SYSTEM PILLAR CONSORTIUM – TASK 1
UIC AND UNIFE

Energy saving in Rail:
Consumption assessment, efficiency improvement and saving strategies, overview report

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1. Executive Summary

Rail is an innovative industry, striving to find new and adaptive techniques to reduce energy use and improve efficiency. Rail companies are large consumers of energy and are often the single highest electricity user in their country.

Following recent steeply rising energy prices and problems with supply and energy security in 2022-23, the UIC Energy Saving Taskforce was launched for members as well as other rail industry partners to share solutions and strategies to mitigate the impact of these circumstances.

In order to know where savings in energy use can be achieved, it is important to understand where energy is consumed within the railway system (given in section *3 Energy consumption in rail*). A survey was conducted with European rail infrastructure managers and operators and then compared to published literature. The survey revealed that a large proportion of the energy used today in European railway operations is for traction energy (the movement of trains). A total of 86.7% of energy was reported to be used in freight and passenger traction power. The report includes a breakdown of where energy is used in traction, including where losses have been observed. After traction, infrastructure operations (for example, signalling and telecommunications) are the second largest consumer, at approximately 7.9% and the third and smallest energy consumer is from buildings (5.5%).

The report was commissioned by EU-Rai to ensure that the output would reflect the broader consideration including (beside UIC taskforce work) the outputs of S2R and EU-RAIL R&I. The report collects and assesses energy saving approaches in all relevant subsystems of the railway sector (following the methodology as set out in section *4 Assessment of energy saving measures*). This report contains a catalogue (section *5*

Energy saving measures) of solutions that have been trialled or used in the European rail sector, with a specific part for rail research programmes (section *6 European research and innovation project solutions*). The purpose of the report is to collaboratively share knowledge on energy saving with recommendations on how to support the accelerated deployment of these solutions (in *7 Regulations: Constraints and challenges* and *8 Discussion on the incentives and challenges for implementation*).

The catalogue includes a set of solutions, grouped by main focus in a template summary table. The tables give a description of the solutions with comments on the experience gained, and the benefits and constraints. The report organises this catalogue of solutions into the following subsections:

- **Rolling stock** solutions
  Any hardware improvements
- **Operations**
  Any solution to improve the energy efficiency of operations or avoid consumption
- **Infrastructure** solutions
  Any solution to save energy in railway asset management and improve efficiency
- **Buildings** (including stations)
  Energy saving solutions for stations and buildings
- **Processes**
  Any improvement to a railway management or operational process that could result in energy savings

A review of the implications for the European railway regulatory framework was also undertaken, highlighting the challenges for the European railway energy market and in implementing innovations as follows:

- Equipment lifespan
- Human Resources and factors
- Customer comfort
- The pay-back period, uncertainty, and change
- Energy production
- Decarbonisation and phasing out fossil fuels
- Information and metering
- Industry structure challenges

The report concludes by reporting on industry reported priorities and future research needs.

2. Introduction

2.1. Rail is inherently energy efficient

Due to the interaction between rail tracks and wheels having low friction, as well as trains having a high capacity for the mass transport of both passenger and freight, rail is inherently energy efficient. According to the IEA, on a "well-to-wheels" (wing/wake) basis, rail greenhouse gas (GHG) emissions per passenger-kilometre currently average around one-sixth of those of air travel (Figure 1). Furthermore, emissions from electrified passenger rail are even lower, particularly when powered by renewables or nuclear energy.

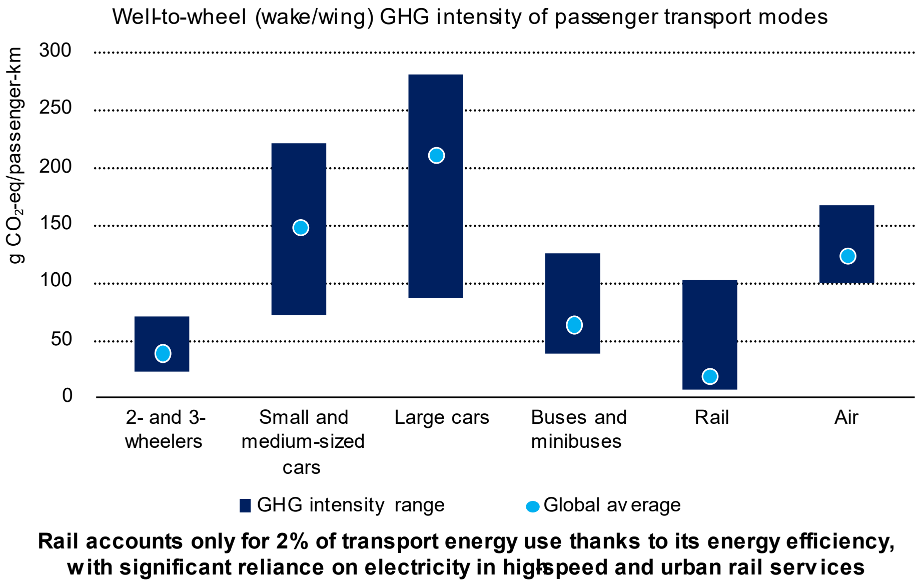

Figure 1: IEA, well-to-wheel (wake/wing) GHG intensity of motorised passenger emission factors in grams of CO_2 equivalent (greenhouse gas) - range according to transport mode[1]

The railways are in fact so inherently energy efficient, that when the IEA published their "7 ways to save energy"[2], greater use of public transport was a key recommendation.

"For longer distances where walking or cycling is impractical, public transport still reduces energy use, congestion and air pollution. If you're going on a longer trip,

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[1] IEA, Paris https://www.iea.org/data-and-statistics/charts/well-to-wheel-wake-wing-ghg-intensity-of-motorised-passenger-transport-modes-2, IEA. Licence: CC BY 4.0

[2] https://www.iea.org/spotlights/7-ways-you-can-save-energy

consider leaving your car at home and taking the train. Buy a season ticket to save money over time. Your workplace or local government might also offer incentives for travel passes. Plan your trip in advance to save on tickets and find the best route."

One crucial way for the railways to save energy, is to attract more traffic away from aviation and road transport, especially private cars and trucks. In fact, by engendering a modal shift, the railways must increase their energy consumption by transporting more people and goods, in order to save energy for the transport sector in a general sense.

UIC holds data on the energy use from railway operators in Europe, as part of the Environment Strategy Reporting System (ESRS), which, in 2022, was renamed as the Traction Energy & Emissions Database.

The 2023 data collection campaign (reporting 2022 data) shows that the effects of the pandemic (SRAS-COV2, COVID-19), are still being felt in terms of energy consumption, due to reduced demand and occupancy, although it is now much closer to pre-pandemic levels. This is illustrated in Figure 2, with the total energy consumption of the reporting railways being shown.

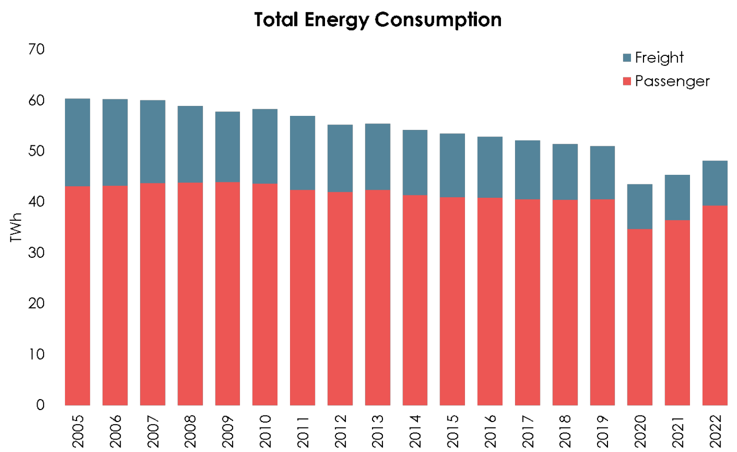


Figure 2: Total tractive energy consumption (for both passenger and freight services, electric and diesel traction), in terawatt-hours. UIC Traction energy & emissions database, 2023

Details of the increased efficiency by service, and the specific trends in the reduction in energy consumption in kilowatt-hour per passenger-kilometre and tonne-kilometre are given in Figure 3.

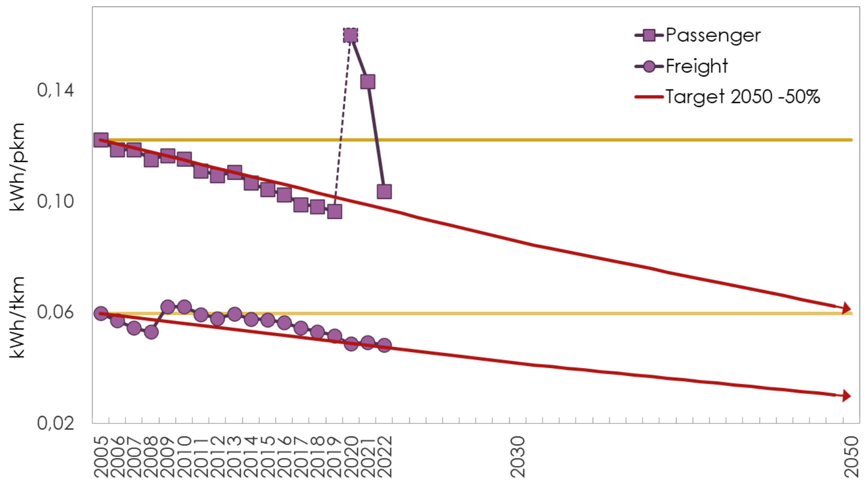


Figure 3: Energy efficiency of passenger trains in kilowatt-hours per passenger-km, and of freight trains in kilowatt-hours per tonne-km (for both electric and diesel traction), UIC Traction energy & emissions database, 2023

Overall, total energy consumption has decreased between 2005 and 2022 (Figure 2), which can be explained by various cumulative factors, such as less diesel freight trains being in operation, less freight trains running in general, or simply the reporting companies carrying out less freight activity, besides the obvious impacts of COVID-19. It is clear that, from an efficiency perspective, trains running with fewer passengers will have a much higher energy consumption per passenger kilometre. Fortunately, as COVID-19 becomes less of a concern, the usual efficiency levels are recovered as passenger flows return closer to normal levels. As visible in Figure 3, this effect does not apply to freight trains, as the load factors remained stable throughout the crisis (regardless of the number of trains).

It was also expected that the energy crisis, that started following the early stages of the 2022 war in Ukraine, has an effect on this trend, as well as on the energy efficiency of operations. As assumed, energy saving strategies undertaken in 2022 have already had a visible effect on efficiency, alongside the market recovering from the effects of COVID-19.

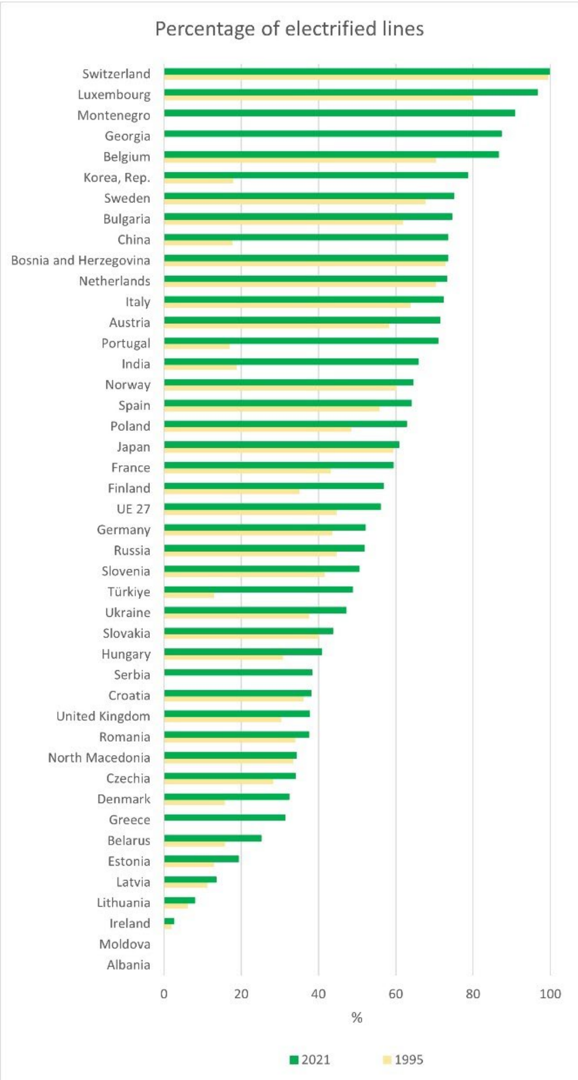
2.2. Electrification in Europe

Some European railways count among the most electrified in the world (e.g., Switzerland). Of the EU 27 countries, 56% of the lines are electrified, with these including the lines with the highest traffic volumes, therefore accounting for a large proportion of passenger and tonne-kilometres travelled by rail in Europe.

According to UIC's Traction energy & emissions 2022 data, 88% of passenger train kilometres were ran on electricity for reporting (main) European operators. The ratio is at 90% for freight reported train kilometres (note that the number of operators reporting is not representing the whole freight market).

Figure 4 ranks the level of electrification by country, as well as the increases in electrification implemented between 1995 and 2021, showing that countries such as Denmark, Portugal and Turkey have rapidly rolled out electric overhead contact lines.

As a result of this high level of electrification, the railways have some of the lowest greenhouse gas (GHG, and other pollutants such as nitrous oxide (NOx) and particulate matter (PM) or dust) emissions of any mode of transport. This also partially explains the high efficiency of railways per passenger-kilometre, although, at the same time, means that large rail operators are often one of the largest end users of electricity in their country.



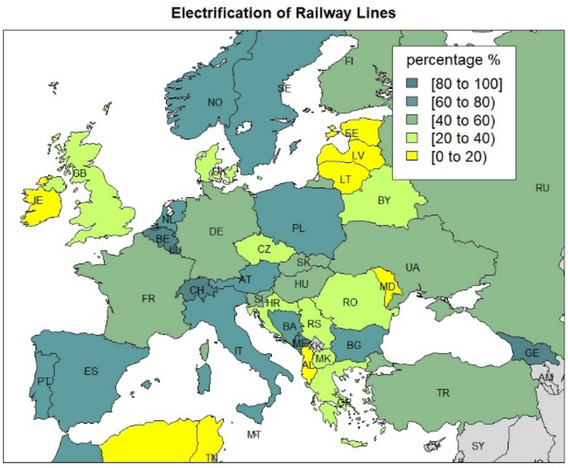


Figure 4: Reported European electrified lines – Eurostat and UIC RAILISA (RAIL Information System and Analyses, UIC Statistics Database)

2.3. The energy crisis

In the context of climate change, soaring energy prices, increasing energy supply insecurity (as illustrated in Figure 5 and Figure 6), and the fact that railways are often significant consumers of both electricity (Figure 6) and diesel, with their demand also matching peak energy demand times, railways have both the urgent need and responsibility to find practical ways to reduce their energy consumption.

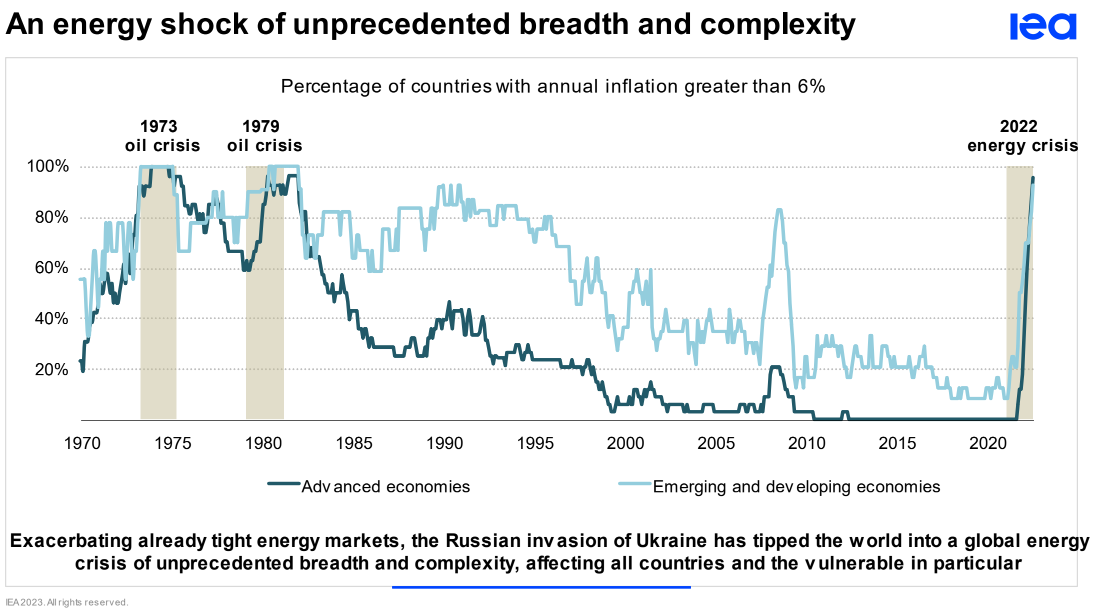


Figure 5: Inflation in emerged and emerging countries (IEA – World Energy Outlook, 2022)

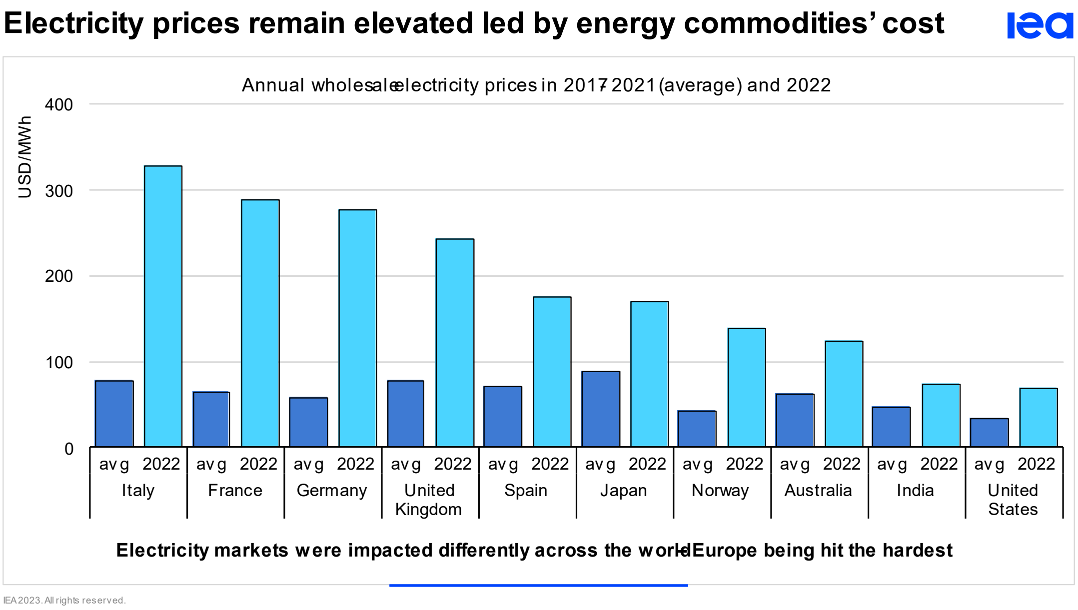


Figure 6: Average annual wholesale electricity prices (2017-2021) compared to 2022 (IEA – Electricity market report, 2023)

In 2022, in response to this price shock, the European Commission and the International Energy Agency asked businesses to involve their employees in finding ways to improve energy efficiency, facilitating the networking of multiple companies to simultaneously develop their energy audits or energy management systems, sharing best practices, and running joint training sessions.

It is interesting to note that for some countries, contextual aspects had an increased effect on the electricity prices (therefore railways), as for example the unusually low nuclear production in France.

2.4. Purpose of this report

Rail is a highly innovative industry and is already finding new and adaptive techniques to reduce energy use. This report brings together a broad range of solutions for energy saving that have been trialled or used in the European rail sector.

The purpose of this report is to collaboratively share knowledge with recommendations on how to support the accelerated deployment of these solutions.

This report sets out the following key practical information to support rail organisations in saving energy:

- The main energy consumers in the railway system (*3 Energy consumption in rail*)
- An assessment and classification of sets of solutions, according to their benefits over costs (difficulty, cost, time) (*4 Assessment of energy saving measures*)

- A catalogue of selected solutions with the potential to save energy, from the experiences of the European railway industry, infrastructure managers, undertakings (*5 Energy saving* measures), and rail research programmes, including Shift2Rail and Europe's Rail Joint Undertaking (ERJU) (*6 European research and innovation project solutions*)
- A review of any implications on the European railway regulatory framework (*7 Regulations: Constraints and challenges)*
- Recommendations for ways to achieve widespread and fast deployment (*8 Discussion on the incentives and challenges for implementation*)

As part of Europe's Rail Joint Undertaking – LOT 2 System Pillar, the production of this report has been commissioned by the European Commission EU-Rail JU to:

- support the railway sector by compiling energy saving approaches for railways,
- provide EU decision makers with a clear overview of existing or upcoming solutions to remove, where needed, any possible legal barriers for their adoption.

The objective of the report is to compile and assess energy saving approaches in all relevant subsystems of the railway sector, including rolling stock, operations, infrastructure and buildings. It includes short-term approaches, which can be achieved without extensive investment, as well as long-term approaches.

The work also takes relevant research activities in the railway sector, the practical experiences of stakeholders (best practices) and the work carried out within Shift2Rail and EU-Rail innovation on energy saving approaches into account.

This report draws information from several sources and organisations, making a compilation of solutions for energy saving. Solutions presented are being developed, trailed, and tested within the European rail sector and have been shared with the report authors for the benefit of the whole sector. Sources include:

- Solutions for energy saving developed under the Shift2Rail programme
- The UIC special taskforce for energy saving, set up in October 2022 in response to the energy crisis, the group including Operators, Infrastructure managers, manufacturers and academia, met online to share their knowledge and experiences on energy saving solutions
- Energy projects developed in the UIC Rail System Forum and Sustainability Platform

The report features solutions finding their origin in many different company/institution specific projects, with different boundaries and assessment methods. Therefore, and since the aim is to give an overview, it was not possible to normalise the quantitative results to a common methodology, in order to allow for full comparability of the obtained energy saving values given the railway system specificities by country/IM or operator/vehicle types. Qualitative or quantitative information in the report should serve as hint to the reader/user and the reader is invited to carefully consider the differences for each assessment/boundaries before trying comparing results from different projects. For the same reasons, it was not possible to align all solutions introduced to their respective technology/market readiness level.

