However, the practical actuation of incentive schemes poses the following challenges:

- What is the appropriate timeframe to quantify the loss savings
- How frequently should the DSO survey networks for losses
- What tools can the DSO use to incentivise repairs outside of their control area that have a negative impact on their network area.

2.1.3.2 CO_2 reduction

There are stringent CO_2 reduction targets set both attentionally and internationally through local governments and cross-border organisations. In Europe, there have been a reduction of 22% of CO_2 emissions with reference to 1990[3] and future targets are even more ambitious. For example, in the UK the target is to cut more than 74% of the CO_2 emissions by 2050, as shown in Figure 2-3.

Decarbonising heating in buildings has significant impact of CO_2 reduction but also has infrastructure implications. The most efficient pathway to the 2050 CO_2 reduction target is likely to involve an increase in heat sourced from district heating ('heat network') schemes and from heat pumps. These require the roll-out of heat networks and strengthening of local electricity distribution networks in the right locations.

Electrifying transport is also a main measure to reduce CO_2 towards 2050, including both rail and road vehicles. Analysis suggests however that an infrastructure strategy should include investment in a large number of rapid chargers to accelerate the uptake of EVs. Allocation of these charging points will have to accommodate both the drivers' convenience but at the same time will need to be smartly managed by the grid to avoid any negative impact on losses, power quality or security of supply.

[3] https://ec.europa.eu/clima/sites/clima/files/docs/pages/vision_1_emissions_en.pdf

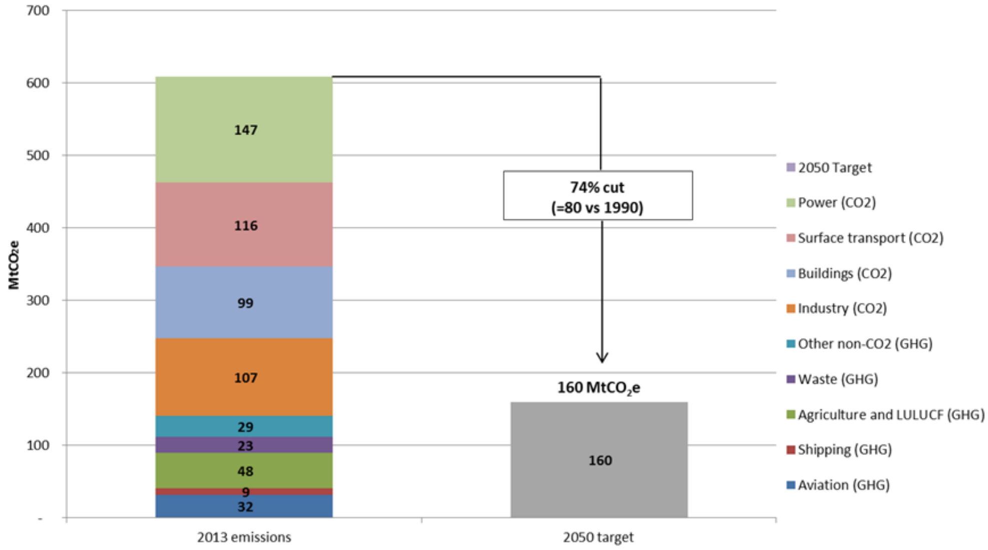


Figure 2-3. UK CO_2 emissions target for 2050 Source: Committee on Climate Change (CCC)[4] .

2.1.3.3 Emerging role of Distribution System Operators

The role of DSOs is extending to provide services. The transition to a new DSO role will require an increased visibility of energy flows at all voltage levels; to achieve this, recording frequency will need to be increased through the addition of extra monitoring points. New and existing metering at strategic locations will need to provide directional MW and MVAr measurements. There may also be the need to have network trends stored at a higher sample rate than half hourly averaged, due to intermittent generation and demand technologies connecting to the network causing fluctuations within a half hour.

This transition is fundamentally based on intelligent monitoring and integration of devices within the LV distribution. The main drivers for this transition are:

- The increase of low carbon technologies connecting to the distribution network causing uncertainty in network power flows. In particular, bi-directional power flows and power factor variations;
- Rolling out smart grid network solutions and smart grid alternative connection solutions;
- A requirement for better understanding of pre-fault and post-fault network conditions; and
- Requirement for improved accuracy on network losses.

Automation of LV networks will have a positive impact on losses reduction in distribution as it facilitates smart technologies implementation to provide grid services. As a result, losses should be dealt with a whole system approach that ensures network decisions are made using appropriate techno-economic analysis. In this way, losses would be appropriately valued and the entire power system would be committed to provide the best aggregate benefit to customers in carbon reduction as well as economic terms.

2.1.4 EU studies of energy losses in distribution networks

An investigation on the subject related to losses in the Distribution Network System has been carried by carefully analysing different EU projects[5], and by taking into account different aspects and technologies of energy losses mitigation. A short description of the following projects from EU portal is indicated below.

<u>EVOLVDSO</u> - Development of methodologies and tools for new and evolving DSO roles for efficient DRES integration in distribution networks – GA 608732 – 2013-2016

The project aimed at creating a more active distribution management approach, with investment optimization. It did so by developing a menu of improved approaches for the DSOs addressing their needs for priorities such as:

- improvement of network planning and operation processes;
- flexibilities at different timeframes to solve specific network constraints;
- regulated services based on data management.

The project defined the roles of DSOs based on future European electricity systems scenarios, as well as plugging research and technological knowledge gaps.

One of the ambitions of the EVOLVDSO project was the creation of realistic future scenarios. The electricity generation mix, the evolution of demand and the degrees of technological flexibility have been analysed in the framework of the project. Each scenario was developed according to a set of parameters, which vary with time.

Thanks to these scenarios the project was able to develop 10 innovative tools, focused on planning, operations, maintenance and coordination needs. One of these tools is able to estimate realistic values of active and reactive power, for the power flow exchanged at the boundary nodes between the transmission and distribution networks (primary substations).

The project was able to map each tool's capability to fulfil the services linked with the new role of DSOs as well as their evolution. Furthermore, specific scope of the project was to assess the replicability and scalability potential of each of the tools, as well as perform a high-level cost-benefit analysis. For the tools tested in real environments, the project was able to define the enabling as well as limitation factors related to each of the countries involved (Belgium, France, Germany, Ireland, Italy and Portugal). Moreover, a forecast for their anticipated adoption timelines was provided.

<u>INCREASE</u> - INCreasing the penetration of Renewable Energy sources in the distribution grid by developing control strategies and using ancillary services – GA 608998 – 2013-2016.

The objective of the INCREASE project was to create a model with a significant increase of distributed renewable energy sources (DRES) at the low voltage distribution grid and a large wind or solar plant farms installation at the medium voltage (MV) level.

As a matter of fact, the massive integration of DER in low (LV) and medium (MV) networks has led to a bidirectional power flow which determined the need for new operational and control strategies in order to maintain the ability of the system to provide the consumers with distribution network reliability, security of supply at distribution level and an acceptable power quality level.

The project aimed to solve these problems with innovative three-phase grid-connected inverters and new operational and control strategies in order to maintain the ability of the system to provide the consumers with reliable supply of electricity at an acceptable power quality level.

[5] https://cordis.europa.eu/projects/home_en.html

More in detail, the main scope of the INCREASE local control strategy was the continuous mitigation of over voltages and voltage unbalance in low voltage distribution networks. Actually, the increased penetration of renewables can lead to voltage problems in the low voltage distribution grids which in severe cases results in a disconnection of the solar inverters from the grid.

The local control strategy is implemented in the inverter that connects the solar panels to the grid. The inverter measures the voltage and power at terminals by deciding then accordingly what has to be done. There is no need for communication with external parties, the inverter works independently.

The INCREASE simulation platform has enabled the validation of the proposed solutions and provides the DSOs with a tool they can use to investigate the influence of DRES on their distribution network. The INCREASE solutions have also been validated by lab tests, as well as in four field trials in the real-life operational distribution network of Energienetze Steiermark in Austria, of Eandis in Belgium, of Elektro Gorenjska in Slovenia and of Liander in the Netherlands.

GRID4EU - Large-Scale Demonstration of Advanced Smart GRID Solutions with wide Replication and Scalability Potential for EUROPE – GA 268206 – 2011-2016

The project was led by six European DSOs covering more than 50% of the electricity supply in Europe: CEZ Distribuce (Czech Republic), Enel Distribuzione (Italy), ERDF (France), Iberdrola Distribucion (Spain), RWE (Germany) and Vattenfall Eldistribution (Sweden).

The main objectives of Grid4EU were:

- The development and testing innovative technologies,
- The definition of standards through the set-up of large-scale demonstration,
- Guaranteeing the scalability of the developed new technologies,
- Favouring the replicability of the project solutions over Europe,
- Analyzing Smart Grid Cost-benefits (business models for storage, DR market mechanisms, etc.).

In the framework of Grid4EU, each DSO participating to the project implemented a demonstrator tested over a period of four years.

The main research and development challenges of the project have been:

- Improving renewable energy integration through connection to distribution networks
- Implementing more efficient participation of consumers in demand response scheme
- Securing energy supply - Distribution network reliability
- Distribution network monitoring technologies and Grid Automation:
    - LV network monitoring and control
    - MV network monitoring and control
- Improving peak load management (load shaping) through demand response scheme
- Integration of demand-side management (DSM) into DSO services

2.2 Components and sub-systems installed in the DSO network

2.2.1 Conventional components

The application of traditional reinforcement measure increases capacity and hence reduces power flows in individual circuits and consequently reduces losses. This is explained in the following.

2.2.1.1 Transformers, overhead lines and cables

During power transmission some losses are unavoidably lost in the form of heat in cables, overhead lines and transformers. These components are either using copper or aluminium conductors. As the conductors heat up due to the power flow, their resistances increase causing more energy to be lost. The increase in temperature can occur as a result of heating due to current flow as well as from climatic

conditions. Losses in the conductors are directly related to the square of the current. Hence, upgrading the network with a parallel cable does have a positive impact in reducing the power losses.
In general terms, reduction of technical losses can be achieved through optimisation of transformers and conductors.

As set out within "commission regulation (EU) 548/2014" the maximum load and no-load losses for a three-phase dry-type medium power transformer can be seen in the Table 2-1 below.

Some DSOs have active plans to replace transformers manufactured before 1962 to decrease the losses of distribution transformers.

The 33/11kV transformers typically installed in pairs, mainly to provide security of supply. These will share in most cases the load equally. Under low loading the no-load (iron) losses saved by switching off a transformer can be greater than the increase in on-load (copper) losses in the remaining transformer(s). In these cases, electrical losses may be reduced by having one transformer switched off during low load periods. This however risks the security of supply. Using sSOP to equalise the transformer loading when one transformer is lightly loaded while another transformer is heavily loaded was successfully trialled[6] to reduce losses and maintain security of supply.

Table 2-1. Maximum losses for a three-phase dry type medium power transformer

	Tier 1 (1 July 2015)		Tier 2 (1 July 2021)	
Rated Power (kVA)	Maximum On-Load Losses (W)	Maximum No-Load Losses (W)	Maximum On-Load Losses (W)	Maximum No-Load Losses (W)
400	5500 (1.35%)	750 (0.19%)	4500 (1.1%)	675
630	7600	1100	7100	990
800	8000 (1%)	1300	8000	1170

2.2.1.2 Reactive power compensation

Poor power factor contributes to higher currents and thus higher losses. There are connection regulations that set compliance limits on reactive power at the connection points. Loads with significantly low power factor are required to install power factor correction units at their respective point of connection.

2.2.1.3 Metering

Electricity leaves the network at consumers premises and is metered at this point. However, it is used also for street lighting, traffic bollards, telecommunications cabinets and similar applications without being metered and thus called unmetered supplies.

Meters consume a small amount of power whether or not there is any consumption to record. Although this is a small amount, it scales up for instance to about 2 to 3% of the total amount of technical losses with all installed meters in the UK (about 500MWh[7] per annum).

[6] FUN LV (Flexible Urban Networks Low Voltage) project, Ofgem funded, January 2014 to December 2016.
[7] An estimate based on 26TWh total technical losses.

2.2.2 Losses and conventional energy efficiency measures

Other EU projects have investigated the process of generation and transmission of the electrical energy from the power plant in which it is produced, to the points where it is consumed (vehicles and fixed transport installation)[8]. The objectives of the EnerTrans project are the following:

1. Identify the losses that occur in the system due to the generation of electricity (losses in the conversion of primary energy into electrical energy) as well as the losses due to the transport and distribution (losses in the power lines, transformers, etc.)
2. Estimate the emissions associated with the consumption of electricity, which will be related to the technologies used in the generation.

2.2.2.1 Typical types of losses in distribution networks

Power losses are a consequence of transporting electricity across the power grid. In this context, the technical component of losses (i.e. transformed energy to heat and power) represents the main contribution. However, also non-technical components, that include the energy delivered but not metered or billed, are non-negligible.

Power generated in power stations run through a large and different networks and equipment like transformers, overhead lines, cables before reaching the end users. Generally speaking, with respect to distribution networks, annual electricity losses have been estimated to be in the range 2-12% in the European Union countries according to ERGEG Position Paper on Treatment of Losses by Network Operators, see Figure 2-4. In parallel, the European Energy Efficiency Directive (Art. 15.2) requests all Member States to estimate the capabilities for energy efficiency and to define measures to improve them. Losses mitigation is becoming essential for all European countries.

The new technologies concerning smart metering and sensors provide a large number of operational data on the grid often in real time whereas ICT and data mining techniques ensure to manage a considerable volume of data to evaluate and to detect locations losses.

[8] EU EnerTrans project

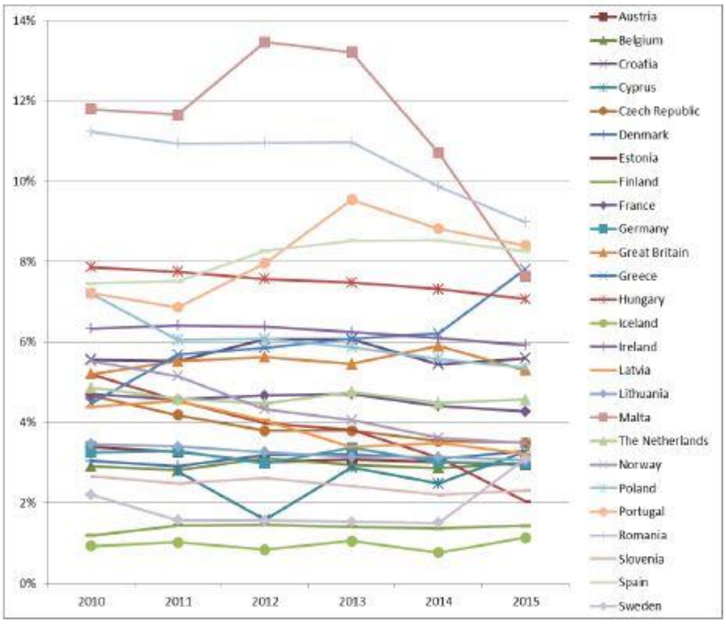


Figure 2-4. Losses in distribution network as percentage of total injected energy in different European countries[9].

The above-mentioned analysis refers to the path followed by electricity from generation to consumption points and calculates the loss coefficients associated with the transportation of electricity. The ohmic losses depend on the distance that the electric power has to travel as well as on the voltage (higher voltage, lower losses).

The losses in the network correspond to the energy dissipated in the form of heat in the lines and in the transformers. These losses depend on the distribution of the electricity along the lines of the network, which change throughout the day as can be seen in Table 2-2 and Table 2-3.

Table 2-2. Standard loss coefficients

Loss coefficients (%)	*Total*	*Period 1*	*Period 2*	*Period 3*	*Period 4*	*Period 5*	*Period 6*
BT	13.81						
1kV <V< 36kV	5.93	6.8	6.6	6.5	6.3	6.3	5.4
36kV <V< 72,5 kV	4.14	4.9	4.7	4.6	4.4	4.4	3.8
72,5kV<V< 145kV	2.87	3.4	3.3	3.2	3.1	3.1	2.7
220kV	2.26	2.68	2.53	2.53	2.53	2.53	2.08
400kV	1.24	1.47	1.39	1.39	1.39	1.39	1.14

[9] CEER (Council of European Energy Regulators) – Report on Power Losses; Ref: C17-EQS-80-03

Table 2-3. Period for standard loss coefficients

	Type A	Type B	Type C	Type D
Fee Period	*M-F working day (high season)*	*M-F working day (medium season)*	*M-F working day (low season, except August)*	*S-S and August*
P1	From 16 to 22 h	-	-	-
P2	From 8 to 16 h	-	-	-
P3	-	From 9 to 15 h	-	-
P4	-	From 9 to 15 h	-	-
P5	-	-	From 8 to 24 h	-
P6	From 0 to 8 h	From 0 to 8 h	From 0 to 8 h	From 0 to 8 h

Distribution network losses are usually classified into two categories:

- Technical losses (TL)
- Non-technical losses (NTL)

Further classifications can be done by distinguishing losses in transmission and distribution grids. Electricity transmission runs at high and extra high voltage and it is reasonable because high voltage transmission level implies a low current level and a low level of losses.

2.2.2.2 Technical losses

Technical losses in power systems are a natural effect related to the energy dissipation in electrical equipment (e.g. lines, transformers, connections, measurement systems and other component) that move energy towards and from customers. This kind of losses are also defined **'Physical losses'** as they consist in energy converted to heat and noise during electricity transmission and, therefore, physically lost.

Basically, technical losses represent a direct consequence of the physical characteristics of the electrical component used in distribution networks. They are also due to the design of the power grid, the voltage and transformation levels and the length of the power lines.

Technical losses stand for 6-8% of the cost of generated electricity and the 25% of the cost to dispatch electricity to the customer.

Technical losses affect the investment in equipment (lines, transformers) and the operational expenditure.

Technical losses can be classified in the following way:

a) Variable losses (load related)
b) Fixed losses (not related to load)
c) Network services (uncontracted consumptions of network equipment)
d) Secondary factors

Fixed	Corona losses Leakage current losses Dielectric losses Iron losses / No load losses
Variable	Joule losses Copper losses / Load losses Losses caused by contact resistance Consumption in protection systems
Network services	Losses caused by continuous load of measuring elements Losses caused by continuous load of control elements

Figure 2-5. Technical Losses discrimination[10].

- **Variable losses**

Variable losses are strictly connected to the heating effect of energy flowing inside conductors in lines and cables and also in the copper inside transformers. Variable losses are proportional to the square of the current and to the conductor resistance. Consequently, any efforts to minimize variable losses will focus with decreasing the system power flows or the resistance of the transport distance. All conductors passed through electric current have an internal electrical resistance which induce them to heat. Conductors means coils in transformers, aluminium or copper wires in overhead lines or cables and even in switchgear, fuses, or metering equipment. Since energy losses are directly connected to the dissipation of heat to the environment and they change with the current flowing through conductors in electrical networks, these losses are called 'variable losses'. These losses are also usually referred as 'ohmic losses', 'copper losses', 'Joule losses', 'resistive losses' or I^2R losses.

Obviously, distribution networks have a higher level of losses. Further issues such as the impact of network imbalance, power factor and power quality can also affect variable losses, as they modify the value of the currents flowing through conductors.

The line resistance depends on many factors, including the length of the line, the effective cross-sectional area, and the resistivity of the metal of which the line is made. Indeed, cable length and resistivity of the metal are directly proportional to the resistance contrary to conductor cross-section area that is inversely proportional. Therefore, the effect of losses is limited with larger cable sizes. A similar principle also applies to the variable losses in transformers, where the cross-sectional area of windings, and the materials used in them, influence the variable losses.

Inadequate connections between network equipment and deteriorated conductors can also represent one of this type of losses, since they are the possible origin of hot spots due to a raise in the equivalent resistance.

Other types of losses are related to contact resistance that is the resistance to current flow, caused by surface conditions, when contacts are touching one another also in the closed condition of the device. This can happen between contacts of:

- Breakers
- Contactors

[10] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

- Relays
- Switches
- Connectors
- Other switching devices.

Generally speaking, variable losses contribute roughly between two-thirds and three-quarters of the total power system technical losses and they can be reduced manipulating two influencing factors: power flows and resistance.

- **Fixed losses**

Some electrical energy is dispelled by network components and equipment such as transformers or conductors as a result of being connected to the network and made 'live' (energized). Even if no power is distributed to customers, the system has losses just due to electrically energized. These losses are called 'fixed losses or 'no-load losses', because they are independent from the amount of electrical energy delivered by the network.

Transformers' energization is one of the main causes of the fixed losses (although it also plays its part to variable losses). These losses are located in the transformers' core and are called 'core losses' or 'iron losses'.

Two types of core losses are known:

- 'Hysteresis losses' are losses that have their source in the reversal of magnetic polarity of the steel in transformer cores in every AC cycle. This is reflected in the material pulsing (it emits a humming noise) and heating up. They are originated in a reduced perfect permeability of the core material.
- 'Eddy current losses' are losses that stem from induced currents that pass through conducting parts that are not copper windings, for example the iron body or steel core of the transformer.

The core losses in a transformer are typically most relevant in magnitude than the copper loss. It is the result of eddy current losses and hysteresis losses. These losses are regarded as constant for an energized transformer and as independent from the transformer load. Usually transformer core losses are modeled as a resistance in parallel with the transformer's magnetizing reactance.

One of the most important elements to evaluate core loss is the manufacture of the core. The physical construction of the core has serious impact on the amount of core loss that exist in the transformer.

The copper losses in transformers can be deemed very similar to those in the power distribution lines, they are calculated using the I2R relation. These losses are smaller in magnitude than the core ones. These losses occur in the windings of the transformer, both primary and secondary, in the form of heat produced by the current. An increase of power, either real or reactive, will result in a raise of current flow and a correspondingly greater amount of loss in the transformer.

Additionally, an unbalanced system load will increase transformer loss due to the squared current relationship. The winding resistance also has an impact on the amount of copper loss and is mainly limited to the total length of the wire used, as well as the size. The temperature of the winding will modify the resistivity of the wire, as a result of the overall resistance and the copper loss. Even if the smallest distribution transformers have some type of cooling system, i.e. oil- based immersion, the temperature effect on losses is usually minimal.

The core loss in a transformer is usually larger in magnitude than the copper loss. It is made up of eddy current currents in the core, and hysteresis losses, which occur because of the less than perfect losses, which are due to magnetically induced permeability of the core material. These losses are relatively constant for an energized transformer and can be considered to be independent of the transformer load. Transformer core losses have been modeled in various ways, usually as a resistance in parallel with the transformer's magnetizing reactance.

Since the core loss is relatively independent of loading, the most important factor when considering core loss is the manufacture of the core. The physical construction of the core has serious consequences on the amount of core loss occurring in the transformer. For instance, eddy currents are greatly reduced.

It is further necessary to analyze also losses connected to electrical insulation in network equipment. They are due to imperfections in electrical insulation that allow a flow of infinitesimal currents across them in transformers, lines, cables, and other equipment. These types of fixed losses are defined 'dielectric losses' or 'leakage current losses'.

Among the other source of fixed losses, there are the so-called corona losses that occur in high voltage lines. They go in parallel with voltage level and physical wire diameter and with weather conditions such as rain and fog. Corona losses make generally a very small contribution to overall system losses.

While fixed losses do not change with current, they strictly depend on the applied voltage. When the network equipment is energized, the applied voltage is relatively stable and consequently losses are essentially fixed. Therefore, fixed losses depend also on the number of energized components. Transformers connected in the energy distribution network are connected permanently to the power supply system; therefore, the no-load losses of the transformers must be taken into consideration.

- **Network services**

Further equipment connected to the network may cause dissipation of energy. Network control, measuring elements placed along electrical lines and meters located in customer facilities, both mechanic and electronic, are identified as uncontracted consumptions. Losses consumptions related to network equipment have a fix and a variable component and a variable component (depending for instance on the ICT devices according to data frequency and volumes).

- **Secondary factors influencing technical losses**

Secondary types of electrical energy losses also occur in the network. These secondary losses are caused by circulating currents in the network, voltage regulation equipment, techniques and equipment used to balance the voltage phases of the network and equipment to correct the power factor of the network.

- **Voltage regulation**

Line losses in an electricity distribution network increases with the square of the load current when the resistance is constant. Maintaining or decreasing the voltage across the load, the line losses of the electrical distribution network would be reduced.

- **Phase balancing**

Phase balancing has a relevant significance when the electrical distribution network becomes massively overloaded. With the purpose of minimizing the electrical power losses in an overloaded network, the phase load maximum deviation must be below 10 %.

- **Power factor**

A unity power factor ensures that the current value is minimum and also the connected losses. Reactive component will cause an increase in current with a resultant increment of the real power loss of the electricity distribution network. In distribution networks with large inductive loads, losses resulting from inductive energy (VArs) become relevant.

2.2.2.3 Non-technical losses

Non-technical losses are referred to energy delivered and consumed, but somehow not registered by a meter. Not all of the energy passing through the distribution network and consumed by end users can be measured or accounted-for. These losses refer to a 'lost energy' and are completely independent from the physical technical characteristics of the network. Non-technical losses are also described as ‘black losses’ or ‘commercial losses’, since they are not directly charged by suppliers or distribution companies as an inaccurate energy flow.

When there is an undiscovered load connected to the system, the real losses increase while the losses forecasted by the utilities will remain the same. The incremented losses will be visible on the utilities’ accounts, and the costs will be moved to the customers as distribution charges.

Non-technical losses are related to the consumer management process and can be classified as follow:

- Network equipment issues
- Network information issues
- Energy data processing issues

Type of non-technical losses could be the following:

- Hidden losses: they are conventionally related not only with in-house consumption, but also with electricity consumed with the aim of cooling transformers and operating the control system.
- Non-metered supplies: they include public lighting, telephone booths, traffic lights etc. For practical reasons, consumption of these electrical installations is calculated on the basis of equipment inventories, estimated use or known hours of operation, which sometimes could be rather faulty.
- Theft: it consists of tampering with meters and operating illegal connections. It is onerous to check the exact size of this type of losses and a large part of it go undetected.
- Damage to electrical equipment.
- Further errors: they occur from the time-lag between meter readings and statistical calculations.

2.2.3 Emerging distribution subsystems

Even if the following technologies are not new, their use for providing grid services is relatively recent and not fully exploited especially in relation to losses reduction.

2.2.3.1 Distributed Generation (DG)

Distributed generation (DG) is connected closer to the consumption than conventional large-scale generation. This results in reduced power consumption transmitted over the distribution system. Hence, the introduction of DGs does somewhat reduce the losses in the LV network. However, with further increase in the amount of DGs, the losses during reverse power flow will start to dominate. Estimating the increase or decrease of losses due to DG is very much dependent on where they are connected from the loads, the network demand at the maximum reverse power flow and the network parameters. Additionally, the increase in losses can be compensated by a reduction at another moment in time or at another location. Hence, the introduction of DGs is not a measure for impacting the losses of the system on its own right.

However, the electricity balancing market has seen a high contribution from DGs as single or aggregate generators. Although the balancing of electricity distribution and consumption is not directly done to reduce losses, having these DGs contributing to this market allows for regional losses reduction and opens up additional income streams and incentives for increased uptake of DGs.

2.2.3.2 Energy Storage

The introduction of energy storage for grid services is also emergent. Figure 2-6 maps different storage technologies against their potential use for grid services. In particular, demand shifting and peak reduction using flywheel and Battery storage technologies are seen as potential methods to decrease the losses in distribution.

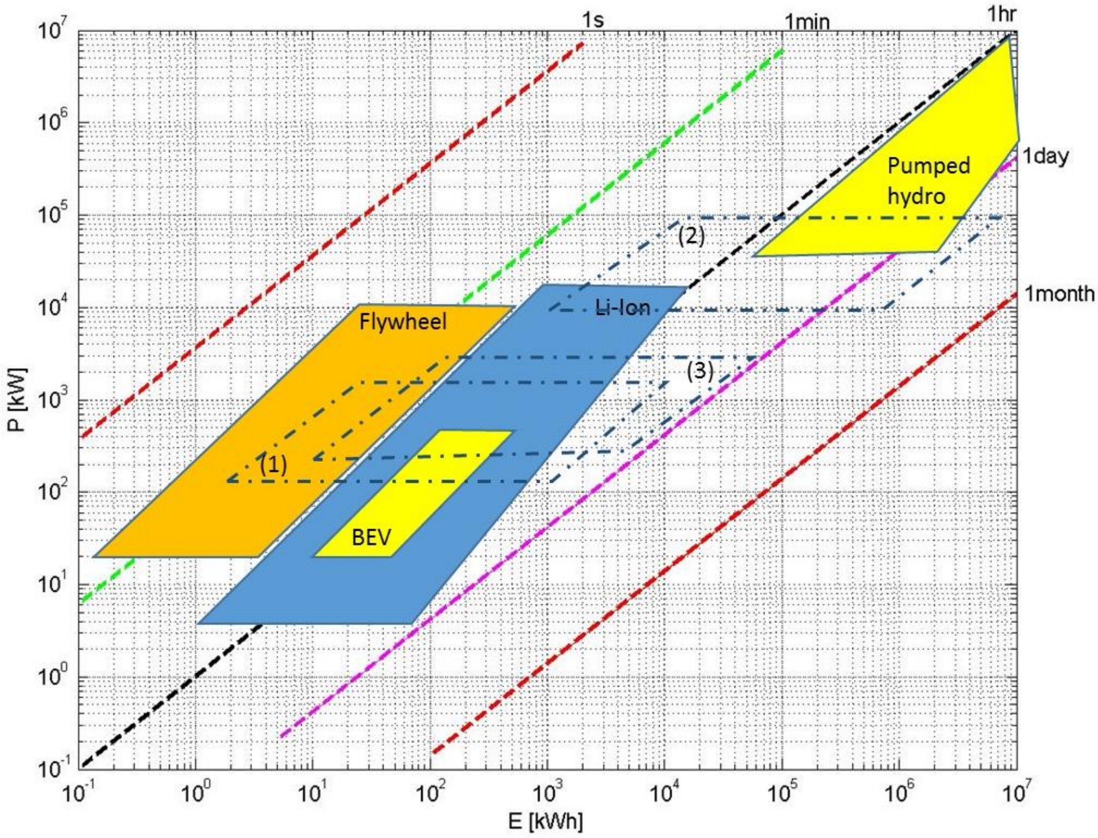


Figure 2-6. Ragone plot showing Energy storage technologies against short term capacity balancing requirements: (1) Demand shifting and peak reduction in urban networks, (2) off-grid support replacing /displacing diesel units in rural grids, (3) Distribution line upgrade deferral through voltage support.

2.2.3.3 EV Smart Charging infrastructure

Electric vehicles are a leading technology to achieve a near zero-carbon transport system. Widespread uptake of EVs will require roll-out of supporting infrastructure, including the deployment of a national network of rapid charge points along major roads. Electricity distribution networks will need strengthening to accommodate these chargers. Combining these high-power chargers with solar generation and energy storage, for instance with PVs installed on the canopies of car parks, positively impact the losses through optimising the local assets utilisation and efficiency.

2.2.3.4 Demand Side Response (DSR)

A responsive demand that interacts with the grid, following a request signal to decrease or increase, has a positive impact on losses. DSR signals are released to manage the grid within its regulatory and design conditions and eliminate deviations that cause losses and other power quality events.

2.2.3.5 Smart Meters

Firstly, it must be noted that to provide the increased functionality of Smart Meters, the meters will require more energy to operate. This increase although small at the micro level has a significant aggregated effect; estimated at an increase of 150GWhs per annum across SEPD and SHEPD licence areas[11]. Despite this local loss, smart meters allow better quality data collection in shorter time frames and hence better measurement of losses and better understanding of the measures that can be put in place to improve the losses on a microscale. They are also expected to facilitate significant reductions in peak demand from the implementation of Time-of-Use tariffs and hence directly reduce losses.

2.2.3.6 Automatic load transfer (ALT)

ALT is a technique used to move the position of normally open points on the 11kV network in an effort to improve the networks performance. Moving normally open points has an effect on the networks losses, voltage and capacity headroom. The sSOP is one technology that provides highly dynamic open points with potentially autonomous control.

2.2.3.7 Active Network Management (ANM)

ANM schemes are conventionally used to limit the DG power in case of grid congestion to manage thermal and voltage constraints. These schemes can be combined with other technologies to release the capacity, for instance from energy storage, at times when needed. This will allow ANM in the future to manage other network limitations such as voltage step change, power quality, losses and fault level.

2.2.3.8 Embedded DC-links

DC links in distribution allow for mitigation of different power quality issues to penetrate from one grid area to another connected through the link. They also allow independent reactive power control on each end which represent a measure to improve the voltage profile and hence improve the losses.

For example, Scottish Power Energy Networks in the UK is converting a 33kV AC line to DC to assess the benefits for the grid operator when embedding DC-links[12].

2.3 Technologies to reduce energy losses

All distribution losses reduction technologies can be categorised into three main streams as suggested by Figure 2-7. Note that the distribution refers to the transmission of power and not including the efficiency improvement of individual components. And hence power losses reduction is achieved through the balancing of demand and production over a certain time frame.

Reduction strategies vary in cost, complexity, impact and in most cases not scalable. An estimated allocation of where the emerging technologies lie regarding balancing services is shown in Figure 2-8.

[11] SSEPD RIIO-ED1 Losses Strategy, April 2016.
[12] ANGLE-DC project funded by Ofgem, January 2016 to April 2020.

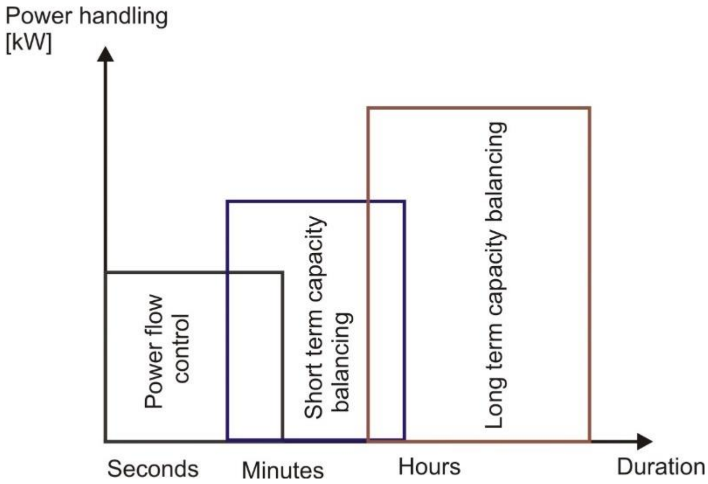


Figure 2-7. Main categories of distribution losses reduction.

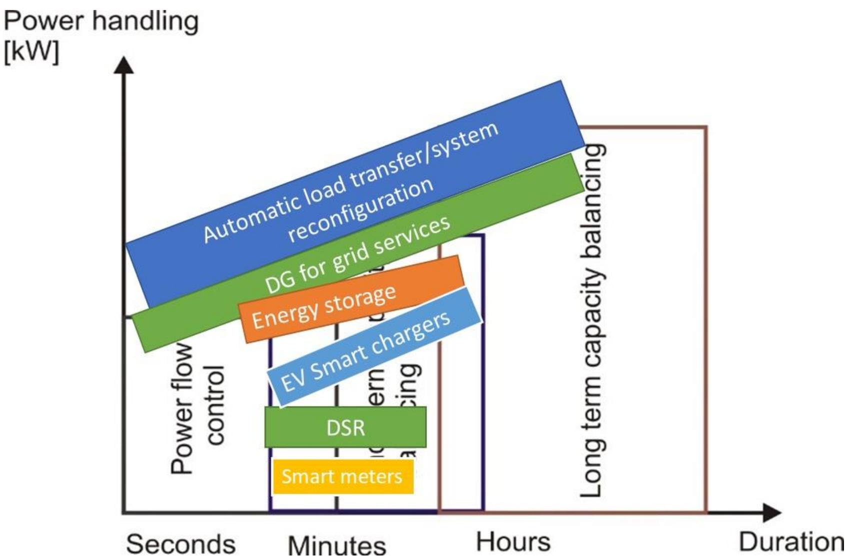


Figure 2-8. Technology mapping to reduce losses.

2.3.1 Reduction of losses of distribution networks

In this part of the handbook, different type of technical losses as well as their size have been investigated before moving towards their mitigation in electrical distribution system. Network losses are responsible for about 8 percent to 12 percent of the total energy allocated in the distribution system and the cost would be projected in millions of Euros every year. For the utility companies, energy losses represent an economic leak. For this reason, loss minimization is most important target in optimizing the distribution system and reducing energy bills.

One of proposed method is to increase power capacity of distribution system by adding new equipment. This action realizes an energy loss reduction by optimization of power flow and cost-benefit in parallel. For example, transformer upgrades could help to reduce the energy loss and it could be able to remarkably improve the performance of distribution system. The transformer cost could be balanced by the loss reduction if its installation is properly planned, placed and operated. Logically network reconfiguration should be appropriate, if not, it leads to increased energy losses.

A separate metering of TL is not possible in networks, particularly in low voltage networks, where NTL are quite high. The estimation of TL is possible particularly using the availability of information for different networks related to the voltage levels and to the country.

There are several reasons to reduce the TL, i.e. distribution system operators want to decrease expenditures on their networks or there are reasons directly connected to TL reduction incentives included in political framework and regulation. "For example, the 2012 EU Energy Efficiency Directive has established a set of binding measures with respect to energy efficiency. The requirements outlined in the directive include a 20% increase in energy efficiency by 2020 across the entire value chain. More recently, the 2016 "Winter Energy Package", first proposed by the EU on the 30th of November 2016, includes a stricter 30% target, along with measures to ensure the new target is met [2].

Table 2-4. TL % in the French and Northern Germany distribution networks (2013)[13]

Grid levels	Northern Germany	France
HV/MV substations	10%	17%
MV grid level	34%	28%
MV/LV substations	14%	36%
LV grid level (lines, connections, ...)	42%	19%

Table 2-4 give an indication of the typical level of TL using as an example the case of France and North Germany distribution networks. Figure 2-9 illustrates instead how TL are split in rural and urban types using as an example the case of Great Britain. Both graphs show that technical losses are strongly linked to the type of grids. Actually, in Figure 2-9, the majority of losses occur on the high voltage part on the rural network, while on urban network, losses occur mostly in distribution transformers and on the low voltage network.

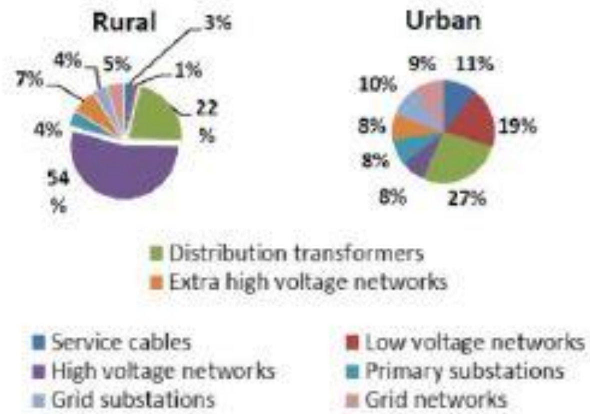


Figure 2-9. TL% in Rural and Urban distribution networks in Great Britain[12].

Energy of TL in urban distribution networks in European countries can be averaged at 3.5% of the energy delivered, while TL in rural networks may be up to twice as much higher.
All countries consider TL with a great concern pointing out the main differences between the fixed components that constitute network investments and the variable components that are identified in energy efficiency.

Some conventional ways to reduce losses are mentioned here below:

- Use of proper jointing techniques, holding the number of the joints as minimum.

[13] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

- Plan carefully regular inspection of the connections, isolators, drop out fuses, LT switches, transformers, transformer bushing-stem, and other distribution equipment.
- Provide a selection of conductor size and of transformer in terms of efficiency, size and location. It is fundamental to take into account that MV transformers are designed considering contingencies circumstances and that distribution transformers needs to be located at the load centre and their number hold as minimum.
- Feeding heavy consumers directly to MV or HV dedicated transformer.
- Maintain the network components and replace those that are non-performing, worn out or faulty.
- Provide an adequate proper load management and load balancing.
- Use of electronic meters which are errorless and tamper-proof.
- Improving power factor by inserting shunt capacitors.

2.3.2 Technologies for technical losses mitigation

TL can be minimized in several different ways. The core losses in transformers can be mitigated by introducing more efficient transformers, but they cannot be cancelled.
The literature indicates that variable losses contribute more than fixed losses to the total amount of losses in power system. For this reason, a great part of the efforts is spent to mitigate TL focusing on the reduction of variable losses.

2.3.2.1 Component replacement

Increasing the voltage level in distribution networks decreases the currents appropriate to distribute the same amount of power, increases current capacity of the grid and minimizes voltage drops and line losses. However, it must be taken care during the implementation of this solution as an insulation damage may take place.

Fixed losses can be also mitigated without replacing equipment by reducing the number of energized transformers in the network. It can be achieved by eliminating transformation steps and coupling directly higher voltage levels to lower ones without intermediate voltage level transformers. It is recommended the use of a single transformation step.

Increasing cross-sectional area of cables leads to a reduction of variable losses, see Table 2-5. Conductors with higher cross-sectional area have lower resistance. As an alternative, it is possible to replace conductors with high-temperature superconductors (HTS) which have an infinitesimal resistance at the temperature of -180°C. HTS can transmit a current value equal to five times of a conventional cable system with the same outer dimensions. The only losses in these systems are caused by the energy needed to perform the cooling mechanism.

Table 2-5. Electrical losses for different cross-sectional area of 400V cable[14]

Input parameters

Max Load current, A	50.3
Loss Load Factor	0.25
Length cable, km	0.3
Lifetime, Years	40

Electrical loss and emission for different conductor sizes

Size, mm^2	R, mΩ	Ducted Rating, A	Utilisation (Ipeak / Irated)	Loss @ peak load, kW	Annual E Loss, MWh	Annual tCO_2 emiss.	40 Yrs tCO_2 emiss.
95	96	201	0.25	0.73	1.59	0.86	34.2
185	49	292	0.17	0.37	0.82	0.44	17.5
300	30	382	0.13	0.23	0.50	0.27	10.7

[14] Identifying Energy Efficiency improvements and saving potential in energy networks, including analysis of the value of demand response; Tractebel Engineering, Ecofys; 18 December 2015

For example, DSO has to choose the right cross section on a long-term techno-economic optimization, balancing losses savings and current capacity and taking into account equipment over-costs of a bigger cross section.

Inside transformers variable and fixed losses occur. Transformer replacement represents an adoptable solution to reduce losses instead of changing cables or lines. The replacement strategy depends on the various factors: state of the population, the age, size and type of transformers. The transformers lifetime is usually around 40 years and it means that efficient transformers can have a long-term impact on the TL in the network.

It is important to remark that transformer capital costs are similar to the cost of losses, see Table 2-6. Furthermore the optimal utilization of transformers is identified between 60% and 100%. This ratio is the results of a techno-economic evaluation that includes the acceptance of occasional lower values, the complete costs and operational constraints.

Table 2-6. Least-cost Distribution Transformer for case discount rate of 3.5% over 45 years [15]

Rating (kVA)	CAPEX (£)	Peak demand (kVA)	Cost of losses (£)			Total cost (£)	Peak Utilisation Factor
			Load losses	No-load losses	Total		
315	13,137	315	9,254	6,984	16,238	**29,375**	100%
500	14,168		5,249	10,277	15,526	29,694	63%
630	15,020		3,928	12,272	16,200	31,220	50%
500	14,168	500	13,173	10,277	23,450	37,618	100%
630	15,020		9,858	12,272	22,130	37,150	79%
800	15,199		6,373	12,711	19,084	34,283	63%
500	14,168	630	21,066	10,277	31,342	45,510	126%
630	15,020		15,764	12,272	28,036	43,056	100%
800	15,199		10,191	12,711	22,902	38,101	79%

The distribution transformers are in second place as a potential for power efficiency improvement after power lines.

Other losses are induced in continuous load of measuring and control elements, these elements have their own small energy consumption of elements. The quantity of meters and control components is sizable, in this way it is not possible to ignore it. Modern electronic meters have consumption lower than electromechanical meters, but the implementation of smart meter leads to a growth in consumption again, as the communication system will be more stressed.

Another source of losses is represented by current flowing through connectors of conductors. Very small resistances are at stake, but the number of connectors is sizable again. The resistance level is higher in case of loose connections, even it could cause of power outage. Thermography is the most used methods for detection of these connections. The utilization of more efficient insulation piercing connectors can decrease this type of TL. International and national standards for IPC (Insulation Piercing Connectors) are crucial to secure safety and reliability. However, no current standard is seriously considering how efficient LV connectors are or could be. LV IPC connectors have their own resistance and do contribute to the overall LV network efficiency. While the actual resistance of an LV connector may seem insignificant, it turns out that there could be very wide discrepancy in the overall resistance of LV connectors. LV connector efficiency are considered to be of decisive importance taking into account that the number of connectors installed on any network amounts to some millions and

[15] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

that every kWh achieving each meter shall pass through 4 or more of these connectors. Amount of protection systems is sizable, so it is not possible to ignore it, much like in case of meters.

An additional source of losses is characterized by current flowing through protection system (effect of I2R). The installation of more efficient protection systems can mitigate this type of TL.

2.3.2.2 Feed-in Control and DG

The technique defined Feed–In Control deals with implementation of control actions for local balancing between demand and supply in distribution grids. It produces a reduction of variable losses connected with the following key factors**:**

- reduction of energy transportation distance (energy is consumed locally)
- reduction of marginal losses (by a flattening of flow profiles).

A measure to reduce losses is locating generation closer to demand both in terms of time and space, reducing the number of voltage transformation levels and the distance over which electricity is transported. It is fundamental to find the appropriate level of DG penetration in every network that can contribute to decrease TL. By analyzing Figure 2-10, it is noticeable that the increase penetration of DGs (Distributed Generation) in the network beyond a certain limit implies an increase in network flows, these flows are reflected in a reverse flow moving from distribution networks to transmission networks.

Introducing small amounts of distributed generation (DG) results in decreasing the power losses until reaching a minimum level. If DG penetration level still increases, after have reached the minimum losses level, the losses can start again to grow and if DG penetration levels increase further, then the resulting losses can be even higher than those without DG connected.

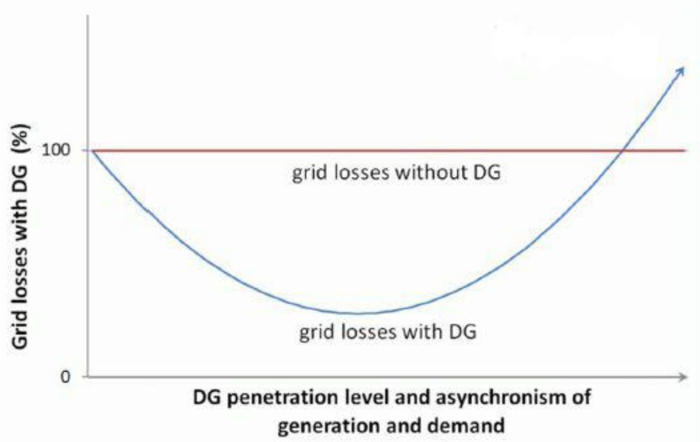


Figure 2-10. Impact of increasing DG penetration level to grid losses[16].

Actually, DSOs have obligation to connect increasing penetration of DGs (Renewable Energy Sources).

Smoother loading profiles lead to consequences in term of decrease of losses in the system, up to 20% by flattening of flow profile. Figure 2-11 shows two different types of load curves and compared with its base load curve. The blue smoothed load curve shows a reasonable amount of reduction in

[16] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

these losses, while the green load curve shows a large reduction in the same. Both load profile carries the same energy, but the difference between three loading profiles is represented by different variability, which contributes to lower system efficiency.

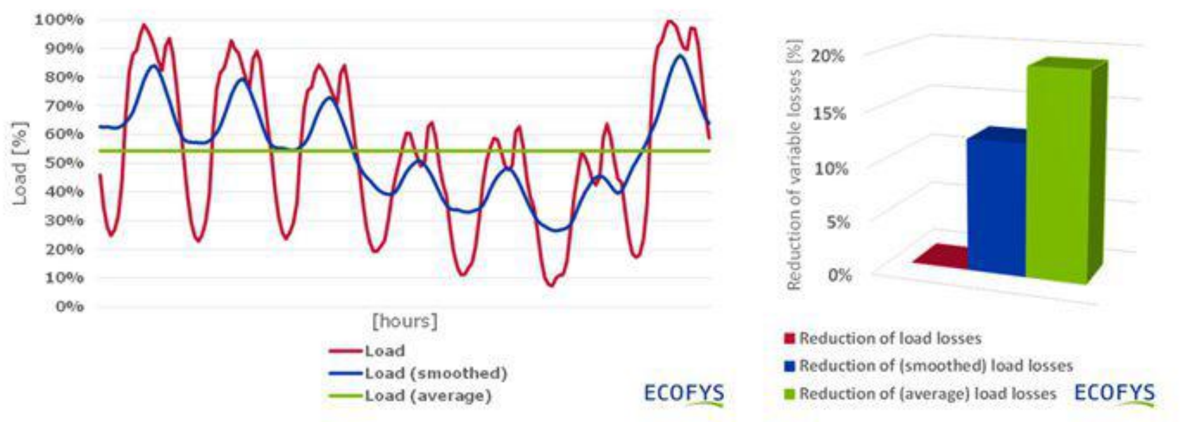


Figure 2-11. Impact of increasing DG penetration level to grid losses[17].

2.3.2.3 Grid management

Remove transformation steps would be a long-term action and an alternative solution could be detected in the grid management solution as switching off transformers during periods of low demand specifically for substations designed with multiple transformer in order to meet peak load or for redundancy.

Open loops are a typical configuration of MV networks and they are controlled in order to be able to isolate faults and restore power. Often the configuration of a specific network is not optimal, as the choice is often made on the basis of the local needs and any upgrade is driven by changes of the local demand. Reconfiguring the network might therefore be a possible solution to provide shorter, more direct paths to where highest demand is situated as a result of minimization losses.

Reducing distribution feeder losses, load balancing and improving system security can be achieved through a crucial automated distribution systems function: Feeder reconfiguration. Loads can be conveyed from feeder to feeder by modifying the open and close status of the feeder high-speed switches. The best reconfiguration model follows the changes in the network topology by switching the automatic breakers installed in the network.

Another strategy for reducing losses is related to voltage control and it aimed to minimize electricity load. Some electricity loads are voltage dependent, such as motors, resistive heating, etc and for this very reason lowering the voltage, the power demand may be reduced in connection with reduction in network losses. The voltage control technology can be implemented at the system level by Optimizing position of tap-changing transformers or the application of voltage optimization technologies as PowerPerfector at the customer connection points are the most relevant technologies to control voltage level through the electrical system.

Reactive power injection or absorption is the most widely accepted local action to supporting voltages and reducing reactive losses in distribution networks. Reactive power compensation can be

[17] Congrès International des Réseaux Electriques de Distribution International Conference on Electricity Distribution - Reduction of Technical and Non-Technical Losses in Distribution Networks - CIRED WG CC-2015-2;

obtained by installing capacitor banks in the networks or through the compensation of distributed generation connected to the network.

A useful strategy in reducing losses consists in minimizing the reactive power load. Active and reactive power flows contribute to the overall losses in an AC network. In this context, it is described the impact of installing power factor correction to minimize the reactive power load.

These aspects are is analyzed in the paper '*Imperial College London - Strategies for reducing losses in distribution networks'* through different scenarios presented in Figure 2-12. The first scenario supposes that the base power factor is 0.95 and after the application of power factor correction, the power factor is equal to 1. The second, third and fourth scenario consider that the reference power factor is 0.9, 0.85 and 0.8 respectively. For each scenario, the losses in the case of power factor correction are compared with the losses in the starting case both for LV and HV networks.

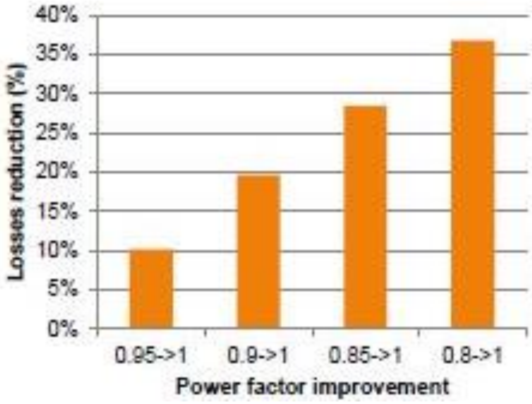


Figure 2-12. Impact of power factor correction on LV and HV networks[18].

The results show (Figure 2-12) that power factor compensation can determine very significant reduction of losses, up to 29% reduction in LV networks and 36% reduction in HV networks. However, in the case of base power factor equal to 0.95, the achieved reduction of losses is still remarkable, 7% in LV networks and 10% in HV networks.

Some of the current that passes through the resistance of conductors carries real power, but some flows to supply reactive power that provides magnetizing for motors and other inductive loads.

Critical factors as the location and the size of the single point power factor compensation shall be evaluate in order to maximise the benefit of this investment. Figure 2-13 demonstrates a feeder with uniformly distributed load along its length and the subsequent modification in current related to the power factor compensation through the deployment of a bank capacitor. This model indicates how to derive location and size of the compensation.

Based on the above model, the substation is considered as reference point, the optimal location is defined at 2/3 of the feeder length and the optimal size of the compensation is 2/3 of the reactive power load, in case of feeders with uniformly distributed load.

Imbalances in the loading between the three phases are a common phenomenon in LV networks where single-phase or double-phase consumers are connected to the three-phase system. These imbalances induce to have one phase carried with higher currents and to raise variable losses. The measure is to statically or dynamically transfer loads from one feeder to another to Balance the total load is realized transferring statically or dynamically loads across multiple feeders and transformers. An optimal Load balance should be performed in short time periods and following the demand changes.

[18] Imperial College London - Strategies for reducing losses in distribution networks - Goran Strbac, Predrag Djapic, Danny Pudjianto, Ioannis Konstantelos, Roberto Moreira (February 2018);

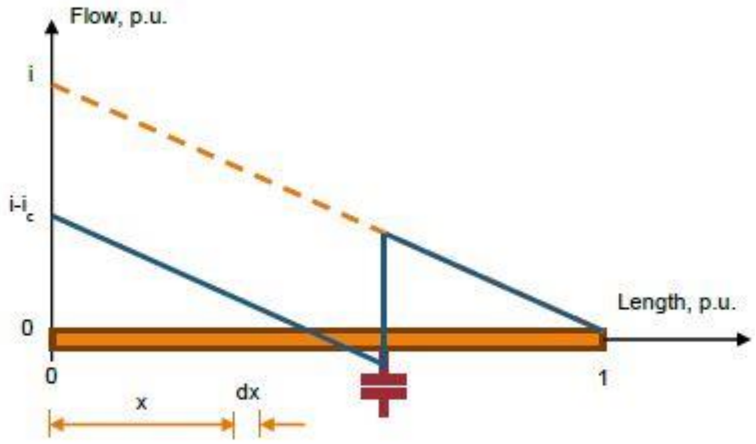


Figure 2-13. Illustration of radial feeder and change in current due to deployment of compensation[22].

A large-scale diagnostic could be important to find out possible sources of losses. Dashboards generated by developed system reveal to be very useful to detect LV grids being close to constraints as follow: overloaded transformers and feeders with excessive voltage drops. In any cases, phase-unbalance is the source of these drops. Indicatively, 50% of LV feeders can take advantages from phase balancing, meaning that their losses and power quality can be better thanks to few smart phase switching.

Smart-Grid (SG) solutions could help to detect network failures, and thus support to improve component optimization. It also assures new possibilities for grid and feed-in control management.

DG operates at unity power factor and this is performed by internal compensation of the DG's reactive load. When the system voltages, flows, and losses are being managed with an active control approach, there may be the chance to use this "hidden" reactive capability to manage the voltages and losses in the system.

A series of studies have examined the advantages of controlling DG's reactive power capability in UK. UK Power Networks have actively boosted significant growth in connection of renewable generation. More than 230 MW of DG have been already connected. The DG's reactive power capability has been controlled by an active network management and the volume of DG curtailment can be reduced from 2.4% to 0.2% and the losses also decrease from 2.9% to 2.6%. The reactive power from DG can be employ to control system voltages and mitigate the voltage-driven network constraints. In this case there is a compromise between cost of losses and cost of DG curtailment. The study suggests that the reduction in losses starts to saturate at 0.95 PF.

2.3.3 Technologies for non-technical losses mitigation

The actions listed below are the base to locate and identify the measure to reduce NTLs:

- Target inspections and audits, including audit related to unmetered supplies and updating records to ensure accuracy of the estimates.
- Perform investigations e.g. investigate parties who applied for connections but didn't complete the process, or to ensure that energy theft isn't repeated in the same place.
- Define a team to identify parts of the network that produce the significant technical or non-technical losses and implement mitigation measures.
- Perform risk assessments.
- Identify tampering or bypassing during smart meters installation.
- Use network and smart customer metering to identify areas with high levels of NTLs especially in secondary substations.

- Improve accuracy of records for unmetered supplies.
- Normalize or repair tampered installations and other equipment.
- Address unrecorded energy.
- Create liaisons with other stakeholders in the industry.
- Provide appropriate training and awareness.
- Update records to reduce billing errors.

The inaccuracies related to the estimation of NTL have to deal with increased or improved measurements and modelling of the network. Another significant measure is the implementation of the use of smart meters and monitoring of secondary substations.

Methods for examine losses should be simple, transparent, predictable and with a reasonable cost and they should allow losses to be monitored and compared over time. TL are complicated to be reduced in the short term due to the long life of plant, but NTL may be more amenable by increased attention to theft prevention and to the data acquisition procedures.

A model of implementation of smart metering on the secondary substation is reported below and it is extracted from the previously mentioned Imperial College London paper:

"The Spanish DSO Iberdrola has implemented Power Line Carrier (PLC) technology between smart customer meters and secondary substations which have supervisory meters in the secondary side of each MV/LV transformer. The customer and supervisory hourly values of their meters are sent from the secondary substations to a central system with regular communication.

This allows balancing between customer energy usage and energy supplied by the secondary substations to be performed, which in turn allows secondary substations with high losses to be identified for inspection and determination of the cause of the losses.

Iberdrola is also working on an innovation project with advanced supervisory meters on each line of the secondary substation. These meters have higher supervisory capabilities than normal, such as recording the load curve with per-second resolution" [19].

[19] Imperial College London - Strategies for reducing losses in distribution networks - Goran Strbac, Predrag Djapic, Danny Pudjianto, Ioannis Konstantelos, Roberto Moreira (February 2018)

3 Rail electrification networks

This chapter reviews the main topologies and characteristics of railway electrification networks. An in-depth analysis of the causes of power losses is undertaken that leads to the enhancement of future railway electrification networks towards the concept of smart grids.

3.1 Overview of railway electrification systems

3.1.1 Electrification schemes for DC railways

Most of DC railways are treated as a private customer specially underground ones and they have their own distribution grids. In just specific location it could be a connection to local grid just for emergency load, but it cannot be customised to most of passenger stations. It is better to draw attention to MV distribution network rather than LV 400 V grid. Still by regeneration energy stored in storage and by peak shaving could reduce losses in distribution network

A typical scheme for the electrification of DC railways is shown in Figure 3-1. The railway line is fed by a number of traction substations distributed along the track approximately every 2 km. The DC voltage level is variable for each specific installation, but recurrent values are 600 V (trams and metro systems), 750 V (trams, metro systems and railways), 1500 V (metro systems and railways) and 3000 V (railways). The sections of the DC electrification can be isolated (single-end and dual-end feeding) or more commonly interconnected (mesh feeding as in Figure 3-1), albeit sectioning is always possible to enable the disconnection of faulty sections. The DC supply voltage is generated by transformer rectifier substations that convert AC power from a medium voltage (MV) bus bar (11 kV or 15 kV in the example of Figure 3-1) into DC power. These units are typically formed by three-winding transformers, whose secondary windings feed two 12-pulse rectifiers connected in parallel on the DC side.

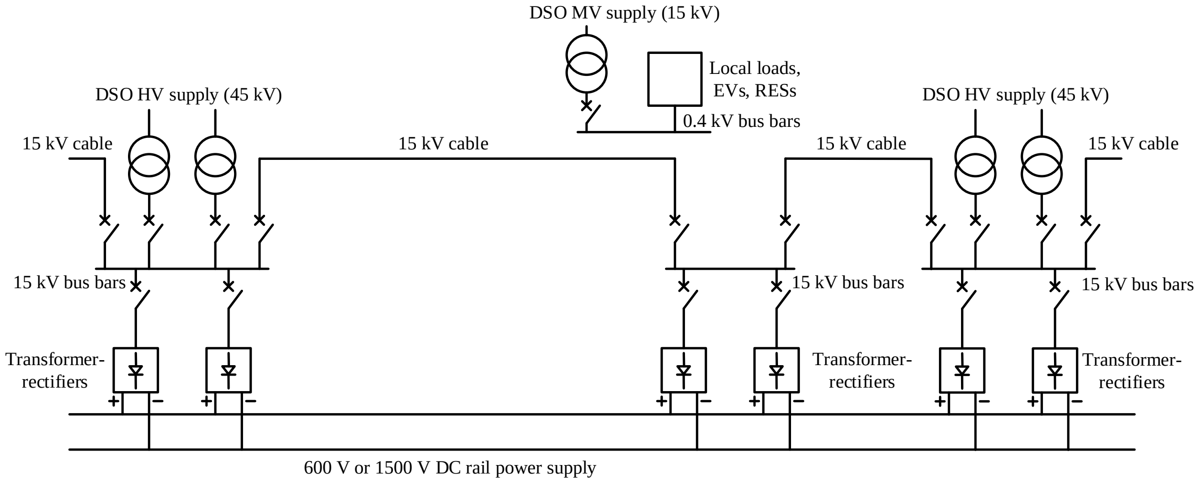


Figure 3-1. Typical electrification scheme for DC railways.

The MV bus bars are connected together via one or more MV cables that run approximately in parallel with the railway track. There are various possibilities of the connection of these cables and the most common are the mesh feeding and the open ring feeding. Some of the MV bus bars are connected to the network of the distribution system operation (DSO) via transformers, with a typical 100% redundancy to enable the continuation of the service when a transformer is faulty or under maintenance. The DSO network can operate at various voltage levels depending on the location of the connection. Possible values are 20 kV, 33 kV and 45 kV.

In the mesh feeding, the bus bars are interconnected, so the DSO feeders operate in parallel. The advantage is that the equivalent impedance of the MV rail network is smaller, so the DSO network is less affected by the traction load. Therefore, this scheme is more suitable for heavy railways. Additionally, there is a high level of redundancy if there is more than one cable interconnecting the bus-bars. The disadvantage is that the power flows are more complex and appropriate protection systems are needed to identify faults (e.g. impedance relays with directional overcurrent relays)

In the open ring feeding, at least one disconnector switch between two consecutive DSO supply points is open. The advantage is that the protection system is simpler because the power flow is unidirectional. The disadvantage is that the impedance is higher, so there is a higher regulation effect of the DC voltage at the substations. Therefore, this scheme is more suitable for trams, metro systems and light railways.

In addition to the railway electrification network, railways need power for their auxiliary systems and station loads. This can be taken from the same network, but it is often taken from other networks of the DSO, especially for low-voltage loads, e.g. 400 V in Figure 3-1. This network is connected to the MV network of the DSO and it is often a different node from that of the traction power. Therefore, this low voltage network, which in the following will be called local network for its limited extension, can be considered independent from the railway electrification network. The local network can feed a number of loads of various customers and can host renewable energy sources, energy storage and charging stations of electric vehicles (EVs).

3.1.2 Electrification schemes for AC railways

Three typical electrification schemes for AC railways are shown in Figure 3-2. The simplest form of electrification is to use the running rails (RR) as the return conductor, which may also be reinforced by additional conductors such aerial earth wires (AEW), and recently, return screening conductors (RSC). However, historically classic electrification was based on using booster transformers (BT) in Figure 3-2, which are designed to force the return traction current to flow in additional conductors installed on the OLE masts; these conductors are known as return conductors (RC). This system was introduced as a modification to the RR system at the turn of the twentieth century when telegraph and telephone lines were introduced. When these lines run in parallel to railway lines, the BT system helps to minimise interference from traction current, hence EMC immunisation was introduced first.