The report did not focus on techniques to reduce greenhouse gas emissions, since the emphasis was on energy supply. Nevertheless, any energy saving will also reduce emissions, provided that the energy comes entirely or partially from fossil fuels.

3. Energy consumption in rail

This section provides a summarised overview of the main energy consumers in the railway system, with the aim of identifying how energy is used in the railways and the areas where the energy demand is the greatest.

Energy use within the rail system is classified into two categories: traction and non-traction.

Traction energy consumption includes the energy used to move the train and its auxiliary systems, therefore covering the power required to operate rolling stock.

The term "non-traction" includes the energy consumed in buildings (including in offices and stations, such as lighting, cooling/heating, IT systems, escalators, and lifts), depots including maintenance and cleaning equipment, and in other infrastructure operating systems such as signalling, trackside lighting, points heating, and telecommunications.

The consumption can be broken down into the following areas or type of activity (UIC-FFE Technologies and potential developments for energy efficiency and CO_2 reductions in rail systems, 2017):

- Traction energy
  - Movement of trains
  - Auxiliary systems of the trains

    Technical auxiliary systems in vehicles are necessary for the vehicles to operate correctly (fan engines, compressors, etc.), and commercial auxiliary systems are necessary for passenger comfort or to conserve goods (heating systems, cooling systems, lighting, etc.)
- Non-traction
  - Auxiliary systems of the infrastructure

    These include, for example, energy consumption for lighting in tunnels or track sections, point heating systems, signalling and communication systems, etc.
  - Stations, workshops, and other uses

This is the energy consumption for the lighting and air conditioning of stations, terminals, freight marshalling yard, parking lots, workshops (incl. maintenance), tracks maintenance and offices

Academic research shows that traction energy accounts for the largest share of energy used in the railway system, usually at between 60% to 80%[3][4][5][6]. On the other hand, non-traction energy use is less covered in published research, and therefore in order to confirm assumptions and understand energy use in greater detail, a survey was conducted within the UIC Energy Saving Taskforce.

It is important to note that there is a very high customer sensitivity to train service offers, so that reducing energy consumption is not as simple as it looks, which in turn could also have an increased impact on profitability (e.g., if savings make timetabling/comfort less attractive). Railways have to find the optimal balance between energy restraint and their appeal to passengers and shippers. Faster or more frequent operations, and increased comfort, always mean higher energy consumption. Fine tuning all of these aspects is always a challenge, given the scale that most European railways operate on.

Aside from this, railways contribute to a reduction in the transport sector's societal impacts (or external costs), and therefore, to what extent costs to society to be borne by mode are balanced out, will play an important role for the railways' profitability.

Unfortunately, railways do consume high amounts of energy, but this is related to their nature as a mass (centralised) mode of transport, for which the ratios of energy consumption by transport service, and societal impacts by transport service, are much lower than other modes.

Another important thing to note is that reducing rail energy demand and emissions is a long sought-after goal. This report's featured solutions have often already been studied on either a small or large scale, and over the long term, as illustrated by the survey results (Table 1) of the *UIC-IZT-Macroplan Non-traction energy consumption*

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[3] Ding Y, "Study on Train Movement Calculation and Operation Optimization Simulation System," PhD thesis of Beijing Jiao tong University, 2005.
[4] Gu Q, Tang T, Song Y-D. A survey on energy-saving operation of railway transportation systems. Meas Control 2010;43:209–11.

[5] RSSB. T913: strategy research programme: whole life carbon footprint of the rail industry. London: RSSB; 2010.

[6] González-Gil A, Palacin R, Batty P, Powell JP. A systems approach to reduce urban rail energy consumption. Energy Conversion and Management 2014, 80, 509-524.

study from June 2012 (although these should not be confused with the survey carried out as part of the 2023 energy saving activities).

Table 1: List of non-traction energy efficiency solutions, and to what extent it was explored by 22 participants of the survey for the UIC Non-Traction Study 2012

Energy efficiency activity	implementation level				
	implemented	pilot projects	investigations	not a topic	Total answers
New lighting systems for station buildings		12	6	4	22
New lighting systems for platforms	1	10	5	6	22
Optimized heating systems	3	8	6	5	22
Optimized air conditioning and cooling	1	6	7	8	22
Energy efficient equipment (e.g. escalators)	5	5	6	6	22
Energetic overhaul of buildings	5	6	5	6	22

For example, the list in Table 1 shows that at least 5 out of 22 participants were looking into and/or actually optimising lighting, heating/cooling, or insulation.

The energy crisis has only served to make railways think about accelerating the implementation of these solutions, whenever possible and applicable, on a larger scale or on a case-by-case basis. Therefore, sorting each solution by its cost/benefits ratio following a top-down approach was challenging given the fact that each company is at a different implementation stage for a specific solution.

Energy Consumption Survey

- Methodology

Primary data on consumption was collected via a survey sent to the UIC Energy Saving Taskforce on energy use in the railway system. This took place between June and July 2023 using a template spreadsheet (with the format being collaboratively agreed upon in advance to be suitable for all participants, as illustrated in Figure 7, Figure 14 and Figure 15). As the taskforce members represent freight and/or passenger operators and/or infrastructure and stations managers, the range of activities the members are involved in is reflected in the data coverage. Some members have 'holistic' data providing information on all railway energy use, while others only have data on the energy used by trains (traction and the onboard auxiliary systems). Different data collection and sub-metering practices are in use, and therefore the level of detail available varies widely between companies. Information on both electricity (AC and DC) and diesel energy was requested, with diesel being converted into Gigawatt hours equivalent for comparison. The participants were requested to input a value in Gigawatt hours and/or a share, in percent, representing the energy consumption of each item and sub-item.

- Participation

Survey participants: 13, 2 of whom are not listed below for confidentiality reasons.

Table 2: List of companies that provided an input to the survey

Company	Country	Type
Bane NOR	Norway	IM
CP	Portugal	RU
Infrabel	Belgium	IM
MÁV	Hungary	Integrated
NMBS/SNCB	Belgium	RU
Network Rail	UK	IM
ProRail	Netherlands	IM
SBB	Switzerland	Integrated
Trafikverket	Sweden	IM
ZSSK	Slovakia	RU
ZSSK Cargo	Slovakia	RU

The holistic data received mostly regarded the first two levels (lowest detail, from left to right), given in Figure 7. Thus, the most representative consumption profile was built illustrating the percentage split for the categories:

- Infrastructure
- Real estate
- Passenger services
- Freight services

Not all companies were able to share details of traction energy consumption, and therefore it was useful to build an energy-use profile for companies that did include traction energy values, as well as a profile of companies who did not. Additionally, given the different operating scales of the railways that participated in the survey, absolute energy consumption values were not considered, with percentages being used to analyse and illustrate the breakdown.

3.1. The rail system's consumption

To consider as many aspects of energy consumption for railways as possible, a consumption mind map was created as top-down holistic approach (considering that the entire railway system includes traction and non-traction energy consumption).

Figure 7 illustrates the four consumption categories as given above:

- Infrastructure management - covering the majority of track and platform access management, their maintenance, and the power supply for all the associated equipment
- Real estate - which considers all aspects of building management, including technical buildings and offices
- Passenger and freight transport - covering the consumption for the operation of the services themselves

Figure 7: Railway system consumption map

The consumption mind map, and Figure 14 and Figure 15 for traction, were used as the input fields for the UIC member survey.

For infrastructure managers, according to the UIC-IZT-Macroplan Non-traction energy consumption study, June 2012, two major sources are signalling/telecoms and switch heating, each counting for approximately 20% of overall energy consumption. Energy consumption in stations is around 30% (lighting, equipment, passenger information) while another 20% is energy for other infrastructure (lighting and other buildings). The final 10% is for offices/administrative buildings. This split was inspired by the ProRail breakdown from UIC-IZT, 2012.

For countries that have a colder climate, switch/turnout heating can represent a challenge in terms of consumption. In 2013, switch heating accounted for 50% of non-traction energy use.

Survey output - rail system consumption

The tables below show the repartition of energy consumption by category, by percent share. Table 3 introduces the proportions as an average for the companies capable of reporting both traction and non-traction consumption. Table 3 shows that the energy consumption for passenger services is by far the highest, and while traction for freight is much less substantial, it is still much higher than the other categories.

Table 4 introduces the averaged percentages for the companies that reported non-traction consumption alone, as well as the companies that reported both, however, with the traction energy use discounted. Table 4's consumption profile still includes transmission energy losses, so to keep considering the existence of rail infrastructure ready to supply traction energy, and to better understand the consumption profile from an infrastructure manager's point of view.

Table 3: Energy consumption profile including all aspects of traction energy

	Consumption profile with Traction
Infrastructure	7.9%
Real estate	5.5%
Traction – passenger	71.9%
Traction – freight	14.8%

Table 4: Energy consumption profile only considering non-traction energy

	Consumption profile without traction
Infrastructure	40.3%
Real estate	25.1%
Traction - passenger	28.3%
Traction - freight	6.3%

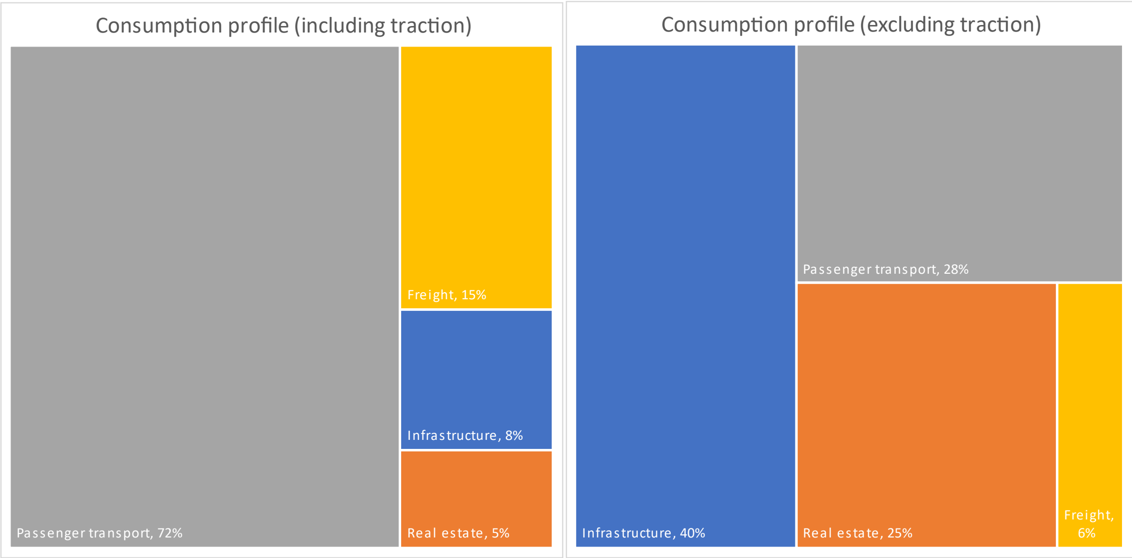

Figure 8: Consumption profiles by main category based on UIC Members responses to the survey. Left square (100%) includes energy consumption for traction. Right square (100%) excludes traction.

When looking at Table 3 and Table 4, both confirm that traction uses the most energy in absolute values, and is therefore the most impactful category for railway activity. The second largest energy user, after traction energy, is infrastructure, which includes maintenance depot operations, signalling and communications (Table 4). Real estate including stations and offices are the third and lowest energy consumer. Nevertheless, as put into perspective with Figure 8, without traction, they still represent opportunities to save energy.

Therefore, the energy consumption survey has confirmed the assumption that traction energy accounts for the largest proportion of energy use in the railway system. Adding freight and passenger traction together, traction energy accounts for more than 86% of the energy used by survey participants (See Table 3).

An example of the repartition in energy consumption can be seen within the SNCF group (independently built by SNCF beside the survey for this report).

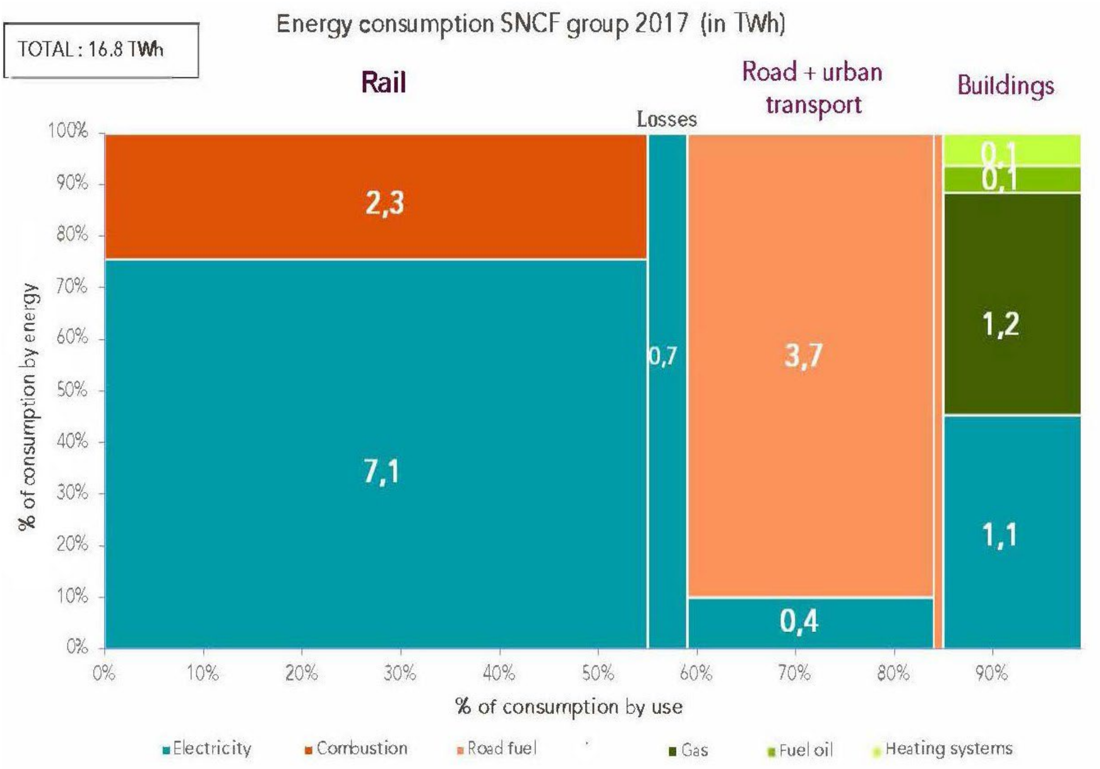

Figure 9: Energy consumption for the SNCF group in 2017 (in TWh) Source: SNCF

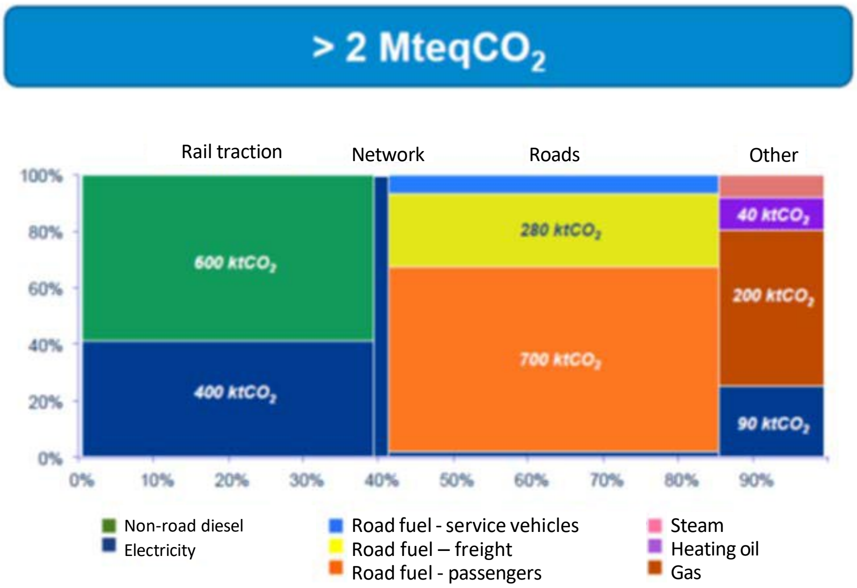

Figure 10: CO_2 emissions due to SNCF energy consumption

To further illustrate the repartition of energy consumption when considering infrastructure management, a breakdown of data (survey input) from MÁV, the

Hungarian State Railways, is given as an example. The main areas of consumption were identified as:

- Public accessibility 51.24%
- Train control systems 25.30%
- Telecommunications 11.50%
- Tracks & technical centres 12.00%

Figure 11 illustrates the split for the consumption categories for infrastructure listed above.

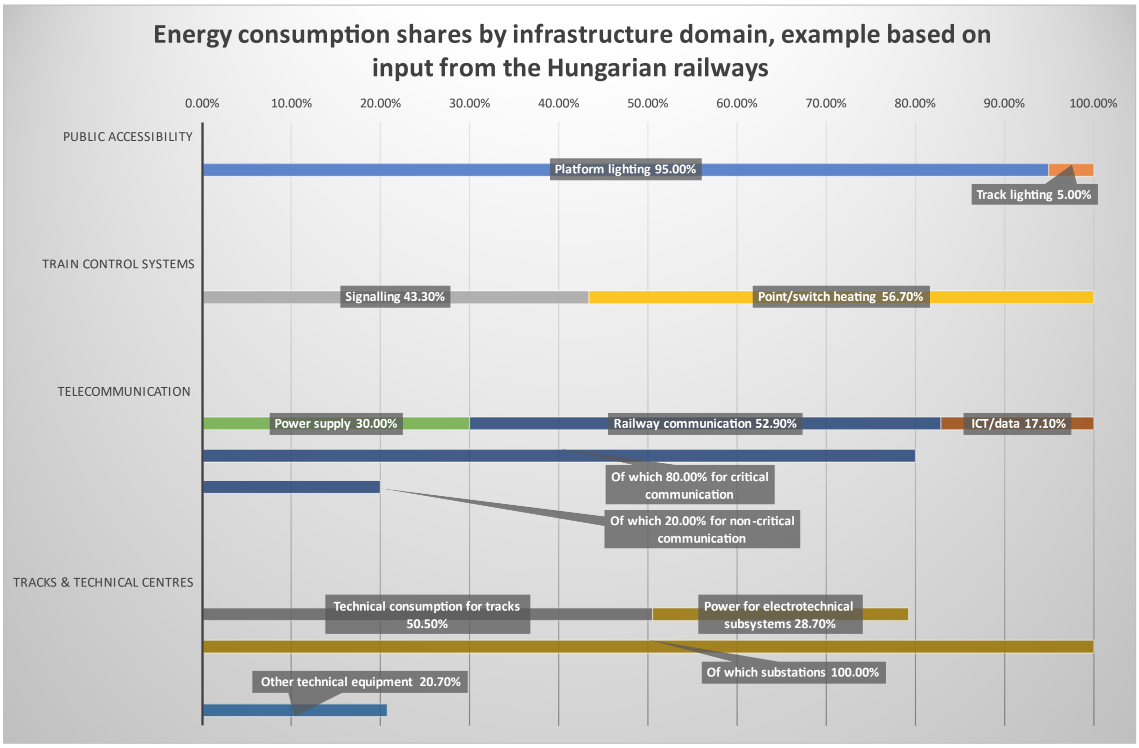

Figure 11: Energy consumption by consumption category in infrastructure management based on the Hungarian State Railways' (MÁV) input

These examples give an overview of what the split for an integrated railway company or infrastructure manager may be. Certain consumption categories can be worth focusing on for improvement in a specific situation. For example, according to M.M Pigeaud/ProRail, 2022, station lighting accounted for 30% of ProRail's total energy consumption, necessitating the launch of the "Lighting Programme", a large-scale project to refurbish and future-proof lighting and contribute to sustainability by reducing the energy consumption of station lighting by 50% (15% of Prorail's total energy consumption). Another 50% was saved by dimming the lighting in the absence of passengers (*see 5.4.6 Smart and efficient LED* lighting).

3.2. Traction energy consumption

Figure 12 shows a typical energy flow sent from the power grid to the train's traction system for conversion into kinetic (*mechanical*) energy. As a train can recover energy from electrodynamic braking, energy is converted back into electrical energy through the train's traction system, which then can feed the auxiliary systems (reducing auxiliary energy needs), or is sent back through the transmission system. This energy then either feeds another train's traction energy demands or flows through the substation for b a net recovery.

Energy losses are present throughout the traction system including during transmission, in the substation, catenary and through aerodynamic and rolling resistance (red arrows in Figure 12). Traction losses are due to inefficiency in converters, motors, the transmission system and in braking. However, as mentioned above, energy can be recuperated through regenerative braking where the rolling stock and infrastructure has the capability, although there are also losses when this energy is converted.

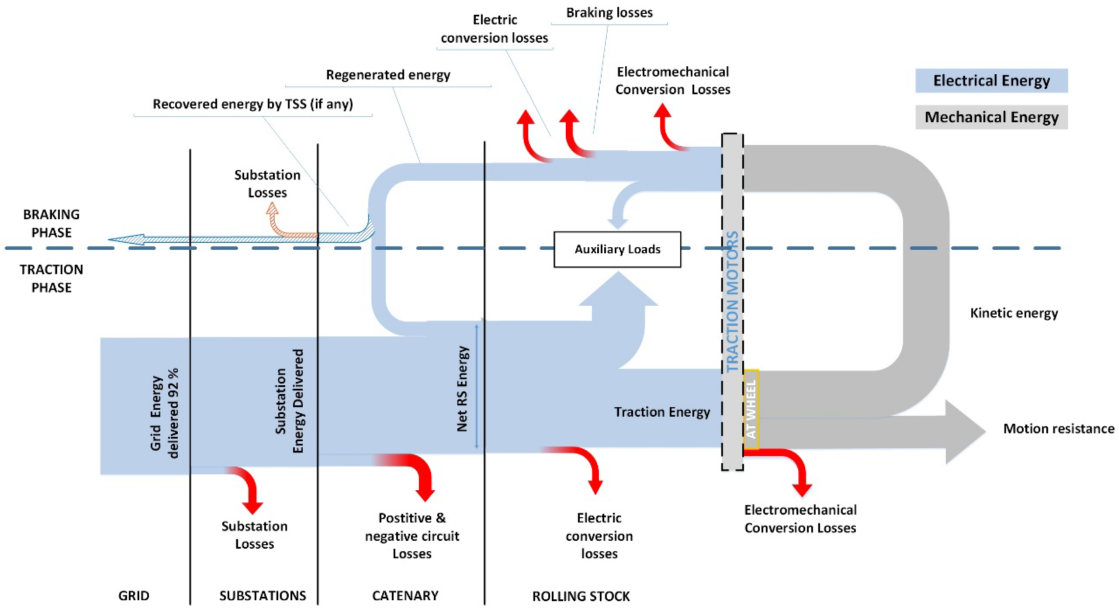

Figure 12: Energy flows within the AC traction energy supply system for train operation (UNIFE, EU-Rail Energy saving WG)

With regard to the energy spent to create mechanical energy, as pointed out in UIC-FFE 2017 and Figure 13, it is useful to emphasise that train mass has a substantial impact on energy consumption for all service types and especially for heavier and frequently stopping trains.