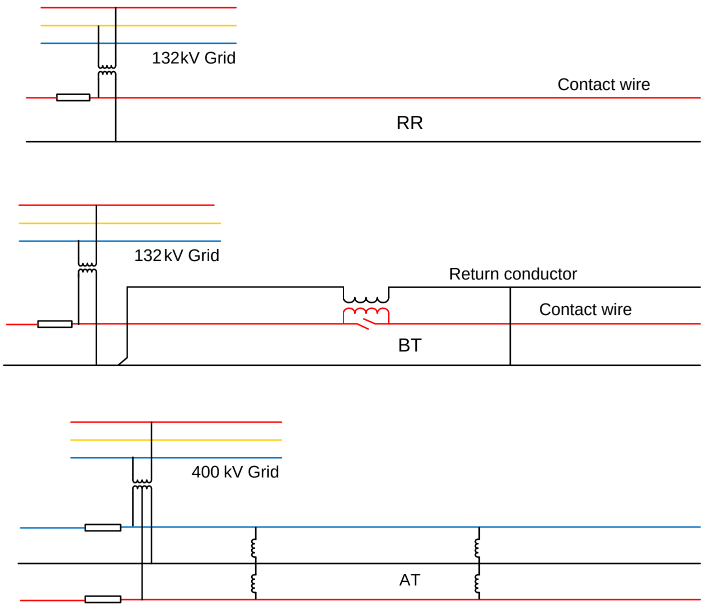


Figure 3-2. Three typical electrification schemes for AC railways.

RR and BT systems are usually fed from 132 kV supply using single phase transformers. The FS usually incorporates a split bus bar and fed from two different phases. The aim is to balance the load at the HV grid when multiple FS are fed of the same 132 kV supply. A maximum permissible level of negative phase sequence (NPS) is normally allowed which depends on the fault level of the HV grid. In many cases the NPS limit is the restraining factor of the traction load permitted to be drawn.

Recently, and due to increased load levels, auto transformer (AT) systems in Figure 3-2 have been introduced. These systems are capable of providing much larger load levels allowing for longer feed sections to be used. Given that the traction loads are considerably larger and concentrated in fewer locations the transformers of the ATFS are connected to the 400 kV grid. This allows for larger levels of NPS and load to be drawn. RR, BT and AT traction supply systems are all currently in use.

3.2 Power Losses in railway electrified networks

In Table 3-1, the values of the losses for each supply voltage used in Spain (reference case for the E-LOBSTER demonstrator) are shown, as well as the characteristic parameters used for the calculation like the distance between substations, catenary and substation resistance.

As a summary, the next tables show the coefficients of energy losses that include:

1. the losses linked to transport and distribution (see Table 3-1 and Table 2-2)
2. the losses linked to the traction network for the railway system (see Table 3-2).

Table 3-1. Indices of typical losses in traction network according to voltage

	Losses [%]	*Losses [kVA]*	I_{train} [A]	P_{train} [kVA]	D_{subst} [m]	R_{subst} [ohm]	R_{caten} [ohm]
2x25 kV AC	2.2	224	400	10000	70000	0.15	4.00E-05
1x25 kV AC	3.5	352	400	10000	40000	0.15	8.00E-05
3000V DC (Commuter)	5.6	129	350	1155	12000	0.012	2.50E-05
3000V DC (generic)	6	66	370	1110	15000	0.012	2.50E-05
1500V DC	10.1	81	500	800	3000	0.012	2.60E-05
750V DC	18.2	136	1000	750	2000	0.01	3.30E-05
600V DC	22	132	1000	600	2000	0.01	3.00E-05

Table 3-2. Indices of losses in distribution, transmission and traction according to voltage

	Voltage	Distrib + Transp Coeff.	Railway network coeff.	Total Coeff.
2x25 kV AC	400kV	101.20%	102.20%	103.50%
1x25 kV AC	220kV	102.30%	103.50%	105.90%
3000V DC (Commuter)	1kV < V< 36kV	105.90%	105.60%	111.80%
3000V DC (generic)	1kV < V< 36kV	105.90%	1.06	112.20%
1500V DC	1kV < V< 36kV	105.90%	110.10%	116.60%
750V DC	1kV < V< 36kV	105.90%	118.20%	125.20%
600V DC	1kV < V< 36kV	105.90%	122.00%	129.20%

3.2.1 Types of losses in DC railway networks

All the active components of the electrical network produce losses when conducting a current. The largest losses are due to the Joule effect, but there are also other losses that must be considered, such as no-load losses of a transformer (Eddy currents, hysteresis, etc...).

The following Figure 3-3 presents the detailed energy chain for electric traction.

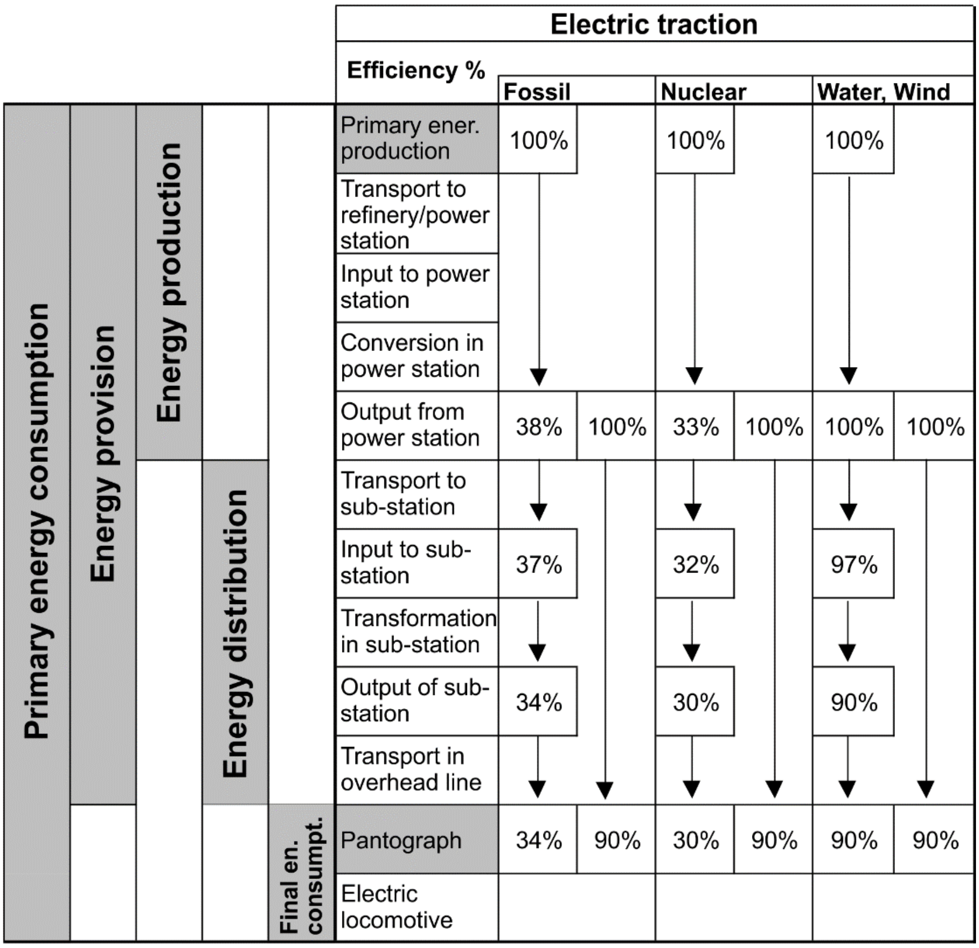


Figure 3-3. Energy Chains and Efficiencies for Rail Electrical Traction.

While analysing the component parts of the infrastructure power supply system, different kinds of energy losses can be identified.

The losses in traction power supply for DC systems with respect to the energy demand of the whole system (point of common coupling), are in the range of 10 % to 35 %. Investments in infrastructure are recommended because of high potential energy savings for DC systems.

Energy losses in the traction power supply system depend on the type of the system[20], i.e. the parameters that influence its specific resistance, namely the material, number of conductors and other factors such as:

- cross-section of contact wires;
- cross-section of catenaries;
- cross-section of support wires;
- length of supply sections;
- wear and tear of contact wires;
- conductor temperature;
- presence of a track sectioning cabin;
- distance between the substations.

Energy losses occurring 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.

Energy losses on the internal resistance of the substation[21] 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;
- number of diodes in a branch in the case of a series connection.

Energy losses in a cathode choke depend on choke resistance. Energy losses in the traction power return system depend on:

- type of rails (their specific resistance);
- condition of the railway subgrade and inter-rail and inter-track connectors;
- length of a supply section.

Resistive losses in conductors, passive components, terminals and connections represent the major part of losses in the power infrastructure. Resistances of conductors can be calculated with great accuracy at DC and at the power frequency. Similarly, the resistances of the transformers' windings can be derived from the transformers test certificate, where the short circuit losses are measured.

[20] Ireneusz Chrabąszcz et al. "Evaluation of energy losses in dc railway traction power supply system" Technical transactions, electrical engineering - 2016

[21] Ireneusz Chrabąszcz et al. "Evaluation of energy losses in dc railway traction power supply system" Technical transactions, electrical engineering - 2016

Additional losses in the line conductors and in the rails are normally negligible with respect to power frequency or DC losses with the typical harmonic content of traction currents.

Losses in the iron core of transformers: the magnetising resistance of the transformers used for representing the iron losses can be calculated from the no-load test normally available in the test certificate of the transformers.

Losses in semiconductor devices: switching and conduction losses of rectifier diodes can be easily accounted for with simple diode models, but it should be considered that related amount in a DC traction system is a very small percentage of the total losses.

Losses in transformers and autotransformers: copper (i.e. load, short circuit) and iron (i.e. no-load, magnetisation) losses are considered at power frequency. Harmonic losses are inherently included in transformers for DC substations (due to the significant harmonic content of the rectifier currents), with the only approximation that such losses occur in the winding resistances calculated at power frequency. Skin and proximity effects are not considered causing resistance increase, but harmonic losses are calculated in the resistances at power frequency. Such assumption is generally acceptable for DC substation transformers (considering also that the total losses in the substation in DC systems are a small part of the total system losses). Similar considerations can be made with regard to the iron losses and the related representation with the constant resistance evaluated at power frequency.

Rectifiers: losses in diodes and auxiliary devices (parallel passive components) will always be a small contribution to the total losses.

Filters: resistive losses in the inductor of DC substation filters can be included.

3.2.2 Types of losses in AC railway networks for different feeding configurations

In this paragraph, three different feeding configurations are compared from energy loss and system efficiency point of view.

3.2.2.1 Single-phase transformers

The most commonly used solution consists of two single-phase transformers per substation, connected to alternative phases of the 3-phase grid in order to compensate the voltage unbalance produced by single-phase traction load.

The losses of this configuration consist mainly in transformer losses, which are relatively low in comparison to other feeding systems. Also, no cooling is normally needed due to the typical ONAN transformers and their outside location. The loss of the control and protection circuit is negligible in comparison to the transformer losses and only auxiliary transformer losses are considered, additionally to the traction transformer losses. Nevertheless, it is important to underline that this feeding system allows for the supply of the traction section from only one end, as sections with different phase angles cannot be connected and must be separated by the neutral sections. This causes higher voltage drops and currents in the overhead line equipment, and thus higher losses in general in the downstream network. The losses of the overhead line equipment are usually higher than the feeding system losses, and therefore, even if the substation losses (transformer losses in this case) are relatively low, the loss of the traction transmission system is high due to single-end supply of the section. It is possible to reduce voltage drops and currents via interconnection of all the traction sections together, using 3-phase to 1-phase converters in order to control the voltage wave shape at the traction side.

3.2.2.2 Frequency Converters

Installing frequency converters will reduce drastically the voltage unbalance in the public grid and also allows for the interconnection of all the traction sections, reducing voltage drops, currents and losses in the catenary system.

The static converter equipment contains several elements such as transformers, filters, power electronic, switchgears, reactors, control and protection equipment, cooling system, auxiliary transformers, etc. Due to all these components, the efficiency of the static converter results to be lower than the efficiency of the typical single-phase transformer efficiency, but the losses of the catenary system are reduced. Furthermore, there are many other advantages, for example the possibility to control the reactive power injected into the 3-phase grid.

3.2.2.3 Phase Balancers

The active balancer improves the voltage unbalance produced by the railway system and allows controlling the reactive power injected into the 3-phase grid. Due to all the components contained in the balancer, the efficiency is lower than for the single-phase transformer feeding configuration, and the losses in catenary system are still high due to the single-end section feeding.

While balancer and frequency converter provide similar improvements at the public grid level, the main difference between these technologies is at the TPS side. In fact, the deployment of balancers does not allow in general to remove the neutral sections on ETS, whereas the frequency converter can offer this possibility, which would translate, among the other things, into lower power flows and voltage drops in the railway grid and reduced power losses.

3.2.3 EU studies of the energy losses in the electrified transport network

3.2.3.1 Energy and CO_2 reduction targets

The European Railways have committed to ambitious CO_2 and energy consumption reduction targets[22,23]. These targets are monitored with data provided by the UIC Energy & CO_2 database. Furthermore, the data is used for sector communication purposes. In order to use the data for the above-mentioned purposes the data has to fulfil high quality standards in order to be accepted and credible. It is of highest importance for the European Rail Sector to be able to monitor and control its energy and CO_2 data and use consistent data for communication in order to support the ecological advantage of rail with scientific truth.

Thus, the UIC has built up a database on Energy and CO_2 emission data for the European Rail Sector, which serves as the basis for:

1. Monitoring the CER CO2 reduction commitment (-30% specific CO_2 by 2020 compared to 1990)
2. Monitoring the UIC/CER long-term Environmental Strategy 2030 and beyond (-50% specific CO_2 emissions by 2030 and -30% specific energy consumption compared to 1990)
3. Feeding the EcoPassenger and EcoTransIT eco-comparison tools
4. Use for consistent sector communication (such as UIC/CER brochure "Facts & Figures" and UIC/IEA energy data brochure).

[22] CER CO2 reduction commitment

[23] UIC/CER long term environmental strategy 2030 and beyond

Today, the UIC Energy & CO_2 database consists of 1990 data and 2020 forecasts and a time series of data from 2005 to 2009. The UIC project P000252 reviewed the quality of the existing European UIC Energy & CO2 database in order to:

1. Enhance the quality of the energy & CO_2 data and thus provide credibility and scientific proof for the data
2. Ensure acceptance by third parties for the UIC energy & CO_2 data

Additionally, this project provides an analysis and benchmarking with energy & CO_2 data, which will be used to find energy saving potential at member's level and define further background information for energy road-mapping for the European Rail sector.

3.2.3.2 Previous EU projects

Several EU projects[24] have investigated the subject of electrified transport networks, considering different aspects and technologies to reduce energy consumption and energy losses. The following of this section reports a short description of the main projects relevant to energy efficiency in railway transport networks.

In2Rail project (Innovative Intelligent Rail – GA 635900 - 2015-2018) aimed at setting the foundation for a resilient, consistent, cost-efficient, high capacity, and digitalised European rail network, through a holistic approach covering Smart Infrastructures, Intelligent Mobility Management (I2M) and Rail Power Supply and Energy Management.

One of the specific objectives of In2Rail was relevant to Rail Power Supply and Energy Management. This focused on the design of a future AC Rail Power Supply System with minimised energy losses (up to 50%) and optimised loads and the implementation of an efficient energy management system allowing understanding of energy flows within the railway system, a reduction of the energy consumption and cost, optimised asset management and enabling better use of the railway capacity.

Within **Railenergy** project (Innovative integrated energy efficiency solutions for railway rolling stock, rail infrastructure and train operation – GA 31458 – 2006-2010), the railway industry developed a holistic framework approach, new concepts and integrated solutions to improve energy efficiency in the railway domain under specific constraints (technical, operational, socio-economic etc). The overall goal of Railenergy was to cut the energy consumption within an optimised railway system contributing to a reduction in the life cycle costs of railway operation and of CO2 emissions per seat/kilometre or tonne/kilometre. Project partners have delivered relevant baseline figures and scenarios for selected reference systems, a system-based concept for modelling energy consumption, a common and standardised methodology to determine energy consumption by rail sub-systems and components in the development and procurement phases, an integrated simulation tool for energy consumption and LCC, an integrated railway energy efficiency management approach and decision support tool, strategic energy efficiency targets for rolling stock, infrastructure and traffic management, an Energy Management Module which could provide the operator with a diagnostic of their complete installation, new validated energy efficiency-oriented railway technologies for trackside and on-board sub-systems and equipment, and best practices for Railway Operators and Infrastructure Managers, strategies for incentives, pricing, and policies.

The aim of the **MERLIN** project (Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimisation approach – GA 314125 – 2012-2015) was to

[24] https://cordis.europa.eu/projects/home_en.html

investigate and demonstrate the viability of an integrated management system to achieve a more sustainable and optimised energy usage in European electric mainline railway systems. MERLIN provided an integrated optimised approach to support operational decisions leading to a cost-effective intelligent management of energy and resources via improved design of railway distribution networks and electrical systems and their interfaces; better understanding of the influence of railway operations and procedures on energy demand; identification of energy usage optimising technologies; improved traction energy supply; understanding of the cross-dependencies between technological solutions; improving cost effectiveness of the overall railway system; contribution to European standardisation.

OPEUS project (Modelling and strategies for the assessment and OPtimisation of Energy USage aspects of rail innovation – GA 730827 – 2016- 2019) main aim was to develop a simulation methodology and accompanying modelling tool to evaluate, improve and optimise the energy consumption of rail systems with a particular focus on in-vehicle innovation. The OPEUS concept is based on the need to understand and measure the energy being used by each of the relevant components of the rail system and in particular the vehicle. This includes the energy losses in the traction chain, the use of technologies to reduce these and to optimise energy consumption (e.g. ESSs). Specifically, the OPEUS approach has three components at its core: i) the energy simulation model ii) the energy use requirements (e.g. duty cycles) and iii) the energy usage outlook and optimisation strategies recommendation.

3.2.4 Global consumption maps and analysis

The Merlin project described the electrified transport network, characterising each components and sub-systems of a mainline railway system and developing a global energy consumption map, defining levels of energy consumption of each components and sub-systems[25].

An energy consumption map is a comprehensive and graphic way of representing the energy flows in the whole railway power supply systems. These maps provide a good overview of the energy, allowing a better understanding of what the energy has been used for (running the trains, operating stations or workshops, etc.) and they are a powerful tool to identify when and where measures oriented to increase energy efficiency can be implemented.

A general representation of the power supply infrastructure was established and infrastructure managers were requested to provide data of network topologies and energy consumption for their networks in a homogeneous manner both for: (i) the Traction and auxiliary systems and (ii) the Infrastructure itself (stations, workshop, infrastructure consumers, etc.). Essentially, the Swedish network of Trafikverket, the British network of Network Rail, the French network of RFF and the Spanish network of ADIF provided valuable information for the most relevant power supply systems and architectures that can be found in electrified railways in Europe today.

Below, the main findings achieved in this study are summarised. This information, which corresponds to year 2011 (unless other year is explicitly mentioned), has been provided by: RFF (France), Network Rail (UK), Adif (Spain) and Trafikverket (Sweden).

3.2.4.1 France

Table 3-3 shows the energy consumption and the energy regenerated measured in the traction substations used to feed railways in France. The energy used to feed the auxiliary services of the

[25] Global consumption map and analysis, MERLIN Project

infrastructure, such as signaling, switches, etc. is shown in Table 3-3. Table 3-4 and Table 3-5 show the energy consumption for other uses different to traction. The losses related to the transmission and distribution grids and the substations are shown in Table 3-6.

Table 3-3. Energy consumption at traction substations, French case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total energy consumption measured at traction substations (per year)	7,795,700	MWh
Total energy regenerated measured at traction substations (per year)	54,800	MWh

Energy consumption at traction substation level split by input voltage and output voltage

Input voltage [kV]	Type input	Output voltage [kV]	Yearly energy consumption [MWh]	Yearly energy Regenerated (MWh)
400	3 phases 50 Hz	25kV / 2x25 kV	337,100	54,800
220	3 phases 50 Hz	25kV / 2x25 kV	2,994,600	
90/63	3 phases 50 Hz	25kV / 1.5kv cc	4,213,000	
<50	3 phases 50 Hz	1.5kV cc	251,000	

Table 3-4. Energy related to the auxiliary services of the infrastructure (signalling system, switches, etc.), French case

Energy, measured at traction substation, not devoted to traction (signalling system, switches, technical

Supplied voltage [V]	Yearly energy consumption [MWh]	Description
90 / 63 / <50	150,000	

Table 3-5. Energy purchase for other uses different to traction (stations, workshops, etc.), French case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total purchased directly for other uses diferent to traction (per year)	650,000	MWh

Energy purchased directly for other uses diferent to traction (stations, workshops,…)

Input voltage [kV]	Yearly energy consumption [MWh]	Use description (stations, workshops…)
<50	650,000	estimated

Table 3-6. Energy losses, French case

ELECTRICAL ENERGY

3. ENERGY LOSSES

Public transport and distribution electric network

Voltage level (kV)	Losses (%)
400	
220	

Traction transport and distribution electric network

Voltage level (kV)	Losses (%)
2x25 kV ac	5%
25kV ac	4%
1.5kV cc	19%

Electric railway network (catenary)

Voltage level [kV]	Losses (%)
25kV / 2x25 kV	3.5%
25kV / 2x25 kV	2.7%
25kV / 1.5kv cc	16%
1.5kV cc	16%

Traction substations

Voltage level [kV]	Losses (%)
25kV / 2x25 kV	1.5%
25kV / 2x25 kV	1.3%
1.5 kV cc	3%

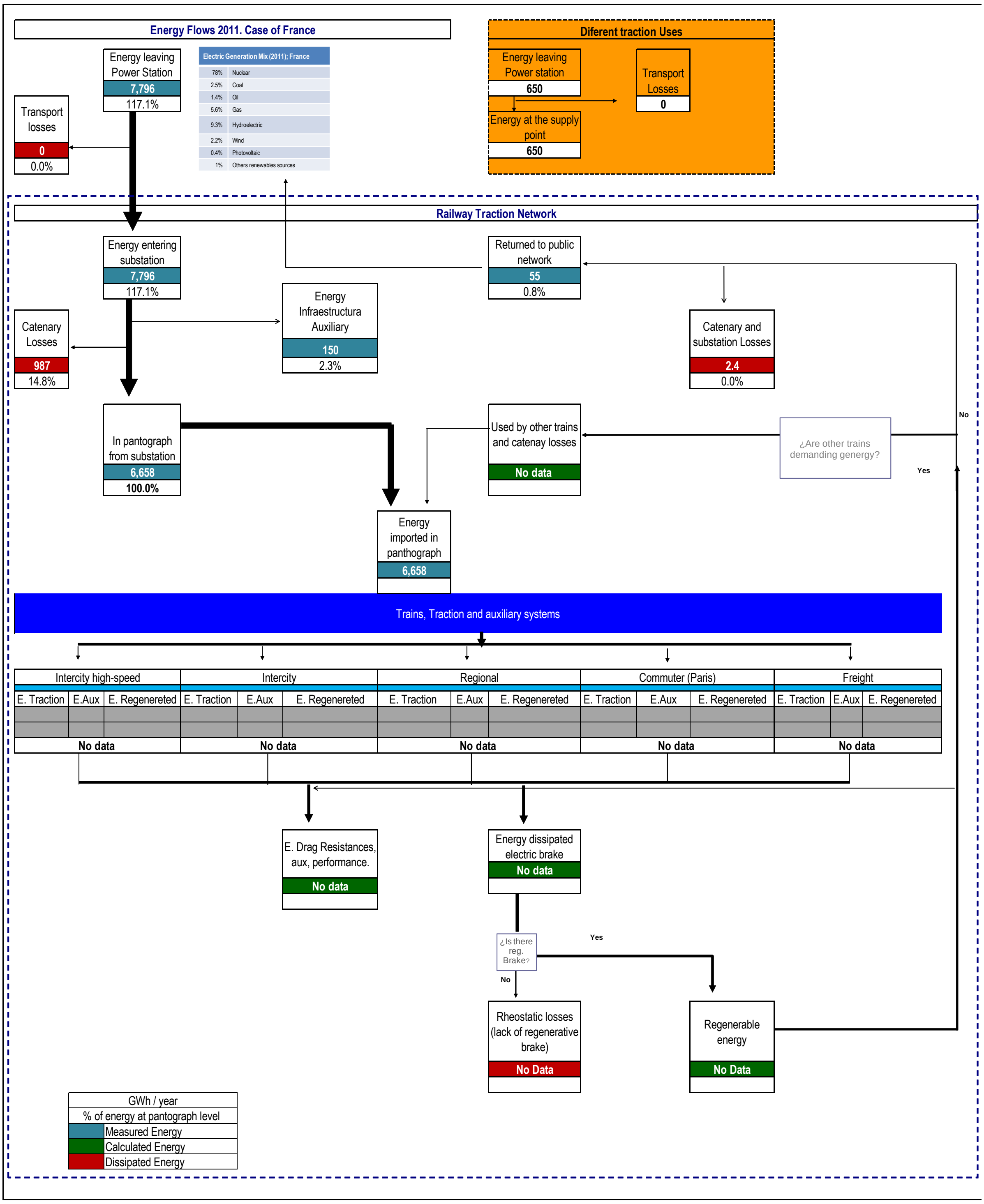


Figure 3-4 - French consumption map (Independently produced).

3.2.4.2 United Kingdom

Table 3-7 shows the energy consumption and the energy regenerated in United Kingdom in 2011, estimated in the supply point of the traction substation. The energy consumption of the auxiliary services of the infrastructure in Great Britain is indicated in Table 3-8. The energy purchased by the infrastructure manager to feed loads different to traction is 449,2 GWh, as indicated in the Table 3-9. The different losses considered for the British consumption map are shown in Table 3-10. The traffic characterization, the energy consumption and the energy regenerated by each type of considered service is indicated in Table 3-11.

Table 3-7. Energy consumption at traction substation, British case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total energy consumption measured at traction substations (per year)	3,074,752.5	MWh
Total energy regenerated measured at traction substations (per year)	52,777.0	MWh

Energy consumption at traction substation level split by input voltage and output voltage

Input voltage [kV]	Type input	Output voltage [kV]	Net Value (MWh)	Yearly energy consumption [MWh]	Yearly energy Regenerated (MWh)	
400	3 phases 50 Hz	2x25 kV	114,636.2	118,299.40	3,663.19	Estimated only based on 132 kV site
400	3 phases 50 Hz	1x 25 kV	268,057.3	276,623.04	8,565.74	Estimated only based on 132 kV site
275	3 phases 50 Hz	1x 25 kV	54,607.9	56,352.90	1,744.99	Estimated only based on 132 kV site
132	3 phases 50 Hz	1x 25 kV		1,238,386.26	38,347.10	
66	3 phases 50 Hz	1x 25 kV		25,066.84	456.00	
66	3 phases 50 Hz	1x 0.75kV		221,252.77		No DC export
33	3 phases 50 Hz	1x 0.75kV		1,076,129.14		No DC export
22	3 phases 50 Hz	1x 0.75kV		3,995.54		No DC export
11	3 phases 50 Hz	1x 0.75kV		16,976.29		No DC export
11	3 phases 50 Hz	1x 0.65kV		41,670.36		No DC export

Table 3-8. Energy related to the auxiliaries of the infrastructure (signalling system, switches, etc.), British case

Energy, measured at traction substation, not devoted to traction (signalling system, switches, technical buildings,…)

Supplied voltage [V]	Yearly energy consumption [MWh]	Description
25kV AC	9,943.53	Includes allowance for losses, 100% estimated
2x 25kV AC	3,916.50	Includes allowance for losses, 100% estimated
0.75kV DC	52,470.83	Includes allowance for losses, 32% estimated
0.65kV DC	14,104.45	Includes allowance for losses, 15% estimated

Table 3-9. Energy purchase for other uses different to traction (stations, workshops, etc.), British case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total purchased directly for other uses diferent to traction (per year)	449,235.98	MWh

Energy purchased directly for other uses diferent to traction (stations, workshops,…)

Input voltage [kV]	Yearly energy consumption [MWh]	Use description (stations, workshops…)
HV	231,288.50	Mixed
LV	217,947.48	Mixed

Table 3-10. Energy losses, British case

ELECTRICAL ENERGY

3. ENERGY LOSSES

Public transport and distribution electric network

Voltage level (kV)	Losses (%)
400V to 132kV	7.8% (*)
11kV to 132kV TRACTION ONLY	3.35% (**)
400kV	2% (***)

(*) For all UK distributed electricity; includes transmission losses; 2010 data
(**) Rail traction only; includes transmission & distribution losses, 2012 data
(***) Rail traction only; transmission losses only, 2008 data

Traction transport and distribution electric network

Voltage level (kV)	Losses (%)	
650/750 VDC	16.80%	Estimated
25 kVAC	3.85%	Estimated

Electric railway network (catenary)

Voltage level [kV]	Losses (%)
<- included	
<- included	

Traction substations

Voltage level [kV]	Losses (%)
<- included	
<- included	

Table 3-11. Traffic description and energy consumption, British case

ELECTRICAL ENERGY

2. TRAFFIC DESCRIPTION

Service type	Annual TKBR	Annual train kilometers	Annual number of trains
Express Passenger		114,127,603.6	
Ordinary Passenger		123,454,460.3	
Freight	4,063,162,604.8	4,643,013.8	
Empty Coaching Stock		13,579,003.1	
Other Consumption (metered services only)			

	Average energy				
Service type	% of train with regenerative brake	Intaking at pantograph level [kWh]	Regenerated at pantograph level [kWh]	Energy disipated at rheostatic brake [kWh]	Devoted to auxiliary systems [kWh/km]
Express Passenger	100%	1,625,958,629	125,980,400		
Ordinary Passenger	99.9%	1,598,791,772	80,195,601		
Freight	N/A	93,752,990			
Empty Coaching Stock	91%	209,852,447	10,739,361		
Other Consumption (metered services only)	N/A	54,631,111.8	3,438,764.8		

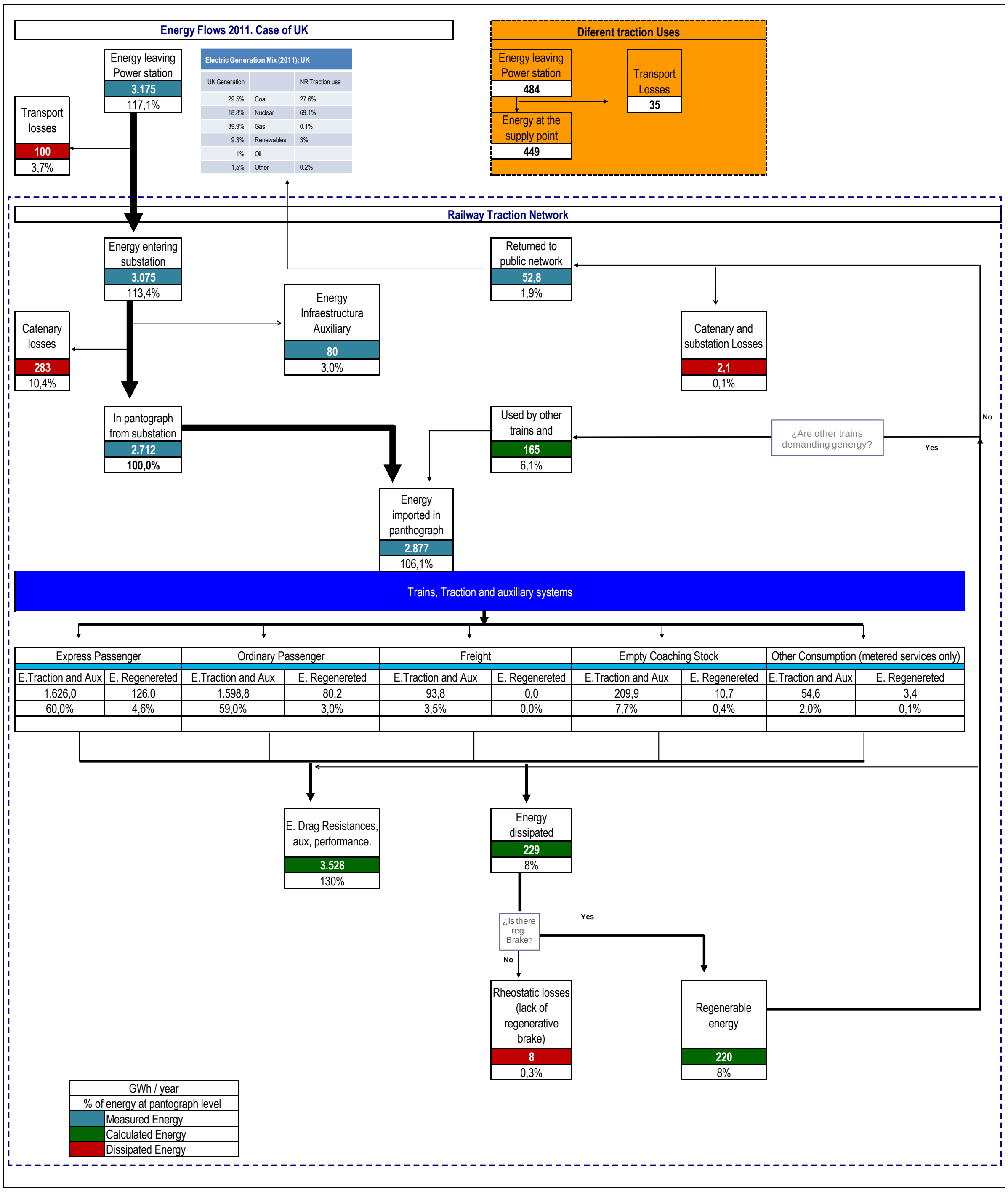


Figure 3-5 - British consumption map (Independently produced).

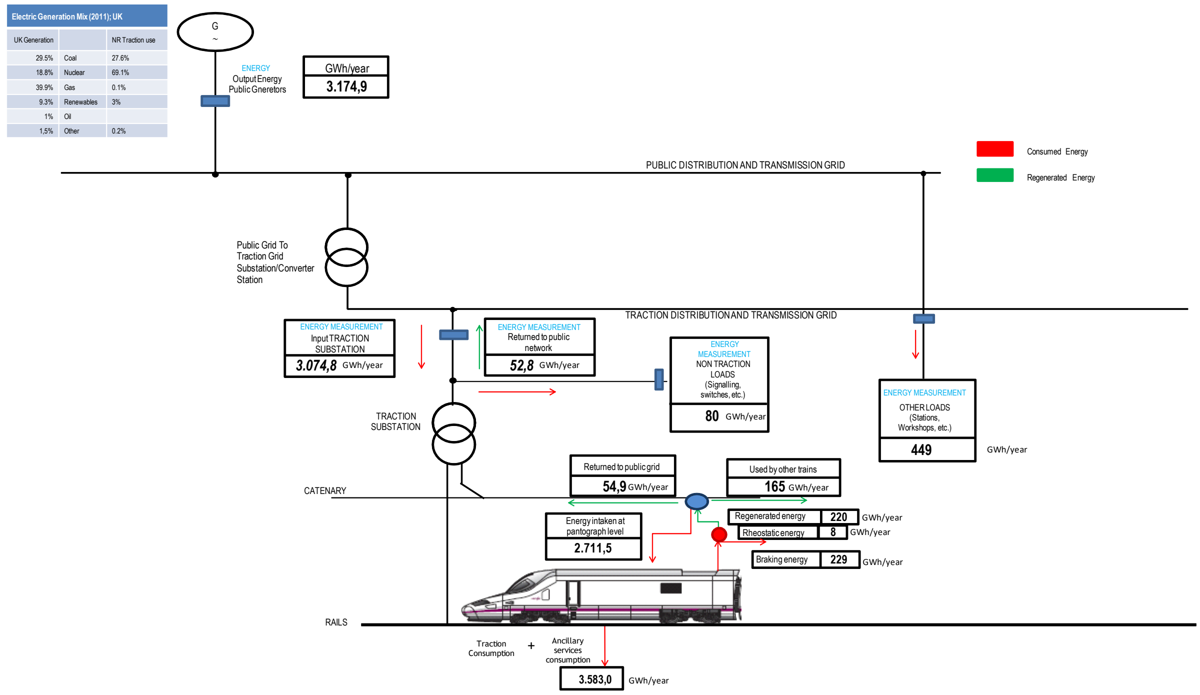


Figure 3-6 - Energy flows for the British case (Independently produced).

3.2.4.3 Spain

Table 3-12 shows the energy consumption and the energy regenerated measured at the supply point in all the traction substations in Spain. The energy used to feed the auxiliary services of the infrastructure, such as signaling, switches, etc. is shown in Table 3-13. Table 3-14 shows the energy consumption for other uses different to traction. The losses in the case of Spain are shown in Table 3-15. Finally, the energy consumption and the traffic characterization are shown in the Table 3-16.

Table 3-12. Energy consumption at traction substation, Spanish case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total energy consumption measured at traction substations (per year)	2,363,243.87	MWh
Total energy regenerated measured at traction substations (per year)	62,601.65	MWh

Energy consumption at traction substation level split by input voltage and output voltage

Input voltage [kV]	Type input	Output voltage [kV]	Yearly energy consumption [MWh]	Yearly energy Regenerated (MWh)
11	3 phases 50 Hz	3	4,770.03	
15	3 phases 50 Hz	3	10,354.79	
20	3 phases 50 Hz	3	106,390.19	
22	3 phases 50 Hz	3	46,481.93	
25	3 phases 50 Hz	3	408,124.12	
27	3 phases 50 Hz	3	1,222.93	
27.5	3 phases 50 Hz	3	8,641.67	
30	3 phases 50 Hz	3	113,476.90	
33	3 phases 50 Hz	3	1,798.82	
35,999	3 phases 50 Hz	3	594.94	
44	3 phases 50 Hz	3	150,561.50	
45	3 phases 50 Hz	3	256,189.29	
46	3 phases 50 Hz	3	26,798.26	
50	3 phases 50 Hz	3	15,558.45	
52	3 phases 50 Hz	3	7,906.24	
55	3 phases 50 Hz	3	13,996.41	
66	3 phases 50 Hz	3	229,664.31	
132	3 phases 50 Hz	3	102,847.99	
132	3 phases 50 Hz	1x25	45,489.56	1,278.03
220	3 phases 50 Hz	1x25	243,215.43	10,108.14
145	3 phases 50 Hz	2x25	21,319.16	1,424.52
220	3 phases 50 Hz	2x25	129,208.70	12,402.58
380	3 phases 50 Hz	2x25	111,849.36	7,087.21
400	3 phases 50 Hz	2x25	306,782.88	30,301.18

Table 3-13. Energy related to the auxiliaries of the infrastructure (signalling system, switches, etc.), Spanish case

Energy, measured at traction substation, not devoted to traction (signalling system, switches, technical buildings,…)

Input voltage [kV]	Supplied voltage [V]	Yearly energy consumption [MWh]	Description
11	11,000	630.720	
15	15,000	587.796	
20	20,000	7,370.664	
22	22,000	3,127.320	
25	25,000	20,455.476	
27	27,000	201.480	
28	27,500	429.240	
30	30,000	10,736.256	
33	33,000	236.520	
35.999	35,999	148.920	
44	44,000	16,154.316	
45	45,000	42,652.440	
46	46,000	1,611.840	
50	50,000	3,744.024	
52	52,000	4,616.520	
55	55,000	840.960	
66	66,000	26,668.068	
132	132,000	15,757.488	
132	132,000	613.200	
220	220,000	30,912.726	
145	145,000	963.600	
220	220,000	16,645.314	
380	380,000	4,846.032	
400	400,000	24,717.216	

Table 3-14. Energy purchase for other uses different to traction (stations, workshops, etc.), Spanish case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total purchased directly for other uses diferent to traction (per year) 300,486,293 kWh

Energy purchased directly for other uses diferent to traction (stations, workshops,…)

Input voltage [kV]	Yearly energy consumption [kWh]	Use description (stations, workshops…)
BT (220-230-380-400V)	25,270,316	
6.3	445,678	
10 kV (10-11-12-12.1kV)	9,039,188	
13 kV (13-13.2-13.8kV)	27,340,295	
15 kV (15 a 17kV)	104,168,548	
20 kV (20-22kV)	82,310,792	
25 kV (25-27.5kV)	22,495,110	
30-33 kV	4,474,167	
36 kV (35.9-36kV)	9,763,832	
45	517,799	
66	7,468,567	
220	7,192,001	

Table 3-15. Energy losses, Spanish case

ELECTRICAL ENERGY

3. ENERGY LOSSES

Public transport and distribution electric network

Voltage level (kV)	Losses (%)

Traction transport and distribution electric network

Voltage level (kV)	Losses (%)
BT	13.8%
1 kV < V < 36 kV	5.9%
36 kV < V < 72,5 kV	4.1%
72,5 kV < V < 145 kV	2.9%
220 kV	2.3%
400 kV	1.2%

Electric railway network (catenary)

Voltage level [kV]	Losses (%)
600 V CC	22.0%
750 V CC	18.0%
1500 V CC	10.0%
3000 V CC (normal Traffic)	6.0%
3000 V CC (commuter)	5.6%
1x25 kV CA	3.5%
2x25 kV CA	2.2%

Traction substations

Voltage level [kV]	Losses (%)
AC	1%
CC	4%

Table 3-16. Traffic description and energy consumption, Spanish case

ELECTRICAL ENERGY

2. TRAFFIC DESCRIPTION

Service type	Annual TKBR	Annual train kilometers	Annual number of trains
Intercity high-speed	11,612,917,682	27,386,780	67,206
Regional high-speed	1,689,059,472	6,330,765	34,335
Intercity that uses a part of HS lines	-	9,777,705	30,661
Intercity	10,226,228,175	28,105,866	42,951
Regional	4,419,292,184	20,131,001	129,501
Commuter	13,659,710,886	53,447,851	1,052,604
Freight	14,500,000,000	20,220,593	80,444

(1) All is referred to electrical traction

Service type	Average energy				
	% of train with regenerative brake	Intaking at pantograph level [kWh/km]	Regenerated at pantograph level [kWh/km]	Energy disipated at rheostatic brake [kWh/km]	Devoted to auxiliary systems [kWh/km]
Intercity high-speed	89%	15-20 kWh/km	9-18 %		0.5-1 kWh/km
Regional high-speed					
Intercity that uses a part of HS lines					
Intercity	100%	8-12 kW/km	9 - 11%		1-2 kWh/km
Regional	42%	4-6 kWh/km	0 - 3,46%		1-2.5 kWh/km
Commuter	100%	4.84-7.13 kWh/km	10-33%		0.5-1.5
Freight	42%	8.5-15 kWh/km	10-18 %		0

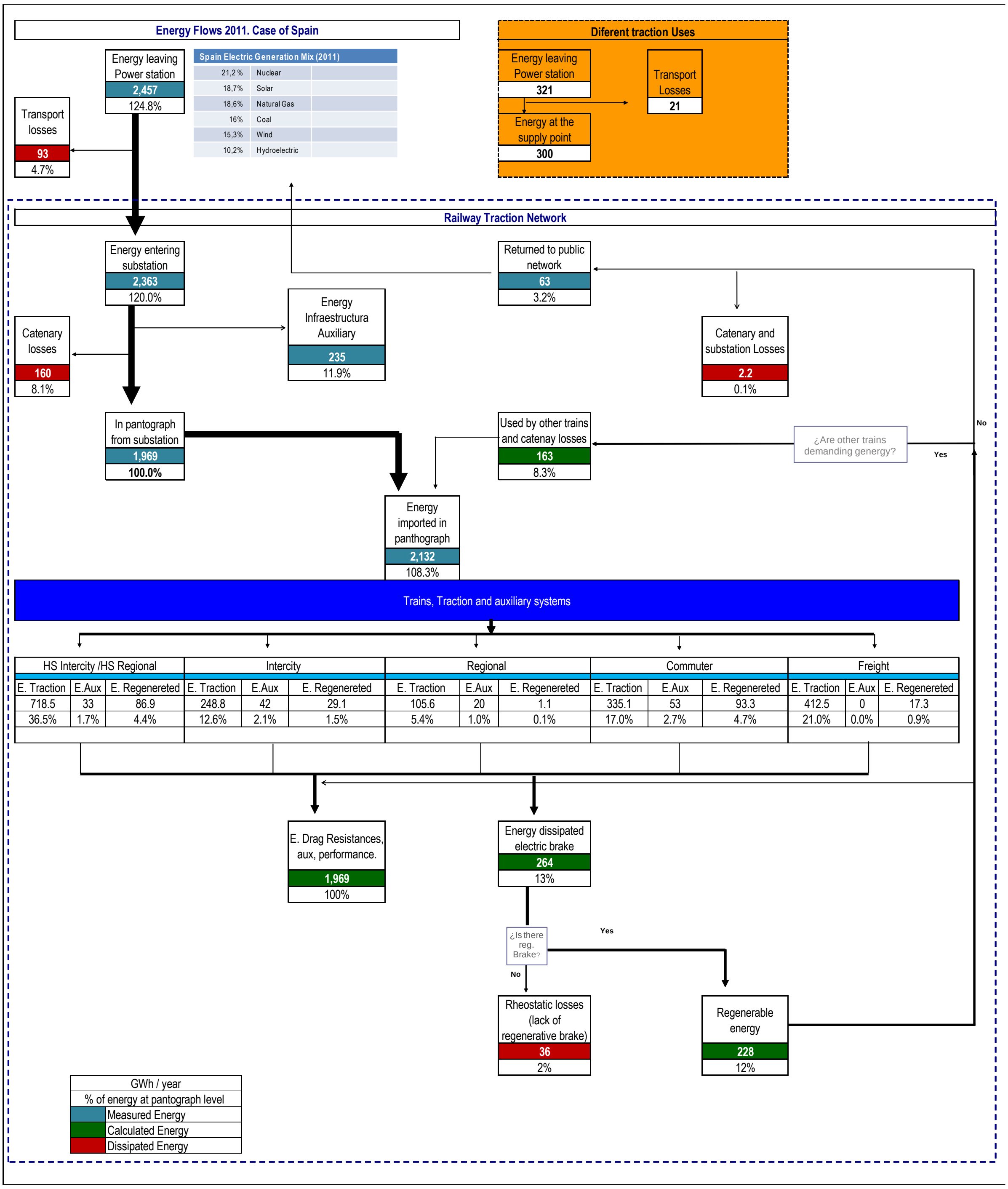


Figure 3-7 - Spanish consumption map (Independently produced).

3.2.4.4 Sweden

In the case of Sweden, the energy consumption and the energy regenerated at supply point of the substation are shown in Table 3-17. The amount of energy needed to feed the auxiliary services of the infrastructure is 113 GWh, as shown in Table 3-18. The energy consumption for other uses different to traction (as stations, workshops, etc.) in Sweden in 2011 is indicated in Table 3-19. The percentage of losses in the Swedish Public Grid and the electric railway network (transmission, distribution, substation, converter stations and catenary) are included in Table 3-20. The traffic characterization of the Swedish network and the energy consumption related to the different services considered are shown in Table 3-21.

Table 3-17. Energy consumption at traction substation, Swedish case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total energy consumption measured at traction substations (per year)	2,159,000.00	MWh
Total energy regenerated measured at traction substations (per year)	0	MWh

Energy consumption at traction substation level split by input voltage and output voltage

Input voltage [kV]	Type input	Output voltage [kV]	Yearly energy consumption [MWh]	Yearly energy Regenerated (MWh)
6.3 - 200	3 phases 50 Hz	15 kV//16,7 Hz	2,159,000	None
50.00	3 phases 50 Hz	15 kV//16,7 Hz	150,000	None
130.00	3 phases 50 Hz	15 kV//16,7 Hz	150,000	
22.00	3 phases 50 Hz	15 kV//16,7 Hz	200,000	
6.30	3 phases 50 Hz	15 kV//16,7 Hz	1,659,000	

Table 3-18. Energy related to the auxiliaries of the infrastructure (signalling system, switches, etc.), Swedish case

Energy, measured at traction substation, not devoted to traction (signalling system, switches, technical buildings,…)

Supplied voltage [V]	Yearly energy consumption [GWh]	Description
11/22 kV	113	Auxilliary at supply stat intake.

Table 3-19. Energy purchase for other uses different to traction (stations, workshops, etc.), Swedish case

ELECTRICAL ENERGY

1. TOTAL ENERGY CONSUMPTION

Total purchased directly for other uses diferent to traction (per year)	35.00	GWh

Energy purchased directly for other uses diferent to traction (stations, workshops,…)

Input voltage [kV]	Yearly energy consumption [GWh]	Use description (stations, workshops…)
	35.00	undergoing liquidation

Table 3-20. Energy losses, Swedish case

ELECTRICAL ENERGY

3. ENERGY LOSSES

Public transport and distribution electric network

Voltage level (kV)	Losses (%)
400	1.9%
200	1.9%

Traction transport and distribution electric network

Voltage level (kV)	Losses (%)
130	1.9%
22	3%
6.3	3%
50	3%

Electric railway network (catenary)

Voltage level [kV]	Losses (%)
	Estimations
16.5	4 - 28%
depending on type of traction equipment	
AT or BT system and power factor conditions	
Average losses for all of Sweden	
is around	10%

Traction substations

Voltage level [kV]	Losses (%)
	Supply station
	estimated average
	8.50%

Table 3-21. Traffic description and energy consumption, Swedish case

ELECTRICAL ENERGY

2. TRAFFIC DESCRIPTION

Service type		Annual TKBR (Millions Gross-tonnes-km)	Annual train kilometers (thousands)	Annual pass-km (millions)	Annual number of trains
Intercity high-speed	SJ2000, SJ3000, speed 200km/h	Blank = No data		2,827.00	No data
Regional high-speed	A-train: X3				
Intercity	SJ2000, Rc+coaches, speed 160 km/h				
Regional	Skånetrafiken, DSB, Botnia, SJ, Jönköping,SWT Swedtrack, skan jernbanor, Tågkompaniet, Veolia, Östgöta, Upplands länstr, Bergslagernas jv			5,184.00	
Commuter/regional freq. Stops	SL, Västtrafik, X11/14, X60/61			1,279.00	
Total passenger		**21,684.00**	**94,619.00**		
Freight		42,304.00	39,900.00		
Total		**63,988.00**	**134,519.00**	**11,378.00**	

		Average energy					
Service type		Total net consumption at pantograph [kWh]	% of train with regenerative brake, preliminary	Intaking at pantograph level [kWh/km]	Regenerated at pantograph level [kWh/km]	Energy disipated at rheostatic brake [kWh/km]	Devoted to auxiliary systems [kWh/km]
Intercity high-speed	SJ2000, SJ3000, speed 200km/h	110,404,838	100%		9%	No data	20% of net consumption
Regional high-speed	A-train: X3	17,045,909	100%		20.00%		20% of net consumption
Intercity	SJ2000, Rc+coaches, speed 160 km/h	136,196,289	9.1%		2.00%		20% of net consumption
Regional	Skånetrafiken, DSB, Botnia, SJ, Jönköping,SWT Swedtrack, skan jernbanor, Tågkompaniet, Veolia, Östgöta, Upplands länstr, Bergslagernas jv	516,025,048	89.4%		20%		20% of net consumption
Commuter/regional freq. Stops	SL, Västtrafik, X11/14, X60/61	228,815,153	40.3%		10%		20% of net consumption
Total passenger		**1,008,487,238**					
Freight		780,375,089	34.9%		1.00%		6% of net consumption
Total		**1,788,862,327**					

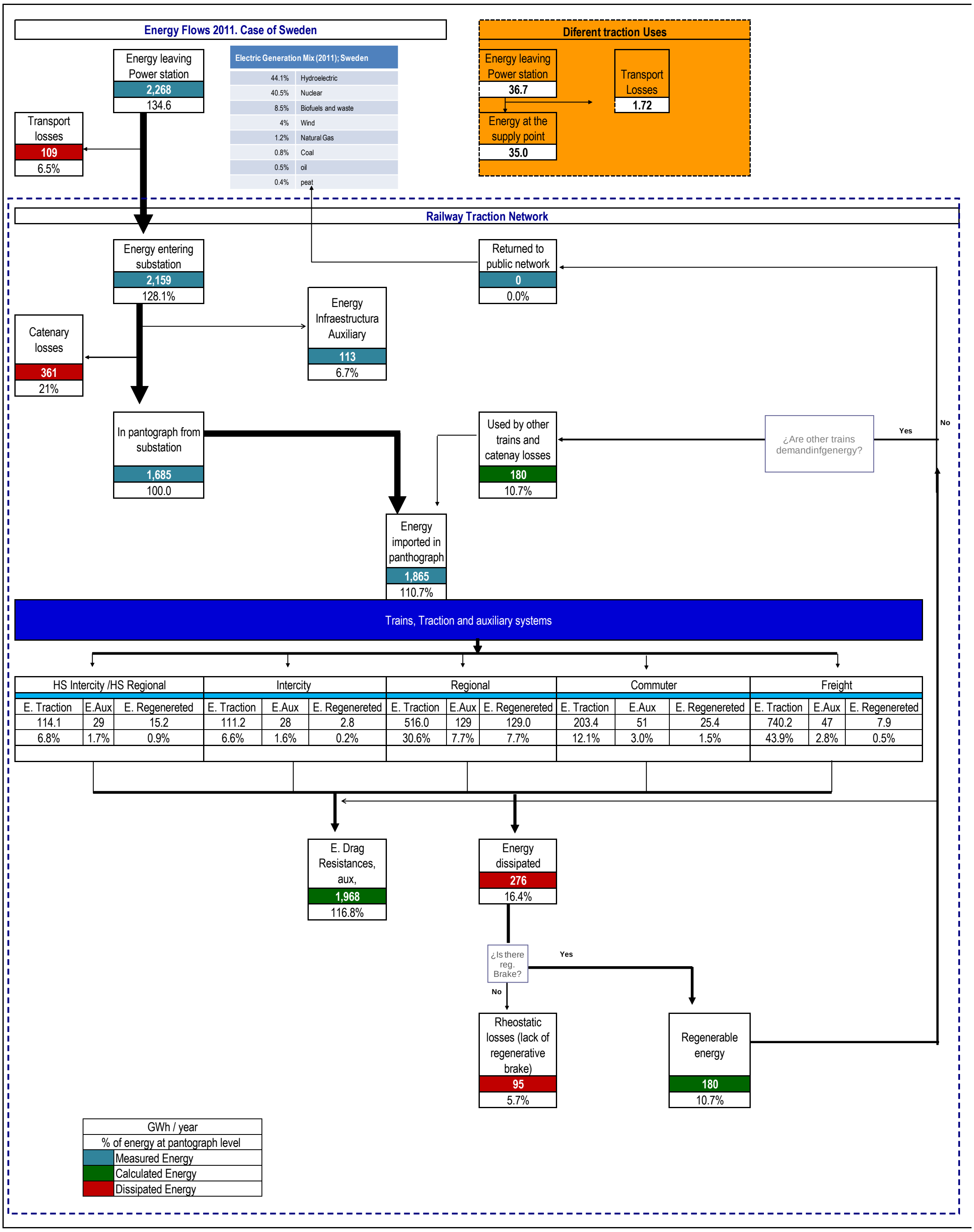


Figure 3-8 - Swedish consumption map (Independently produced).

The main conclusions reached in this analysis are:

1. Due to the fact that the energy provided data is measured up to the supply point in the traction substations, the calculation of the energy flows has considered all the losses upstream and downstream produced in the electrical path (public transmission and distribution grid, railways

transmission and distribution grid, converter station, connection stations, substations, catenary, etc.).

2. The amount of energy generated that fees the different railway systems varies between 2,268.4 GWh (Sweden) and roughly 3,174.9 GWh (United Kingdom), with the exception of the French railway network that needs approximately 7,800 GWh. These amounts give a clear idea of the size of the analyzed systems.
3. The energy balance changes substantially, depending on whether the train has regenerative braking or not and how it is used. As we can see in the different maps, the annual lost energy due to the lack of regenerative braking is in the range of 36 GWh (Spain) -117 GWh (United Kingdom), which is a similar amount to the energy required to feed the auxiliary services of the infrastructure.
4. The amount of energy regenerated by all trains and returned to the public grid is very similar in all the analyzed scenarios (between 53 GWh and 63 GWh), with the exception of the Swedish case; due to its architecture, all the regenerated power is consumed internally by other trains.

Regarding the energy consumption for other uses different than traction, it has been assessed to be a considerable amount. In the Swedish case it represents 2% of the energy imported at pantograph level, but in the other analyzed cases it represents between 10% (Spain) and 17% (France) of the energy imported at pantograph/shoe level (between 300 GWh in Spain and 650 GWh in France).

3.3 Technologies for the reduction of losses of electrified transport networks

An overview of the technologies used to reduce energy losses in the railway electrified networks is presented in this section.

3.3.1 Improving the efficiency of traction energy use

This section explores the way in which the railway industry consumes energy and identifies opportunities for saving traction energy, ranked in accordance with the potential savings, timescales and cost/benefit case. Four areas have been identified where quick wins can be made[26]. These include reducing the stabling load on electric passenger trains, running shorter electric suburban trains off peak, improving energy efficiency through improved driving techniques and better train regulation, and reducing diesel engine idling. It is estimated that the annual potential saving from these opportunities is in the region of 26% of total consumption and a further 10% of total diesel consumption. Taking as an example the case of the UK, in financial terms this is worth around €84 million and could save more than 500 million kg CO_2 emissions.

A further eight areas have been identified where there are potentially significant savings to be made in the longer term. These include hybrid drives, improvements to heating and cooling systems, fuel additives, weight reduction of trains, dual power source trains, intelligent control of diesel engines and aerodynamic drag reduction. It is estimated that the annual potential saving from these opportunities is in the region of a further 7% of the total consumption and a further 24% of total diesel consumption. With reference again to the UK, in financial terms this is worth around €72 million and could save more than 460 million kg CO_2 emissions.

In order to optimise the prospects for energy efficiency, it is vital that the approach is one of considering energy efficiency as an integral part of the rail industries decision making processes and seeing rail as a whole system. Some of the opportunities identified can be addressed in isolation but others will only meet their full potential with a systems approach.

[26] RRSB project T618

It is therefore recommended that the rail industry works collaboratively to ensure that the appropriate level of integrated thinking takes places in order that energy efficiencies are optimised. In some cases, this may require changes to contractual and regulatory arrangements to ensure energy efficiency is adequately considered, and the associated costs and benefits are distributed equitably.

3.3.2 Improving efficiency of non-traction energy use

This section deals with non-traction energy efficiency, which is defined as the buildings and infrastructure associated with the rail industry, such as station buildings, depots, and car parks. These areas are responsible for over 10% of the energy used in the rail industry and represent a significant business improvement opportunity. Consequently, the way in which the rail industry consumes traction and non-traction energy has been researched to identify the potential for making savings[27].

A number of significant opportunities for saving energy have been identified, some of which can be realised in the short-term by the relatively straightforward action of a single party. Longer-term opportunities are typically more complex and may require a number of parties to take coordinated action, the development of emerging technologies and projects related to progressive replacement of long life, high value assets. The work has also looked at the energy performance of both electric and diesel passenger trains and how they compare with other transport modes in terms of CO_2 emissions.

Retrofit energy efficiency improvement measures that are suitable for non-traction aspects of the rail industry include:

1. Energy, environment, and sustainability managers
2. Station managers
3. Procurement teams
4. Facilities managers
5. Budget holders

By improving energy efficiency, operators across the rail industry will be able to reduce their carbon emissions and achieve cost savings, allowing money to be directed back into improving customer experience and overall company performance.

The focus of this guidance is on retrofit energy efficiency measures (that is, those measures that can be applied to existing facilities). However, all aspects of the guidance are appropriate for consideration at the design specification stage.

3.3.3 Double-end feeding

This principle originates from AC 16,7 Hz and DC power supplies. It substantially reduces the impedance and losses. In addition, the voltage drop is reduced, so that the voltage available at the pantograph of the trains will be higher. Hence, the power consumption of the trains leads to lower currents on the catenary line, reducing transmission losses even further. Double side feeding provides a parallel path to the public grid for the power respective current flow. Such currents drawn from the three-phase high-voltage network through the railway network would lead to an increase in energy losses and a reduction in the capacity of the catenary in relation to the loads for railway traction. Moreover, smooth load curves would result in lower peak power demand and could allow for reduction the installed power equipment.

[27] RRSB project T618

3.3.4 Reversible Traction Substations[28]

This provides the capability of feeding the train regenerative braking energy (up to 100%) to the external power distribution network, whilst maintaining the exchange of energy among trains on the traction supply line. The system receptivity is improved by feeding the excess of regenerative braking energy to the upstream network and this improvement is more effective in railway systems that are characterised by a low value of system receptivity. In addition, further benefits are related to the minimization of line and distribution losses as well as to the balancing of the paralleled substations' loads in order to optimize energy flow.

Conventional DC traction substations do not support capability of regenerating energy outside the DC network because the diode rectifiers only allow unidirectional flow of power. Therefore, in this case, the excess of regenerated energy is generally dissipated by using braking resistors in order to prevent the DC bus voltage from rising above the trip level.

The objectives of a reversible DC substation are to regenerate up to over 99% of the braking energy, allowing the removal of on-board braking resistors, realizing dynamic power balance between adjacent substations and compensate for dynamic fluctuations of primary voltage. It should also control overloads, meet relevant standards for total harmonic distortion and finally, it should be able to compensate for the reactive power which is generated to ensure it is not wasted.

The Power Electronic Converter (PEC) is controlled by a power electronic control unit that generates the pulses controlling a IGBT bridge and the thyristor bridge. The PEC also allows voltage and current regulation and the bridges' protection. It provides both active filter and inverter functions to the IGBT bridge. It sets the sequencing and can provide auxiliary functions; the converter can regulate the output voltage on the DC side. It can also dynamically regulate each substation's load in both traction and regenerating phases. This load regulation helps limiting the overload in each substation. This load balancing allows a better current distribution in both normal and degraded operation, thereby minimizing losses and overloads.

3.3.5 Reduced line impedance

The approach of the technology "reduced line impedance" consists of the reduction of losses along the line of electrified railway systems. The losses are caused by the impedance or resistance of the contact line system and the current which is supplied to the locomotive vehicles. The reduction in impedance or resistance is achieved through higher conductivity of the materials of the contact line systems and/or by enlarged cross sections of contact line systems.

Where reinforcing feeders are used, the appropriate cross sections and conductivity should be optimised, especially with regard to losses. In case of DC-systems, the increasing of the effective copper cross section of DC-lines is done in order to achieve reduced line losses by means of lower resistance and reduced voltage drop.

3.3.6 Eco-driving

3.3.6.1 Driving strategies

How trains are driven (and regulate its operation) can involve a significant impact on energy consumption.

[28] D1.1 Railway network key elements and main sub-syst ems specification – MERLIN Project GA 314125

"Eco-drive" is a way to drive the train that allows a lower energy consumption rather than driving at "full speed" or "minimum driving time", which implies driving at the maximum allowed speeds on each point.[29]

Normally, timetables are built calculating, for each journey, the shortest time strategy in first place. This strategy has the following characteristics:

1. Full acceleration up to maximum speed.
2. Speed holding at maximum speed until the train has to start braking.
3. Braking at the latest possible point in order to come to stop when reaching the station.

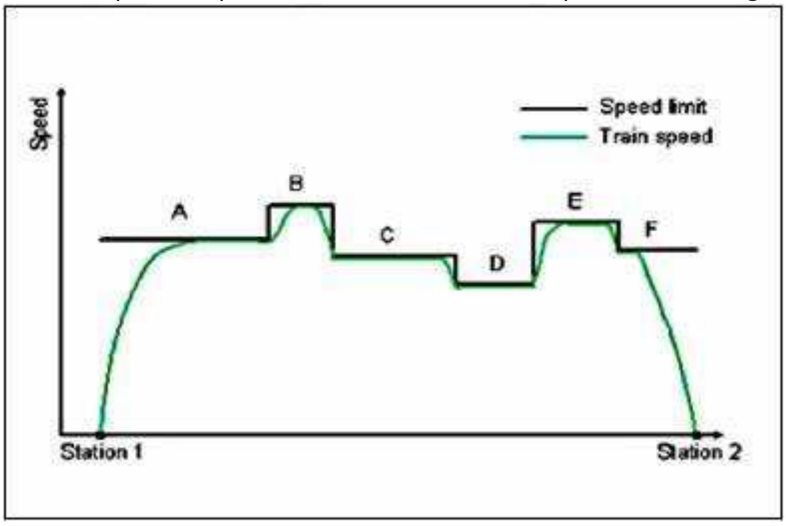


Figure 3-9. Hypothetical example of shortest time driving strategy[30].