	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

Figure 13: Influence on consumption (delta Cons) of variations in train mass (delta Mass), or variations in the drag coefficient (delta Coef.C) (UIC-FFE, 2017)

The rolling stock's aerodynamic efficiency, illustrated with the drag coefficient for each train will also have an impact on consumption, especially relative to the operating speed and tunnels, and, as consumption is cumulated over time, it is always important to consider both (meaning any aerodynamic or mass improvement will have cumulative savings over time).

As for the entire railway system, a consumption map has been created to focus on the traction energy consumption chain of passenger and freight services (as introduced at the bottom of Figure 7).

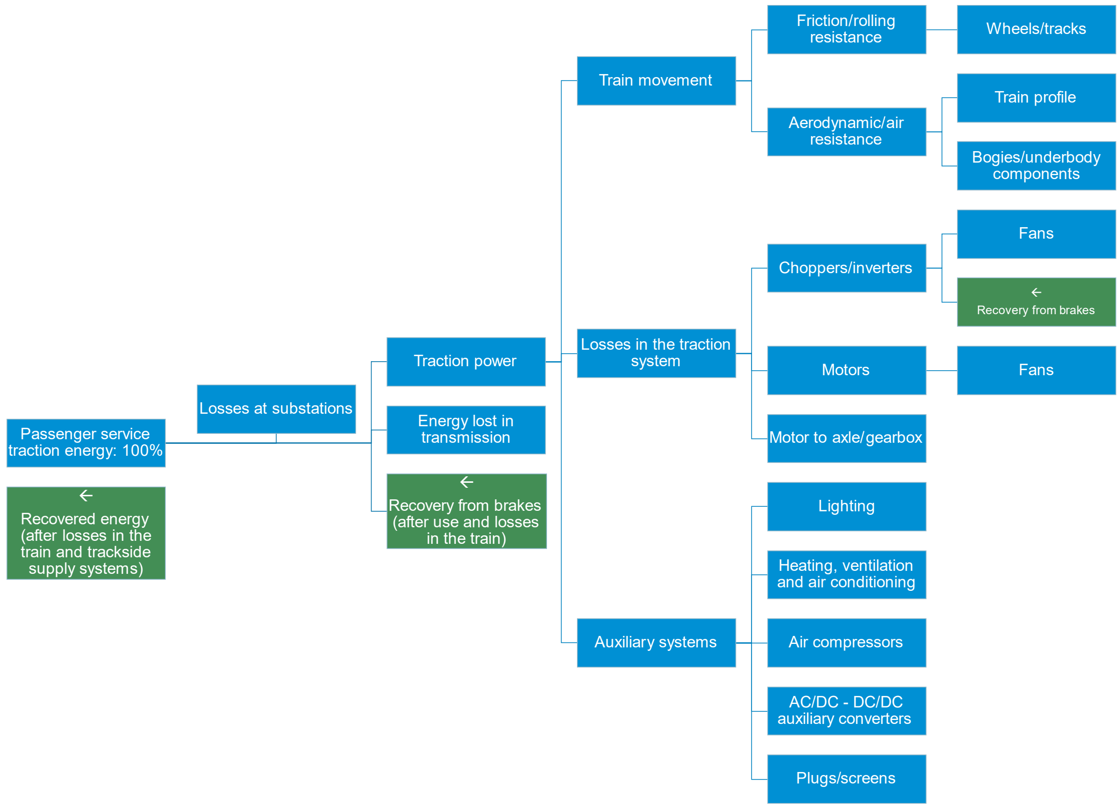

Figure 14: Passenger train energy consumption map

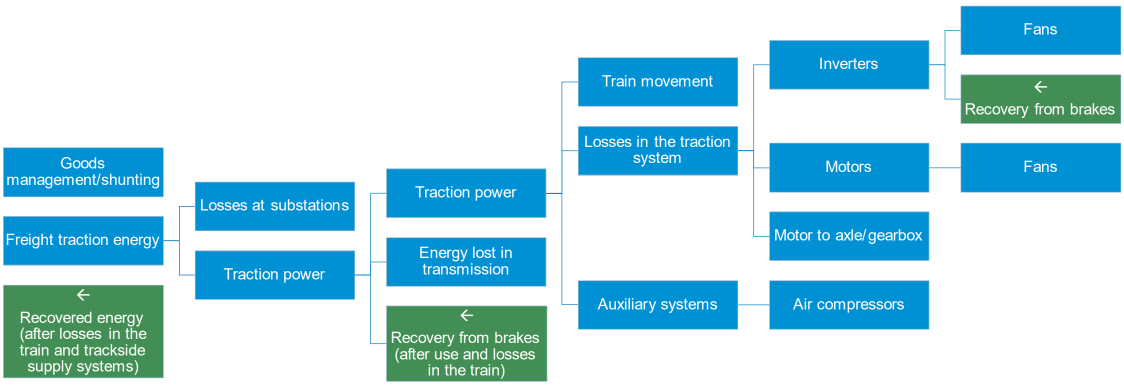

Figure 15: Freight train energy consumption map

Survey results - traction energy consumption

Based on the detailed data received from MÁV, it was possible to create a consumption breakdown throughout the traction chain, following the statistics for their commuter or regional trains, and electric (AC, DC), and diesel freight trains (Figure 16). This showed that energy losses are lower for DC traction systems than for AC systems (3% vs 12.7%). It certainly translates the consumption of transformers for the use of the alternative current. On the other hand, auxiliary systems are more energy-intensive on the same DC trains (17%) compared to AC trains (9.3%) although is compensated for by significantly more energy being recovered from DC trains. Overall, DC train energy use is much lower (1.5GWh) than for AC trains (611.5 GWh), meaning that this does not represent a definitive trend.

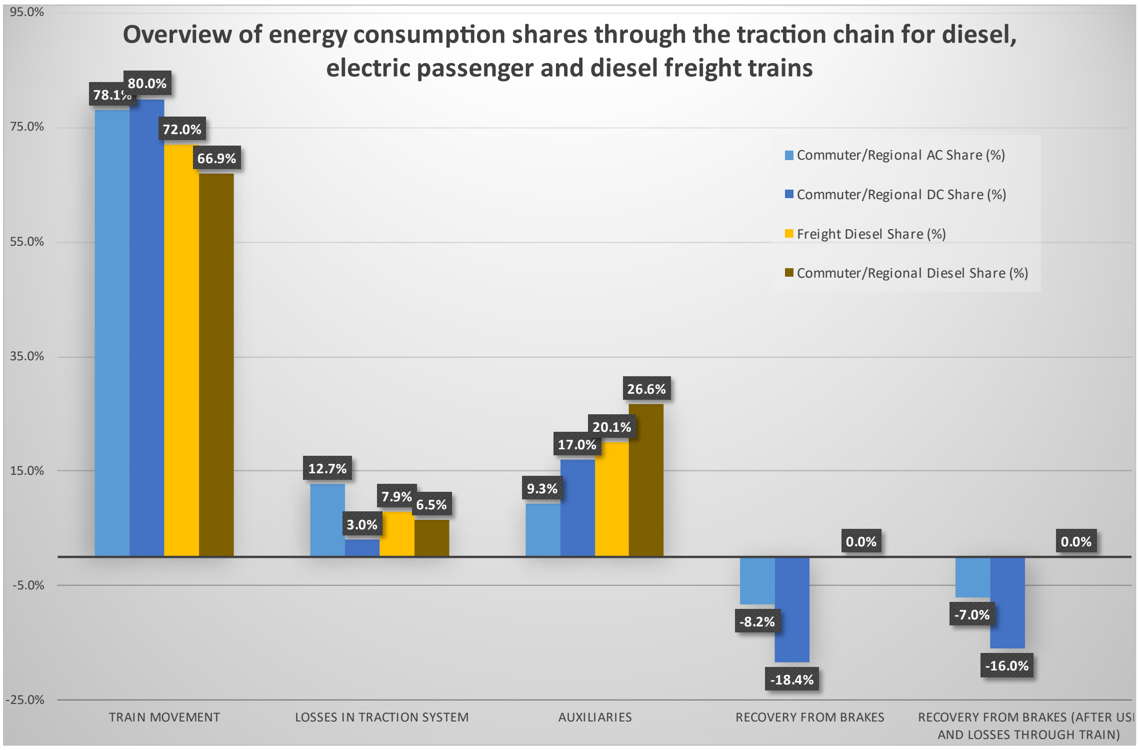

Figure 16: Shares of energy consumption by type of use in the traction chain for electric AC, DC and diesel commuter trains and diesel freight trains at MÁV

Since the amount of energy spent is higher for electric AC trains, with losses in the traction system also being higher, the apportionment for the latter was further looked into (Figure 17). Fans on choppers/inverters were reported to divert 22.9% of the energy sent to choppers/inverters. Fans on motors were reported to divert 19.5% of the energy sent. It shows that fans can indeed represent a substantial part of the energy consumption through the traction system (of the 12.7% lost through traction, 52.6% are going into choppers/inverters, of which 22.9% a spent by fans).

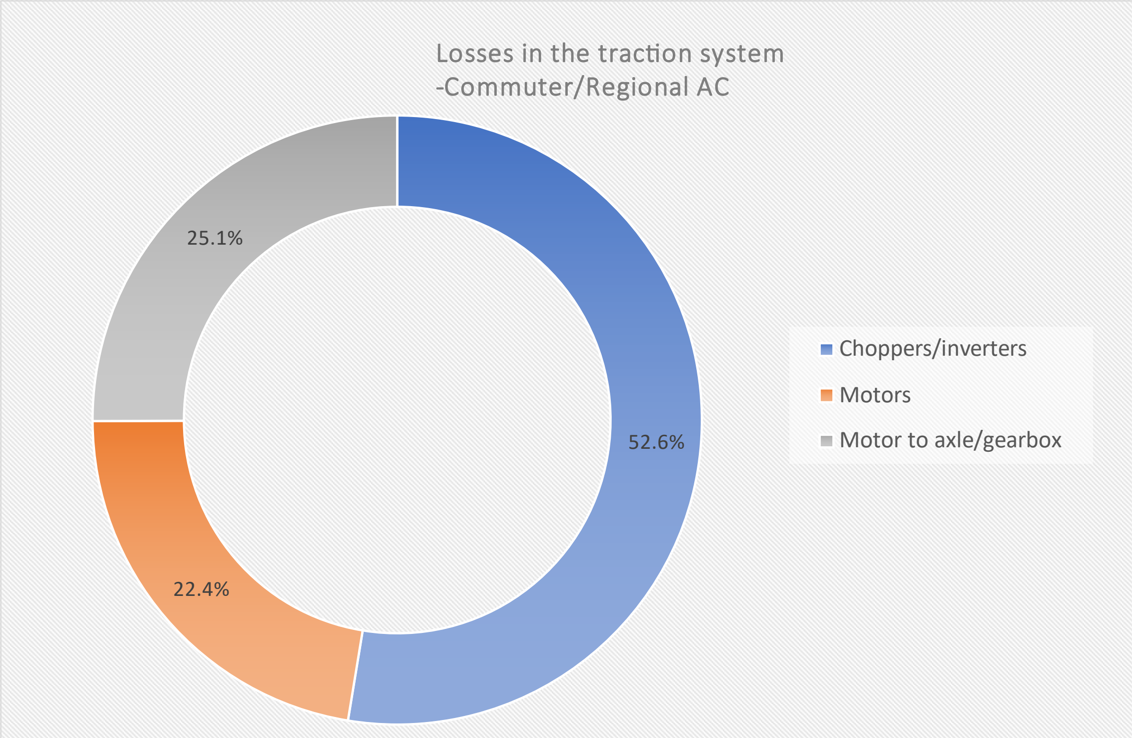

Figure 17: Energy losses in the traction system (over the 12.7% total of the energy input)

To illustrate the energy consumption for auxiliary systems, the most interesting profiles were collated in Figure 18, showing the distribution of energy into the auxiliary systems of AC commuter trains and diesel commuter trains. This facilitates a deeper understanding of which components use the most energy.

Aside from the fact that the amount of energy sent to auxiliary systems is much higher for the diesel train with 26.6% of the traction energy (important to keep in mind while reading Figure 18, versus 9.3% for AC trains), it shows that heating, ventilation and air conditioning also account for a substantial share of the total, with the greatest difference being between auxiliary converters (7.1% for AC, 23.7% for diesel). It is also interesting to note that air compressors have a slightly higher percentage for AC trains than for diesel trains, although this can be explained by the fact that other components might be used differently between diesel and electric traction.

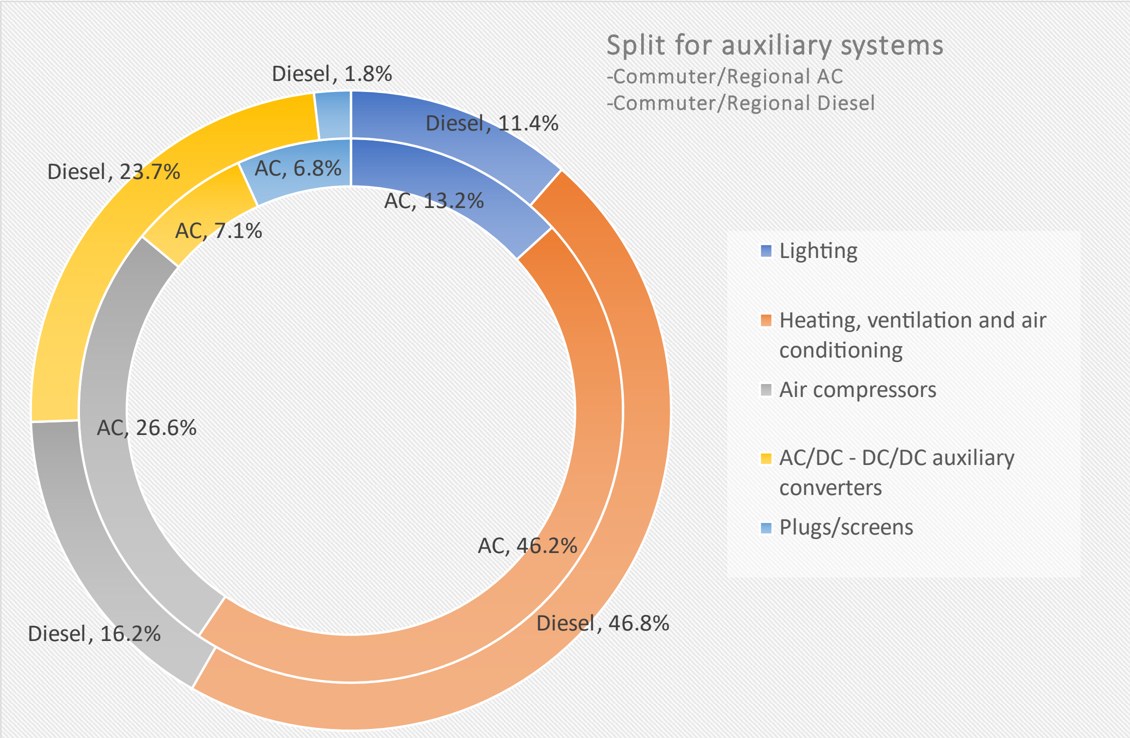

Figure 18: Energy split auxiliary equipment in commuter/regional AC trains (9.3% of the total energy input) and commuter/regional diesel trains (26.6% of the total energy input)

Figure 19, shows a different perspective, from SBB, the Swiss Federal Railways, on how energy is spent in their long-distance trains and related components.

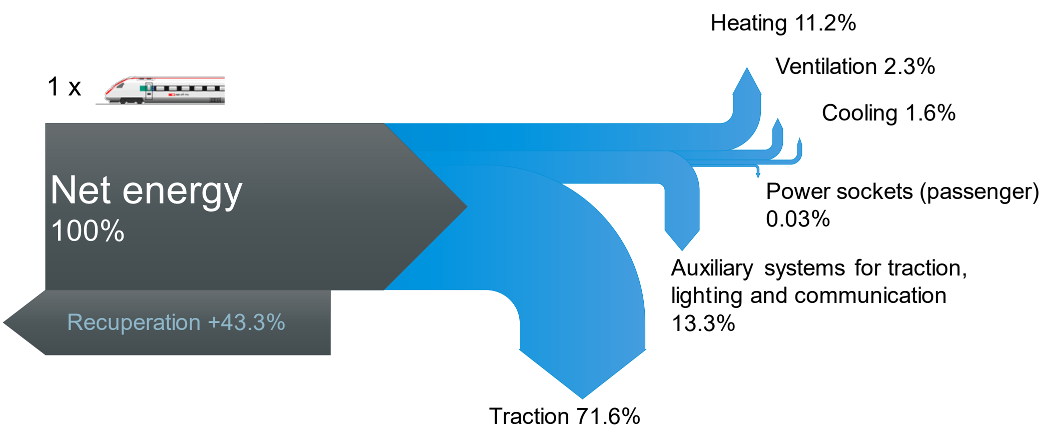

Figure 19: Traction energy consumption percentages, assessed by SBB for their long-distance passenger rolling stock

The consumption shown in Figure 19 can be considered comparable to the previous figures and graphs even with the slight differences in the breakdown of the traction component data, though the expenses for comfort appear to be higher than for Hungarian AC trains: 15.13% in total (11.2% + 2.3% + 1.6% + 0.03%). But this is expected given the type of service offered by "long-distance" trains.

4. Assessment of energy saving measures

This section aims to highlight the most recommended and prescribed solutions among the participants, for quicker and more cost-efficient implementation. The assessment was carried by having the group sharing knowledge and experiences of the different energy saving solutions that were tested (see point *2.4 Sources of information*

4.1. Methodology

Each of the solutions contained within chapter 4 have been reviewed and assessed in terms of their impact and necessary investment.

The assessments are work of qualitative expert judgment and no system approach was made in the document. The solutions are single and non-comparable examples and evaluated by expert qualitative judgment. Experts involved in EU-Rail or S2R projects also contributed to the set. Multiple solutions related to a same field can be retrieved in a same table, including S2R solutions related to energy saving.

The assessments were carried out by comparing and judging the solutions relative to each other, across five categories:

- **Rolling stock** solutions
  Any hardware improvements
- **Operations** solutions
  Any solution to improve the energy efficiency of operations or avoid consumption
- **Infrastructure** solutions
  Any solution to save energy in railway asset management and improve efficiency
- **Buildings** (including stations) solutions
  Energy saving solutions for stations and buildings
- **Processes** solutions
  Any improvement to a railway management or operational process that could result in energy savings

The assessments are plotted against two axis, "ease of implementation" (costs, timeframe, and effort) and "energy saving potential" (Benefits). The solutions were placed on these two axes by collective consensus during a series of online UIC Energy Saving Taskforce meetings, through a discussion and judgment of the solution using collective experience. The estimated benefits are relative to the usual equipment/use/area of rail operation. The registered participants and contributors of the taskforce are listed in Appendix 1.

The assessment was validated against literature on the highest users of energy in the railway system. The authors of this report also professionally reviewed the document for quality management purposes.

4.2. Assessment and classification of rolling stock solutions

From an operator's point of view, procuring new rolling stock is the simplest way to make sure that their operations will benefit from the most modern efficiency levels for all electrotechnical, aerodynamic and rolling resistance aspects as well as for auxiliary system efficiency and their smart management. Of course, this means that the supplier will have had to embed state-of-the-art innovation for the systems' efficiency into the rolling stock. Nevertheless, it is important to upgrade the equipment, according to the compatibility of the rolling stock (however, to the extent that the saving is worth the cost for the upgrade). Therefore, the catalogue in section *5*

Energy saving measures will only focus on the specific potential upgrades that could be applied to existing rolling stock or included in recently developed rolling stock.

Enabling and improving regenerative braking is considered a sound strategy for immediate energy saving, however, when rolling stock is not equipped with regeneration-capable brakes, the change is expensive, as shown in Figure 20.