It is important to understand that a shortest time strategy (as the one show in Figure 3-9) is very energy consuming, so it should be avoided if possible.

There are many possible driving strategies that can lead to the same travel time with different consumption. Thus, the most appropriate would be the one in which for the same time given the minimum consumption is achieved.

[29] Grabocka, J. et al. Realistic Optimal Policies For Energy-Efficient Train Driving. University of Hildesheim (Germany).

[30] Salvador, P. (2008). Estrategias para el ahorro de energía en la explotación ferroviaria. Universidad Politecnica de Valencia. Valencia (Spain).

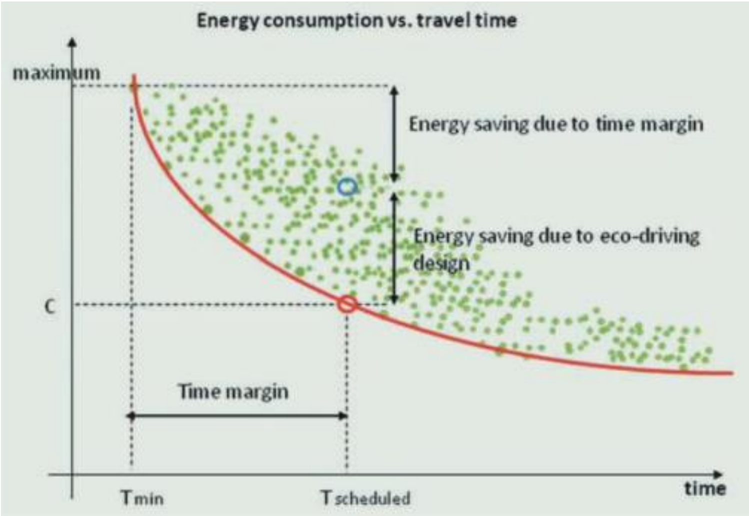


Figure 3-10. Relationship between travel time and energy consumption[31].

Figure 3-10 shows the result of consumptions and travel times in a certain route. In the scatter plot, it is possible to see:

1. The general trend is the longer the travel times, the lower energy consumption.
2. For each travel time there are several possible energy consumption rates depending on the driving strategy.
3. There is a Pareto optimal curve in each path between stations, which provides the minimum consumption for each travel time.
4. The Pareto optimal curve has a form of descending parabola. This means that small increases in travel time allow relatively significant reductions in energy consumption. On the other hand, the strategy rooted on large increases in travel time, will produce small reductions in consumption.

Having a time frame in which the amount of time between the minimum time that the train needs to travel a certain distance and the time available is a necessary condition. In this way, the driving style will have an impact on energy consumption.

Regarding Eco-driving, the driving strategies between two stations or stopping points may be the following:

1. Limiting the maximum speed.
2. Accelerate the utmost, keep maximum speed and reduce speed by coasting before each of the points where it is necessary to slow down.
3. The third one is the same as the previous strategy, with the application of coasting just until a speed higher than the necessary to stop is reached, called, "minimum speed drift", below which the service brake is applied to slow down.
4. Accelerating as much as possible, then do coasting to lose some speed and after that accelerate again to recover the maximum speed and so on (coasting-remotor).

Achieving maximum efficiency depends on the driving strategy chosen by the driver. Each route and service should be studied in detail, but there are some generic strategy advices that can help reduce energy consumption, for both Eco-driving, with and without regenerative brake:

1. Accelerate the utmost.

[31] Cucala, P. et al. (2013). Reducción del consumo energético en el ferrocarril. Anales de mecánica y electricidad (38-41) July - August 2013. Madrid (Spain).

2. Coasting (using kinetic energy to overcome the drag). This is especially suitable for high speeds in which the time losses during the coasting are reduced, and the drag is very high. By contrast, at low speeds coasting supposes wasting time with little energy reduction. For this reason an intuitive driving economic criteria could be to use only drift above a certain speed, below which the service brake is used.
3. Coasting-remotor. Sometimes, when the speed profile is homogeneous, this strategy at high speeds is used. It implies coasting after reaching the maximum speed, leaving the train at drift until a specific speed, from which traction is reapplied, is the best strategy. Applying several coasting-remotor cycles, instead of a single drift at the end of the route or upon arrival of a stop, may be more beneficial, due to the drift is performed at a higher speed and therefore losses in travel times are lower.
4. The strategy of limiting the maximum speed is based on traveling at a slower speed in order to reduce the drag, but as the previous strategy, it finds its maximum application at high speeds.
5. Coasting before reaching the starting point of a downhill, in order to prevent braking on it (mainly in steep slopes) and avoiding dissipating energy in brakes. In this case an efficient strategy would be to allow trains to exceed the maximum speed on downhill slopes (obviously without exceeding the safety limits).

In addition, it is necessary to highlight that driving strategies are radically different when the trains are equipped with regenerative brake and the regenerated energy can be used, compared to those performed by trains without regenerative brake or compared with those in which the percentage of energy returned to the catenary is low. It is very important to emphasize this because there is a general trend to implement Eco-driving strategies designed for services which do not have regenerative brake or with low use of it in services which has it and vice versa.

For example, strategies based on coasting have interest when there is not a high use of regenerative brake or the energy generated in the regenerative brake is lost, as otherwise it is not possible to use it either on the same train, either by other train, or returning the energy to the grid.

On the other hand, in case of having regenerative brake, the most appropriate strategy would be limiting top speeds, except in steeper downhill slopes, in order to reduce the drag, and applying the regenerative brake in each stop and speed limitation[32]. Another possibility to perform Eco-driving strategies is to accelerate at maximum speed, do a shorter coasting, and then brake as much as possible, in order to take full advantage of the recovered energy.

The following figures show the different Eco-driving strategies and/or a combination of them explained.

[32] Scheepmaker, G. M. et al. (2015). Effect of regenerative braking on energy-efficient train control. Delft (The Netherlands).

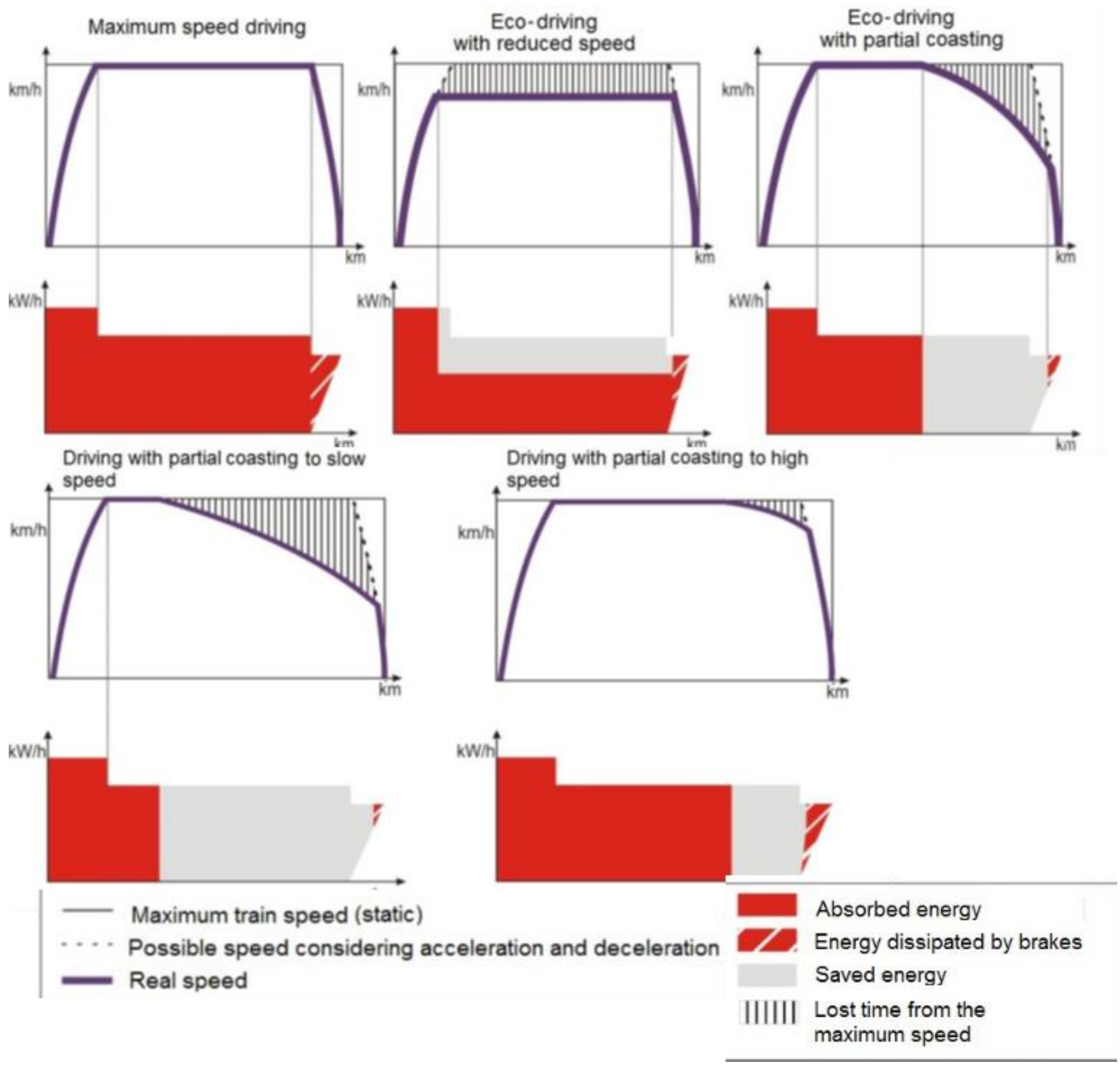


Figure 3-11. Different driving strategies[33].

In the following pictures some other benefits in energy optimization as a result of implementing energy Eco-driving strategies in a Czech Republic railway line. The graphics show the increments of times that are necessary to perform an Eco-drive strategy and the associated energy reductions.

[33] García, A. (2016). Energía y emisiones en el transporte por ferrocarril. Fundación de los Ferrocarriles Españoles. Madrid (Spain).

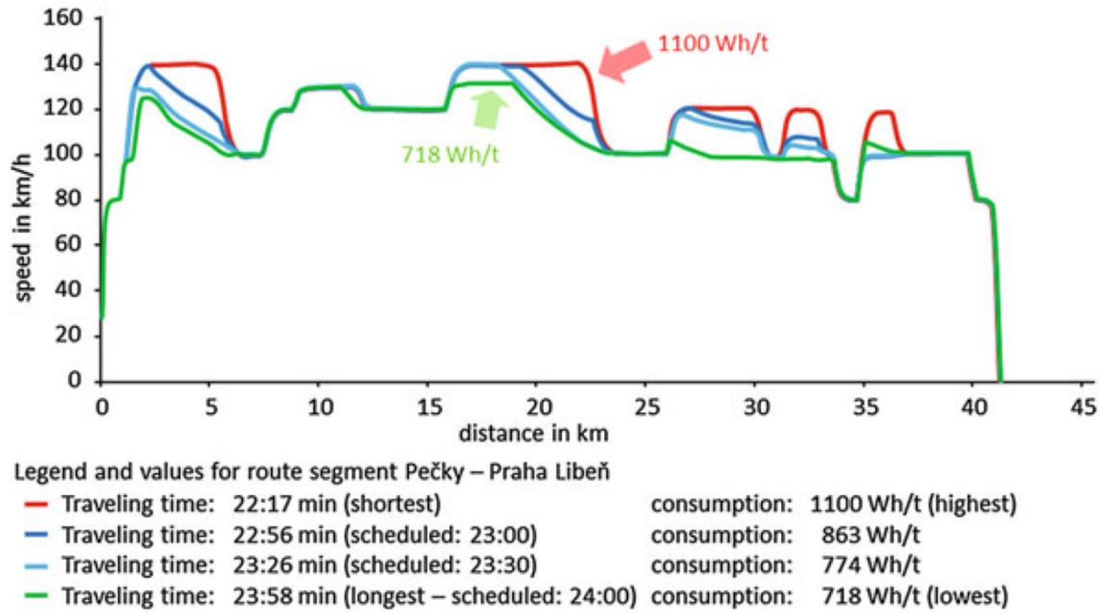


Figure 3-12. Energy consumption for different travel times.

The data from the last example allows calculating the elasticity of energy over time, giving the values that are shown in Table 3-22.

Table 3-22. Elasticity for energy over time

Travelling time (hh:mm:ss)	Energy cosnmed (Wh/t)	Elasticity
0:22:17	1110	
0:22:56	863	-738,62%
0:23:26	774	-574,26%
0:23:58	718	-459,71%

As it can be seen, a slight increase of travelling time can produce a significant reduction on energy consumption. For example, in the case shown in a Czech Republic railway line, increasing travelling time only 1min and 41s, means a relative increment of 7.6%, energy which can be lowered down to 2/3 of its initial value. This means that if time tables allow buffers, which don't need to be very significant, a great saving of energy can be achieved, and the train would still run on time.

Table 3-23. Examples of field application of eco-driving

Author	Explanation	Benefits
Europe: Netherlands, Slovenia, Slovakia, Italy, Greece, Portugal[34]	Many Eco-driving programs are being developed in different European countries to teach drivers how to do the best ecological and economical driving.	The results of the TRAINER program in 2009, were an annual 0.15 Mton CO2 emission avoidance through

[34] Monteiro, J. N. (2014). Condução Energeticamente Eficiente na Exploração Ferroviária em Portugal Aplicação ao caso dos serviços regionais na linha do Douro. Lisbon (Portugal)

	TRAINER is a program that was developed and implemented to streamline measures of enhancing energy efficiency by railway operators.	the training of 19,500 train drivers.
Renfe, Spain	A simulator has been the tool of this experience which took place in the Madrid-Seville line. By manipulating the simulator, the drivers were urged to improve consumption. This driving simulator considered aspects of coasting, reduced the maximum speed and reduced acceleration.	The results in the simulation were very satisfactory with an energy reduction between 10% and 20%.
Renfe, Spain	After teaching drivers how to do an Eco-driving with the simulation tool a real experience driving on that line, Madrid-Sevilla has allowed to observe that with a five minutes increase in the travel time, a reduction in energy consumption is suitable, due to the possibility to perform coasting approximately trough sixty percent of the journey.	A real reduction of 8%, has been proved in the Madrid-Sevilla line.
Comboios de Portugal	A model studies the Eco-driving based on the energy-efficient drivings state of art applied to railways. The studies of the model developed, evaluate the differences between actual driving ways with efficient driving strategies.	The results obtained in the evaluation of the model developed for comparing actual driving with efficient driving strategies, indicate a potential of energy savings up to 15%.
Salvador, P. (2008)	He explains the influence of trains' energy consumption in the Lötschberg line (Switzerland), which, before drivers were instructed, energy consumption for Bern-Thun section was 373 kWh, while for the same trip with an economic driving after those Eco-driving programs, energy value reached 305 kWh	A real application demonstrated that driving in an economic way can save 22% of the energy consumed in traction.

3.3.6.2 Driving Advisory Systems

Driving Advisory Systems (DAS) are on board tools giving recommendations to drivers towards a more energy efficient driving style. The DAS represents a human-machine interface (HMI) which supports the exchange of information between the railway system and the human operator (the driver). The human operator needs to process the information received, and produce instructions or control actions.

This software has many different versions and may tell drivers what to do in every moment in order to perform the optimal drive in terms of energy-efficiency. The instructions that are given to the drivers are:

1. Acceleration rate to apply.
2. Optimal train speed for each instant.
3. Exact moment for shutting power down and start coasting.

4. Exact time for applying train brakes, and braking rate.

The outlined architecture and interfaces for a generic DAS can be seen in Figure 3-13.

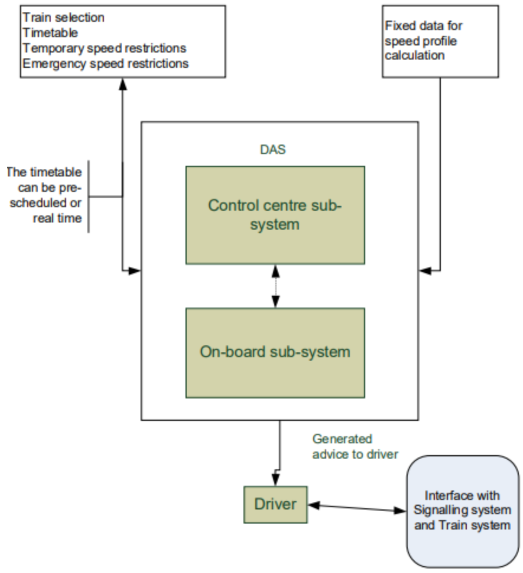


Figure 3-13. DAS architecture[35].

The on-board system calculates an energy efficient speed profile to achieve the pre-planned or dynamically updated train timings, and generates detailed driver advice to follow the profile and achieve the travel schedule. This architecture allows optimises running to a pre-defined timetable, without a real time data link between the train and control centre.

According to this, energy efficiency can be improved because a DAS can calculate the optimal ride between two stations better than train drivers taking into account the state of the signalling, the maximum speeds and the railway layout.

With the drivers training it is possible to reduce energy consumption, due to the driving performance improvement. Furthermore, what a Driving Advisory System improves regarding experienced trained drivers is that DAS are aware of the traffic situation, which makes them to be able to drive in conflictive situations while keeping energy consumption in minimum levels.[36]

The data that the Driving Advisory Systems need can be grouped in four types, according to its needed frequency:

1. Permanent data: Vehicle data.
2. Long-term data: Track data base (to be updated annually).
3. Mid-term data: Time table.
4. Short-term data: Data on temporary low-speed sections (to be updated daily or even in real-time).

The following figures show an example of two trains in conflictive situation with a necessary stop or speed reduction, without and with a Driver Advisory System.

Figure 3-14 shows the unplanned situation without a Driver Advisory in which the energy consumption is 350 kWh in a runtime of 651 sec (incl. unplanned stop).

[35] Jianhong Jin, et al. (2011). Driver Advisory Information for Energy Management and Regulation. RSSB (UK).

[36] Panou, K et al. (2013). Railway Driver Advisory Systems: Evaluation of Methods, Tools and Systems. 13th WCTR, July 15-18, 2013 – Rio de Janeiro (Brazil).

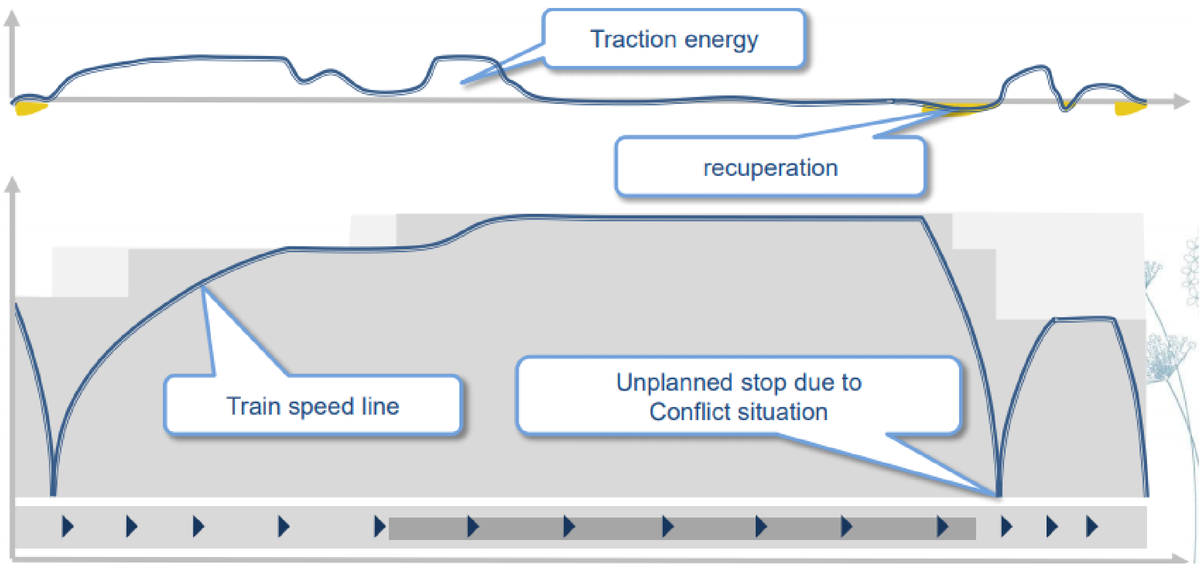


Figure 3-14. Train route: Gelterkinden-Olten[37].

Figure 3-15 shows the unplanned situation with a Driver Advisory in which the energy consumption is 204 kWh in a runtime of 626 sec, which implies the that there is a 40% of energy consumption and a 25 sec train runtime saved.

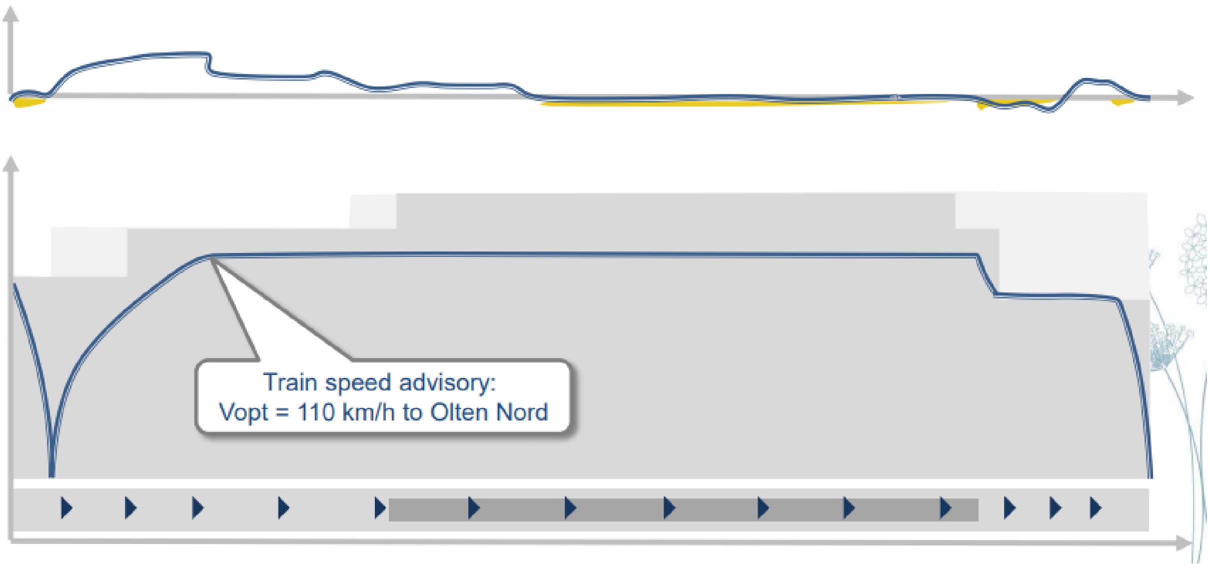
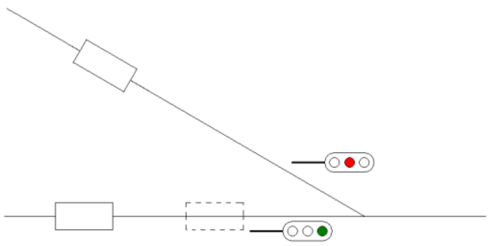
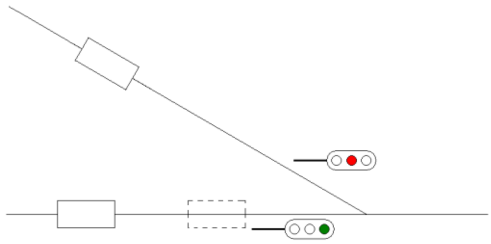
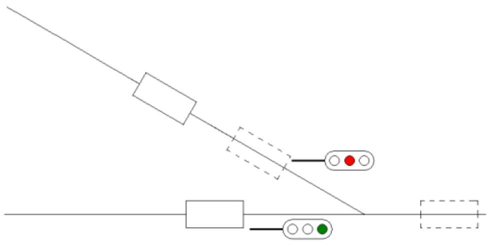
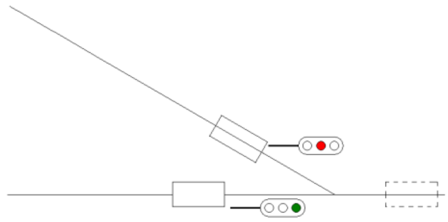
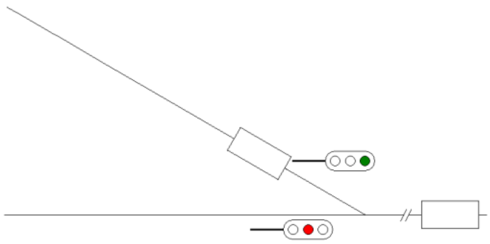
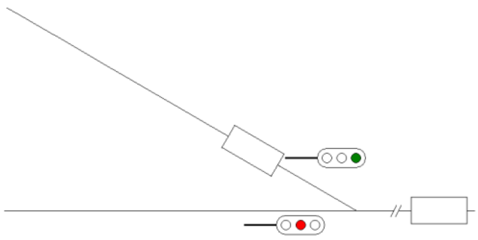


Figure 3-15. Train route: Gelterkinden-Olten with DAS.

As an example, the following comparison in a railway node is shown, by using a Driver Advisory System and without using it, in which Train A should reach the crossing at 8:00 and train B at 8:05.

[37] Trümpi, A. (2014). Conflict handling and fluent traffic sbb traffic system. UIC energy efficiency days June 2014, Antwerpen (Belgium).

Table 3-24. DAS behaviour

DAS implemented	DAS not implemented
8:00 h. Train A has a 5 minutes delay, but still has preference over train B. The DAS tells to train B to drive slow enough to reach the crossing after 8:06 h. 	8:00 h. Train A has a 5 minutes delay, but still has preference over train B. 
8:05 h. Train A reaches the crossing. Train B still is not there 	8:05 h. Train A and B reach the crossing. Train B must stop at the red signal. 
8:07 h. Train B reaches the crossing by the time the light signal turns on green, so it does not need to stop and later accelerate. 	8:07 h. Signal is now free for train B, which needs to restart its running. 

A Driving Advisory System can be used to manage the speed profile of each train to extend the running time to incorporate the unused allowances, so that the train arrives at the station or junction at exactly the right time. This will allow energy savings in the following circumstances:

1. When a train delay due to the actual temporary speed restrictions on the route is less than the engineering allowance.
2. When a train is running on time and the performance and pathing margin are not required to achieve on-time arrival.

3. When a train is capable of shorter point to point timings than those used in the timetable planning. The benefits from implementation of a Driver Advisory System (DAS) include reductions in energy consumption by avoiding unnecessary braking and running at reduced speed whilst maintaining on-time arrival. Operational benefits include reduced train delays and better utilisation of track capacity by running through junctions and station approaches at higher speeds whilst reducing maintenance costs as a result of reduced brake wear. There are also potential safety improvements through fewer red signals approached if the DAS is effectively implemented across the network.

Table 3-25 shows the Benefit to Cost Ratio (BCR) considering a range of train installation costs and service life over which the equipment will be operated. There are 3 basis cases in which the initial cost is higher according to the quality of the DAS.

From Table 3-25 it can be concluded that there is a positive business case in all cases except for the highest installation cost option on the shortest life of rolling stock.

Table 3-25. BCR for fitment options over different periods

Fitment option \ over		10 years	20 years	30 years
Cab based:	Low	2.3	2.7	2.8
	Medium	1.3	1.8	2.0
	High	0.8	1.2	1.4

The key findings from the simulations for energy savings can be seen in the Table 3-26.

Table 3-26. Simulation results – energy savings from DAS

	Energy Savings from DAS			
	Typically Perturbed Timetable (95% confidence interval)		Unperturbed Timetable	
	No Energy Recovered	90% of Braking Energy Recovered	No Energy Recovered	90% of Braking Energy Recovered
Individual Train DAS	14.36% ± 0.53%	8.42% ± 0.33%	26.68%	15.15%

From Table 3-26 it can be concluded that, assuming no energy recoverable, DASs save over 14% of energy in typical line peak timetable operation, and over 26% of energy in ideal unperturbed operation of the same timetable. If 90% of the energy lost through braking is recoverable, then the energy savings are still over 8% and 15% for typically perturbed and unperturbed timetable operation respectively.

For the safety performance, the simulation results have shown that DAS reduces red signal sightings by around 11% in typical line morning peak timetable operation, and by over 22% in ideal unperturbed operation of the same timetable.

Table 3-27. Practical application of DAS implementation

Author	Explanation	Benefits
LEADER Knorr-Bremse	It calculates train behaviours on the basis of rolling stock and infrastructure data and energy efficient driving strategies for the train drivers.	Reduce energy consumption. Reduce the in-train forces. Provide optimal driving advisory strategies

MetroMiser Siemens, Germany[38]	This system makes a timetable energy optimizer and it has an on-board unit to calculate and provide optimal driving advisory information.	Provide energy efficient driving with energy optimized timetables.
FreightMiser TTG Australia[39][40]	This type of DAS for freight trains calculates optimal speed with different journey time, optimal coasting points during the journey and provides the information to the drivers.	Improve energy consumption. Improve punctuality of freight rail.
GEKKO DSB Denmark	This system is implemented with a PDA device which request timetable and infrastructure information to calculate optimal speed profiles for the drivers.	Indicate drivers to be on correct pathway.
AVV AZD, Czech Republic	This type of DAS is able to reduce train speed or stops the train in accordance with absolute speed limits, signal indications and timetabled station stops.	Save energy using advanced train control.
Driving Style Manager (DSM) Bombardier	It produces an energy-optimised driving style (EODS) with the consideration of temporary or dynamic speed indications and signalling information.	Advise drivers about speed, acceleration and deceleration to minimise the energy consumption.

3.3.6.3 Timetable compatibility

The design of schedules is a method whereby energy consumption can be reduced without additional cost, this makes this measure one of the best methods to reduce energy consumption.

It is necessary to clarify that this measure does not work alone, actually the use of the regenerative brake is a crucial condition for any energy reduction.

There are three aspects that have to be taken into account to reduce energy consumption. The first one is related to the margins of regularity and their compatibility with Eco-driving; while the other two are related to the coincidence between departures, or between departures and arrivals at the same station.

I) Frame times match with Eco-driving:

As explained in Driving strategies, doing an efficient and economical driving consists in taking full advantages of the degrees of freedom offered by the timetables (journey time) in order to reduce energy consumption.

Moreover, the train schedules need "regularly margins" to be more robust and reliable. As the margin of regularity is often larger than the one needed for Eco-driving margin, it is possible to leave a small amount of time for performing an Eco-driving strategy where there is no scheduling requirement, and distributing the rest of the frame time between the points that require punctuality. Another possibility is to reduce time at stops and adding the reduced time to the Eco-driving time frame.

II) Avoiding simultaneous departures:

[38] UIC 2003. Energy efficiency technology for railways - http://www.railway-energy.org/tfee/index.php
[39] http://www.ttgtransportationtechnology.com/energymiser/
[40] Ghys, S. (2016). Optimising the world's railways an Australian technology perspective. Australasian Railway Association Telecommunications & Technology Forum. 14 & 15 July 2016. Melbourne (Australia).

The several tracks of the same station are normally fed from the same substation, even in some cases several stations are fed by the same substation, as it can be seen in Figure 3-16.