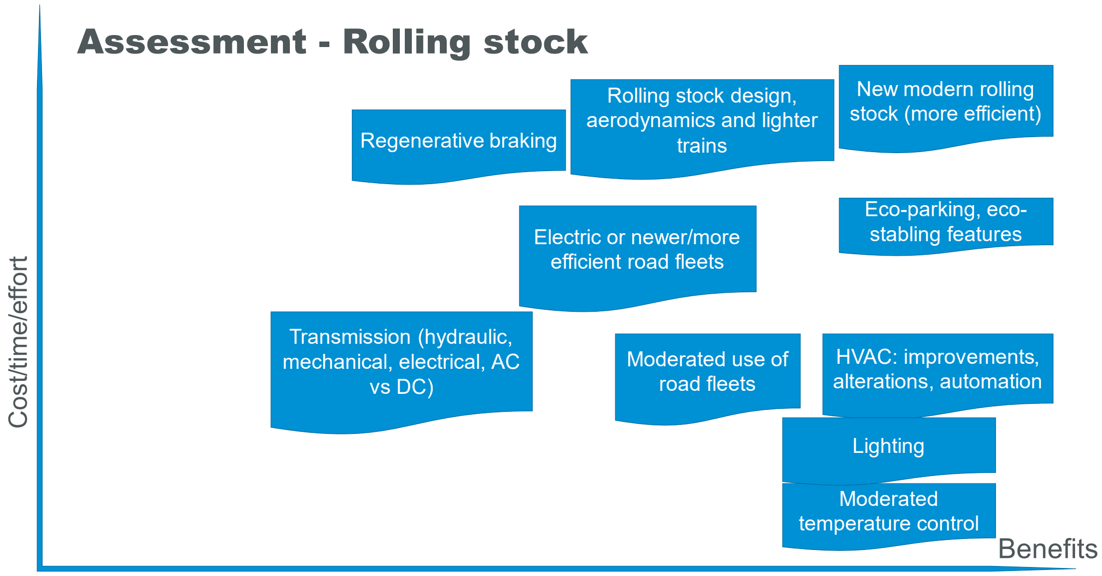

Figure 20: Main potential energy saving solutions for railway rolling stock sorted by cost/benefit ratio assessment

4.3. Assessment and classification of operation solutions

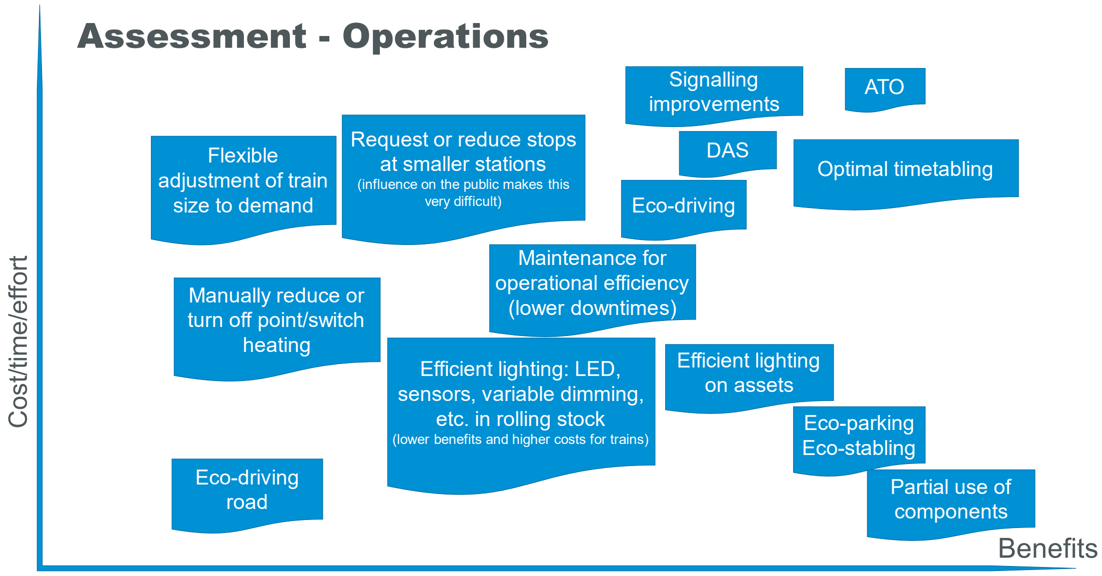

Figure 21: Main potential energy saving solutions for railway operations sorted by cost/benefit ratio assessment

4.4. Assessment and classification of infrastructure solutions

The benefits of renewable energy production are not always clear as purchased energy can also be green, therefore this can merely be seen as changing the source of energy, however:

- Renewable energy production replaces energy purchasing (of potentially more expensive electricity)
- Green energy supply - no emissions related to power generation
- Benefits to being independent from the public grid
- Proximity means less transmission losses

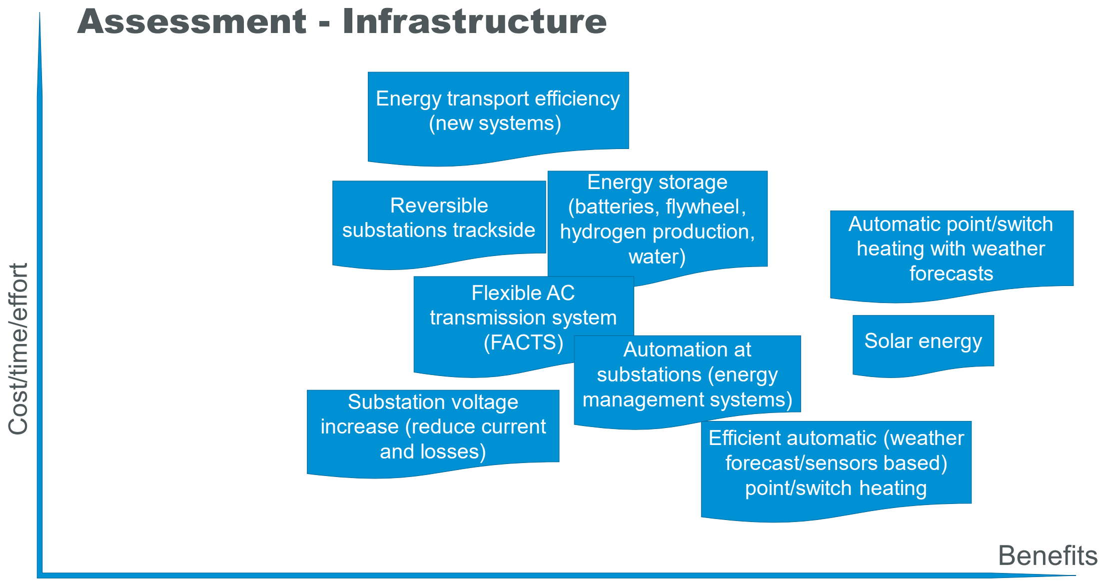

Figure 22: Main potential energy saving solutions for railway infrastructure management sorted by cost/benefit ratio assessment

4.5. Assessment and classification of building solutions

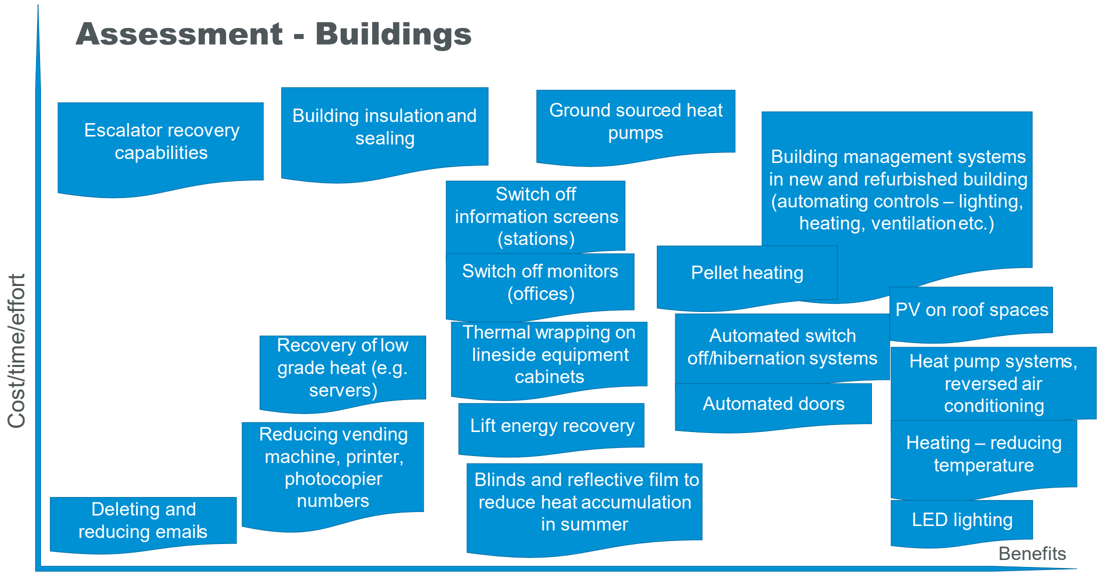

Figure 23: Main potential energy saving solutions for railway building and station management sorted by cost/benefit ratio assessment

4.6. Assessment and classification of process solutions

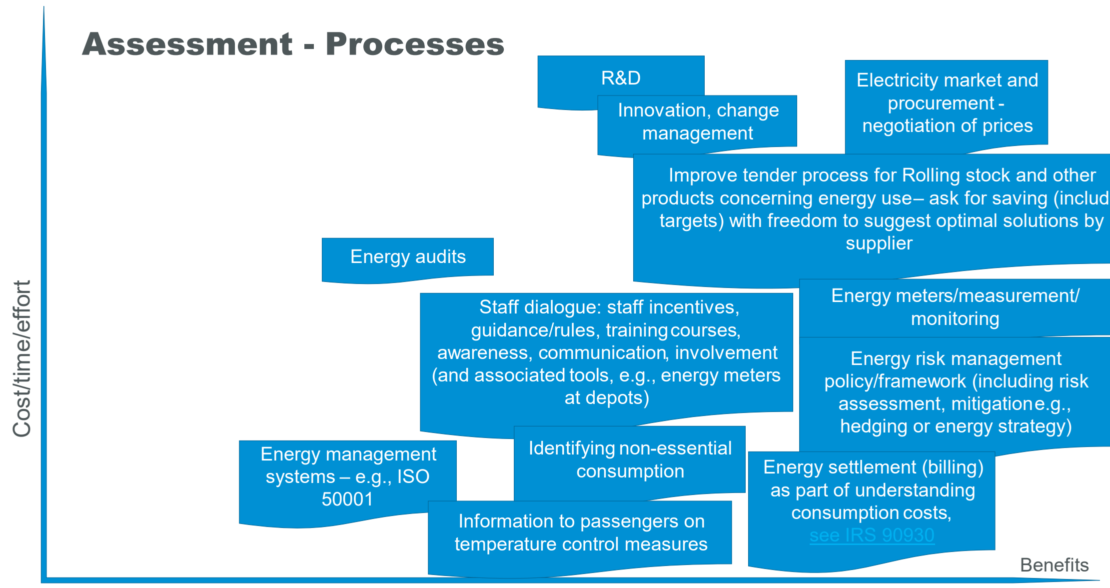

Figure 24: Main potential energy saving solutions for railway management processes sorted by cost/benefit ratio assessment

5. Energy saving measures

One of the UIC Energy Saving Taskforce's goals was for UIC members to share and highlight the measures that were implemented immediately in reaction to the energy price surges. On a larger scope, medium- or longer-term solutions that were important to accelerate or consider in the close future were also listed.

The first output of this activity is therefore a catalogue of new or known solutions, listing simple and complex solutions that UIC members have implemented and could implement to further save energy. As for the initial assessment, the set of solutions was broken down as follows:

- **Rolling stock** solutions
  Any hardware improvement
- **Operations**
  Any solution to improve the energy efficiency of operations or avoid consumption
- **Infrastructure** solutions
  Any solution to save energy in railway asset management and improve efficiency
- **Buildings** (including stations)
  Energy saving solutions for stations and common buildings
- **Processes**
  Any improvement to a railway management or operational process that could result in energy savings

For increased clarity, the solutions will be marked according to the following criteria (adding to the assessment made during Taskforce meetings):

- Innovation (to what extent the solution is pioneering)

	Innovation
Low	Technique has been known for many years and is widespread
Medium	Technique is known, recent and/or moderately used
High	Innovative technique, recently developed

- Ease/rapidity/affordability (considering the costs, time, effort to be spent on the solution)

	Ease/rapidity/affordability
Low	Expensive, long and/or complicated to implement
Medium	Moderate investment, moderate time and/or efforts required
High	Easy to implement, lowlight investment, time and/or efforts

- Benefits (level of reported benefits from trialling/implementing the solution)

	Benefits
Low	Very moderate and/or small-scale energy saving
Medium	Moderate savings and/or with a good systemic effect
High	Substantial savings and/or wide-spread benefits

This scale will be shown as follows:

Levels	Low	Medium	High

UIC Energy Saving Workshop

Alongside the recurring online sessions, it was also suggested that a conference and workshop be held to address the issues by specific category.

On 1 March 2023, a workshop was created to host 3 sessions, merging 6 important topics as addressed in this report:

1. Rolling stock and operations (abbreviated to RS/OPE)
2. Infrastructure and stations (and buildings) (abbreviated to Infra/Stations)
3. Energy procurement, contracts, and partnerships (abbreviated to Energy markets)

The workshop and sessions welcomed one or a few experts from the following companies, each session welcoming between 8-12 experts of these:

AIIB - Asian Infrastructure Investment Bank
ALSTOM
Amtrak
Bane NOR
BLS AG
CAF
CER
CFL
CFL cargo SA
CFL Multimodal
Connected Places Catapult
CRRC ZIC
East Japan Railway Company Paris Office
Eurostar - Thalys
Fundación de los ferrocarriles españoles (FFE)
Infrabel
Jernhusen AB
Junta de Seguridad en el Transporte (JST)

Knorr-Bremse
KORAIL
Lineas
MTA Metro-North Railroad
Network Rail
NMBS
NS
ÖBB-Holding AG
ÖBB-Infrastruktur AG
PKP Energetyka
ProRail
Rail Business
Rail Cargo Austria AG
SBB AG
Siemens Mobility GmbH
Slovenske železnice, d. o. o.
SNCB NMBS
SNCF
SNCF RESEAU
SNCF Voyageurs
Strukton
SYSTRA
Thalys
UIC

Each session was chaired by a duo of experts.

Overviews of the solutions mentioned by the Taskforce Members were created for each category and occasionally adjusted. An overview of the outcomes, discussions, and solutions of these sessions is featured below, feeding into the different parts of the report.

The participants of the *Rolling stock and operations (RS/OPE)* session made a ranking of preselected solutions and estimated the average costs in terms of investment, effort and time compared to their benefits. The results are shown in

Topic	Cost in million EUR (indicative)	Time (indicative)	Complexity	Benefit
1. Eco-driving training for drivers	0.1	8 months	Low	2% (1%-3%)
2. DAS	0.8	2.5 years	High	6%-7% (3%-10.5%)
3. Connected DAS (additional UNIFE input)	1.5	1.5 years	High	11% (5.5%-16.5%)
4. Eco-stabling (manual)	0.01	1 year	Medium	1.8% (0.9%-2.7%)
5. Eco-stabling HVAC (automatic)	0.24	1 year	Medium	1.8% (0.9%-2.7%)
6. Optimise traction converter software	0.8	2 years	High	4% (2%-6%)
7. Occupancy-dependant fresh air intake	0.1	1.5 years	Medium	0.6% (0.3%-0.9%)
8. HVAC heat pumps	0.4	2years	High	0.7% (**0.1%-10%**)
9. Optimise traffic management	1.2	3 years	High	4% (2%-6%)

Remark: All values are given as an indication by the participants, typically with a range of + / 50%

Complexity scale

Low (only one system affected) Medium (> one system or 2 units) High (>2 systems and more than 2 units)

Table 5 below.
The numbers indicated here are indicative, after a group assessment during the session.

Topic	Cost in million EUR (indicative)	Time (indicative)	Complexity	Benefit
1. Eco-driving training for drivers	0.1	8 months	Low	2% (1%-3%)
2. DAS	0.8	2.5 years	High	6%-7% (3%-10.5%)
3. Connected DAS (additional UNIFE input)	1.5	1.5 years	High	11% (5.5%-16.5%)
4. Eco-stabling (manual)	0.01	1 year	Medium	1.8% (0.9%-2.7%)
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9. Optimise traffic management	1.2	3 years	High	4% (2%-6%)

Remark: All values are given as an indication by the participants, typically with a range of + / 50%

Complexity scale

Low (only one system affected) Medium (> one system or 2 units) High (>2 systems and more than 2 units)

Table 5: Rolling stock and operations solutions as rated during the UIC Energy Saving workshop session

1. Participants at the *Infrastructure and stations (Infra/Stations)* session gave a detailed set of focus areas for the solutions and challenges related to infrastructure management activities:

Infrastructure focus areas & specific solutions

- Traction system losses
    - Efficient timetabling

- Connected driving advice for drivers (IM timetable & IM disruption management for operators)
- Optimal track setup (gradients, curves, and speed limits)
- Maximising energy recovery from braking
- Efficient distribution of recovered energy (reuse in the IM grid or transfer to the public grid)

- Avoid peak demand to reduce losses
- De-icing and point/switch heating saving potential

Building and station focus areas

- Monitoring
  - Unclear about the costs: storing and analysing data
- Lighting & dimming
  - LED since stations require a lot of lighting
- Behaviour
  - Involvement of staff by any means
- Technology
  - Cost & time for installing renewable energy
  - Cost & time for installing energy storage systems

2. The *Energy procurement, contracts, and partnerships (Energy markets)* session addressed the specificities of energy purchasing setups for railways in European countries via a questionnaire, and identified the common challenges. As a start, Figure 25 shows how the interactions of railways with the energy market may be organised, considering that, in some cases, the railways themselves can be an energy market stakeholder too.

Market types

	Simple contract	Developed contract
RU contract with supplier	• Simple market with choice • Choice of suppliers • RU energy procurement • Standard energy rates • Little complexity	• Developed market • RU energy procurement • Wide choice of purchasing strategies available • Choice of suppliers • Risk on RU side
IM* contract with supplier or National Body	• Simple market • IM energy procurement • Standard energy rates for users • Little involvement from RUs	• Developed IM market • IM energy procurement • RUs can negotiate their own conditions • Risk on RU side

Figure 25: Defining the possible setup for a railway's management of energy contracts in a country

According to the information collected on market organisation during the session, it was possible to show where each participating country would fall within the possible setups (Figure 26).

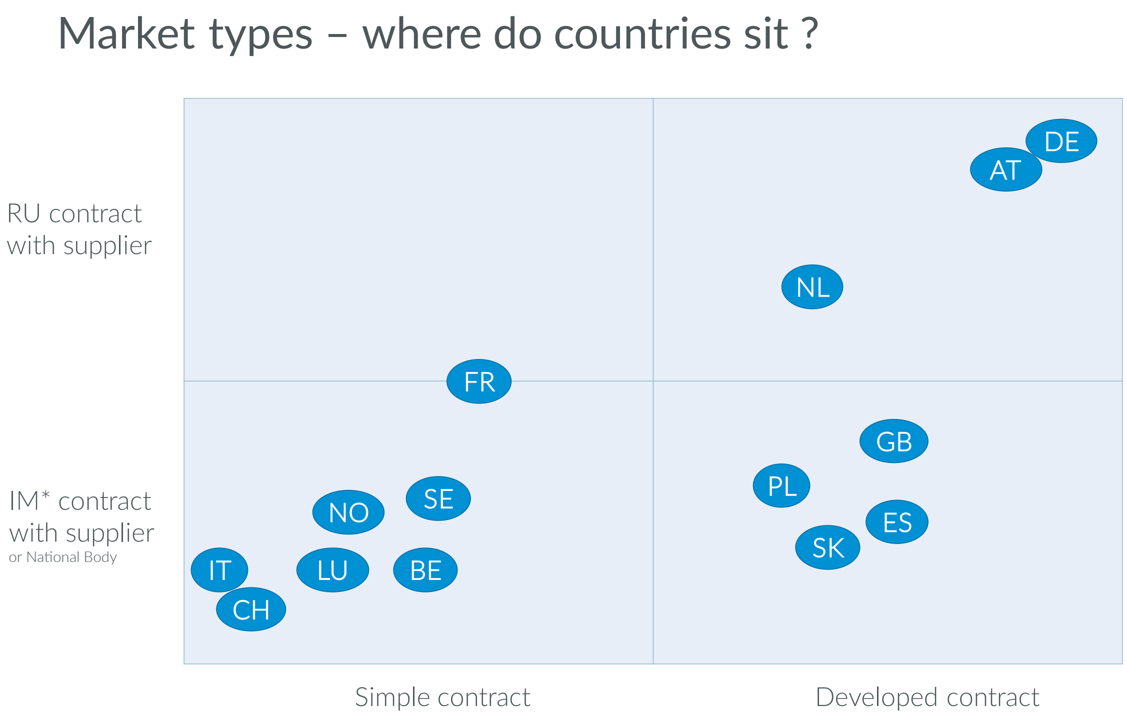


Figure 26: Energy market type by country, according to setups defined in Figure 25

To summarise the session:

- Energy management for the railway market is organised differently from country to country, which makes a unified approach challenging
- The railways invest substantial effort in connecting railway infrastructure to renewable energy, which helps limit exposure to electricity price fluctuations, as battery trains (and energy storage in general) could also partially help to reduce stresses on the energy grid at peak times.
- Railways want to support countries in reaching their climate transport goals. But, with the energy market's strategy being to shift risk onto the end consumer, and due to prices in 2023 being higher than in previous years, it is hard for railways to stay profitable and viable. If rail is not a competitive transport mode, transport demand will shift to more polluting and less energy efficient but cheaper modes of transport (likely with higher external costs).

5.1. Rolling stock

This section introduces a set of solutions that were shared among the UIC Energy Saving Taskforce members regarding measures or actions to be undertaken on rolling stock and its hardware to improve efficiency and save energy.

As introduced in the assessment of measures to reduce traction energy consumption, by Douglas et al. 2015, the main energy saving principles for train design are to:

- Maximise drive-chain and motors efficiency through their design

- Reduce the resistance to motion with:
    - A reduction in train mass (the energy saved is approximately half of the mass reduction, eg -10% mass would save 5% energy)
    - More aerodynamic trains (even though the benefits are not as high at lower speeds, and resistance is always present and amplified in tunnels. The consumption resulting from a poor aerodynamic profile, although small, cumulates over time, and may be worth streamlining for all trains), *see 5.1.9 Aerodynamic efficiency Aerodynamic efficiency of* rolling stock
- Be equipped with efficient and smarter auxiliary systems (computer-based management), (see *5.1.6, 5.1.7)*

For a proper understanding, section *5.1 Rolling stock*, refers to measures on the rolling stock's built-in hardware energy consumption, and anything to do with adjusting the rolling stock's equipment management or software enhanced management for energy saving is described in section *5.2 Operations.*

Overview of rolling stock solutions

The following diagram (Figure 27) gives an overview of the solutions for improved rolling stock equipment.

This overview is not an exhaustive list, but the result of brainstorming for, and during the Energy Saving workshop mentioned above. More specific solutions forming part of the catalogue may not be appear here.