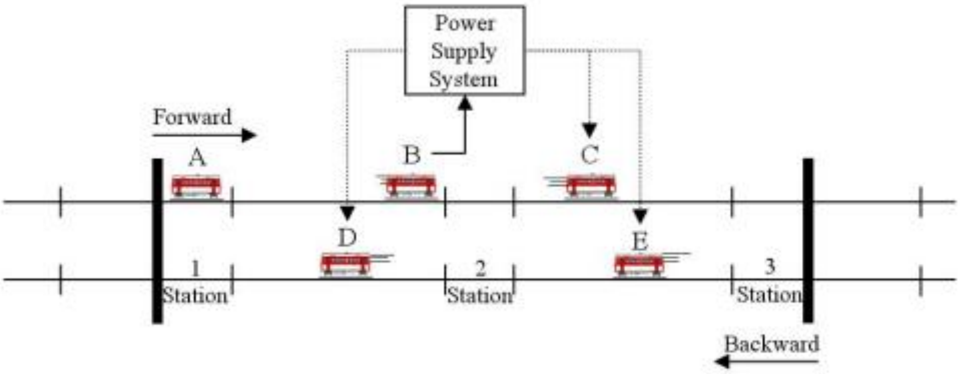


Figure 3-16. Group of stations[41].

Therefore, if a simultaneous departure of multiple trains occurs, an increase in the power peak required is produced, which implies an increase of the ohmic losses, and consequently the energy required is bigger. Moreover, an installation of higher power is required and therefore an increase of the investment is needed, as is shown in Figure 3-17.

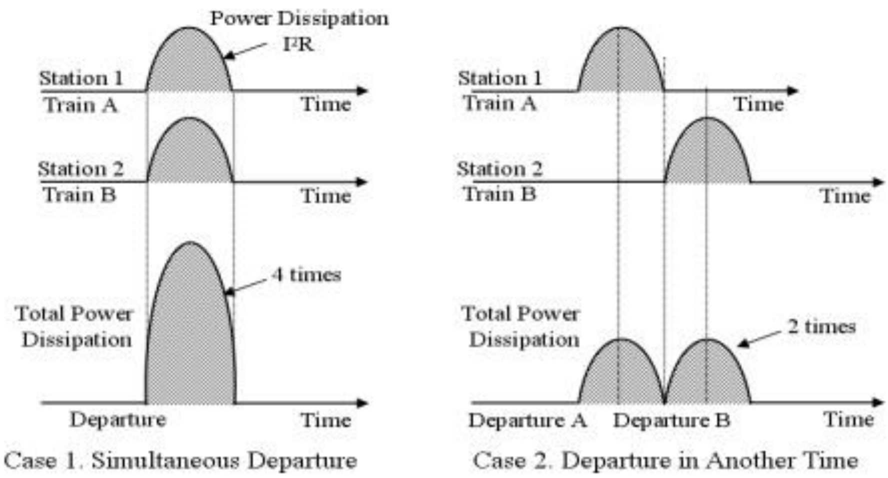


Figure 3-17. Power dissipation in traction phase.

(III) Mach arrivals and departures at the same station.

In a line with frequent stops and trains with regenerative brake, simultaneous departure and arrival in the same station at the same time, energy saving can be facilitated, since the energy regenerated by the train arriving (brake) may be exploited by trains leaving the stations (accelerate)[42], as it is shown in Figure 3-18.

[41] Kim, K. M. et al. (2010). A Model and Approaches for Synchronized Energy Saving in Timetabling.

[42] Fernández-Cardador, A. et al. (2008). Sincronización de arranques y paradas en metropolitanos para el uso eficiente del frenado regenerativo. II Jornadas Estrategias de Ahorro y Eficiencia Energética en el Transporte Ferroviario. 5-6 June 2008. Sitges (Spain).

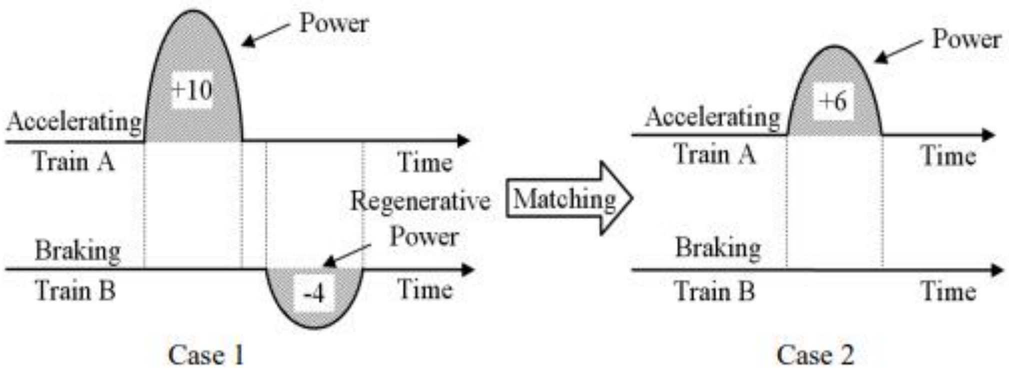


Figure 3-18. An example for synchronized driving.

Time compatibility can help reduce the energy consumption and energy costs, with a similar travel time and almost zero investment.

Table 3-28 shows a simulation between Madrid and Zaragoza in which, with minimal changes on the timetable in arrival and departure times at the inter-stations, it is possible to perform an Eco-driving strategy, which implies an energy reduction of approximately 33.33% [43]

Table 3-28. Results of journey times and energy consumptions for commercial and optimised timetable

	Commercial timetable with flat-out driving				Optimised timetable with energy efficient driving			
	timetable Ri hh:mm:ss	Flat-out time Rmi hh:mm:ss	Slack time hh:mm:ss	Energy consump. flat-out kWh	Opt. timetable Ri hh:mm:ss	Designed slack time hh:mm:ss	Opt. energy consump.n kWh	Energy savings %
Madrid-Guada. Guada.-Cala. Cala.-Zrg	00:23:00 00:39:00 00:26:00	00:18:48 00:35:15 00:22:26	00:04:12 00:02:45 00:03:34	1,690.826 2,730.136 1,445.056	00:21:04 00:41:04 00:25:52	00:02:15 00:04:49 00:03:26	1,245.029 1,835.773 841.643	26,37% 32,76% 41,76%
Total	1:28:00	1:17:30	0:10:30	5,866.02	1:28:00	0:10:30	3,922.455	33.63%

Table 3-29 shows the energy savings in a simulation performed in line 3 in Madrid subway. It is important to notice that the total savings are approximately of 3,5%, this reduction is lower than expected, as the schedule is made with a time step of one minute with respect to the original schedule. This new timetable allows coordinating arrivals and departures; while one train is arriving, other is departing. This measure also implies that the power peak at the substation is considerably lower, with respect to the original schedule, due to the affordable use of the regenerated energy[44].

[43] Sicre, C. et al. (2010). A method to optimise train energy consumption combining manual energy efficient driving and scheduling. Madrid (Spain).
[44] Plan de eficiencia energética del metro de Madrid (2013). Madrid (Spain).

Table 3-29. Average of the total energy consumption at substation [45]

Substation	Energy consumption (kWh) Inicial h.	Designed h.	Differences
SUB 1	767	694	10.33%
SUB 2	2,308	2,261	2.01%
SUB 3	4,000	3,917	2.60%
SUB 4	3,806	3,472	9.43%
SUB 5	4,361	4,417	-1.38%
SUB 6	2,703	2,578	4.87%
Total	**17,944**	**17,333**	**3.52%**

Figure 3-19 shows the block diagram for optimising train energy.

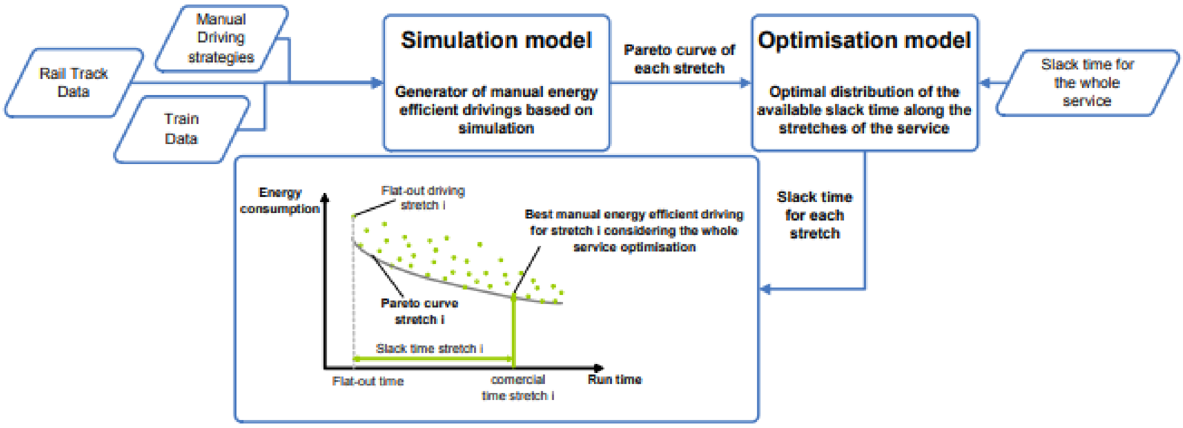


Figure 3-19. Block diagram for optimising train energy consumption.

Table 3-30. Examples of optimisation based on timetabling

Author	Explanation	Benefits
K. M. Kim (2010)	This paper that proposes a mathematical approach that can increase energy saving in timetables. The energy-efficient timetabling method maintains the planned traveling time between stations, but coordinates the train departure times at the starting station from current timetable to minimize the power peak and simultaneously to maximize the re-usage of regenerative energy.	The model is verified using real data of Seoul Metro line 4. It can reduce the power peak up to 40%, and in addition, it can improve the re-usage of re-generative energy approximately 5%.

[45] Peña, M. et al.(2010). Diseño de horarios ferroviarios para maximizar el aprovechamiento de energía procedente de sistemas de frenado regenerativo (Spain).

Siemens and the Technical University Berlin	Metromiser is a driving advisory system for suburban and metro systems developed by Siemens and the Technical University of Berlin. The Metromiser consists of two components: an on-board unit (OBU) and the timetable optimiser (TTO): The timetable optimiser is an off-board based software program checking the energy efficiency of timetables. Using basic data (acceleration, rolling behaviour of the train, topology, passenger flows, etc.) it draws up a new energy-optimised timetable fitting in with the existing running schedule of the railway network.	The study claims an average of 15% of every saving achieved with the use of Metromiser.
Peña, M. et al. (2010)	It has developed the model of economic gears for the efficient operation of the lines in rush hours, maximizing energy savings by implementing coasting orders of motor velocity and reduced brake rates, managing travel times and downtimes in station allowing to reduce the energy consumption.	This synchronized schedule was implemented in test mode for a week and the energy savings at substations were 3% less over time unsynchronized.

3.3.7 Infrastructure upgrades: Railway layout

To achieve an efficient design of the railway layout, it is necessary to take into account the following measures:

3.3.7.1 Homogeneous speed profile

This is one of the most important measures to reduce energy consumption. A homogeneous speed profile may reduce the use of the brake and therefore reduce losses. Figure 3-20 shows several maximum speed profiles in different Spanish routes (high speed lines and conventional lines). The differences in energy consumption are big, for example the Alicante-Barcelona speed profile, in terms of energy consumption, has the same effect of having a stop every 17 km, otherwise, the Madrid-Barcelona profile has the same effect of having a stop every 550 km.

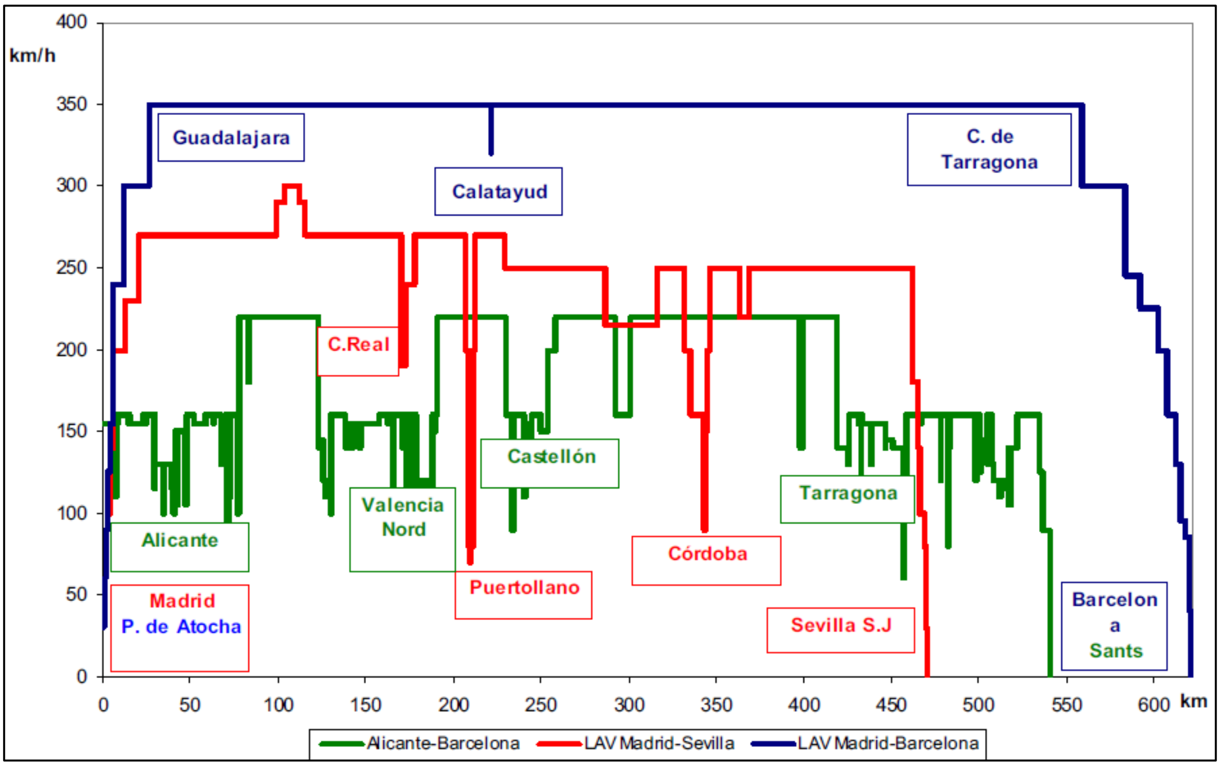


Figure 3-20. Maximum speed profile per route in several Spanish rail lines[46].

3.3.7.2 Avoid punctual speed restrictions.

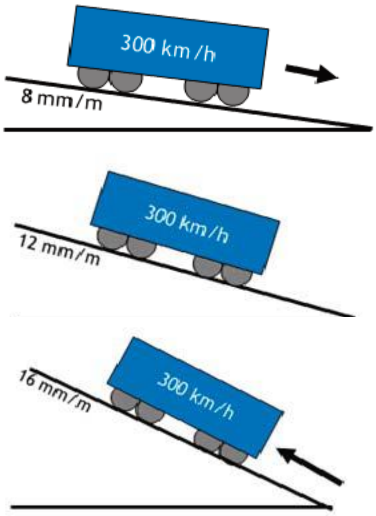
Another measure of layout design that reduces consumption is to avoid specific relevant speed limits (lower than 50 km/h) or sharp speed reductions, which represent large losses of time, greater amount of energy dissipated in the brake and lower aerodynamic savings.

The punctual speed restrictions have an important effect on the commercial speeds. If it is necessary to keep the timetable in a route, its effect on the energy consumption can be analysed in two different assumptions: (i) it is necessary to reduce the length of the line where coasting is performed and therefore energy consumption increase and (ii) it is necessary to increase the maximum speed in other line sections which means an increase of energy consumption.

3.3.7.3 Slopes adapted to speed.

To reduce energy consumption, it is appropriate to adjust the value of downward gradients with the train´s maximum speeds allowed. If the actual gradient coincides with the gradient of repose, it is not necessary to accelerate or brake to maintain the speed, thus the energy consumption is reduced.

[46] García, A. (2009). Energía y trazado ferroviario. Curso de diseño de ferrocarriles. CEDEX. Madrid, November de 2009



1. If $p < pe_{Vmax} = a + b * V_{max} + c * (V_{max})^2$

   It's necessary to accelerate in order to maintain V_{max}

2. If $p = pe_{Vmax} = a + b * V_{max} + c * (V_{max})^2$

   It maintains V_{max} without accelerating or braking

3. If $p > pe_{Vmax} = a + b * V_{max} + c * (V_{max})^2$

   It's necessary to accelerate brake in order to not exceed V_{max} **Therefore, energy is lost**

Figure 3-21. Three possible cases for maintaining the maximum speed (300 km/h) on a downgrade[47].

3.3.7.4 Raise the station gradient

In sections where the train needs to reduce its speed, the existence of an upward gradient implies less brake use and therefore less energy dissipated. There are some energy advantages when the station is located on a higher point than its collateral sections. In this case, when the train approaches the station through an upward gradient it helps its deceleration and reduces the use of the brake. And when the train leaves the station a downward gradient reduces the power need. This configuration is particularly suitable for underground stations.[48]

Figure 3-22. Metro line model Noord/Zuidlijn Lijn line in Amsterdam.

[47] González Franco, I. (2012). Effect of increasing the maximum speed of high-speed trains on downgrades on energy consumption and journey time. UIC.

[48] Clemente Lázaro, I. (2005). "Reducción del consumo energético por elevación relativa en la cota de altura de las estaciones ferroviarias". Proyecto de Fin del Master de Sistemas Ferroviarios ICAI curso 2003-2004

The main objective is the energy reduction through the efficiency layout design. Trying to avoid the frequent accelerations and decelerations for rail transit trains, which adversely affect in the major performance of travel time, traction energy consumption and breaking wear.
Table 3-31 listed, for different slopes and declarations, the energy saved in a station in which, 200 trains of 250 tons, stop each day in each direction. It is compared with the number of houses that consume the same energy per day, as well as CO2 emissions generated by a car to produce the energy which is avoided (indicated in the number of km that a car needs to be driven to produce it).

Table 3-31. Energy and emission saving by not placing a station on a higher elevation than collateral tracks

			No Regenerative Brake		Taking the 50% form the regenerative Brake	
Initial speed (km/h)	Final speed (km/h)	Saved energy (kWh)	Nº of houses	Km to cover on a car	Nº of houses	Km to cover on a car
80	0	21.43	787	10,104	315	4,042
100	0	33.49	1,229	15,788	492	6,315
160	0	85.73	3,146	40,417	1,258	16,167
80	15	20.68	759	9,749	304	3,900
100	15	32.74	1,201	15,433	481	6,173
160	15	84.98	3,119	40,062	1,247	16,025

As it can be seen, for a Metro line in which a slope of 38 mm/m (corresponding to a deceleration of 0.4 m/s2) is designed and assuming an initial speed of 80 km/h and a final speed of 15 km/h, the energy saved in the station is the equivalent to the energy consumption per day of 759 homes or 304 homes considering regenerative brake. Moreover, CO2 emissions that are avoided per day are equivalent to those produced by a car which drives 9,749 km and 3,900 km.

3.3.7.5 Homogeneous speed profile

A comparison between the energy consumption of a high speed train in a high speed line and a conventional train in a line with maximum speed of 200 km/h; both lines with the same length and number of intermediate stops, it has shown that the energy dissipated by the high speed train is a 58% lower than the energy dissipated by the conventional train (see Figure 3-23).

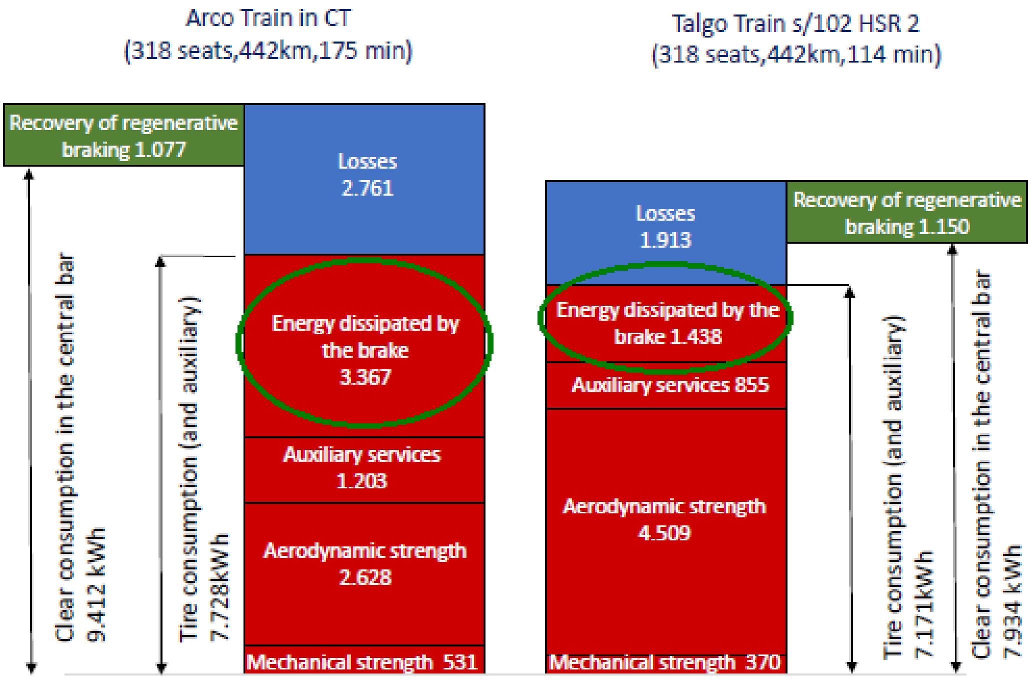


Figure 3-23. Comparison of the energy consumption disaggregated by a high speed train (right) and conventional train (left).

3.3.7.6 Avoid punctual speed restrictions

In 1996 in the Madrid-Sevilla high speed line a 120 km/h speed restriction in a 12 mm/m slope implies of 2.5 minutes lost and a decrease of the energy consumption of 3%.

3.3.7.7 Slopes adapted to speed

In Madrid-Barcelona high speed line with maximum slopes of 25 mm/m, trains should use the brake in order to avoid exceeding maximum line speed. According to García Alvarez, A (2009), a high-speed train running at 300 km/h of maximum speed dissipate in the brake 1,260 kWh (11% of the energy imported). The same train running at 350 km/h reduces the energy dissipated in the brake up to 392 kWh (approximately a 3% of the energy imported). A paradox occurs in this case, as it is not only the energy consumption is reduced but also the journey time. A summary of these studies are reported in Table 3-32.

Table 3-32. Examples of optimisation based on slope adaptation

Author	Explanation	Benefits
Shu-Ta Yeh (2003)[49]	The simulation is based on one-directional train movements on vertical track alignments between stations. The train movements were computed using relations of vehicle kinetics, resistances, tractive effort, power, propulsive, energy consumption, and braking energy consumption in different cases.	The study shows that using dipped vertical alignments[50] it is possible to improve the travel time, tractive energy and breaking energy. The maximum savings observed, for a case with 12,500 feet station spacing, are: 6.53% in travel time, 5.23% in tractive energy consumption and 23.62% in breaking energy.
García, A (2009)	In the Madrid-Barcelona high-speed line in 2007 the maximum speed on the stretch from Madrid to Camp de Tarragona changes from 280 km/h to 300 km/h.	It allowed an energy consumption reduction of about 3%, and moreover a simultaneous reduction in travel times was introduced.

3.3.8 Train design improvements

3.3.8.1 Architecture of trains

At high speeds, aerodynamic gains even greater significance because as speed increases energy consumption increases as well.

In Intercity and high-speed trains, 60% of the traction effort is lost due to aerodynamic drag and friction in typical operation cycles. By reducing the drag by 25%, it is possible to save between 8 - 15% of traction energy.

Rail vehicle aerodynamic enhancement may have a major impact on improving energy efficiency. As well as being aesthetically appealing and dynamic in design, a streamlined train has lower drag leading to reduced energy consumption.

Another significant measure to reduce energy consumption, taken into account by rolling stock manufacturers in their future models, is to reduce train mass (without reducing the adherent mass). It supposes a reduction of the energy needed to overcome inertial and grade resistance.

Mass reduction is typically achieved through reducing the weight of specific components (e.g. car bodies, bodies, bogies, etc.) or through a system-based approach to light weighting (e.g. the articulated train design favoured by Alstom, which reduced the number of bogies by around 20% by placing them between cars). Mass reduction will benefit services with less homogeneous speed profiles (more accelerating and decelerating)[51].

[49] Shu-Ta Yeh (2003). Integrated analysis of vertical alignments and speed profiles for rail transit routes. Master of Science, University of Maryland. Maryland, (USA).

[50] Kim, M et al. (2013). Simulation-based rail transit optimization model. Master of Science, University of Maryland. Maryland, (USA).

[51] Yamamoto, T. (2015). "Recently Studies and Developments of Energy Saving Technologies in the Field of Railway Vehicles". QR of RTRI, Vol. 56, Nº 4. November 2015.

At speeds above 200 km/h aerodynamic drag dominates resistance to train motion.[52] The following figure shows a breakdown of a train drag by component, where surface friction and drag around the bogies dominate aerodynamic drag.

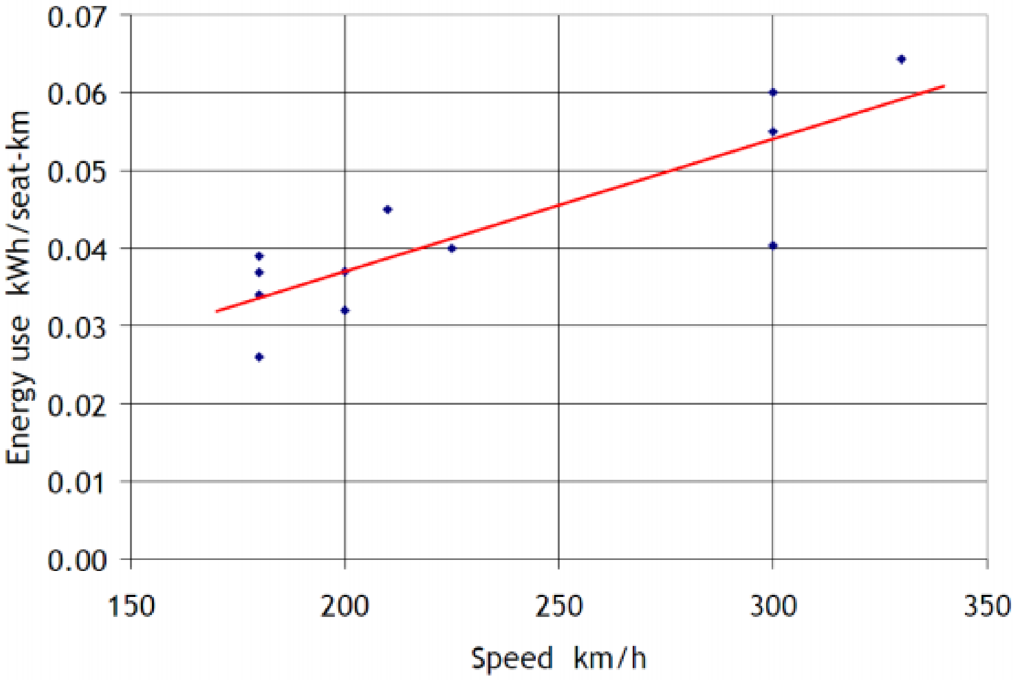


Figure 3-24. Relationship between energy consumption and speed in rail vehicles.

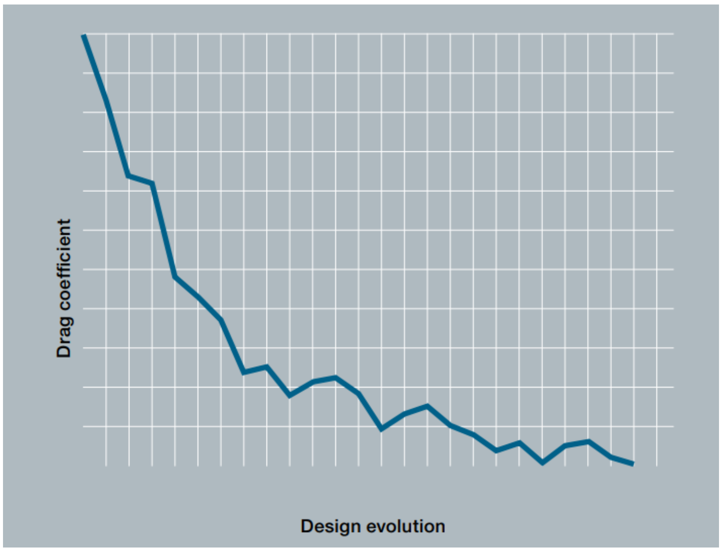


Figure 3-25. Iteration process from the initial design to the optimized shape[53].

[52] Comparing environmental impact of conventional and high speed rail. Planning and regulation. Network Rail.
[53] AeroEfficient Optimized Train Shaping. EcoActive Technologies. Bombardier.

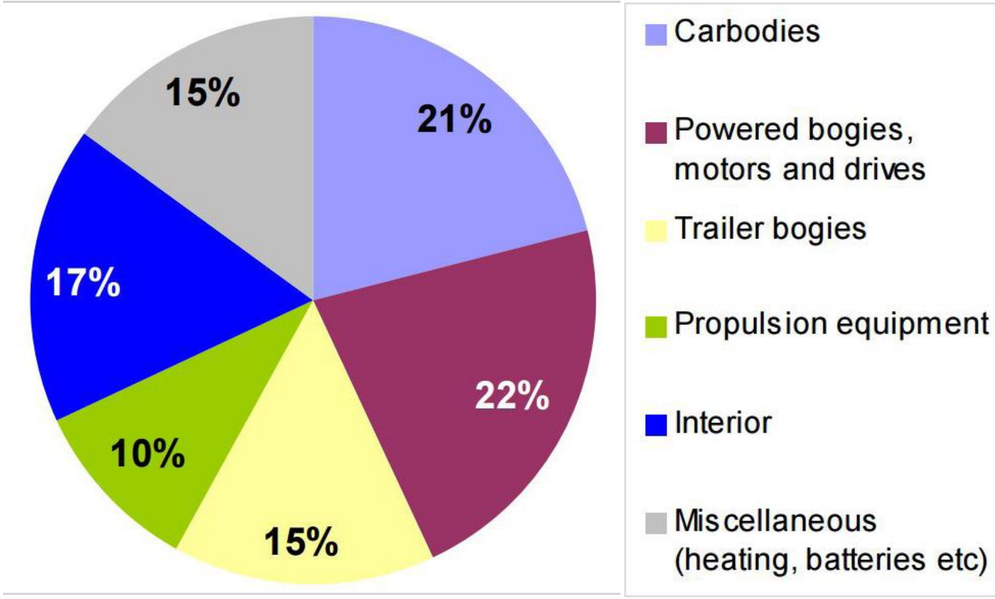


Figure 3-26. Typical breakdown of components in electric multiple unit trains by weight. Source: UIC EVENT (2003).

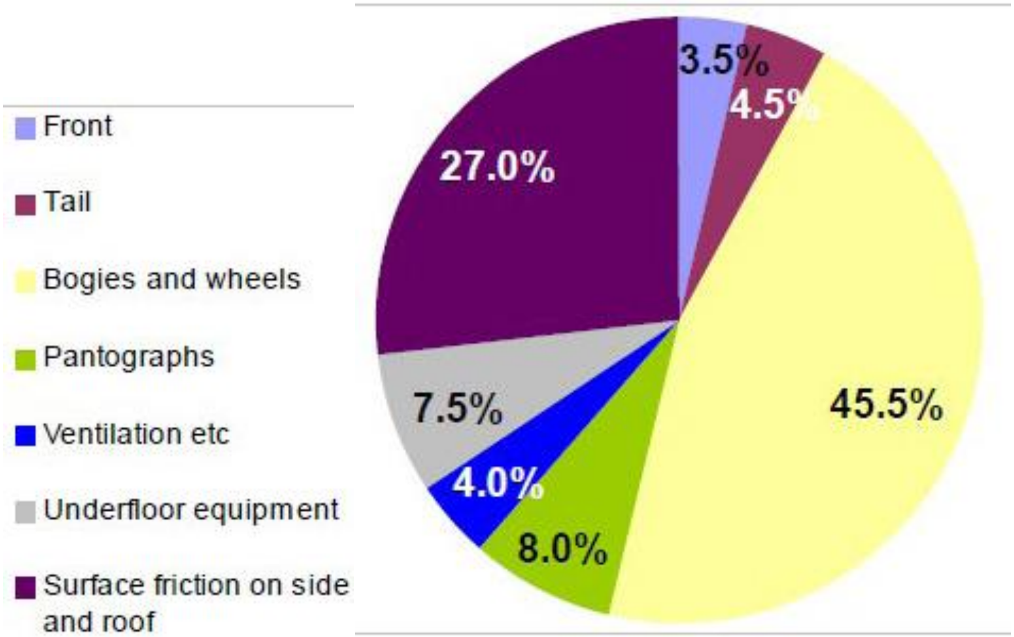


Figure 3-27. Typical breakdown of components contribution to drag in electric trains. Source: UIC EVENT (2003).