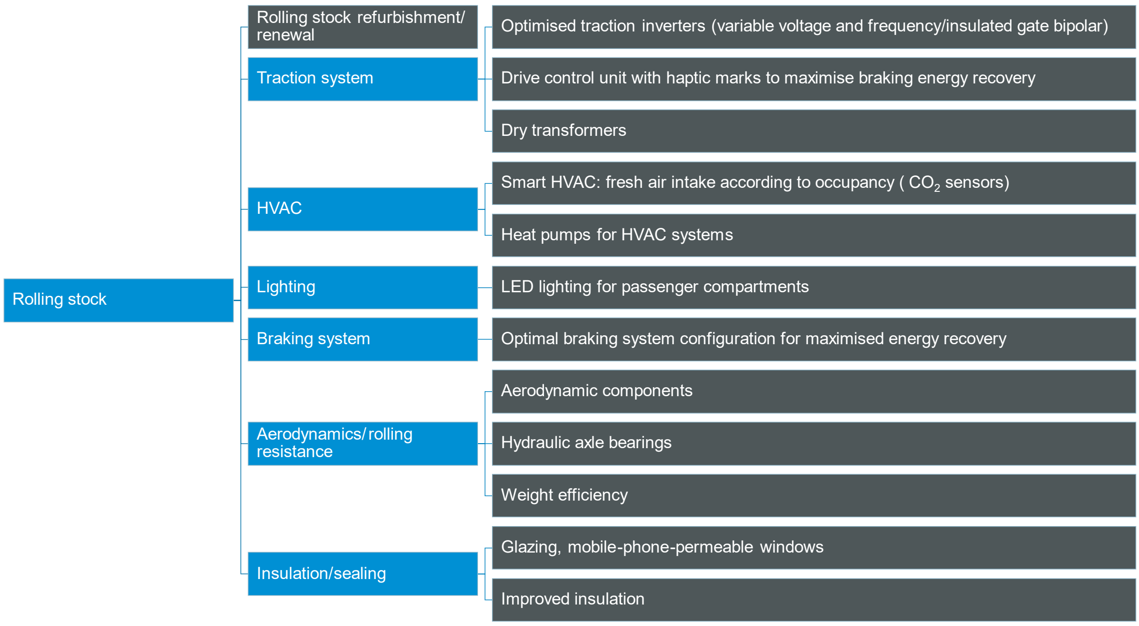


Figure 27: Overview of rolling stock hardware upgrade solutions, as an outcome of the rolling stock and operations session of the UIC Energy Saving workshop

5.1.1. Master Silicon Carbide (SiC) semiconductors

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	Traction systems
Solution	Use new breakthrough semi-conductor technologies within traction systems components
Description	State-of-the-art trains are equipped with IGBT converters. In the future they will be replaced by silicon carbide converters, that allow a higher switching frequency and cause lower losses within the propulsion system. Due to the higher switching frequency the harmonics of the input and output currents are reduced. This leads to lower harmonic losses of the motor, inductor and transformer. Furthermore, silicon carbide converters have a lower weight what further reduces the energy usage.
Objective	More efficient traction systems thanks to new SiC semi-conductors i.e. very low losses technology
How to	The technology can be applied to converters for new or refurbished trains.
Costs and resources required	Power electronics price category. Refurbishment efforts and investment and/or new vehicles procurement investment.
Benefits Effects	Reduced life cycle cost thanks to lower maintenance (up to -15%) and energy costs (up to -20%) and capital cost reduction via virtual validation & certification Benefits compared to silicon based technology (Knorr-Bremse, UIC Refurbishment of rolling stock 2016 workshop): • 8x higher switching frequencies lead to smaller magnetic components • Higher breakdown voltage • Better thermal management • Potential converter weight reduction by ~20% • Potential converter size reduction by ~20%
Effects (CO_2)	Related to energy saving and electricity generation mix
Ease of implementation	Applied to rail traction systems (tramway, metro, sub-urban, regional)
Constraints, challenges, or lessons learnt	-
S/M/L term	Medium term
Efficiency	Reduced losses. Knorr-Bremse achieved 3% savings in 2017 by only focusing on size and weight.
Maturity	Solutions ready for prototype testing
Mentioned by	• Shift2Rail PINTA projects • SNCF (*5.3.17 Medium voltage direct current electrification systems*) • Knorr-Bremse
Experience	-

Comment	-

- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA2
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA3

5.1.2. Insulated gate bipolar transistor (IGBT) traction converters

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	Optimal energy consumption for operations
Solution	Wideband electronic power semiconductors that can replace silicon-based components (insulated-gate bipolar transistor (IGBT))
Description	Retrofitting traction converters to insulated gate bipolar transistor (IGBT) inverters
Objective	Reduce losses in energy conversion for traction. Fixes possible obsolescence due to the non-availability of parts for older traction converters
How to	Replace older traction converter units or switch modules within a traction converter with more efficient IGBT technology
Costs and resources required	Hardware upgrade: High cost, high risk solution for older locomotives and EMUs Software optimisation: Approximately 0.8 million euro per locomotive.
Benefits Effects	Hardware upgrade: Reduce losses in energy conversion for traction. Fixes possible obsolescence due to the non-availability of parts for older traction converters. Can extend the service life of locomotives or EMUs Software optimisation: Around 4% improvement in energy efficiency over the total traction energy consumption (evaluated by SBB over 100000 commercial operations with different coaches to figure the energy savings).
Effects (CO_2)	According to the electricity production mix for a reduction of around 4% in traction energy consumption
Ease of implementation	Hardware upgrade: High risk, lots of engineering required
Constraints, challenges, or lessons learnt	Hardware upgrade: Can have an impact on other systems like odometry, train protection systems, accreditation
S/M/L term	Hardware upgrade: Long-term Software optimisation: Mid-term
Efficiency	For SBB, very high (4-8%), depending on the current traction converter 12,4% of traction energy saving compared to GTO traction converter (NomadTech, UIC Refurbishment of rolling stock 2016 workshop)
Maturity	High
Mentioned by	SBB, DB, Shift2Rail, NomadTech

Experience	See above
Comment	-

- https://news.sbb.ch/artikel/117742/modernisierung-re-460-der-erste-prototyp-ist-auf-der-schiene
- https://news.sbb.ch/artikel/73490/modernisierungsprogramm-fuer-die-re-460
- Reference for the energy saving assessment: https://news.sbb.ch/artikel/98756/das-zugpferd-der-bahn-2000-faehrt-immer-klimafreundlicher

5.1.3. Electromechanical Brake System (EMB)

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	Braking system
Solution	New generation of Electromechanical Brake System
Description	New generation of Electro Mechanic Brake devices that enables the transition towards the air-less trains, simplifying the train's architecture (brake-by-wire) and supports the removal/reduction of air compressor (weight and energy reduction)
Objective	Achieve weight and energy consumption reduction
How to	-
Costs and resources required	-
Benefits Effects	• Energy savings of up to 15% • Weight reduction • Efficient regeneration • Reduced use of material (copper)
Effects (CO_2)	-
Ease of implementation	Rolling stock compatibility or procurement
Constraints, challenges, or lessons learnt	Research Early adoption
S/M/L term	Long Term
Efficiency	-
Maturity	Expected to be ready for serial production in 2026 Good applicability perspectives for all types of passenger trains, linked with effective migration to air-less solution of other sub-systems (e.g. suspension, pantograph, MTB)
Mentioned by	Shift2Rail PIVOT projects
Experience	-
Comment	-

- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot2

5.1.4. Maximise braking energy recovery

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

Field	Optimise energy consumption during operation
Solution	Prioritise regenerative braking over other braking systems, and give haptic feedback regarding maximum braking efficiency to drivers
Description	The use of regenerative brakes should be maxed out before other brake systems are blended in For passenger trains, it is possible to define a notch (one for driving, one for braking) at the brake handle at points of high system efficiency to give haptic feedback to the driver
Objective	Maximise regenerative braking and optimise train operation
How to	The brake forces of modern trains are operated with a single brake handle. Define a notch on the handle at the point of highest drive efficiency, approx. 75%. Define a notch on the handle at the point where only regenerative braking is applied for the majority of the time, approx. -50% Which brake system is used at which point of operation is determined by the train TCMS which must be programmed accordingly The blending and switch-over timing between the different braking systems must consider different failure scenarios, friction conditions and must comply with local standards Support effectiveness by accompanying this solution with driver training
Costs and resources required	Engineering to calculate points of efficiency TCMS programming plus testing and approval Installing notches on the brake handle
Benefits Effects	• Maximise regenerative brake energy being fed into the grid • Reduce the wear of mechanical brakes
Effects (CO_2)	Dependent on the primary energy mix
Ease of implementation	Medium
Constraints, challenges, or lessons learnt	• Sole use of regenerative braking and the possibility of feeding back the regenerated energy into the grid may be limited in some countries • TSI Requirement, see EN 50388-1
S/M/L term	Long term
Efficiency	High (SBB has managed to recover more than 43% of long-distance trains' traction energy thanks to an efficient regenerative braking strategy, including this solution. Long-distance trains have an optimised journey profile thanks to their adaptive driving app. Therefore, the maximising of regeneration levels in deceleration phases (coasting & braking) will result in optimal recovery levels. It also considers recovered energy in the rail grid.)

Maturity	Mature
Mentioned by	SBB, BLS, SOB, Renfe (optimal recovery with rolling stock)
Experience	Involve senior train drivers at an early stage to implement a usable and accepted solution
Comment	Complementary driver training is highly recommended

5.1.5. Dry transformers

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Special note More experience sharing needed

Field	Optimal energy consumption for operations
Solution	Vehicles with a dry transformer require less energy than comparable vehicles using a conventional, oil-cooled transformer
Description	• Due to the oil-free operation and the resulting reduced weight, the active mass of the conductor materials can be increased. The losses are reduced, both in terms of purchasing electrical energy and of recuperation • Pumps and sensors for monitoring and circulating the oil are completely omitted in a dry transformer, which reduces the energy requirements of auxiliary operations. In addition, the costs for maintenance are reduced correspondingly
Objective	To reduce the vehicles' energy requirements
How to	• Due to the oil-free operation and the resulting reduced weight, the active mass of the conductor materials can be increased. This reduces losses, both in terms of purchasing electrical energy and of recuperation • The pumps, sensors, etc. required for monitoring and circulating the oil are completely eliminated. E.g., the 2.9kW transformer oil pump is no longer needed, which reduces the need for auxiliary operations
Costs and resources required	SNCF: Expensive hardware
Benefits Effects	A more than 7% reduction in a vehicle's energy consumption by no longer using an oil-cooled transformer Annual saving by using dry transformers is approx. 9000CHF (approx. 9400€/10300$) per vehicle. In addition, the specific energy consumption per gross tonne-kilometre changes
Effects (CO_2)	-
Ease of implementation	-
Constraints, challenges, or lessons learnt	The double traction measurement runs show savings of between 7.5% and 12.5% of the total energy consumption. The reported potential of 7% to 10% therefore seems realistic
S/M/L term	-
Efficiency	A potential saving of 78.9MWh per vehicle per year
Maturity	-

Mentioned by	-
Experience	SBB's pilot: • An oil transformer vehicle draws a total of 393.5kWh of energy, 168.7kWh of which are recuperated. The net demand is therefore 224.8kWh • A dry transformer vehicle draws 368.7kWh of energy (-6.3%), of which 171.9 kWh is recuperated (+1.8%), the net demand is therefore 196.8 kWh (-12.5%)
Comment	-

- https://news.sbb.ch/artikel/117742/modernisierung-re-460-der-erste-prototyp-ist-auf-der-schiene
- https://news.sbb.ch/artikel/73490/modernisierungsprogramm-fuer-die-re-460
- Reference for the energy saving assessment: https://news.sbb.ch/artikel/98756/das-zugpferd-der-bahn-2000-faehrt-immer-klimafreundlicher

5.1.6. Heat pumps for enhanced HVAC efficiency

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Low	High

Special note More experience sharing needed

Field	Optimal energy consumption for heating, ventilation, air conditioning and cooling (HVAC)
Solution	Replacing conventional heating systems with the most efficient type of heating or cooling system. Also enabling the use of natural refrigerants (hence avoiding potential leaks of powerful greenhouse gas), for an eco-friendly air conditioning (S2R)
Description	Heat pumps are inherently more efficient than common electric heaters; The use of heat pumps may lead to substantial energy savings in heating as their performance is between two and four times above common electrical resistors. Moreover, heat pumps are capable of working as air-conditioning units when cooling is required, avoiding the need for double the equipment and consequently allowing for weight savings Their capacity can also be optimally regulated according to demand, for instance by means of variable frequency compressors (A. González-Gil et al., 2014). S2R: A heat pump can be integrated to reduce the energy usage for heating. This technology can be applied for new trains or during the refurbishing of existing trains. Additionally, future systems for HVAC use natural gases like air or CO2. Compared to state-of-the-art HVACs with artificial gases they have a highly reduced climatic impact.
Objective	Save energy spent for heating, cooling, or ventilation for rolling stock (and avoid artificial refrigerant leaks, i.e. powerful greenhouse gas emissions)

How to	Using inherently more efficient (known) heating and cooling technologies. Heat pumps having the specific advantage to being able to provide both heat and cold air, thus can help reduce the overall weight of a train.
Costs and resources required	Refurbishment efforts and investment, according to HVAC system complexity, and/or new vehicles procurement investment.
Benefits Effects	Reducing traction energy consumption: • By reducing the train's weight • By increasing the HVAC system's efficiency S2R: • Energy savings up to 20% due to integrated heat pump • Reduction of global warming due to avoidance of synthetic refrigerants like R134a • Overcome the constraint to use synthetic refrigerants
Effects (CO_2)	Avoiding artificial/fluorinated (powerful greenhouse gas) refrigerants, thus avoiding stray leaks of usual air conditioning systems
Ease of implementation	According to HVAC system complexity for refurbishment. Easier if the technology is directly designed for use in the new rolling stock
Constraints, challenges or lessons learnt	The complexity of rolling stock HVAC systems makes it hard to implement. Easier if the HVAC system is centralised
S/M/L term	Short/medium term
Efficiency	-
Maturity	S2R: Good perspectives, applicable for all passenger train segments. Expected to be ready by 2024
Mentioned by	SBB, UIC, S2R PIVOT projects
Experience	-
Comment	-

https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot

https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot2

5.1.7. Smart/automated heating, cooling and ventilation (HVAC)

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Special note More experience sharing needed

Field	HVAC energy saving
Solution	• Automatic HVAC adjustment to carriage CO_2 levels • Automatic HVAC adjustment to carriage thermostats • Automatic HVAC adjustment to weather data and forecasts • Auxiliary converters with variable frequencies to supply HVAC systems (condensers and compressors)
Description	• This HVAC system can adapt the ventilation to current needs for passenger compartments based on CO_2 levels or live temperature
Objective	Reduce the energy consumption

How to	Smart HVAC management: CO_2 monitoring tends decrease energy costs by cutting ventilation, heating, and cooling at off-peak times. By fitting CO_2 detectors, the onboard HVAC system can monitor the air quality and evaluate the number of passengers. Using this information, the system can control fresh air intake from the outside (e.g., flaps with 3-4 positions), and accurately regulates temperature according to passenger requirements, therefore reducing power consumption
Costs and resources required	Price of retrofitting HVAC system with sensors, or with new rolling stock
Benefits Effects	• Energy savings • Improved air quality in wagons, thus improving passenger comfort • Improved temperature regulation, thus improving passenger comfort
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption. Reduced exhaust emissions due to reduced HVAC demand.
Ease of implementation	• Requires upgraded hardware and software in all carriages
Constraints, challenges or lessons learnt	Education of the staff to new systems and proper management
S/M/L term	According to retrofitting possibility: Short term if the HVAC system can easily be paired with sensors Medium/long term if the HVAC system is not flexible, or change is relying on a fleet renewal
Efficiency	High
Maturity	CO_2-adapted ventilation fully developed and deployed by SBB (heating/cooling - not yet)
Mentioned by	SBB
Experience	-
Comment	-

5.1.8. Lighting system upgrades

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium	Medium

Special note More experience sharing needed

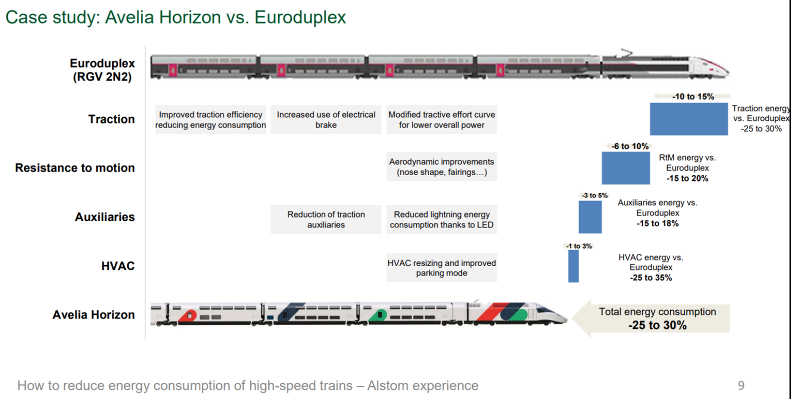
Field	Improvements and alterations to rolling stock
Solution	Upgrading lighting on fleets
Description	Light-emitting diode (LED) lighting has proven to be more energy efficient while having a longer lifespan than previous lighting technologies • Trenitalia: Installed LED lighting where absent (e.g., new Vivalto double-deck carriages and medium-distance coaches) on the DBR (Divisione Business Regionale) (regional trains) fleet and replacing on-board lighting fixtures with LED technology on the entire DBIC fleet • SBB: Switching to LED lighting

Objective	Reduce the energy consumption of current fleet lighting and AC systems. Benefits expected in 2023-2024
How to	Current systems replacement
Costs and resources required	LEDs are slightly more expensive than other types of lamps, but are much more efficient and now have a much longer lifespan
Benefits Effects	Efficiency of LEDs can be much higher for a similar lighting level (LED bulbs use around 80% less energy than incandescent bulbs and 40% less than halogen, according to FS RFI)
Effects (CO_2)	According to electricity production mix for a reduction of lighting energy consumption. Reduced exhaust emissions due to reduced auxiliary system demand.
Ease of implementation	Dependent to the initial rolling stock lighting system
Constraints, challenges or lessons learnt	Retrofitting a specific rolling stock lighting system can add complexity
S/M/L term	Medium (short a small fleet level)
Efficiency	(Cost over effect)
Maturity	Mature
Mentioned by	FS Trenitalia, SBB
Experience	-
Comment	-

5.1.9. Aerodynamic efficiency of rolling stock

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium/High	Low	High
Special note	Inventive solution		

Field	Reducing rolling resistance
Solution	Reduce air resistance to the minimum possible by improving fairing (especially crucial at high speeds but not only)
Description	• SNCF: Improve high-speed train fairings to facilitate airflow in order to reduce the impact of air resistance on rolling stock The most recent fairings are thought to better penetrate the air, reducing friction and decreasing energy consumption. • Aerodynamic effects of tunnels will result in a significant increase in train energy consumption shorten life of railway train/tunnel system, and increase maintenance cost (Niu et al., 2020). Because of that specific constraint, thinking about the most aerodynamic profile for rolling stock that will operate through tunnels (or closed/semi-closed sections) is important (or operate most aerodynamic rolling stock).
Objective	Reduce traction energy consumption by optimising airflows
How to	• New rolling stock • Adaptation of older rolling stock's fairing after study and tests Even though the benefits are not as high at lower speeds, resistance is always present and amplified in tunnels. The

	consumption resulting from a poor aerodynamic profile, although small, cumulates over time, and may be worth streamlining for all trains: Prioritise from higher speeds and highest number of tunnels tracks, to lower. Air resistance can be studied via modelling with computational fluid dynamics software (CFD)
Costs and resources required	-
Benefits Effects	SNCF: A 20% reduction in energy consumption is expected by deploying the new TGV M. (Contribution of both improved traction system's efficiency and improved train aerodynamics of fairing, pantographs and wheelsets (between 15% and 20%))  Source: UIC Alstom (see footer) • Energy saving • Noise reduction • Power management
Effects (CO_2)	According to electricity production mix for a reduction of electric traction energy consumption. Reduced exhaust emissions due to fairing reducing tractive effort required.
Ease of implementation	Costs for studies and testing and for the deployment of the modification Time lost for rolling stock maintenance instead of being in service
Constraints, challenges or lessons learnt	In the equation $F= a+bv+cv^2$, where c (coefficient of friction) increases with the squared velocity (v) is a priority to be worked on In terms of air penetration, the aerodynamic wake of the train is an important issue (the Davis coefficients, a, b, c are constants that are found by analysing the train dynamics, and relate to the static resistance, rolling resistance and aerodynamic resistances respectively)
S/M/L term	Medium/long term
Efficiency	Relative to operation speed and stopping frequency. But any improvement will result in energy savings.
Maturity	High for high-speed
Mentioned by	SBB, SNCF, Renfe
Experience	TGV M, AVE (Pato), Shinkansen
Comment	-

- [French] https://www.rmcbfmplay.com/info-programme/rmc-decouverte/tgv-m-la-techno-du-nouveau-fleuron-de-la-sncf

- UIC High-speed rail Congress, Alstom presentation, 3.3 Operations/Energy efficiency, Morocco, 2023
  https://uichighspeed.org/submissions/

5.1.10. Hydro-elastomeric axle-guide bearings

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High

Special note More experience sharing needed

Field	Reducing rolling resistance
Solution	Hydro-elastomeric axle-guide bearings for double-sided use in axle-guide bearings of rail vehicles.
Description	Hydro-elastomeric axle-guide bearings with internal and/or external hydraulic damping for use in axle-guide bearings Hydro-elastomeric axle-guide bearings have a high longitudinal stiffness during high speeds, and a low longitudinal stiffness, especially during slow cornering, to reduce wheel abrasion and keep wear and maintenance as low as possible
Objective	Reduce wear and wheel and rail abrasion, resulting in decreased energy consumption. Has the same service life as conventional axle-guide bearings.
How to	Hydro-elastomeric axle guide bearings replace conventional elastomeric axle guiding bearings within the bogie as “form, fit” devices.
Costs and resources required	The higher costs of the hydro-elastomeric axle-guide bearings will be compensated for by a reduced cost per kilometre for railway coaches (reduced rolling resistance for each equipped coach/wagon) Possible costs for the approval process
Benefits Effects	Reduced rolling resistance, wear and wheel/rail abrasion, resulting in decreased traction energy consumption
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption. Reduced exhaust emissions due to bearings reducing tractive effort required.
Ease of implementation	Form, fit, function replacement, but possible expenses for the approval process
Constraints, challenges, or lessons learnt	Used in most long-distance railway coaches in Switzerland, that don’t have active axle-guiding systems. Even regional EMUs are being fitted with this technology, due to the benefit of having a lower “train-path price”
S/M/L term	Long-term
Efficiency	Approx. 5 to 7.5MWh per Eurocity coach (single deck) per year (travel distance 300,000km)
Maturity	Approved by SBB after trials
Mentioned by	SBB
Experience	Established
Comment	HALL Hydro elastomeric axle-guide bearings HALL Bearing | Anti-vibration-solutions (trelleborg.com)

5.1.11. Thermal efficiency and insulation of rolling stock

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Low	Medium

Field	Thermal efficiency and insulation of rolling stock
Solution	Improving the capacity of rolling stock to retain heat or cold generated by HVAC systems
Description	Upgrading insulation of rolling stock
Objective	Reduce energy losses due to poor insulation which in turn is compensated for by a more intense use of the HVAC systems

How to	• SBB:
	  ○ Mobile-phone-permeable windows, to decrease the energy consumption of cellular repeaters (HF-Scheiben)
	  ○ Improved insulation and sealing of train bodies
	• S2R: Innovative door leaves and sealing
	  ○ New concept design of metallic door leaves based on metallic architecture introducing plastic/composite parts, innovative filling materials and sealing solutions for thermal insulation, acoustic attenuation, and weight optimisation. It will improve passenger comfort thanks to improved thermal and acoustic insulation, and reduce weight for less impact on the infrastructure or train weight constraints with the introduction of an optimised metal solution or a plastic or composite solution.
	  ○ New door leaves designed for thermal insulation, weight reduction and cost by selecting the best composite materials, manufacturing process and architecture.
	• UIC:
	  ○ Better insulation (properly sealed windows, doors and bodies with auto closing doors (avoiding substantial HVAC energy consumption (parked or not))
	  ○ Triple glazing
	  ○ Vehicle painting (white exteriors in hotter countries can reduce internal temperatures by up to 5 degrees when in full sun, darker paint for colder climates to favour absorption of infrared light over reflection). The use of solar reflective paint can also enhance insulation (reflecting heat into the body)
	  ○ Window films/tint (3M claimed 99% of UV can be blocked using films and up to 35% of heat can be reflected)
	(UIC Refurbishment of rolling stock 2016 workshop)

	○ Smart windows: windows which adjust their opacity according to sunlight levels to save energy on air-conditioning (A. González-Gil et al., 2014)
Costs and resources required	Refurbishment of car body elements, windows and listed elements costs. Rolling stock procurement efforts.
Benefits Effects	• HVAC energy saving
Effects (CO_2)	Related to energy savings and electricity generation mix
Ease of implementation	Windows of rolling stock have to be replaced, the insulation needs to be adapted and fitted to existing stock. Both can be carried out during maintenance work
Constraints, challenges or lessons learnt	Changes have to be compatible with onboard radiofrequencies use cases
S/M/L term	Medium/long term
Efficiency	-
Maturity	HF-Scheiben are fully developed and are currently deployed across different rolling stock Insulation of older rolling stock (EW IV) completed
Mentioned by	SBB, SNCF
Experience	-
Comment	-

5.1.12. Weight and capacity of rolling stock (Innovative materials for lighter car body, doors, and train components)

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

Field	Improved rolling stock capacity and weight
Solution	• FS: Higher capacity and lighter rolling stock (via procurement, whenever the refurbishment cost/benefit ratio is low). • S2R: Light car bodies • S2R: New concept design of metallic door leaves based on metallic architecture introducing plastic/composite parts, innovative filling materials and sealing solutions for thermal insulation, acoustic attenuation, and weight optimisation. • S2R: Lightweight Axle • S2R: Light running gear frame • Lighter components
Description	Optimal capacity on weight ratio. Finding any mean to reduce rolling stock's weight, to reduce impact on traction energy consumption: • FS Trenitalia: Fleet renewal or retrofitting for more energy efficient trains and improved electric train capacity

	• Heat pump HVAC (one system for heat and cold, see 5.1.6 Heat pumps for enhanced HVAC efficiency)
	• S2R: Lighter car body
	  ○ New materials, processes and technologies in the current car body concepts scalable for manufacturing
	  ○ Hybrid solutions with metallic/composites components due to optimal combination of properties and requirements for highspeed trains
	  ○ Substitution of welded extruded aluminium profiles by pultruded Carbon Fiber Reinforced Plastics (CFRP) and/or one-shot infusion panels of sandwich and CFRP
	  ○ Hybrid concept for validation metallic and composites components (manufactured with different technologies) due to optimal combination of properties and requirements
	• S2R: Innovative door leaves and sealing
	  ○ New door leaves designed for thermal insulation, weight reduction and cost by selecting the best composite materials, manufacturing process and architecture
	• S2R: Lightweight axle
	  ○ A new lightweight axle which significantly reduces weight, unsuspended mass, time for wheelset maintenance, production cost while at the same time increases safety against cracks and breakdown
	• S2R: Light running gear frame
	  ○ New materials, processes and technologies in the current running gear frames, substituting welded steel plates and profiles by monocoque CFRP structures and machined high end alloys reaching up to 50% reduction in weight compared to conventional solutions
	• Double deck trains
	• Modular sets

Objective	• Make the most of the existing fleet's capacity (for a better consumption ratio per passenger transported) by retrofitting into or procuring high-capacity rolling stock.
	• Achieve a significant weight reduction for the primary structures
	  ○ Innovations consider new materials and concepts that result in lower boogie weight of and consequently in a reduction of energy usage of the train
	  ○ Increase the performance of current metallic car body shells by incorporating composite materials into hybrid structures

How to	• S2R: For the car body shell or parts of it, composite materials or fibre reinforced plastic may be used instead of aluminium or steel. This reduces the weight and consequently the energy usage of the train. • UIC: See UIC-FFE 2017, part 1.2.2 New materials

	• FS: DBR (regional trains) fleet renewal by purchasing new, more energy efficient trains, such as Pop, Rock, bimodal Blues, and new medium-capacity electric trains with a speed of 160km/h. These trains have a better consumption/passenger ratio For the IC fleet, a call for tenders has started to purchase new IC coaches
Costs and resources required	Large retrofitting costs or investment into new rolling stock. Costs for suggested material might evolve with demand and production costs.
Benefits Effects	S2R: Up to 12% energy savings due to weight reduction. Improved passenger comfort (improved thermal and acoustic insulation) and reduce weight for less impact on the infrastructure or train weight constraints (optimised metal solution or a plastic or composite solution) FS: Reduced traction energy consumption by train-kilometre and by passenger/tonne-kilometre
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption due to lighter and higher capacity train (lower impact by passenger or tonne kilometre). Reduced exhaust emissions due to the reduced tractive effort required.
Ease of implementation	According to the specific improvement for lighter components or capacity upgrades, and rolling stock flexibility to adjustments. Otherwise through the purchase of new rolling stock.
Constraints, challenges or lessons learnt	Existing rolling stock flexibility
S/M/L term	Short/medium/long term according to component maintainability/modularity. Medium/long term for rolling stock heavy refurbishment or procurement.
Efficiency	Cost over effects: Medium, good payback over time
Maturity	S2R: • Light car body: Solutions ready for prototype testing. Applicable to metro/regional/high speed transport. • Door leaves: Solutions available. Mainly applicable to regional / commuter rolling stock market worldwide and extended to tramways, metros and up to very high speed trains market • Lightweight axle: Freight market in test period and subsequently metro application, available after 2023. Applicable to the whole rail market • Light running gear: Solution ready for prototype testing. Applicable mainly to high-speed rail FS: High maturity
Mentioned by	S2R: Shift2Rail PIVOT projects FS Trenitalia
Experience	-
Comment	-

- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=pivot2

5.1.13. High-speed motor on wheel

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	High speed traction systems
Solution	• Distributed traction on independent wheel bogie to increase traction capabilities • Permanent magnet motor with high power and torque density (in terms of weight and volume) • Inclusion of permanent magnet motor to increase traction capabilities
Description	Induction motors may be replaced by synchronous motors with permanent magnets. They have higher energy efficiency, but they require a separate converter for each motor. Permanent magnet synchronous motors may be directly connected to the wheels; hence no gearbox is required. This reduces the vehicle weight and energy usage. The disadvantage is that the motor weight and volume is increased due to the lower rotating speed.
Objective	Lighter and more efficient traction systems thanks to high-speed motor on wheel
How to	-
Costs and resources required	-
Benefits Effects	Reduced life cycle cost thanks to lower maintenance (up to -15%) and energy costs (up to -20%) and capital cost reduction via virtual validation & certification
Effects (CO_2)	-
Ease of implementation	For new rolling stock.
Constraints, challenges, or lessons learnt	-
S/M/L term	Short/medium term
Efficiency	-
Maturity	Solutions ready for prototype testing High-speed trains and very high-speed train markets Applicable for all train segments
Mentioned by	Shift2Rail PINTA projects
Experience	-
Comment	-

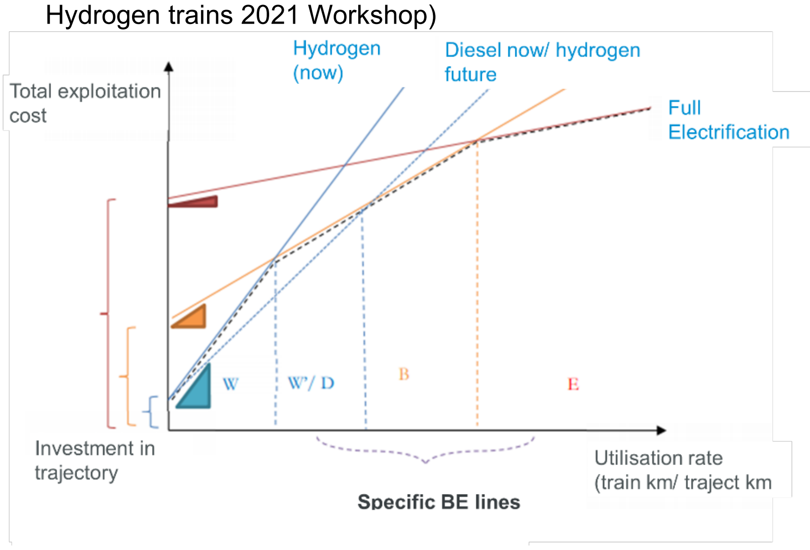
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA2
- https://projects.shift2rail.org/s2r_ip1_n.aspx?p=PINTA3

5.1.14. Alternative traction systems, onboard energy storage & last mile

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	Traction system and hybridisation
Solution	• Battery powered trains & partial electrification • Hydrogen fuel cells (FCH) powered trains • Dual mode/bi-mode (Diesel/battery) • S2R: Last mile propulsion system • Hydrotreated vegetable oil (HVO) • Hydrogen (Ammonia combustion) • Liquefied/compressed natural gas (LNG, CNG)
Description	For operations on non-electrified lines of less than 100 kilometres, it is now possible to use battery trains or hybrid diesel/battery trains. Hydrogen powered trains and alternative fuels can answer the need for longer distance coverage, and shorter down-times (due to avoided charging time) S2R last mile: Since the core freight network is electrified, electrical freight locomotives are used for more than 90% of the rail freight traffic. But for many small terminals the “last mile” to the terminal is not electrified. This requires the provision of diesel locomotives for the last mile and requires time and staff for locomotive change. Even large terminals require diesel traction within the terminal, since within the loading area of the terminals overhead lines are not possible. Future main line locomotives will be equipped with batteries for the traction power for the last mile.
Objective	Implementation and use of more efficient and less emissive traction/propulsion systems
How to	Since non-electrified lines usually host low frequency operations, battery powered trains are an optimal answer to the need to reduce fuel consumption costs and avoid emissions (Trains can take their time to charge). For greater distance or more energy intense transport (freight), alternative fuels can be looked into according to the possibility to retrofit existing (diesel locomotives) fleets, or if procurement of rolling stock is to be planned. Battery trains allow flexibility in the electrification scheme: Avoid difficult/expensive (re-)electrification (tunnels/turnouts) → Better for punctuality and maintenance costs Less power demand on weak spots of the network/public grid → Less investment needed just for one rush hour train per day Possibility to run through earthed route sections → Less impact of work possessions/detours Possibility to avoid non-profitable re-electrifications Extend grid storage capacity for regenerated electricity that can’t be immediately spent With a proper onboard storage and electrification scaling, a lot of non-electrified lines could be covered by battery trains.

<table>
<tr><td></td><td>SNCF identified that 84% of the lines below 80 km services can straight be covered by battery trains. The remaining lines by adjusting:
• Stop/parking times
• Electric supply infrastructure
• Onboard storage / charging speed

• FCH trains make economic sense above all on longer non-electrified routes (more than 100 km)
• FCH trains esp. for last mile delivery & main routes with very low utilisation (<10 trains/day)
• Low electricity costs (<EUR 50 /MWh) & high infra utilisation (HRS) favour FCH technology
• FCH trains has downtimes short than 20 minutes (due to fast refuelling) and withstand long operating hours (up to 18 hours without refuelling)
• Illustration of capital expenditure according to utilisation rate in the frame of a study by Waterstofnet for Belgian lines (UIC Hydrogen trains 2021 Workshop)


S2R last mile: Development of a scalable electric last mile propulsion system (with Li-ion traction batteries) that is capable to complement or replace existing last mile diesel engines.</td></tr>
<tr><td>Costs and resources required</td><td>Retrofitting of traction system, or new rolling stock procurement. Retrofitting is very relevant when adapting combustion engines to work with alternative fuels (via combustion)</td></tr>
<tr><td>Benefits Effects</td><td>• Fuel costs avoided
• Reduced energy consumption (inherent combustion efficiency versus electric traction)
• Avoided noise at stations (electric versus combustion)
• Avoided emissions (greenhouse gas and air pollutants)

S2R last mile: Energy savings due to possibility to store braking energy in the last mile battery, especially under DC networks and on non-electrified lines</td></tr>
</table>

	Three times more peak power compared to diesel "last mile" propulsion
Effects (CO_2)	Avoided diesel related greenhouse gas emission (around 3.8 gCO2e per gram of diesel burnt (EN 16258))
Ease of implementation	Depending on retrofit options according to use cases, and rolling stock flexibility to adjustments. Otherwise through the purchase of new rolling stock.
Constraints, challenges, or lessons learnt	Studies to be made by route use case. Alternatives still are missing design standards, preventing some companies to adopt at this stage.
S/M/L term	Medium/long term S2R: Medium term
Efficiency	According to fuel costs avoided, and to evolution costs.
Maturity	According to battery storage technology and evolving market. Battery packs for the automotive market are more and more accessible and safe/reliable. Alternative fuels are well spread in some countries: HVO in Germany, LNG/CNG in Russia. Solutions have to be explored according to fuel production context. HVO can be produced from waste and there is already good experience for its use. S2R last mile: Solution expected to be ready by 2025. Mainly applicable to freight market, running into non electrified yards, harbours, but also passenger trains market running on non-electrified lines (diesel) with the need to enter sensitive areas, like underground stations.
Mentioned by	Alstom, ProRail, Siemens, SNCF, T&M, TUC Rail, Waterstofnet
Experience	Alstom, ADD, ProRail, RSSB, SNCF, Stadler, TUC Rail
Comment	Decision to switch to a specific traction system is to be made according to each use case, and in views of the long-term greenhouse gas emission-free operation objective

- https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FFL4E
- https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8RAIL
- https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8RAIL%20ii
- https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8RAIL%20iii
- https://projects.shift2rail.org/s2r_ip5_n.aspx?p=FR8RAIL%20iv
- https://alternative-fuels-observatory.ec.europa.eu/transport-mode/rail
- https://storymaps.arcgis.com/stories/f399355bad724c558ac48a22b99b49b5
- UIC "Hydrogen trains" and "Battery trains" workshops, 2021
    - https://uic.org/events/hydrogen-trains
    - https://uic.org/events/battery-trains

5.2. Operations

This section introduces a set of solutions for improving all aspects of train operations (software or management based). As with section 5.1, solutions were shared among the members of the UIC Energy Saving Taskforce, complemented by existing UIC documentation or external studies.

Aside from the solutions given by the UIC Energy Saving Taskforce, this section also gives the common principles for energy efficient operations.

For traction energy saving and operational efficiency:

- Train-run profile optimisation
  Identifying the best running profiles according to the rolling stock's specific characteristics, alignment, objective and running time, adapted into eco-driving/Driving Advisory System (DAS) strategies
- Eco-driving/DAS/ATO and eco-stabling
  See 5.2.2 Eco-driving – saving traction energy, 5.2.3 Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO) and 5.2.9 Eco-stabling, eco-parking
- Power management and timetable optimisation
  The optimal timetable design can reduce energy consumption without additional costs, by optimising energy exchange between running and braking trains which makes this measure one of the best methods to reduce energy consumption.
  This measure relies on:
    - *Optimising the train runs in terms of timetabling, collaborating with IM traffic management (margins of regularity according to an eco-driving strategy)*
    - *Synchronisation between braking and running trains*
    - *Desynchronisation between running trains*
    - *Desynchronisation between braking trains*
- Maximise the train payload
  Maximise the payload, increase occupancy for passenger trains and tons carried for freight trains, will imply a lower consumption per passenger-kilometre or ton-kilometre.
  The average payload factor in railway operation shall be addressed using marketing strategies and more flexible vehicle concepts allowing the train length to be adjusted to variations in demand
  Naturally, an optimal occupancy rate has to be considered for passenger comfort to maintain its appeal, by balancing occupancy, train size and frequency (see 5.2.7 Fine tuning train services)
- Passenger comfort and information energy controls

Of course, as with many other large companies, railways also have energy consumption in other areas, such as road vehicle fleets.

Overview of operational improvements to rolling stock

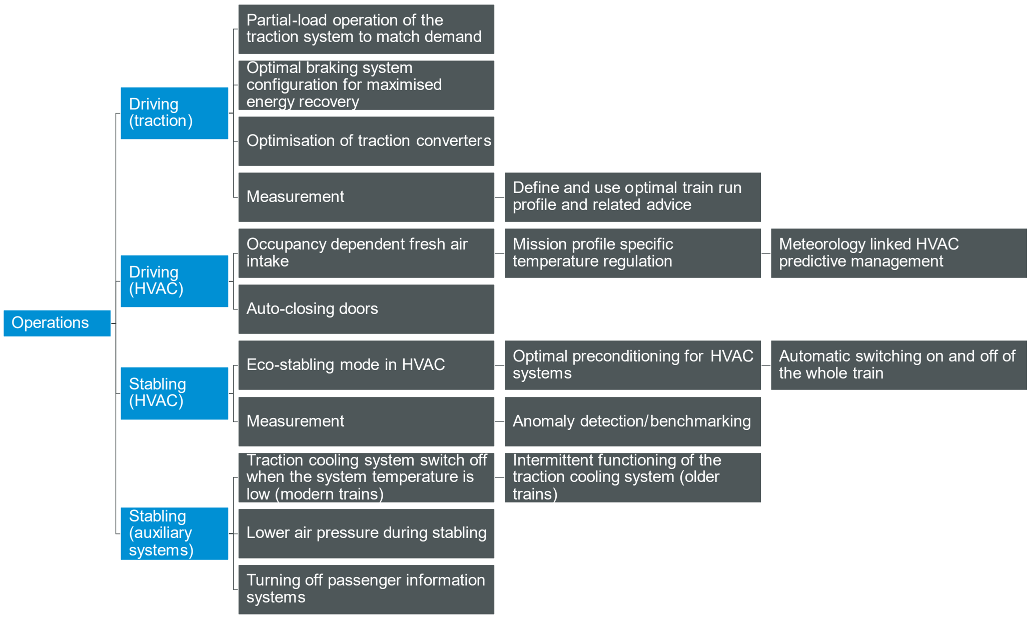


Figure 28: Overview of rolling stock software optimisation solutions as an outcome of the rolling stock and operations session of the UIC Energy Saving workshop

Some of the solutions are the software performance tuning (Figure 28) solutions of previously mentioned rolling stock hardware (upgrades) and are therefore not repeated in the *Operations* section.

5.2.1. Using the most efficient trains for operations

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	High/Medium	High
Special note	More sharing needed		

Field	Electric or a newer/more efficient fleet
Solution	Make use of the most efficient rolling stock (depending on the availability of the fleet)
Description	The decision to pick one type of rolling stock over another can be based on: • Traction type (known inherent efficiency) according to the infrastructure • Known efficiency of a specific electric rolling stock (energy consumption data, see 0)

Objective	Reduced consumption by running the most efficient rolling stock as much as possible
How to	Favouring the use of rolling stock with lower consumption and/or lower total mass (e.g., FS Trenitalia ETR1000 compared to ETR500) SNCF: Use of dual-mode system trains (electric and diesel) or electric and battery or diesel and battery, if needed When refurbishing, there is an opportunity to enhance the fleet by changing the diesel tank and motors for batteries and chargers for a hybrid train with braking energy storage and/or use a diesel motor at its highest point of efficiency
Costs and resources required	Assessment of technical specifications of rolling stock
Benefits Effects	Relative to the difference in efficiency of trains
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption. Reduced exhaust emissions due to the use of efficient trains
Ease of implementation	Medium: according to availability of a fleet, a proper planning/timetabling and timetable flexibility
Constraints, challenges or lessons learnt	Timetable flexibility can cause complexity for the availability of most efficient trains
S/M/L term	Short
Efficiency	(Cost over effect) High
Maturity	High, will become more and more accurate with energy measurement devices increased use
Mentioned by	FS Trenitalia, SNCF
Experience	-
Comment	-

5.2.2. Eco-driving – saving traction energy

Note: Eco-driving is considered here to be managing driving behaviour without tool considerations (with guidelines, incentives or rules), to avoid overlapping with the details of DAS and the different grades of automation solutions.