The main strategies to reduce drag are streamlining the nose and tail profile of the train, reducing flow separation around the bogies, pantograph and train body by streamlining, and reducing the skin friction on the train roof and sides.

It is obvious that, in absolute terms, when a train is smaller, the energy consumption is lower (measured in kilowatt hours per kilometre). However, if it focuses on specific relative values for standard seat offered, small trains no longer offer better results, but on the contrary, larger trains have a lower specific consumption.

The trains size and their configuration affect the energy consumption through two key indicators:

1. Mass per seat (M/seat). Increasing mass produces higher mechanical resistance, and also increase the need to brake in slowdowns and slopes.
2. The drag coefficient per seat (C/seat) which translates in a larger area of section and the "wetted area" or "train skin" leading to a higher drag.

The mechanical and inertial resistance (proportional to the mass) are dominant at low speeds, while the drag (proportional to the C coefficient) is at high speeds. Therefore, it is expected that the effect of a mass variation is strongly dependent on the distance between stops and the effect of C coefficient variation is important at long distances services with high speed trains

Table 3-33 shows, for different services (characterized by their average speed and the distance between stops), the elasticity consumption with respect to the mass and the C coefficient.

As it is shown, the elasticity of consumption with respect to mass variations is very low in high-speed services.

Elasticity of consumption with respect to the C coefficient is very important at high speeds, and it decreases when the average speed decreases until the point where it is almost negligible as in suburban and metro services.

If the mass variation per seat for different configurations and train sizes is analysed, significant variations can be observed as it is reflected in Table 3-33.

Table 3-33. Elasticity of energy consumption with respect to the mass and drag coefficient.[54] ΔCons: Consumption increase. ΔMass: Mass increase C: Drag coefficient

	ΔCons/ΔMass	ΔCons/ΔCoef. C
High speed long distance	0.21	0.43
Conventional long distance	0.48	0.17
High speed mid distance	0.47	0.20
Conventional mid distance	0.61	0.05
Suburban train	0.48	0.03
Metro	0.76	0.01

[54] García, A. et al. (2011). Influencia de la arquitectura y el tamaño de los trenes en sus costes operativos y su consumo de energía. Fundación de los Ferrocarriles Españoles. Madrid (Spain).

Table 3-34. Mass per seat for different configuration

	325 seat	650 seat	dif. 650/325
Composition of classic unarticulated vehicles	969	830	0.86
Trailing. Rodals articulated vehicles	589	563	0.96
Concentrated traction articulated bogies vehicles	1,259	1,150	0.91
Concentrated traction rodals articulated vehicles	943	903	0.96
Self-propelled. Distributed traction. Unarticulated	1,045	943	0.90
Self-propelled. Distributed traction. Unarticulated double track	723	696	0.96
Self-propelled. Distributed traction. Unarticulated	429	426	0.99

Data in kg/seat

From Table 3-34 the following conclusions can be drawn:

- The mass per capacity unit decreases, as might be expected, by increasing the size of the train.
- For the same architecture a double deck can reduce the mass by 31%; and the simultaneity of the double floor and the wide body 59%.
- For the same architecture, articulated trains have 24.9% less weight per seat than non-articulated, while the articulated wheel configurations have 40% less weight per seat than unarticulated bogies train of the same capacity.

As for the variation of C drag coefficient, which depends on the architecture and the train size, Table 3-35 lists the specific values for two train configurations (medium and large size). More specifically, this table shows the following conclusions:

1. Variations of the coefficient "C/seat" regarding the train size are more homogeneous than the mass variations (between 0.75 and 0.87).
2. Differences between single deck, double deck and wide body trains are enormous, much larger than the variations induced by the mass.

Regarding the elasticity of consumption in terms of C coefficient, it is very important for high speed (decreases strongly the average speed of the service) to the point of being almost negligible in suburban and metro services.

However, the latest strategies to reduce drag are based on bionics. It consists of the application of biological methods in nature to the study of engineering systems with the use of sophisticated computer modelling techniques.

Already successfully adopted within the automotive and aerospace industry to create highly energy-efficient designs, bionics science recognizes that Nature's own evolutionary processes may help to ensure continuous improvement in a "survival of the fittest" regime.

Table 3-35. C drag coefficient per seat for different configuration

	325 seat	650 seat	dif. 650/325
Composition of classic unarticulated vehicles	152	125	0.82
Trailing. Rodals articulated vehicles	159	129	0.81
Concentrated traction articulated bogies vehicles	127	110	0.87
Concentrated traction rodals articulated vehicles	160	143	0.89
Self-propelled. Distributed traction. Unarticulated	429	426	0.99
Self-propelled. Distributed traction. Unarticulated double track	119	101	0.85
Self-propelled. Distributed traction. Unarticulated	83	62	0.75

Superimposing the principles of natural pre-selection and evolution to an advanced computer-modelling approach that creates the best possible shape enables the optimization of the latest vehicle designs, creating the lowest energy consumption and maximum stability.

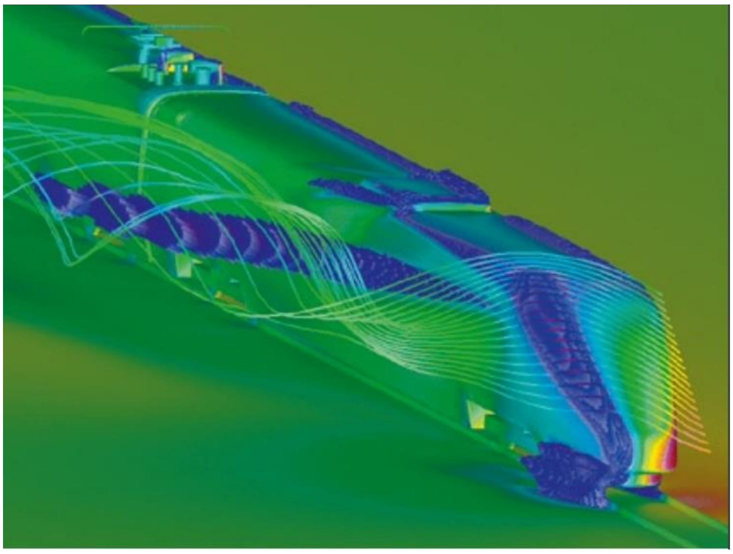


Figure 3-28. Visualization of flow ribbons - simulation of a high-speed train running under cross-wind conditions.

Table 3-36. Examples of train optimisation

Author	Explanation	Benefits
Bombardier Zefiro[55]	It is the new benchmark for high speed trains in terms of low aerodynamic drag combined with high stability, whilst cruising under cross-wind conditions. To achieve this balance, Bombardier has used state-of-the-art Computer Aided Engineering (CAE) methods and tools, incorporating Computer Aided Design (CAD) and Computational Fluid Dynamics (CFD).	Bombardier's aerodynamic modelling ensures the optimum configuration of: •Alternative front and end sections of the train. •Spoilers. •Pantograph integration solutions. •Bogie space envelope and fairings.
Tokaido Shinkansen Line. Series N700	The Series N700, based on the high potential of the Series 700, was introduced in 2005. The rail vehicles have been designed with tilting mechanisms and advanced aerodynamic features to increase its energy efficiency and maximum speeds whilst reducing journey times on the Tokaido Shinkansen.	The Series N700 have 75% more seats and 14% lower mass per train resulting in significantly enhanced speed, comfort and energy performance.
Automotrice à grande vitesse (AGV). France Alstom[56]	The AGV is the most energy efficient rail car designed adhering to the Technical Specifications for Interoperability (TSI) standards. It is the world's first train designed to combine articulated carriage architecture with a distributed traction system and synchronous permanent magnet motors (PMM). It is built with aluminium alloys to reduce the overall weight by 700 kg compared to using steel.	Designed for operation at very high speed (max. 360 km/h), it demonstrates that design efficiencies aimed at reducing weight and increasing seat capacity can deliver energy consumption some 15% lower than that of existing TGVs at 300 km/h.

3.3.8.2 New materials

The railway sector currently uses composites only for non-bearing structural components. It is common to use steel for the car body of a train. In fact, European legislation does not allow train manufacturers to use only composites for train car bodies, although legislation is being adapted to enable using this light, durable material in the construction of trains.

The most important feature governing the choice of material and form of construction for any component is its structural integrity. A designer looking for a substitute for the conventional steel construction method cannot achieve success by using one type of material alone.

In this way, a "Sandwich Construction" is proposed which consists essentially of two outer facing layers and an inner core.

[55] Resistance is futile: how aerodynamics inform train design. Available at: Railway-technology.com (Accessed 29/07/2016).

[56] Energy consumption and CO2 impacts of High Speed Rail: ATOC analysis for Greengauge 21. ATOC.

The core must be rigid enough perpendicularly to the faces to prevent crushing and its shear stiffness must be large enough to prevent shear deformations. A sandwich absorbs the load and distributes the stresses over a much larger area.

Some of the currently used core materials are: [57]

1. Corrosion Resistant Aluminium Honeycomb: It possesses high strength and rigidity-to-weight ratio.
2. Aluminium Flex Core: It is used to manufacture highly contoured sandwich panels.
3. Aluminium Corrugated Honeycomb: It possesses high compressive, shear and crushing strength.
4. Fibre Glass Reinforced Polyimide Honeycomb: It has good dielectric and insulation properties.
5. Aramid Fibre/Phenolic Resin Honeycomb: It possesses high strength at low densities, easily formable, fire resistant, water and fungus resistant, good dielectric and thermal properties.
6. Non-metallic/Reinforced Plastic Flex Core: It is applied wherever extreme curvature dictates a flexible cell.

International experience reveals that the composites being used for various applications especially in railways mostly comprise metal/non-metal honeycomb and sandwich constructions.

Metallic materials are heavier than composites and thus require additional power traction and important energy consumption.

If a train car body is made of composite materials, its weight will be reduced by 20% to 30%. This weight reduction will lead to lower energy consumption and a reduction of at least 5% of CO_2 emissions [58](Martijn Wolf, Technical Consultant at Ricardo Rail).

In the field of very high-speed railways, a weight reduction will result in higher speed, higher transport capacities and/or enhanced passenger comfort whilst keeping a good energy balance. On the other hand, in the field of urban and sub-urban rolling stock a weight reduction will lead to enhance acceleration, hence increasing capacity in terms of passenger flow/hour, provided that the adherent mass is the same.

Composites are able to meet diverse design requirements with significant weight savings as well as high strength-to-weight ratio as compared to conventional materials. [59]

Some advantages of composite materials over conventional ones are:

1. Tensile strength of composites is 4 to 6 times greater than that of steel or aluminium.
2. Improved torsional stiffness and impact properties.
3. Composites have higher fatigue endurance limit (up to 60% of the ultimate tensile strength).
4. Composite materials are 30-45% lighter than aluminium structures designed to the same functional requirements.
5. Lower embedded energy compared to other structural materials like steel, aluminium etc.
6. Composites are less noisy while in operation and provide lower vibration transmission than metals.
7. Composites are more versatile than metals and can be tailored to meet performance needs and complex design requirements.
8. Composites offer excellent fatigue, impact, environmental resistance and reduced maintenance.
9. Composites enjoy reduced life cycle cost compared to metals. [60]
10. Composites exhibit excellent corrosion resistance and fire retardant.

[57] Cheul-Kyu Lee, et al. (2009). Global warming effect Comparison of each material for railway vehicle. Korea.
[58] RailTech. REFRESCO: Construction composite train possible following regulation change. UE
[59] Nangia, S. et al. (2000) “Composites in Railways”. SEARCH, February
[60] Cheul-Kyu Lee, et al. (2016). Application of the integrated ecodesign method using the GHG emission as a single indicator and its GHG recyclability. Journal of Cleaner Production Volume 112, Part 2, 20 January 2016, Pages 1692–1699. Korea.

Table 3-37. Typical structural properties of composites and conventional materials

	COMPOSITES	STEEL	ALUMINIUM
Density [g/cm3]	1.8	7.9	2.7
Tensile Strength [Mpa]	240	250	240
Elastic Modulus [Gpa]	23	210	70
Linear Thermal Expansion [10E-6/°k]	10	12	24

Table 3-38. Characteristics comparison

	COMPOSITES	STEEL	ALUMINIUM
Complex shapes, integrated functions	yes	no	limited
Electrical insulation	yes	no	no
Thermal insulation	yes	no	no
Corrosion resistance	yes	no	average
Low maintenance	yes	no	yes
Durability	yes	average	yes

Table 3-39. Examples of use of new materials

Author	Explanation	Benefits
Alstom[61]	ALSTOM has developed the concept of a "Multi-Material Intermediate Coach" prototype, whose central and end parts are made of composite materials, in order to validate potential weight gain of such a structure, with the mechanical performances maintained and at identical costs. The project has studied the behaviour of different types of composites integrated in the roof or side walls of rail vehicles.	The feasibility and interest of such a change in conventional materials is to improve the performance/weight ratio whilst complying with economic constraints and constraints inherent to passenger transportation in general: safety, ride quality, reliability and maintainability.
NewRail (United Kingdom)[62]	"The Composite Material Research Requirements of the Rail Industry" is a study that belongs to the COMPOSIT thematic network on "The Future Use of Composites in Transport". The report provides an overview of the applications in which composite materials are currently employed.	There are a variety of different processing techniques for the manufacture of composite rail vehicle parts. The objective is to find products that are the same cost, or even cheaper, than equivalent metallic designs. Availability of lighter vehicles.

[61] Campus, E. et al. "Use of Composite Materials in Railway Applications". ALSTOM Transport in collaboration with SNCF Direction du Matériel Centre d'Ingenierie du Matériel.
[62] NewRail (2004). The Research requirements of the transport sectors to facilitate and increased usage of composite materials. Part III: The Composite Material Research Requirements of the Rail Industry.

		Long life taking into account fatigue. Excellent corrosion resistance and fire retardancy.
Indian Railways[63]	Composites have been identified as an important material for application in the Indian Railways for various agencies such as Research Designs & Standards Organization (RDSO)-Lucknow, Integral Coach Factory (ICF)-Chennai, Rail Coach Factory (RCF), Kapurtala and Carriage Repair Workshops. Some of these applications are: Gear case for locomotives, modular toilet units, bulkheads, interior walls and doors and folding tables.	The benefits associated to composite materials have been identified by Indian authorities such as: Lower energy consumption. Lower operation and maintenance cost. Minimal environmental impact.
Korean Tilting Train eXpress (TTX)[64]	The potential of polymer composite car-body structures for the Korean Tilting Train eXpress (TTX) has been investigated.	Compared to the steel scenario, the hybrid composite variant has a lower life cycle cost (16%) and a lower environmental impact (26%).

[63] Biswas, S. et al. (2001) "Composite Technology Development and Commercialization – An Indian Initiative". 6th ASEAN Science and Technology Week, Brunei Darussalam, September 17-19.
[64] Castella, P.S. et al. (2009). Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train. Life Cycle Assessment (2009) 14:429-442. DOI 10.1007/s11367-009-0096-2. Korea.

4 Energy storage

4.1 Review of energy storage technologies suitable for electricity losses reduction in distribution networks and electrified railway systems

4.1.1 Energy storage application requirements

Due to specifics of the considered application (electricity losses reduction in the DN and electrified railway systems), only some of the storage technologies could be considered. The considered application set the following requirements for storage technology to obtain a low total cost of energy storage system ownership:

- high maturity level;
- high power to energy ratio (>3:1);
- long calendar lifetime (>10 years);
- fast startup (~1sec.);
- high round-trip efficiency;
- low-self-discharge and auxiliary power consumption (due to expected longer periods of standby operation); typically, self-discharge with auxiliary power consumption during standby should not be higher than 2%/day of the total energy content.
- no or low small O&M costs;
- high power density (due to limited space available for storage system installation);

4.1.2 Review of energy storage technologies for distribution networks and electrified railway systems

There is a number of different storage technologies available on the market. Electrical energy cannot be stored directly and thus it must be transformed into another type of energy. Storage technologies could be classified in different manners, e.g. depending on storage form (Figure 4-1) or suitability to the specific power/energy window (Figure 4-2). Storage technologies differ in respect to many aspects like the capital expenditures, power and energy, round-trip efficiency, ambient operational conditions, safety, calendar and cycle lifetime, maturity level, depth of discharge, OPEX cost, electrical performance, etc.

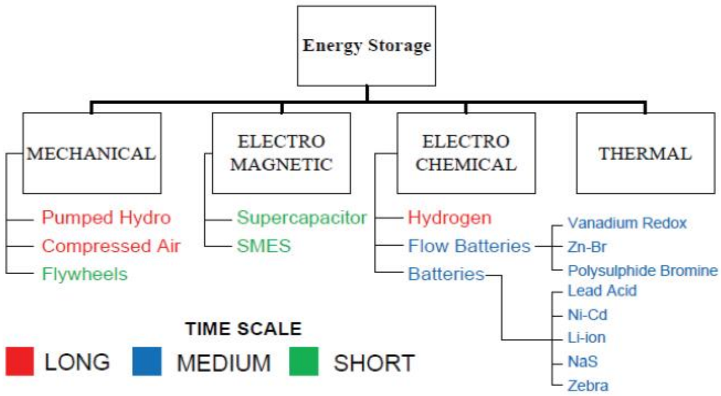


Figure 4-1. Technology dependent classification of energy storage technologies.

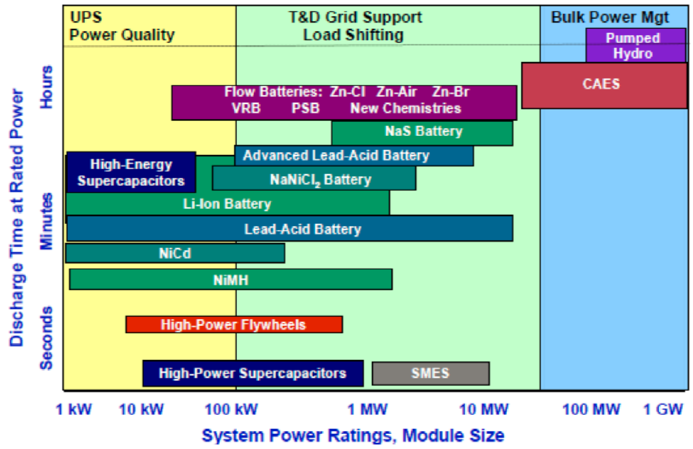


Figure 4-2. Application dependent classification of energy storage technologies (EPRI, Electricity Storage Handbook, 2013).

Table 4-1. Technical characteristics of energy storage technologies (M. Aneke, Applied Energy 179(2016) 350-377)

Technology	Energy density Wh/kg(W h/L)	Power density W/kg(W/L)	Power rating	Discharge time	Suitable storage duration	Life time (years)	Cycle life (cycles)	Capital Cost $/kW	$/kWh	$/kW h-per cycle	Round trip efficiency (%)
Flywheel	10–30(20–80)	400–1500(1000–2000)	0–250 kW	ms–15 min	s–min	~15	20,000+	250–350	1000–5000	3–25	85–95
PHES	0.5–1.5(0.5–1.5)		100–5000 MW	1–24 h+	h–months	40–60		600–2000	5–100	0.1–1.4	65–87
CAES	30–60(3–6)		5–300 MW	1–24 h+	h–months	20–60		400–800	2–50	2–4	50–89
GES											
GPM	1.06(1.06)	3.13(3.13)	40–150 MW		h–months	30+		1000			75–80
ARES			100–3000 MW	34 s	h–months	40+		800			75–86
HES											
Fuel cell	800–10,000(500–3000)	500+(500+)	0–50 MW	s–24+h	h–months	5–15	1000	10,000+		6000–20,000	20–35
Gas engine	33,300(530–750)		0–50 MW	s–24+h	h–months						40–50
Super-capacitor	2.5–15	500–5000	0–300 kW	ms–60 min	s–h			100–300	300–2000	2–20	90–95
Batteries											
NaS	150–240(150–250)	150–230	50 kW–8 MW	s–h	s–h	10–15	2500	1000–3000	300–500	8–20	80–90
NaNiCl	100–120(150–180)	150–200(220–300)	0–300 kW	s–h	s–h	10–14	2500+	150–300	100–200	5–10	85–90
VRB	10–30		30 kW–3 MW	s–10 h	h–months	5–10	12,000+	600–1500	150–1000	5–80	85–90
FeCr	10–50	16–33	5–250 kW	s12+h	h–months				250		70–80
ZnBr	30–50(30–60)		50 kW–2 MW	s–10 h	h–months	5–10	2000+	700–2500	150–1000	5–80	70–80
Zn-air	150–3000(500–10,000)	100	0–10 kW	s–24h+	h–months			100–250	10–60		50–55
Li-ion	75–200(200–500)	500–2000	0–100 kW	min–h	min–days			1200–4000	600–2500	15–100	85–90
SMES	0.5–5(0.2–2.5)	500–2000(1000–4000)	100 kW–10 MW	m–8 s	min–h	20+	100,000+	200–300	1000–10,000		95–98
LAES	97		350 kW–5 MW	1–24 h+	h–months	20+		1000–2000			50–70

4.1.3 Comparison and selection of the most suitable energy storage technology

The process of storage system selection is usually complex and application dependent and it requires a priori knowledge about the application specific mission profile, the storage operating conditions and storage technology itself (Figure 4-3). If the storage system mission profile is known, then the storage system could be sized accordingly and the resulting total cost of storage system ownership and/or levelized cost of energy could be calculated for each storage candidate. In consequence, a quantitative comparison could be performed resulting in storage system selection (Figure 4-3). However, here the quantitative storage system selection will be performed due to a currently unknown exact mission profile of the storage system.

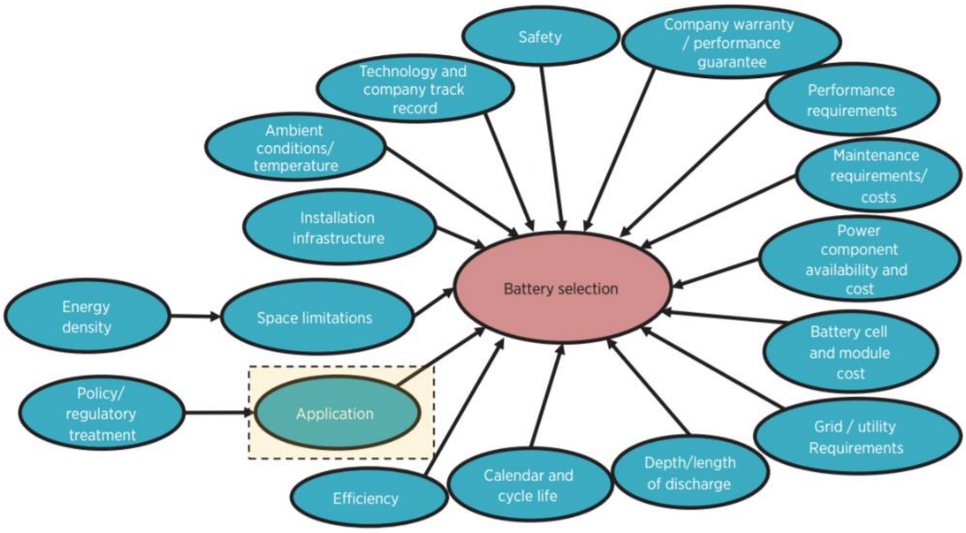


Figure 4-3. Considerations for battery selection (Source: IRENA report 2015).

Due to technical and economic related limitations, only some of the storage technologies are suitable for the considered application. In the next subsections, application requirements stated in section 5.1.1 will be reviewed and juxtaposed with storage technologies which fulfill them.

4.1.3.1 Maturity level

Storage technologies differ between themselves in terms of their maturity level. There are many proven technologies in the numerous applications as well as many emerging technologies which performance and reliability are unknown. Figure 4-4 and Figure 4-5 present maturity level and global installed grid-connected storage capacity. It is clearly visible that in terms of maturity and proven energy storage market penetration, pumped-hydro, compressed air, thermal storage, batteries, and flywheels are predominant storage technologies. Nevertheless, both pumped hydro and compressed air energy storage technologies are out of consideration for the reduction of losses for DN and railway systems application due to installation site dependency on the geographical location. Moreover, they offer low-cycle cost and TCO only for larger systems (> few-several MWs) due to high CAPEX. In the recent two years >90% of new grid-connected battery systems are lithium-ion based.

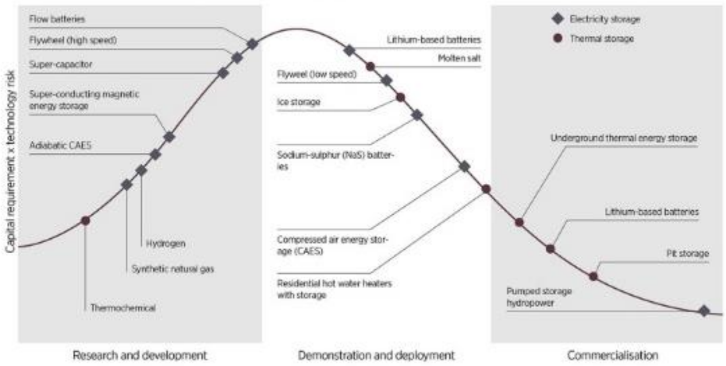


Figure 4-4. Maturity of different energy storage technologies (Source: Schlumberger 2015).

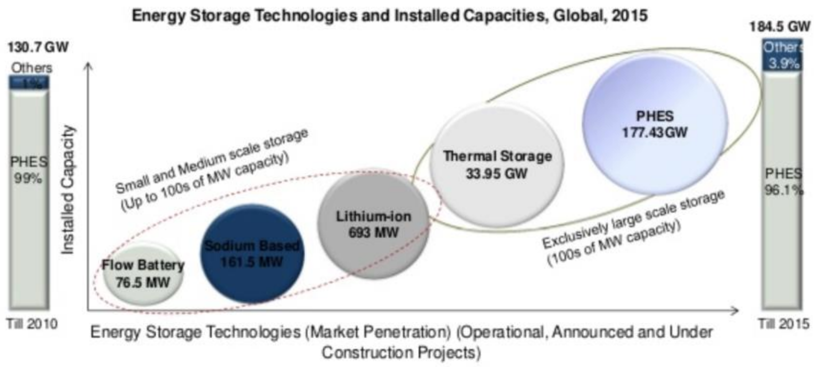


Figure 4-5. Global installed grid-connected electricity storage capacity (Source: Frost & Sullivan, 2015).

4.1.3.2 Power to energy ratio

Some of the storage technologies have power and energy ratio (e.g. flow batteries) decoupled and they can easily be sized in terms of power/energy ratio to the specific application. While for others, power/energy ratios are fixed (e.g. electrochemical batteries) and specific technology needs to be chosen to fit application requirements without costly over-dimensioning of the storage system. For the reduction of losses for DN and railway systems application, storage systems with a higher power to energy ratios (within 3-5) are expected. This would require high power capability and minimum storage duration in the range between 12-20 mins at full power charge/discharge). This requirement eliminates especially flywheels while both SMES and supercapacitors are becoming significantly more expensive for discharge times in the range of 20 minutes (Figure 4-2). PHES and CAES are also not economic at this power to energy ratio and they are well suited for the bulk energy storage.

4.1.3.3 Calendar lifetime

The storage system is expected to be most of its lifetime in standby (neither charged/discharged). In consequence, calendar lifetime and calendar degradation are of interest. To achieve low TCO, the calendar lifetime of such an installation should be comparable with investment interval (10-15 years). As it can be seen in Table 4-1, this lifetime is achievable for most of the technologies except flow and NiMH batteries.

4.1.3.4 Start-up and reaction time

The considered application requires fast storage response time due to fast-changing application power demand. Storage response times in the range of seconds or less is required. This eliminates PHES, CAES and thermal storage systems which typically have longer response times. All the other storage technologies presented in Table 4-1 are having an adequate response time for the considered application.

However, some of them could be eliminated due to high self-discharge (flywheels), toxicity (NiCd), high operation costs and relatively low maturity (Zebra – $NaNiCl_2$ that are high-temperature batteries). On the other hand, flow batteries could be considered for backup application, but they have a very low energy density, relatively low maturity level, and significant standby operation cost. Thus, the focus here will be put on the Lead acid, Li-ion, NiMH and supercapacitors.

4.1.3.5 Round-trip efficiency

Table 4-1 presents typical round-trip efficiency (during operation) of different storage technologies. It can be noticed that especially electrochemical batteries (in particular Li-ion batteries), flywheels, SMES, and supercapacitors are superior in this case.

4.1.3.6 Self-discharge and auxiliary power consumption

As mentioned before, for the considered application, energy storage system is expected to be most of the time in the standby. Thus, low energy storage self-discharge and low system auxiliary power consumption are extremely important, and they strongly influence storage system TCO. Flywheels, SMES, and supercapacitors are having very fast self-discharge, while batteries and especially, flow and Li-ion batteries are having very low-self-discharge. The auxiliary power consumption of the system is strongly dependent on a number of peripherals required for the storage system to be maintained in standby (e.g. pumps, hydraulics, cooling/heating, etc.). Here, batteries (except flow batteries) are superior as they usually need none or very few peripherals to maintain their SOCs for the longer storage time periods.

4.1.3.7 O&M costs

Similarly, as in the previous case, the fewer peripherals, the less O&M costs. Majority of the electrochemical batteries (except flow batteries) do not require any maintenance requiring peripherals.

4.1.3.8 Power density

Here dominant are flywheels, SMES, supercapacitors but they lack sufficient energy density and they are particularly well suited for applications requiring very high power to energy ratios (> 10) which do not need store energy for a prolonged time. Here, again batteries offer good power density (except flow batteries). Amongst batteries, Li-ion batteries are predominant in terms of both energy and power density (Table 4-1).

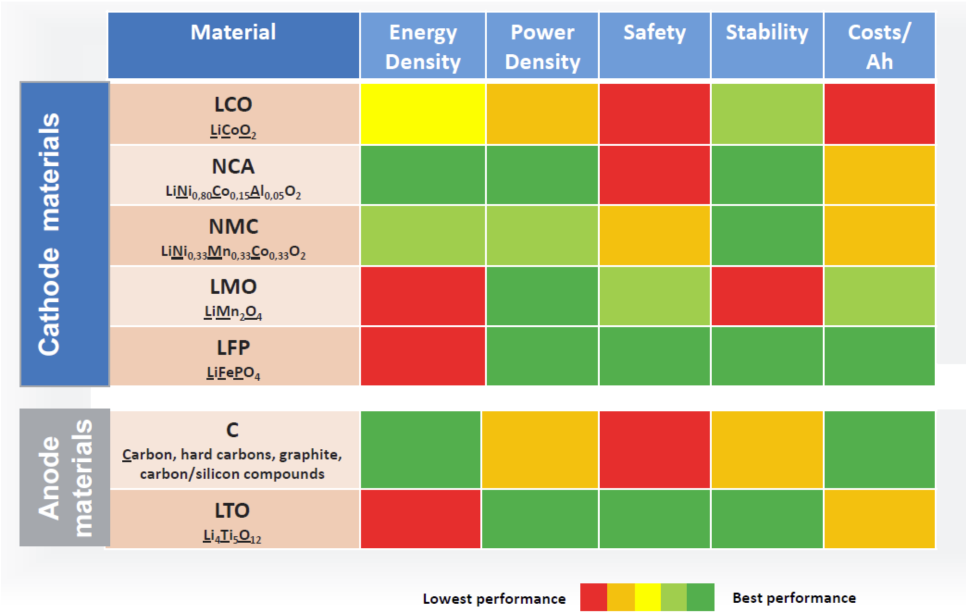
Above mentioned application requirements eliminate most of the storage technologies from Table 4-1 except electrochemical batteries. The three most mature, and best suited for the considered application electrochemical storage batteries are lead-acid, Li-ion, NiMH. (NiCd batteries are not considered due to being practically withdrawn from the market due to cadmium toxicity). Moreover, supercapacitors might also be conditionally suitable (however, they have significant self-discharge). Table 4-2 presents the comparison between these technologies. Li-ion batteries outperform other technologies in performance parameters required for the electricity losses reduction in the DN and railway networks. Moreover, the price for Li-ion batteries is in constant decline in the last years and this trend is expected to continue due to intensive R&D activities, the economy of scale and highly competitive market. Thus, Li-ion battery technology is selected for the considered application in the E-lobster project.