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	High	High

Field	Train operation
Solution	• SNCF Voyageurs: Reducing the energy used for the train traction by giving appropriate instructions to drivers • Trenitalia: Drivers training to eco-drive with specific driving courses • SBB: Reducing train speed in tunnels
Description	Reducing energy used for traction (acceleration and braking adapted to the line profile) In general: • A proper coasting strategy (instead of using the highest braking capacity at the end, will save traction energy. As stated in Figure 12, mechanical energy (grey arrows) for train propulsion has a high impact on the overall energy consumption of the system. Also as stated in *5.1.9* for

	Aerodynamic efficiency of rolling stock of rolling stock, the basic Davis Equation for vehicles also applies for movement resistance, and clearly shows the impact of increasing velocity on energy needs: Movement Resistance = A + B * v + C * v^2 • If feasible and compatible with general service requirements, reducing speed can lead to high levels of energy saving • Trenitalia: Eco-driving on all services (particularly on the 3kV network). Courses to make the drivers aware of economic driving and the use of electric braking approaching the stations • SBB: Since October 2022, the speed in the Gotthard Base Tunnel has been reduced, but only if a train is on time. Since certain time margins are built into the timetable, the speed reduction will not cause delays
Objective	Reduce traction energy consumption generally and through driver training
How to	Identify better speed profiles using a real time calculator (acceleration and braking adapted to the line profile) Providing the drivers with the relevant information or training sessions The drivers then apply an optimised speed profile, resulting in controlled traction energy use. • SBB tries to achieve this with specialised communication to the train drivers (reducing energy based on the same timetables)
Costs and resources required	• Costs of developing guidelines and setting up training • Training courses/information for the drivers • Trenitalia: Training does not require much investment
Benefits Effects	Energy: • SNCF: aiming to reduce traction energy consumption by up to 10% thanks to eco-driving, (contributing to a -10% reduction overall) • Trenitalia: ~1% reduction in energy consumption • SBB: 2GWh/year saving for the speed reduction in the Gotthard Base Tunnel (0.01% over 2021's traction energy consumption)
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption. Reduced exhaust emissions due to the reduced tractive effort required.
Ease of implementation	Needs: - Optimised speed profiles (simulations, tests) - Accurate data about infrastructure, route segments - Education of the drivers • Trenitalia: Easy
Constraints, challenges, or lessons learnt	Possible need for adapting timetables Education of the drivers Human factors: drivers need to follow the guidelines and/or training sessions for results
S/M/L term	Short/medium (setting up training, guidelines, communication to staff)
Efficiency	(Cost over effect)

Maturity	High
Mentioned by	SNCF Voyageurs Trenitalia SBB JRE
Experience	-
Comment	-

- https://www.sncf.com/fr/engagements/developpement-durable/sobriete-energetique
- https://www.sncf.com/sites/default/files/press_release/CP_NR_Plan-de-sobriete-energetique_10-10-2022.pdf

5.2.3. Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO)

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	• Optimal train consumption during operation • Next generation ERTMS
Solution	• S2R/EU-Rail: Moving to higher Grade of Automation (GoA) on ERTMS. Achieving ERTMS/ATO. Deployment and implementation of DAS/ATO, delivering driving advice to drivers or automated train control. The first phase is *Standalone DAS/ATO (S-DAS, S-ATO),* meaning solutions without connection to Traffic Management Systems (TMS), and then *Connected DAS/ATO (C-DAS, C-ATO)* which manage conflicts and harmonise traffic flows at a system level and even allow energy efficiency to be built into system-wide train schedules • SNCF: Real-time calculator for drivers to follow an optimised behaviour for each line and train use. • SBB: Reduction in the energy used for train traction by giving appropriate instructions to drivers • RFI: Increase train run efficiency through the implementation of ERTMS/ATO (Automatic Train Operation over ETCS) for efficient train runs • Trenitalia: Implementation of an efficient driving support system • SBB: Providing the driver with real-time information about the timetable and operating situation through a tablet in the driver's cab (ADL & vPRO), April 2023 PÜA (punctuality display) • RENFE: Efficient driving under DAS & ATO and train protection systems, for energy savings and increased traction energy efficiency
Description	S2R / EU-Rail: The standard solution that EU-Rail is developing for mainline (both freight and passengers) applications in different Grades of Automation guarantees the interoperability and interchangeability of the subsystems (trackside and on-board)

	delivered by different suppliers. As a second automation step trains will run automatically according to an energy-optimised driving style not depending on the individual driving style of the train driver. Therefore the energy usage is further reduced • SNCF: Reducing energy used for traction (acceleration and braking adapted to the line profile) • FS: Trenitalia and RFI evaluate a coordinated implementation approach for an efficient driving support system (e.g., DAS) with fleets having EMS • SBB: The locomotive crew receives comprehensive information about the timetable and operating situation directly to a tablet in the driver's cab. This is the only way to achieve punctual and energy-saving driving • RENFE: Implementation of advanced ERTMS systems as well as advanced communications equipment; acquisition of automatic efficient driving equipment, and development of applications for efficient driving assistance (APP) for high-speed and conventional vehicles Data consumption analysis for decision-making Training of train drivers, both in terms of driving culture and awareness and the use of efficient driving simulators A harmonised DAS data exchange message structure (as proposed and described in IRS 90940) would help any company to deploy a basic set of driving assistance messages in DAS (S-DAS and C-DAS, provided that the IM sends data). It enables a message protocol for seamless cross-border operations with DAS messages from the traffic management to trains (for operating C-DAS over multiple countries, as IMs are able to offer connections to TMS). Enabling real-time messages was proven to enhance punctuality, thus the capability of operators to focus on additional energy savings
Objective	• Reduced traction energy consumption • Reduced energy losses during high levels of power demand due to synchronous traction power via DAS information to drivers (related to timetable optimisation, to reduce energy consumption and peak loads during planning and operation) • To achieve punctual and energy-saving driving Avoid braking (kinetic energy loss) and use recuperation if braking cannot be avoided.
How to	• SNCF: Identify a better speed profile using a real-time calculator (acceleration and braking adapted to the line profile and traffic) Providing the drivers with this information The drivers then apply an optimised speed profile, resulting in controlled traction energy use • Trenitalia: Progressive extension on all trains (given the cost and impact on train stops, to be carried out with a programme spread over at least 5 years); first train ETR1000 + Consumption Monitoring Dashboard: progressive implementation on main DBR (regional trains) fleet • SBB: o Adaptive steering ADL

	Since 2016, the locomotive crew has directly received driving recommendations from the Rail Control System in the event of deviations from the plan, which largely prevents stops before red signals - Optimised driving profile vPRO Since 2020, an optimised journey profile has been calculated for passenger trains shortly before departure based on the latest information on rolling stock, road works and routes. In addition to vPRO, from April 2023, real-time PÜA (=punctuality display). - Updated driving situations With this function, freight locomotive crews receive a quasi-live view of the dispatcher's screen and therefore know about the train's current situation. • RENFE: - New equipment and development of applications for efficient driving assistance (APP) for high-speed and conventional vehicles - Data consumption analysis for decision-making - Training of train drivers, both in terms of driving culture and awareness and the use of efficient driving simulators Deploy a basic set of driving assistance messages in DAS (S-DAS and C-DAS, provided that the IM sends data) using a harmonised DAS data exchange message structure, as proposed and described in IRS 90940, helps any company (DAS provider, IM and RU) to achieve traction energy saving through sober driving.
Costs and resources required	• SNCF: - Costs related to investing in and maintaining the calculator - Costs related to giving information to the drivers - KPI management • RENFE: Costs of driver training Costs for automatic efficient driving equipment Costs for developing apps to help efficient driving (APP) Cost of data collection and processing
Benefits Effects	Energy: • S2R/EU-Rail: Energy savings of up to 45% through optimised speed profiles • SNCF: Aiming to reduce energy consumption by up to 10% • Trenitalia: Potential savings ~10% of the total consumption for electric traction • SBB: Approx. 25% (130GWh/year) savings, from adaptive steering (70GWh/year), the optimised driving profile vPRO (50GWh/year) and updated driving situations (10GWh/year) • DB Cargo & Knorr Bremse: 6% reduction in energy consumption since 2018 (proven and confirmed by DB Cargo as well as the German Federal Ministry for Economic Affairs and Climate Action) over a fleet size of 650 freight locomotives in permanent operation, with a DAS providing live traffic information – the next train behind and in front are shown to the driver (refer to DB's green functions). The next step is to have

	active management/reduce traffic conflicts to realise more regenerative braking and/or coasting potential. • RENFE: Potential savings of on average 8-10%, across high-speed, commuter, and freight trains • UIC: Average potential savings on a system level of between 5% and 10% for S-DAS/ATO without TMS connection, between 8% and 12% for C-DAS/ATO, and above 10% for solutions which manage conflicts and harmonise traffic flows at a system level and even allow for energy efficiency to be built into system-wide train schedules (UIC OPEUS D4.1). Aside from enhancing punctuality and thereby operational efficiency, thanks to a harmonised DAS data exchange message structure: ○ RUs can choose their preferred DAS products and increase their energy savings ○ IMs can offer a single interface to all RUs regardless of the DAS supplier ○ Migration between products (e.g. to other train protection systems or to other ATO systems) is facilitated ○ RUs and IMs ensure higher consistency and compatibility for the solutions that they invest in *Note: DAS can help achieve ATO benefits earlier, hence the similar expected improvements. ATO would make it perfectly reliable but DAS can already help achieve optimal driving profiles.* *A harmonised data exchange protocol to be used with DAS, as generic data exchange framework for seamless cross-border activities and DAS compatibility between RUs and IMs (IRS 90940) would enable achieving these benefits, regardless of the DAS products provided they allow the use of the harmonised data structure.*
Effects (CO_2)	DB Cargo & Knorr Bremse: Between 5 and 12% (depending on the type of DAS) of traction energy correlate to potential reduction in CO_2 emissions. The type of energy production (renewable energy/fossil) determines the potential CO_2 savings.
Ease of implementation	• SNCF requirements: ○ Optimised speed profiles (simulations, tests) ○ Accurate data about infrastructure, route segments Drivers education • DB Cargo & Knorr Bremse: ○ Accurate and accessible data on infrastructure, topography and ideally energy metering systems is needed ○ Educating drivers is the initial step, but an intuitive and valuable system that really supports the driver is a key for successful implementation
Constraints, challenges or lessons learnt	• Implementation of C-DAS is dependent on a country's infrastructure manager's capacity to handle the IM-side delivery of harmonised/standard (DAS) messages to operators • Drivers' adaptation to and acceptance of the new tool/digital system • SNCF: ○ Education of the drivers ○ Human factor: convince the drivers to use the tool • RENFE:

	○ Training of drivers ○ Driving culture and awareness of drivers
S/M/L term	S2R/EU-Rail: Medium/long term Short/medium for S-DAS: already available Short/medium/long for C-DAS (according to the S-DAS and data exchange readiness in each country – for example, already partially available in Germany/Switzerland, so shorter term to deployment) Long term for ATO RFI: Medium/long term implementation (due to the length of the development and implementation phases) RENFE: medium-term for DAS and long-term for ATO
Efficiency	High: accurate reduction of delayed or early trains, hence train consumption accurately adapted to train run needs
Maturity	• S2R/EU-Rail: ○ Good implementation perspectives for all types of trains (mainline/high speed, urban/suburban, regional and freight lines) ○ ATO GoA2: solution ready ○ ATO GoA3/4: ready for prototype testing from 2023 S-DAS: Mature C-DAS: Mature/pilot projects/deployment projects ATO: Prototype/pilot projects • SNCF: 80% mature • SBB: 90% mature for DAS (incl. infrastructure timetable information, not live but uploaded before driving) and live information about punctuality according to the operating/dispatcher's timetable. • RENFE: DAS mature, ATO innovation projects (participating in ERJU)
Mentioned by	• Shift2Rail X2RAIL projects • SNCF Voyageurs • FS • RENFE Viajeros SFERA WG (Bane NOR, DB, Infrabel, NS, ÖBB, ProRail, SBB, SNCB/NMBS, SNCF, Trafikverket)
Experience	SBB, DB Cargo, SNCF, NS, ProRail, SNCB, Infrabel, ÖBB, Trafikverket (All part of the UIC SFERA Working Group) RENFE Viajeros (on-going energy management programme, started 2019, for S102, S112 and S130 for two Spanish lines)
Comment	• SNCF: Possible need for adapting timetables. Next step connected DAS • SBB: vPRO • UNIFE: It helps to show the driver the topography ahead so that the driver can anticipate up/downhills and can adapt speed/traction accordingly

- https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-1
- https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-2
- https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-3
- https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-4
- https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-5
- https://bahninfrastruktur.sbb.ch/de/digitale-bahn/optimiertes-fahrprofil-vpro.html

- [UIC IRS 90940: Digitalisation, Data, Emerging Innovations - Exchange of Data - Data exchange with Driver Advisory Systems (DAS) following the SFERA protocol]

5.2.4. Partial equipment usage: adaptation of equipment use according to load/needs

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	High	High

Field	Optimal energy consumption for operations
Solution	Partial use of traction engines according to load (partial switch-off when coasting) • SBB: Step-by-step introduction of partial-load operations on the modernised RE 460
Description	• SBB: To protect the SBB locomotive 2000 (class Re 460) intermediate gear bearings in the gearboxes from excessive wear, the two bogies of the locomotive have so far been tensioned against each other in terms of tractive force. The same challenge was also encountered with BLS's Re 465, where burnished bearings were eventually used as a solution. For several years now, SBB's Re 460 has also been fitted with burnished bearings, so that the mechanical prerequisites for partial-load operations have now been fulfilled. Trials with the bogie tension removed (a preliminary stage to partial-load operation) were carried out on the Re 460 and successfully completed. In autumn 2019, as part of the project "Pilot operation Re 460 Partial load operation", the first three prototypes were equipped with partial-load operation, and have been in regular operation since. Inspections of the critical intermediate gear bearings in the gearbox are carried out at specified intervals. The proof of the activation frequency of the partial-load operation, in relation to distance and running time, confirms the expected values of 16%. A final assessment of the bearings has to be carried out, but this must wait until the full mileage is reached in summer 2023. Until then, the prototypes will continue to be monitored to detect potential long-term damage.
Objective	The primary aim of partial-load operation is to save energy by switching off drive trains at lower tractive forces and allowing the remaining drive trains to apply the required tractive force.
How to	By switching off motors, inverters, and drive losses can thus be reduced, while the active motors and inverters are operated at a better efficiency range. • SBB: For Re 460, two drive trains of a common bogie are controlled in a so-called group drive, i.e. in partial-load operation, both drive trains of a bogie are switched off.
Costs and resources required	The cost-effectiveness of partial-load operation is backed up with evidence of energy savings.
Benefits Effects	Energy consumption data proves that partial-load operation saves energy:

	• SBB: Partial load operation reduces the energy consumption of the Re 460 by 1.5% or 5GWh per year, extrapolated for the entire fleet.
Effects (CO_2)	-
Ease of implementation	
Constraints, challenges, or lessons learnt	• SBB: After 250,000km in test operation (approx. a quarter of the regular mileage for bearings) signs of wear were noticed on the bearings, which can be attributed to the more frequent load changes from partial-load operation. However, these were so small that three more vehicles were added to the trial operation in spring 2021 to obtain more data for the project.
S/M/L term	
Efficiency	
Maturity	• SBB: The first prototypes have been equipped. Partial-load operation has already been installed as a software option on all Re 460s and can be quickly activated by software after a positive decision.
Mentioned by	SBB, S2R FINE1 OPEUS
Experience	• SBB: From a technical point of view, Re 460 partial-load operation will function as specified and will also be activated with the expected frequency on the locomotive. The bearing findings and the current course of trial operation have not revealed any critical factors that would stand in the way of a rollout to the entire fleet.
Comment	

- https://www.bav.admin.ch/dam/bav/de/dokumente/themen/umwelt/energiestrategie-projekte/schlussbericht-p136.pdf.download.pdf/136_SBB_Schlussbericht_Teillast_Re460.pdf
- https://opeus-project.eu/#Deliverables

5.2.5. Optimisation of power electronics

	Innovation	Ease/rapidity	Benefits
Level	Medium	High	High

Special note More sharing needed

Field	Increase the efficiency of train traction systems
Solution	Fine-tune parameters for the maximum efficiency of onboard power electronics (Douglas et al., 2015)
Description	A proper software control of equipment can result in a more efficient management of energy flows through the traction system
Objective	Reduce traction energy consumption
How to	Power electronics are typically computer controlled, and by modifying the set points of various parameters, such as the DC link voltage or magnetic flux (Douglas et al., 2015) Assessing effects of adjusted settings is made easier with an energy measurement system

	Another approach is to vary the traction demand depending on the operating conditions, and even switch off if demand allows it (*5.2.4 Partial equipment usage: adaptation of equipment use according to load/needs*)
Costs and resources required	Time to assess effects of various software settings.
Benefits Effects	Energy: Savings of between 1% and 3% are achievable (Douglas et al., 2015)
Effects (CO_2)	According to electricity production mix for a reduction of traction energy consumption.
Ease of implementation	Easy
Constraints, challenges, or lessons learnt	An improper setting can result in an increased consumption
S/M/L term	Short
Efficiency	(Cost over effect)
Maturity	Medium
Mentioned by	(Douglas et al., 2015)
Experience	-
Comment	-

5.2.6. Using energy measurement data

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium	High
Special note	Inventive solution		

Field	Energy consumption data
Solution	When an energy measurement system (EMS) is available for a traction unit (TU), data can be used to: • Analyse, create, and validate consumption models • Define optimised train runs based on actual consumption • Compare rolling stock efficiency • Compare driving efficiency • Exact energy settlement • Evaluate energy saving measures, eg: evaluate the efficiency of driving assistance tools and features • More efficient cross-border activity (less stops at borders) with a more efficient energy settlement process (see challenge *7.2 International traffic*). Renfe: Central onboard measurement device for all energy measurement systems on all electric traction units that comply with EN 50463:2017
Description	The data output from an EMS is valuable for analysing a train run's driving efficiency. Whether it is to improve the eco-driving strategy (specific to a route or not), or enhance driving advice for a DAS. Exact optimal energy consumption and punctuality can be found by analysing data from multiple train runs.

Objective	Learn from data and find energy saving driving patterns
How to	Implementation of energy measurement systems in undergoing across European operators. Energy measurement data will more and more be collected by the settlement services of each settlement area, and it will enable more efficient energy consumption benchmarking and international operation (More information in the sector declaration https://www.cer.be/cer-agreements-resolutions/eu-rail-sector-declaration-on-traction-energy-metering-and-settlement)
Costs and resources required	Fleets upgrading with energy measurement systems or new rolling stock. Proper data collection and data exchange setups for the settlement services.
Benefits Effects	Energy: Data analysis indirectly helps identifying saving potential in train runs or parking/stabling states
Effects (CO_2)	Footprint: N/A
Ease of implementation	Medium
Constraints, challenges or lessons learnt	Long term implementation: • Rolling stock lifespan and compatibility • Energy measurement systems certification
S/M/L term	Long term
Efficiency	(Cost over effect)
Maturity	High
Mentioned by	RENFE (EMS deployment, monitoring and consecutive power management) UIC Traction energy settlement WG – IRS 90930 Maintenance members: ADIF, Bane NOR, DB, FS, FTIA, Infrabel, MÁV, NS, ÖBB, PKP, ProRail, SBB, RTE, SNCB/NMBS, SNCF, SZCZ, Trafikverket
Experience	-
Comment	-

5.2.7. Fine tuning train services

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	Low	High

Field	Train consumption in operation
Solution	Finding the optimal travel times and stopping frequency. Adjusting and reducing train services without impacting passengers, or even improving appeal
Description	Optimal travel times and stopping frequency. Finding the right balance between: • Train frequency • Train size • Stops
Objective	Reduce energy losses due to the train's weight, speed and stopping frequency

How to	• Asynchronous train acceleration to avoid energy use during peak hours and reduce losses (timetabling, power management) • A train's acceleration synchronised with another train's braking (timetabling, power management) • ATO and DAS for the most efficient traction energy use, avoid train stops using information from traffic management See 5.2.3 Driving assistance tools (DAS & ATO) After thorough analysis of passenger flows and demand: • Adjust the number of coaches/wagons during off-peak hours to the expected attendance/load • Run more frequent shorter trains to increase service frequency, instead of less frequent longer trains (more attractive to passengers) • Reduce the number of stops, by skipping (low attendance) stations for frequently stopping trains (faster trains over long distances are more attractive to passengers) • Develop a "request stop" system
Costs and resources required	Analysing and setting up time and costs
Benefits Effects	• Traction energy saving • Train service appeal
Effects (CO_2)	-
Ease of implementation	Related to transport demand at a line level and system to put in place
Constraints, challenges, or lessons learnt	Might conflict with local transport offer agreements, and contractual timetabling. The available capacity of a line/network might also limit related saving opportunities/service optimisation.
S/M/L term	Medium term
Efficiency	High (traction energy saved as soon as a stop is avoided)
Maturity	-
Mentioned by	All companies apply some or all of these principles to a certain extent [Request stop] Swiss companies and tests to be carried out in France with SNCF (Occitanie, Massif Central)
Experience	-
Comment	-

5.2.8. Efficient heating, ventilation, and air conditioning (HVAC) management

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Field	Optimal HVAC energy consumption for operations
Solution	• Schedule and adapt HVAC strength to weather condition data/forecasts • Adapt HVAC strength to CO_2 levels • Adapt HVAC strength to the temperature

	• Reduce heating (comfort margin) • Timetable-based provisioning time (For eco-stabling, see *5.2.9 Eco-stabling, eco-parking*) • Specific to the type of rolling stock: the staff define the optimal time and strength of manual HVAC • Specific to the type of rolling stock: Adjust HVAC software
Description	• SBB: HVAC system management is scheduled using the weather forecast to avoid excess consumption for heating, cooling, or ventilation • SBB: Adapt ventilation to the current needs in passenger compartments based on CO_2 measurements. (See *5.1.7 Smart/automated heating, cooling and ventilation (HVAC)*) Reduce the temperature in passenger compartments by 2°C (from 22°C to 20°C as new standard) While trains are stabled, heating and ventilation is reduced to a minimum (10°C). Before operation, they receive a startup signal and are automatically heated/ventilated to be ready for passenger transport In winter, as well as in summer, ensure that doors are closed while a train is in a workshop, if they are being heated or cooled • SBB: EW IV/EC/ICN type trains: Implemented by staff according to "best efforts" during commissioning or while driving. The setting must be set again after the vehicle has been restarted RABe511/DTZ type trains: Software adaptations are being tested Flirt type trains: Use of local personnel is being tested
Objective	Reduce energy consumption
How to	• Link HVAC functioning levels/schedule to temperature/weather forecasts for a smart predictive adjustment of HVAC systems in trains • Automatic processes related to the timetables, and educate staff
Costs and resources required	Staff training, upgrade to HVAC with smart management/sensors, identifying best practice
Benefits Effects	• SBB: With HVAC weather forecast scheduling: Around 10GWh per year for a fleet of 400 trains • SBB: Defined rolling-stock specific HVAC measures can save 5000 to 800 MWh from November to February
Effects (CO_2)	Minimal due to reduction in current consumption Very high in depots where numerous trains are stabled
Ease of implementation	• SBB: Adapt CO_2 based ventilation: Requires hardware and software updates in all coaches Reduce carriage temperature by 2°C: Simple - give as an order to the train crew Timetable-based commissioning times: Development and implementation of a system linking the timetables with carriages