The family of Li-ion batteries is broad, and the most important Li-ion chemistries are presented and compared in the table below.

Table 4-2. Comparison of different parameters of selected electrochemical storage technologies (Mathew Aneke, 2016)

Parameter	Lead-acid	Li-ion	NiMH	Supercapacitor
Main types	Flooded, sealed, AGM	NMC, NCA, LFP, LTO, LMO, …		Power or energy optimized
Power density	150 -180 W/kg	500 - 2000 W/kg	250 – 1000 W/kg	500–5000 W/kg
Energy density	30 - 40 Wh/kg	75–250 Wh/kg	60-120 Wh/kg	2.5–15 Wh/kg
Cell voltage	2.0V	2.0 – 3.7V	1.25V	2.7V
Response time	msec	msec	msec	msec
Round – trip efficiency	80 – 85 %	85 – 95%	ca. 70%	90 – 95%
Self-discharge	3 – 20% per month	<5% per month	30%-60% per month	up to 5% per day
Memory effect	No	No	Yes	No
Peukert coefficient	1.1 – 1.4	~1	1.1 - 1.3	~1.05
Balancing circuits	No	Yes	No	Yes
Cycle life	300 – 2000 / 80%	4000 – 16000 / 80%	180 – 2000/80%	1000000/ 80%

Table 4-3. Comparison between major Li-ion chemistries



4.2 Description of the main components and sub-systems of a battery energy storage technology (BESS)

In this section, the most important components of the Li-ion BESS are presented and shortly described. Typical BESS consists of battery system, battery management system (BMS), battery protection unit (BPU), power conditioning unit (PCU), thermal management system (TMS), site controller. In the following subsections, different elements of the BESS are shortly described. Figure 4-6 present block diagram of the typical BESS.

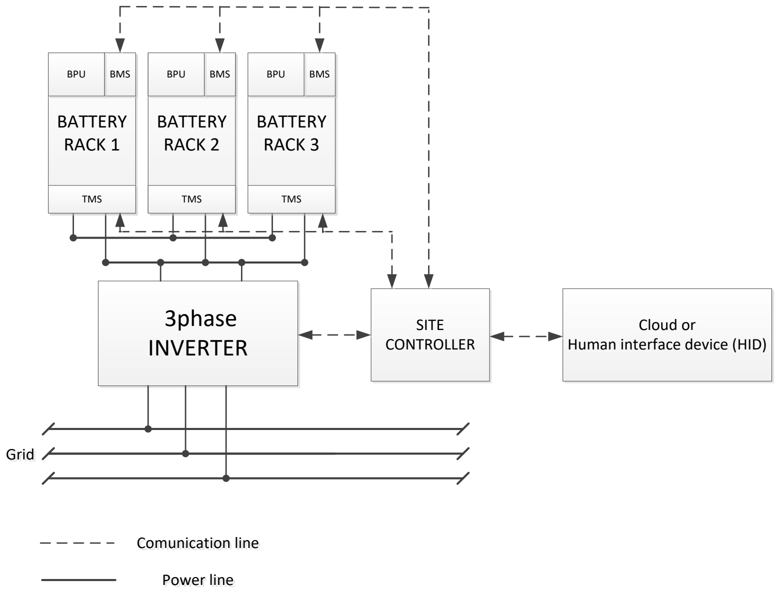


Figure 4-6. Block diagram of the typical BESS.

4.2.1 Battery system

Battery system consists of series/parallel connected electrochemical battery cells that makeup battery modules. Battery modules might be grouped in certain numbers to make up battery packs and later number of battery packs might be grouped to battery racks. For larger BESS (both in terms of power and energy) higher number of battery racks is used to obtain the application required power and energy content. Moreover, the battery system typically contains a few/several protective devices (e.g. fuses) and voltage and temperature monitoring devices connected to the BMS.

4.2.2 Battery management system (BMS) and the battery protection unit (BPU)

Battery management system is the heart of the BESS and it is responsible for battery system monitoring, safety, control of BPU, state estimation, and diagnostics of BESS.
On the other hand, BPU is at a set of switching/sensing and current interrupting devices controlled by BMS to assure safety and performance of the BESS.

4.2.3 Power conditioning unit (PCU)

Power conditioning unit is the electrical interface between the battery system and an external circuit. Its role it is to efficiently transfer energy between battery and external circuit and shape electrical parameters like voltage/current to the acceptable level and quality. For BESS it is typical AC/DC or DC/DC converters with/or without transformers.

4.2.4 Thermal management (TM)

Most of the BESS have a thermal management system to maintain the battery in favourable temperature conditions what assures safety and longevity. TM is typically controlled by BMS or site controller. Many different types of TMS exist, e.g. air-based, liquid-based, phase change material based (PCM). Choice of the specific TMS is a compromise of required, performance, cost, complexity, and O&M cost.

4.2.5 Energy Management System (EMS)

At last but not at least, BESS consists of a device which is responsible for assuring that right power set points are requested from the battery system in the right time instances to assure optimal operation of a storage system in the specific application. EMS could be either realized in a site controller or in another high-level supervisory system (e.g. in the cloud).
Moreover, site controller is responsible for PCU control and BESS safe connection/disconnection, collecting relevant data and transferring them to the energy management system (EMS), self-diagnostics of the entire BESS (battery + inverter + peripherals), receiving control signals (e.g. active, reactive power set points, operation mode) from the EMS.

4.3 Benefits of energy storage systems

Properly sized, located and controlled energy storage system can reduce electricity losses in distribution networks and electrified railway systems. This can be achieved in the following manners:

1. Feed-in control – energy storage is controlled to achieve local balancing of demand and supply in distribution grids, which in result leads to reduction of variable losses due to two the reduction of energy transportation distance (energy is being consumed locally) and the reduction of marginal losses (load smoothing leads to lower variable losses in the distribution networks).
2. Reactive power management – storage systems by means of power electronics can inject/absorb reactive power helping to maintain voltage and reduce reactive power losses.
3. Phase balancing – storage systems by means of power electronics can individually control power (both active and reactive) injected/absorbed to/from each individual phase. Imbalance in the loading between phases leads to higher currents (at least in one phase) and higher losses and it might cause congestion in overloaded phase. Phase balancing with this approach is fast and it can quickly react to demand changes.
4. The regenerative breaking of trains – storage system can store energy released during trains breaking and use it later energy is needed for trains acceleration. This has a positive effect on railway network efficiency (breaking energy is not being lost) and railway network voltage drop is minimized during acceleration (lower voltage leads to higher current demand and higher losses during train acceleration).
5. Grid reinforcement deferrals – storage system is able to defer costly grid reinforcements by shaving the peak power demand

4.4 Investigation of losses of energy storage systems

There many different sources of losses in the BESS. These are presented in Figure 4-7. BESS losses could be divided into conversion losses and system consumption losses. Both types of losses strongly impact the TCO of the battery system and they need to be considered in BESS design process. BESS components are selected to assure good compromise between price and efficiency which result in minimizing TCO of BESS for a specific application. In the next subsections, the main contributors to BESS losses will be briefly described.

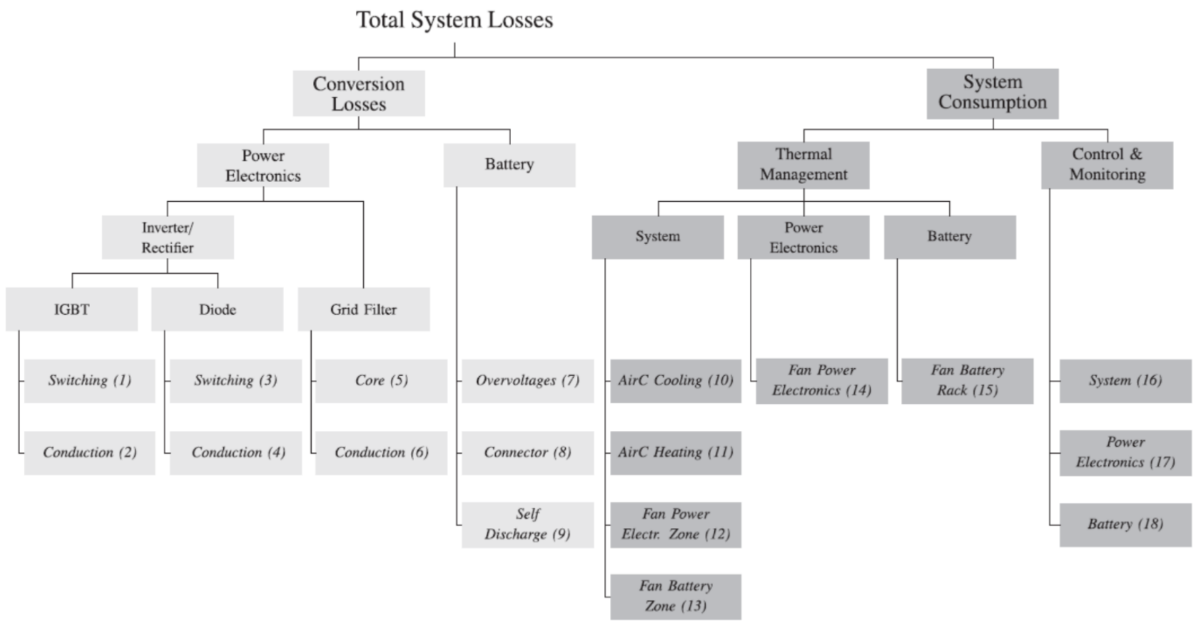


Figure 4-7. Loss mechanisms in the BESS (M. Schimpe et al. Applied Energy 210 (2018), 211-229).

4.4.1 Conversion losses

Conversion losses occur in power conditioning unit and they are related to the semiconductor switch and antiparallel diodes switching and conduction losses. These losses are mainly dependent on converter switching frequency, battery DC voltage (state of charge - SOC) and current and junction temperature of semiconductors. Moreover, grid filter (typically LCL filter) losses are related to the core (dependent on grid voltage and switching frequency) and conduction losses (dependent on current and inductor resistance).

On the other hand, battery system losses are related to self-discharge (dependent on SOC and temperature), polarisation voltage (dependent on temperature, SOC, current and battery state of health – SOH) and interconnector losses (Ohm losses dependent on resistance, current, and temperature).

4.4.2 System consumption losses

System consumption losses are related to auxiliary power consumption of BESS peripherals. These could be divided into thermal management losses and control and monitoring losses.

Thermal management losses could be further subdivided into losses occurring in the thermal management system of power electronics, battery, and system. They are dependent on many aspects including the type of selected thermal management system and control strategy used for thermal management of power electronics, battery, and system.

Control and monitoring losses can be again subdivided into power electronics (e.g. control, monitoring, closing contactors), battery (e.g. BMS and its sensors power consumption) and system losses (e.g. site controller losses).

For a good designed BESS, the average charging or discharging efficiency of PCU is ~96-97% and for battery system also in the same range of ~96-97%. Thus, the average total round-trip efficiency, i.e. one cycle with a charge and a discharge, is in the range of 85-88% including all conversion and system consumption losses.

5 Distribution and rail networks interconnection

The E-LOBSTER uses power electronics and energy storage technologies to interface railway electrification and power distribution networks. Railway electrification networks are DC and fed by AC MV feeders at industrial frequency, i.e. 50 or 60 Hz. Energy storage operates with DC power for many electric technologies, e.g. electrochemical and flow batteries, electrochemical double-layer capacitors (supercapacitors), superconducting magnetic energy storage (SMES), fuel cells fed by hydrogen tanks. For non-electric technologies, e.g. flywheels and compressed air, there is a need of an electric machine and electric drive, which normally includes a frequency converter if connected to the AC system or an AC/DC converter requiring a DC power supply.

Therefore, the power converter needs at least three interfaces: railway electrification (DC or AC at 50 or 16.67 Hz), power distribution (AC at 50 Hz), and energy storage (DC). This can be achieved using three converter sub-modules sharing a common DC bus. The specific connection to the railway and the power distribution grid will then define the main objective of the sSOP and, then, the control targets of the E_LOBSTER control. In the following, three possible schemes for the connection of the converter will be discussed in details.

5.1 Conventional interconnection overview

There are different metrics that are included in a new connection to the DN especially for heavy intermittent loads. The connection process differs for different operators, but there are mainly two aspects that need to be considered:

- The available capacity at the connection point.
- The compatibility of the load to the network regulations and performance requirements.

In case of no available capacity at the requested (near to the load) connection point, the DSO normally reinforces the grid according to a level that takes into account future planning levels for the Point of Connection. The customer normally agrees to pay for the reinforcement if no other connection point is available. The network refinement in this case usually entails to connection of long cable to where the customer premises are, and depending on the size of the customer this connection can be made to a different voltage level and hence may also include a transformer upgrade.

If enough capacity exists, the customer equipment also needs to comply with the allowed Electromagnetic Interference (EMIs) level in addition to local grid regulations. There are international standards that are adopted by most of the grid operators to ensure the robustness and stability of the DNs. These usually specify different levels for acceptable emissions, network planned levels and equipment immunity levels. Figure 5-1 shows a qualitative probability density spectrum for disturbance levels in public DNs.

If the quality of power and emissions are not in compliance with the connection standards, the customer will be required to improve its equipment through local measures and show compatibility before a connection is approved. These usually entail either hardware modification of the equipment or the connection of additional power quality improvement equipment at the customer’s premises; e.g. Static VAR Compensators (SVCs) and STATCOMs.

In relation to railway power grids, in various countries these grids are operated at a different frequency than the public power grid. In the past dedicated power plants were built to supply the single-phase railway grids. Currently, the public three phase AC network is being interconnected to the railway grid via frequency converters. In this case the frequency converters will need to be compliant with grid standards before a new interconnection is made.

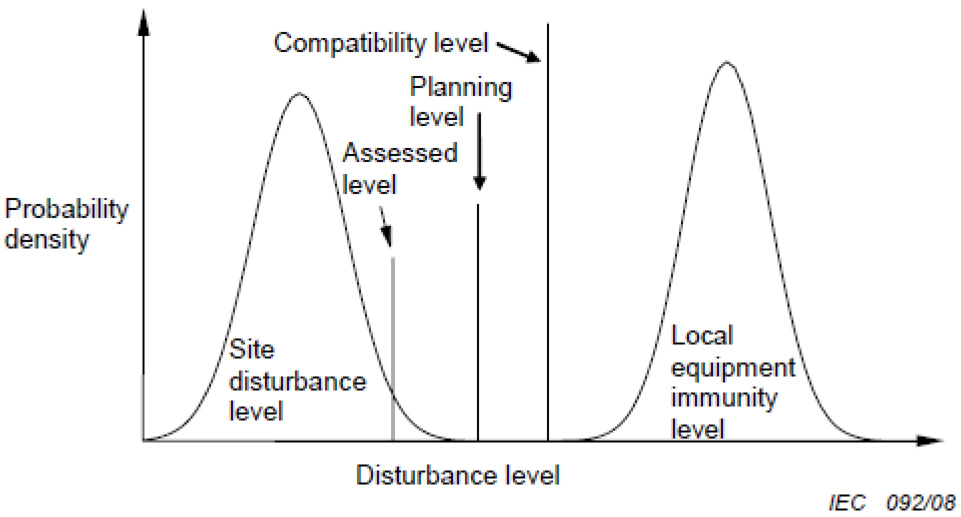


Figure 5-1. EMI levels as defined in IEC 61000 series.

5.2 Smart Grid interconnection

As discussed in Chapter 2 there are innovative methods that provide better performance and more cost-effective solutions to provide a good balancing room for intermittent subsystems connections and hence manage these interconnections in the most optimised way.

Specifically, to show how the use of normally open points to reconfigure the distribution network can impact the losses, an example of the sSOP interconnecting two main feeders is shown in Figure 5-2. Assuming the total losses of the two feeders as base case for each one of the use cases described in Table 5-1, there is a significant losses reduction that can be realised. Of course, as the power system operational point varies, it might not be optimum to use the sSOP to reduce losses at all times. And this is the significant driver of implementing an sSOP as the node intelligence will determine the best control action that is required and control the amount of active power that need to be transferred in real time.

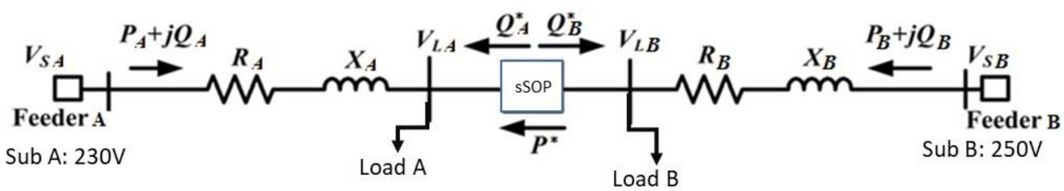


Figure 5-2. sSOP interconnecting two feeders; feeder A and feeder B.

Table 5-1. Use case that show a significant impact on network losses.

Use case	Feeder A length in [m] and load	Feeder B length in [m] and load	Losses reduction in % of case without sSOP
Case 1	150 and high load	300 and low load	31
Case 2	150 and low load	300 high load	28
Case 3	300 high load	300 low load	13
Case 4	300 low load	300 high load	17.9

5.3 Possible Smart Grid Interconnection Arrangements

5.3.1 Configuration 1: Maximum rail regeneration

In this configuration, the power converter is connected to the railway electrification system on the rail power supply, as shown in Figure 5-3, to the local distribution network and to the energy storage. Therefore, it is a three-way converter with DC/DC/AC output. In particular, the three individual converter modules are DC/DC (DC-bus to rail), DC/DC (DC-bus to storage) and DC/AC (DC-bus to grid).

The DC/DC converter can have various topologies depending on the requirements that will be specified in the next sub-sections. On the grid side, an isolation transformer is generally necessary to electrically isolate the local grid from the railway electrification network. Alternatively, the isolation transformer can move to the DC/DC rail converter.

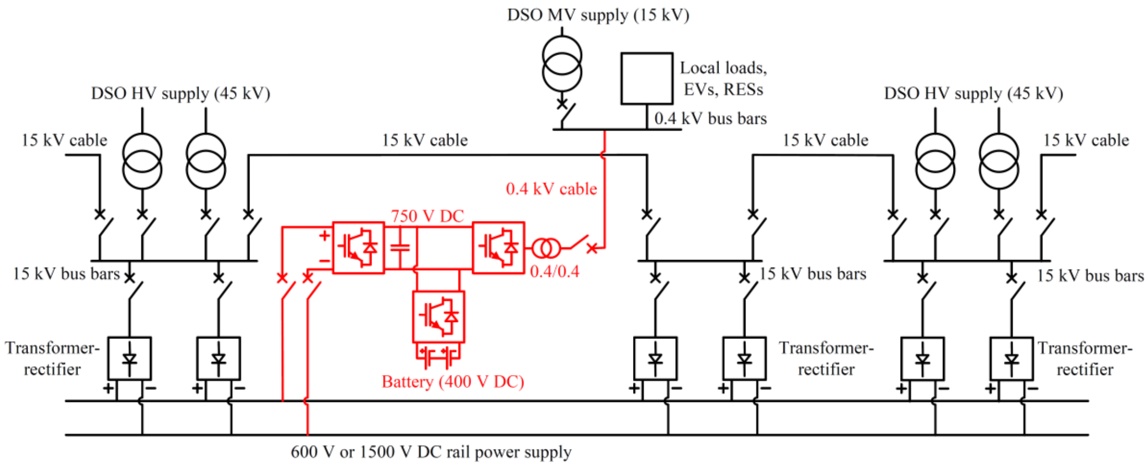


Figure 5-3. Connection of the sSOP to balance railway and local grids.

For this connection scheme, the following mode of operations are possible:

1. Railway traction network supports the local grid during periods of large loads and no trains;
2. Battery supports the local grid during periods of large loads but the railway is in use;
3. Railway traction network recharges the battery when there is no significant load on the local grid and no trains or when a train is braking;
4. The local grid recharges the battery when there is no significant load or there is availability of energy generation from renewable energy sources.

5.3.2 Configuration 2: Balancing the HV DSO grid

In this configuration, the power converter is connected to the MV network of the railway electrification system, as shown in Figure 5-4, and to the energy storage. Therefore, it is a three-way converter with DC/AC/AC output. In particular, the three individual converter modules are DC/DC (DC-bus to storage), DC/AC (DC-bus to 15 kV busbar connected to DSO HV supply 1), and DC/AC (DC-bus to 15 kV busbar connected to DSO HV supply 2). It is worth noting that the connection of the sSOP can be done at only one site by taking advantage of the existing circuit breakers for the sectioning of the 15 kV cable. In this case, by connecting the two DC/AC modules to the input and output of the circuit breaker, there is no need to deploy any additional cable, with significant savings on the installation costs. The sSOP can be operated when the circuit breaker is open and can be bypassed by closing the circuit breaker after the sSOP has been de-energised.

The DC/DC converter is specified in a way similar to the previous case. On the 15 kV side, transformers are necessary to step-down the voltage to levels compatible with the power converters.

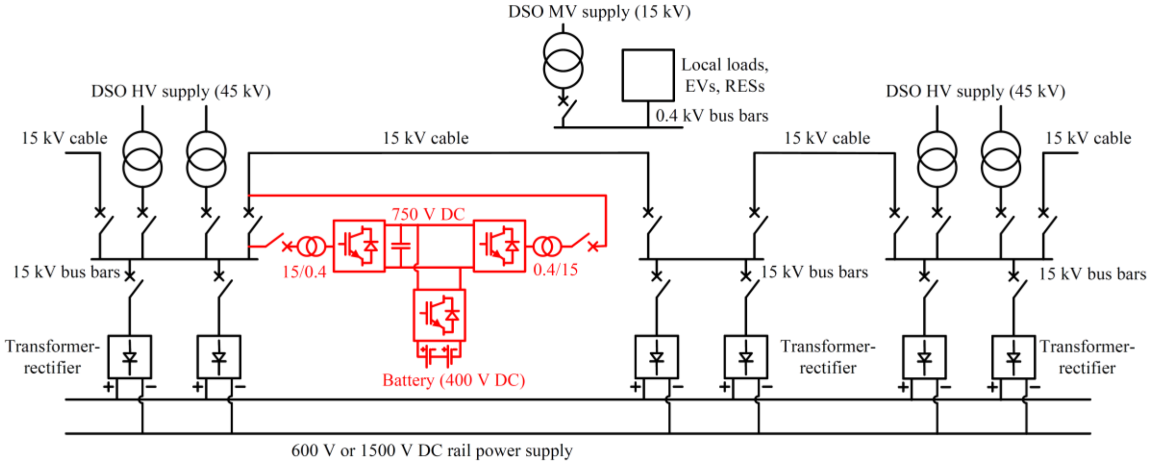


Figure 5-4. Connection of the sSOP to balance the HV connections of the DSO.

The main objective of this scheme is to balance the HV feeders of the DSO and the converter operates more similarly to a SOP. In fact, the DSO will actually see the connection as a closed ring, connected flexibly via the power converter. There are instead no benefits for the local grid, no possibility of improving the conditions for the generation of renewable power sources and no additional possibility of regenerative braking for the trains.

For this connection scheme, the following mode of operations are possible:

1. The HV feeder on the left provide some power to the traction substations supplied by the feeder on the right and vice versa;
2. The HV feeders recharges the battery depending on their loading level
3. The battery supports either HV feeder when the other does not have enough spare capacity.
4. The battery supports the railway reducing the power of the HV feeders

5.3.3 Configuration 3: Balancing the HV DSO grid and the railway

This configuration extends the previous one for the addition of a DC bus bars that interface the SOP with the railway and local loads and renewable energy sources, as shown in Figure 5-5. Therefore, it is a four-way converter with DC/DC/AC/AC output. In particular, the four individual converter modules are, DC/DC (DC-bus to storage), DC/DC (DC-bus to railway), DC/AC (DC-bus to 15 kV busbar connected to DSO HV supply 1) and DC/AC (DC-bus to 15 kV busbar connected to DSO HV supply 2).

The DC/DC converter for the railway is specified in a way similar to the case presented on section 3.1. The DC bus is shared with local charging stations for EVs (e.g. parking lots around the railway) and local renewable power generators (e.g. photovoltaic panels on the roof of stations).

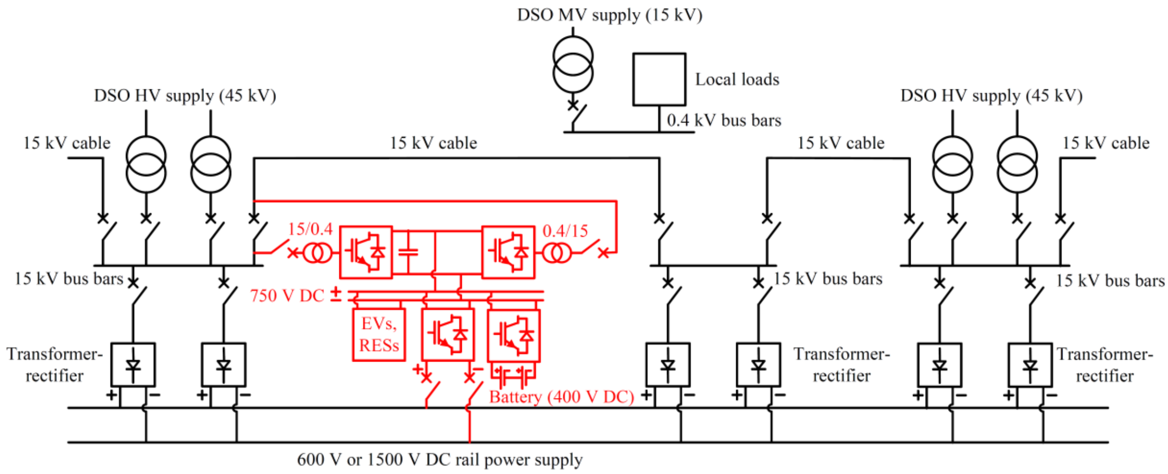


Figure 5-5. Connection of the sSOP to balance railway and DSO grids.

For this connection scheme, the following mode of operations are possible in addition to those already presented in section 3.2:

1. The battery is recharged when a train is braking;
2. Local EVs can be recharged by the 15 kV network or the battery or the electrification network
3. The battery supports the railway electrification;
4. Renewable power generators contribute to the supply of the railway or recharge the battery if the power generated is in excess of the railway requirements.

6 Overview of system requirements

This section of the handbook focusses on the derived requirements for the design, installation and operation of the sSOP across the railway network and the power distribution network specifically for the three possible arrangements described in Chapter 6.

6.1 Requirements for the AC/DC power converters (Configuration 1, Configuration 2, Configuration 3)

Typical power range: 240-400 kVA
AC voltage output: 400 V rms line-to-line
AC voltage frequency: 50/60 Hz
DC-bus voltage: 750 – 800 V
Topology: Three-phase bi-directional bridge circuit
Need for a transformer: yes, if the AC grid has a different voltage or require isolation
Efficiency: more than 98% at full load

6.2 Requirements for the DC/DC power converters connected to the railway (Configuration 1, Configuration 3)

Typical power range: 240-400 kW
DC voltage output: 400-800 V (600 V nominal) or 1,000-1,950 V (1,500 V nominal)[65].
DC input voltage: 750 - 800 V
Topology: bi-directional Dual-active bridge or interleaved half-bridge
Need for isolation: yes, to limit the rail transients penetrating the DC-link, with 100kV isolation impulse withstand (tbc with MDM requirements).
Efficiency: more than 96% at full load

6.3 Requirements for the DC/DC power converters connected to the battery (Configuration 1, Configuration 2, Configuration 3)

Typical power range: 100 kW
DC voltage output: 300-500 V.
DC input voltage: 750 V
Topology: Dual-active bridge (DAB) or a suitable non-isolated buck-boost topology
Need for isolation: Dependent on the connection point of the DC/AC converter to the power system (the isolation point can be at the AC bus).
Connectivity: Compatibility of the protocol of the CAN-bus for the connection to the battery management system (BMS)

6.4 Requirements for the installation of the sSOP

1. For all the schemes:

[65] BS EN 50163-2004 + A1:2007

- Availability of land/building for installation of the sSOP. Indicatively, the dimensions of a 240 kVA sSOP without transformer with outdoor enclosure are 1.4 m (length) x 0.6 m (depth) x 1.2 m (height). A 400 kVA system would be slightly larger and needed to be installed into a separate enclosure made of fiberglass reinforced plastic or otherwise.
- Availability of land/building for installation of the battery
- Outdoor or indoor installation
- Deployment of extra circuit breakers for the relevant voltages, nominal currents and short-circuit currents
- Check that it is possible to install the sSOP next to a circuit breaker and disconnect the current system only in one point (there may be necessity to bend one cable or add an extension with a joint)
- Check the possibility of using the existing circuit breakers

2. For the scheme of Figure 5-3:
   - Availability for the connection to the low-voltage local grid in the vicinity of the railway
   - Deployment of the cable connecting the sSOP with the low-voltage local grid

6.5 Requirements for the control of the sSOP

1. Define the switching frequency of the converter and verify the absence of forbidden frequency bands (e.g. used for signalling)
2. Define the control hierarchy, i.e. sSOP locally controlled or network controlled. In this second case, define the communication link to obtain the power reference
3. Communication between the SCADA systems of the sSOP, the railway network and the power distribution network

6.6 Requirements for the protection of the sSOP

1. Check the requirements for the circuit breakers of the DSO
2. Check the requirements for communication with other DSO equipment
3. Check the EMI with signalling system
4. Check the requirements of keeping uninterrupted the power supply to the signalling system
5. Define the operation during system transients and short duration faults on both the rail and the distribution networks.

6.7 Requirements for the measurement of the energy exchanged between the networks through the sSOP

1. Check the actual meter arrangements on MDM to meter the electricity from the substation and the electricity consumed by the trains
2. Deployment of extra meters if needed
3. Verification of regulations and standards on electricity meters for railways

7 Conclusions of second release

7.1 Conclusions

In this report, the technical losses and non-technical losses in both the distribution and rail networks have been discussed in details. This has provided a tool to identify new cost-effective solutions for electrical losses reduction for the interconnected transport and electricity networks through the discussion of:

- Current practices of infrastructure operators
- Emerging technologies and subsystems introduced by equipment manufactures
- Reported R&D experiences through various EU demonstration projects
- Regulations that may potentially limit or facilitated innovative solutions

A first release of this deliverable was prepared at November 2018 (M6 of the project). This version represents the updated second release completed at May 2019 (M12 of the project).

Among the emerging technologies, it has been verified that the E-LOBSTER sSOP plus battery energy storage system that is capable of managing the energy flow dynamically in real time has a great potential to manage losses in a relatively more cost-effective way as compared to conventional solutions.

In this second release, a more accurate description of the electrified transport network has been provided. A study characterising each components and sub-systems of a mainline railway system and developing a global energy consumption map, defining levels of energy consumption of each components and sub-systems has been reported. Actually, an energy consumption map is a comprehensive and graphic way of representing the energy flows in the whole railway power supply systems. These maps provide a good overview of the energy, allowing a better understanding of what the energy has been used for (running the trains, operating stations or workshops, etc.) and they are a powerful tool to identify when and where measures oriented to increase energy efficiency can be implemented.

Furthermore, special attention in the framework of the report, was paid to the review of energy storage technologies suitable for electricity losses reduction in distribution networks and electrified railway systems. A description of the main components and sub-systems of a battery energy storage technology has been provided too.

Finally, possible Smart Grid Interconnection Arrangements have been presented. Actually, in this report, three possible E-LOBSTER arrangements have been discussed in the light of their requirements specification and foreseen impact.