Constraints, challenges or lessons learnt	Staff education Cost of implementation of new technology
S/M/L term	Short for manual management and rolling stock already equipped with smart HVAC
Efficiency	-
Maturity	SBB: CO_2 adapted ventilation and FVV are fully developed and deployed. Reduced heating is in development. Customer surveys are ongoing
Mentioned by	SBB
Experience	-
Comment	-

5.2.9. Eco-stabling, eco-parking

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	High	High

Field	Train consumption at a standstill
Solution	• SNCF: Reduce train energy consumption when standing still • Trenitalia: Switching off trains in depots, optimal pre-HVAC time. Smart parking through three different phases • SBB: Hibernation mode in passenger rolling stock/switching them off in an energy-optimised manner

Description	Acting on any equipment that is not required at a specific instant, manually or automatically
	Eco-parking: Power-reduced operating (hibernation) state of a stopped vehicle to reduce energy consumption and noise emissions (e.g., active cooling of the main transformer, compressed air generation for pantographs, etc., are still working). Electric rolling stock is still connected to the power grid
	Eco-stabling: Parked train with minimal energy consumption. Electric trains are disconnected from the catenary.
	• UIC: Overview based on surveys and workshops:
	  ○ HVAC idle mode (temperature threshold for optimal consumption and commissioning times)
	  ○ Consumption anomaly detection using energy meter data
	  ○ Engine switch-offs or partial switch-offs and idle modes
	  ○ Independent management of auxiliary systems
	  ○ Remote power management
	  ○ Train consumption dashboard in parking locations
	  ○ Partially switching on or switching off lighting for maintenance
	  ○ Smart management of equipment and automatic-idle modes
	  ○ Ensuring the proper insulation of rolling stock
	  ○ Closing doors/automatically-closing doors
	  ○ Adapted body and window tinting and sealing
	  ○ Frost or heat protection/vehicles under cover

	◦ Organising and making staff aware of energy saving measures via communication (monitoring/data/reporting) and incentives • NS: ◦ Automatic and remote control with EZO mode (Hibernation mode after idle for 60 minutes) ◦ Consumption monitoring using energy meter data ◦ Optimal temperature management: HVAC management for low consumption, maintaining temperatures and short pre-heating times • SNCF: Optimising energy consumption related to stabled trains by stopping the engines or reducing consumption to the minimum possible. Reduce the energy used by stabled trains by: ◦ Using technical systems that automatically control traction, cooling, heating, auxiliary, lighting and door opening and closing systems ◦ Changing the way people perform their duties (manually stopping and restarting engines) • Trenitalia: Reduce the preheating/air conditioning phases, agreed upon with RFI, and for stabling hours, ensure that trains in depots are switched off Smart stabling automatically sets 3 stabling phases depending on requirements: Phase 1 – Sufficient lighting to allow cleaning Phase 2 – Only the control units are powered on Phase 3 – Before service when the air conditioning/heating is switched on • SBB: ◦ In passenger traffic, trains are in operation for between 8 hours (regional traffic) and 12 hours (long-distance traffic) daily and are stabled for the rest of the time. All passenger rolling stock now has a hibernation mode, or is switched off in an energy-optimised manner ◦ Some trains have a "start & stop" system so that they shut off after entering an idle mode ◦ Some trains are equipped with a hibernation system that have an automated shut-down for trains at the end of operation ◦ Traction cooling systems are shut down ◦ Some trains are capable of partially switching off equipment
Objective	Reduce energy used by stabled trains/save energy on heating Decrease energy consumption by ensuring that rolling stock shuts down when in a depot
How to	The vehicle control system automatically calculates the necessary preparation time based on the time and the data available on the vehicle In general, for optimal eco-stabling: The main switch is open, and the pantograph is lowered. The vehicle control technology automatically switches off all equipment, with the exception of monitoring devices and the wake-up command receiver. Only the vehicle systems required

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<tr>
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for minimal monitoring remain switched on. If an anomaly is detected, the vehicle automatically switches itself on to normalise the monitored systems. The vehicle automatically switches back to eco-stabling when all the necessary conditions have been met. When a wake-up command is received, the vehicle automatically switches itself on and switches to eco-parking

SNCF: Defining the rules to apply locally and by rolling stock type.
Providing staff with the relevant instructions for the stabled trains.
Technical devices that automatically control traction, cooling, heating, auxiliary, lighting and door opening and closing systems
Trenitalia: Reducing the energy consumption of stabled rolling stock with a qualified operator (not necessarily a train driver) manually carrying out this 1-2-3 phase sequence and considering switching off the train completely in phase 2 on fleets where smart stabling is not present. RFI switches on the smart-stabling function according tothe network information prospectus (PIR) for trains that are already equipped with the smart stabling method (e.g. Rock)
<table>
<tr><th>Convoy/Fleet already equipped with smart parking</th><th>Smart Parking mode</th></tr>
<tr><td>POP</td><td>Automatic</td></tr>
<tr><td>ROCK/TAF restored</td><td>Automatic</td></tr>
<tr><td>E 464 + coaches</td><td>Manual</td></tr>
<tr><td>2 locomotives E 414 + coaches</td><td>Manual</td></tr>
<tr><td>ETR 500</td><td>Manual</td></tr>
<tr><td>E 401 + coaches + SP</td><td>Manual</td></tr>
<tr><td>ETR 700</td><td>Automatic</td></tr>
</table>

SBB:

Hibernation mode: The vehicles recognise the shutdown signal in the control system with the combination "v < 5km/h" and "light off > 30 min": The heating switches to hibernation mode with an inside temperature of 10°C.
Energy-optimised stabling: The wagon heaters receive the operating times directly from the vehicle schedule via the vehicle’s control system so that the vehicle can be "woken up" in time, or hibernation mode can be activated

</td>
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<tr>
<td>Costs and resources required</td>
<td>

SNCF: Establish a set of instructions to be adapted to each local situation for trains at a standstill
Educate staff (drivers, maintainers, cleaning staff, …)
Invest in technical hibernation systems and implementation work ((studies and tests, deployment of the modifications)
KPI management
Trenitalia: No investment needed

</td>
</tr>
<tr>
<td>Benefits Effects</td>
<td>
Energy saving
Noise reduction
Power management

SNCF: Aim for an up to 15% reduction in energy consumption

</td>
</tr>
</table>

	• Trenitalia: 20% reduction in energy consumption for 2024 (with the trains in depot strategy) Potential savings of about 30-40% solely due to the fleets being equipped with smart stabling • SBB: 61GWh/year savings (50GWh/year with hibernation mode and 10GWh/year with energy-optimised stabling
Effects (CO2)	
Ease of implementation	Trenitalia: Easy SNCF: Needs • Clear instructions for the crew • Education of the stakeholders • Design and installation work for technical hibernation systems (studies and tests, deployment of the modifications)
Constraints, challenges or lessons learnt	Education of the drivers Human factor: convince the drivers to use the tool
S/M/L term	Medium-term
Efficiency	(Cost over effect)
Maturity	Pilot projects for optimal eco-stabling SBB: 60%
Mentioned by	SBB SNCF Voyageurs NS
Experience	-
Comment	Time required to ready a train should not be underestimated, especially when a train is in hibernation mode or energy-optimised stabling. Some systems which were off need to start/reboot and carry out a test (ETCS, BRAKE, NBU etc.).The planned parking length first needs to be assessed before the train is eco-parked

5.2.10. Interval operation of traction coolant pumps during stabling

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Field	Optimal energy consumption during stabling
Solution	Interval operation of traction transformer coolant pumps and ventilation during eco-stabling. Turn off traction converter coolant pumps and ventilation during stabling.
Description	Implement an interval operation of coolant pumps during periods of low or no losses. Coolant pumps for traction can have a high energy consumption, especially when oil is used as a coolant.
Objective	Reduce the energy consumption of coolant pumps and ventilation
How to	During stabling (no current for traction), traction transformer coolant pumps are regulated with interval operation according to the measured currents for auxiliary systems.

	Use a loss function model of the traction transformer to calculate the intervals. Turn on the coolant pumps from time to time to refresh the temperature readings. The pump and ventilation could be supplied with a variable frequency converter and be operated with a minimal frequency when needed Turn off traction converter coolant pumps during stabling mode Turn off the related ventilation when the pumps are not in operation
Costs and resources required	Engineering required to design the interval calculation and measurements for the loss function model Implementation might require the installation of additional hardware, such as contactors and cables
Benefits Effects	Reduces energy consumption and the noise of pumps during stabling, increases pump service life SBB: 10 to 30MWh per year per locomotive. I.e. 30 GWh per year, which is 8% of total energy consumed by the fleet of 119 locos with 8 to 10 coaches each, running at speed up to 200 km/h.
Effects (CO2)	Depends on the primary energy mix
Ease of implementation	Medium
Constraints, challenges, or lessons learnt	Implemented on several locomotives at SBB
S/M/L term	Long-term
Efficiency	Depending on pump size and operational profile
Maturity	Mature
Mentioned by	SBB
Experience	Different projects completed
Comment	-

5.3. Infrastructure

There are two main ways in which infrastructure is implicated in energy saving:

- Traction energy: the traction power supply system generates losses of between 2% and 15% depending on the voltage system used
- Other uses: signalling, control, telecoms, and lighting all need electrical energy. Ageing systems consume a lot of power, with renewal enabling the use of energy efficient systems.

In terms of traction energy, railways and public entities, such as sustainable development agencies, emphasise that the most efficient use of energy is for electric railways. From the infrastructure to the wheels of a traction unit, energy efficiency lies at approximately 90%, depending on voltages. On the other hand, for batteries this figure is at 65%, with other means having an efficiency below 35% (including the known efficiency for any internal combustion engine).

Therefore, electrifying a system (including via battery trains) is often justified, if the project is studied with a systemic view and all aspects are taken into account over the lifetime of the future asset. Its capital expenditure (CAPEX) is high, but its operational expenditure (OPEX) is low, as are the losses, and has a life cycle of 50 years or more with the right maintenance.

At the design phase of a project, all these aspects have to be studied in conjunction with the foreseen traffic levels and the necessary maintenance or OPEX of trainsets, whereby pure electric trainsets have better efficiency and a lower OPEX. This is why a systemic view is so important, as this way of thinking has allowed the major networks to be electrified over the last century, and the new challenges arising from climate change and the energy crisis should naturally lead the best solution in terms of energy efficiency, CAPEX, OPEX and CO_2 emissions being implemented.

New technologies such as power electronics, energy storage, and renewable energy production offer new possibilities in terms of energy management. It is now possible to:

- Link networks, even if they are not directly involved in traction or supplying infrastructure components, this reduces general losses and increases the reliability, availability, maintainability, and safety (RAMS) of the networks
- Manage energy flows from one point to another for the most efficient energy use
- Implement reversible substations for DC to return braking energy to the grid
- Adapt consumption to the available energy and avoid peak hours of demand with higher costs
- Store energy coming from:
    - Braking trains
    - Solar farms, panels, renewable intermittent production
    - Any electricity production

  And re-use it at the best time, i.e., during peak demand, for:
    - Traction
    - Supplying additional systems (escalators, lighting, control-command, etc.)
    - Supplying any external non-railway systems
- Implement high power converters in traction substations, where necessary, i.e., to:
    - Generate 16.7Hz or a particular railway traction frequency
    - Balance single phase 50Hz or 60Hz traction
    - Link parallel substations through overhead lines with converters at the end of the sections
- Use substation converters with voltage regulation (i.e., to compensate voltage losses), and monitoring (best possible maintenance and to avoid incidents)
- Improve voltage stability
- Stop the supply of energy to devices if there is no energy consumption and restart this immediately when needed: use only when required (see *5.3.5 Smart control of* power supply*)*
- Enhance the traction power supply system by enhancing the overhead contact line (OCL) voltage using smart rectifiers (changes from 1.5kV to 3kV) or electronic autotransformers (for DC) to adapt the autotransformer principle to DC.

The UIC Energy Saving Taskforce has shared a set of solutions to improve transmission energy efficiency and avoid excess energy consumption. The initial set of solutions was built into a mind map (Figure 29) to be referred to during the workshop, with many specific solutions being added to this section (*5.3 Infrastructure*) of the catalogue following the session.

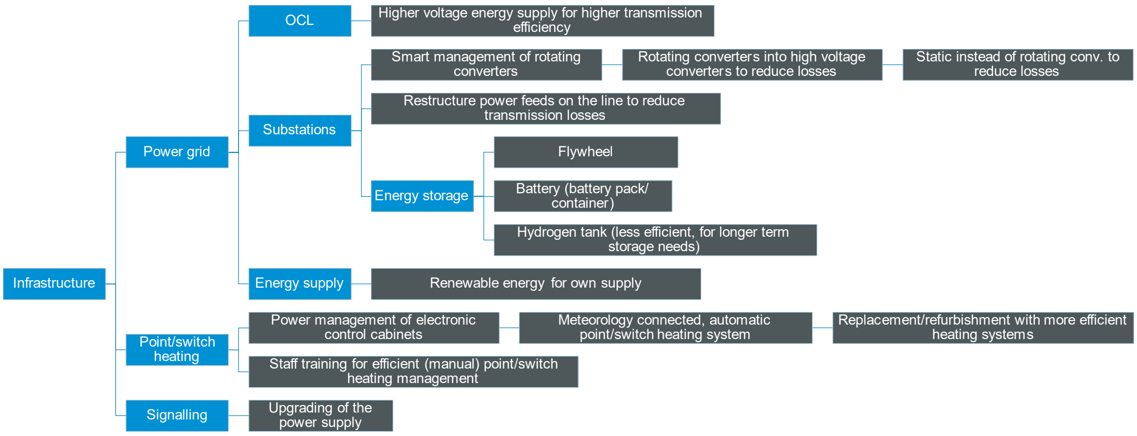


Figure 29: Infrastructure solutions map as proposed for the UIC workshop

For easier understanding, the following solutions were sorted following the levels given in Figure 29.

5.3.1. Railway layout and infrastructure performance

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High

Field	Track design and maintenance Optimised infrastructure and bridges
Solution	RUs & IMs to work on track curve adjustments and gradients to reduce friction and maintain a smooth speed profile (RUs can report to IMs about problematic segments) S2R: Low cost high-speed bridges and long-performing and easily maintained structures
Description	• Maximising curves to avoid reducing speed and decrease kinetic energy losses • Having homogeneous speed profiles

	• Avoid having temporary speed restrictions
	• Reducing gradients
	• Following hump profiles (using the station's altitude or artificially making the stop higher) to potentially convert energy with a descending slope for the acceleration phase, and an ascending slope for the braking phase
	• Optimised tunnel and bridge use to avoid gradients and curves
	• Tunnel optimisation for reduced resistance due to pressure (Niu et al., 2020):
	  ○ Lowered pressure
	  ○ Pressure recycle duct
	  ○ Tunnel portal
	Examples:
	• Alpine tunnels, such as the Gotthard/Lötschberg tunnels, which avoid trains having to climb saves a lot of energy
	• Paris-Lyon's high-speed line where trains adapt their speed and power consumption using the line's gradients to reduce power for acceleration and to avoid braking
	
	S2R: Low-cost high-speed bridges and long-performing structures aim at increasing the longevity of infrastructure before reaching a critical state and structures can be restored quicker without disturbing traffic through regulating speed and structure availability. Structures time of service is extended leading to cost and environmental savings with ensured safety

Objective	Make traffic as smooth and fluid as possible, to improve the timetable and reduce traction energy consumption Using natural and artificial topology to save traction energy S2R: Reduced construction and maintenance related energy consumption
How to	RUs can report to IMs about problematic segments • For new lines, working on track alignment design to maximise the curve radius, efficient tunnel design and avoid frequently changing speed restrictions • For existing line, the same goal stands, working on the speed profile/curves, tunnel pressurisation systems, in order to have smoother trajectories. To the extent that work is possible
Costs and resources required	Requires extensive designing and planning Requires work on tracks and on the ground, halting operations for a certain period on existing lines S2R: Reduced material costs and optimised maintenance costs and efforts
Benefits Effects	Energy: Improves the timetable and reduces traction energy consumption Energy reduction reported to be "high" by ProRail S2R: Energy savings of up to 25% from bridges energy consumption due to reduced material usage and of at least 10 % due to prolonged usage of already existing structures.

	Improved capacity due to reliable infrastructure and less frequent and shorter maintenance times.
Effects (CO_2)	According to traction energy, electricity mix, according to traction energy savings. S2R: Avoided impact of civil engineering energy consumption due to optimised construction and maintenance profiles
Ease of implementation	Implementation is not easy, because it requires track adjustment, so a long period without operation S2R: Works on infrastructure if applicable
Constraints, challenges or lessons learnt	Adjustment/redesign prevents operations
S/M/L term	Short/medium term
Efficiency	(Cost over effects)
Maturity	S2R: Several parts of the solution are ready. Good access perspectives for infrastructure managers that own bridges
Mentioned by	ProRail, S2R IN2TRACK projects
Experience	-
Comment	-

- https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK
- https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK2
- https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK3

5.3.2. Electrification: increased efficiency, renewable energy integration and smart management

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	Low	High

Field	Electrification
Solution	Full or partial electrification of tracks Full or partial electrification of trains Enabling energy recuperation Enabling smart grid management, integrating: • Renewable energy production • Energy storage systems (incl. mobile systems)
Description	Nowadays, electrification does not only mean building an OCL system Energy storage technologies allow electrification with a proper balance between static supply and onboard storage Electrification allows the use of inherently more efficient energy medium Electrification enables the smart management of energy flows, power to load, maximising work efficiency, and power to storage to avoid losses

	Electrification allows the use of a company's own resources and secures a railway's energy supply by using renewable energy Electrification allows regenerated kinetic energy to be used via electrodynamic brakes Partial electrification of vehicles (hybridisation) allows a combustion engine paired with a battery to be set to run at its most efficient point (to generate electricity or on-demand power) Smart grid management helps the most efficient use of renewable energy and energy storage systems (both static and mobile), and the most efficient supply/load balance (peak shaving, delaying production input or delaying consumption) to be made
Objective	Reach peak electric traction efficiency and capabilities
How to	Electrification can be achieved in two ways: • Full: equipment/infrastructure electrification • Hybrid: onboard energy storage and partial static electrification or charging points The second setup adds flexibility when capital expenditure would be too large for a line, for example, when it is only expected to have moderate traffic The railway grid, combined with the public grid and smart management with energy storage, can help to have highly efficient electricity distribution and allocation
Costs and resources required	From least to most expensive: 1. Onboard storage (full electric or hybrid trains), limited range with electricity. Good for short lines 2. Partially electrified line with electric or hybrid trains (charging points or electrified segments). 3. Full track electrification, no need for onboard storage (but will allow any hybrid train to use electricity), for dense traffic
Benefits Effects	Energy: Improved efficiency of both electric and hybrid vehicles, with kinetic energy recovery (reducing fuel costs) Allows renewable energy to be used (reduced costs & energy dependency on the market)
Effects (CO_2)	Footprint: https://uic.org/sustainability/energy-efficiency-and-co2-emissions/article/carbon-footprint-and-sustainability
Ease of implementation	Significant work usually required: study, budgeting, conception, design
Constraints, challenges, or lessons learnt	Capital expenditure is the main challenge
S/M/L term	Mid/long-term
Efficiency	(Cost over effect)
Maturity	Infrastructure: Mature Energy storage: Mature, with ongoing developments
Mentioned by	Multiple
Experience	-
Comment	-

5.3.3. Supply structure/neutral sections

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Low	Medium

Field	Electricity feeding strategy
Solution	Identifying the best supply system locations on a line, according to the foreseen traction power needs and gradients: neutral section to avoid power equipment use and losses
Description	Substations operating in parallel can improve the supply efficiency and reduce neutral sections. Neutral sections in AC electrification do not generally generate particularly high losses and therefore do not have energy saving potential. The issue is more in terms of train dynamics as they may lose speed by crossing them, and no longer respect the timetable. For 75 years now, at the design stage, design studies have tried to: • Find the best neutral sections in sections with low gradients • Avoid neutral sections where traction is necessary • Reduce the length of the neutral sections (i.e., 142m or 400m see TSI or EN 50367) • Automate the link between traction units and infrastructure to avoid manually switching between adjacent overhead contact lines (OCL) Where both a neutral section and traction energy are necessary, it is useful to implement an automated changeover switch system, which makes the neutral section transparent for the traction unit. It is possible to link adjacent OCLs through converter stations. This provides redundancy and better voltages at pantographs with an energy flow from one OCL to another • Energise neutral sections by: ○ Feeding the train through converters stations using a Railway Interline Power Flow Converter (RIPFC): double side feeding, (improving voltage levels, reducing losses and increasing track capacity), peak load reduction (see *5.3.7 Flexible traction energy supply systems*) Note: In Europe, passing through a neutral section [AC-AC (phase) or DC-AC (system)] shall be in accordance with the TSIs and EN 50388 and 50367.
Objective	Define optimal power supply equipment location and setting up

How to	• Locate neutral sections in sections with low gradients
	• Energise neutral sections by:
	  ○ Feeding the train through converters stations
	  ○ Having an automated changeover switch system

Costs and resources required	-
Benefits Effects	Energy: Depends on the specific train operation use case and the solution implemented, double-side feeding and voltage stabilisation can significantly reduce transmission losses

Effects (CO_2)	Footprint:
Ease of implementation	-
Constraints, challenges, or lessons learnt	-
S/M/L term	-
Efficiency	(Cost over effect)
Maturity	-
Mentioned by	S2R FINE2, SNCF Réseau
Experience	SNCF Réseau (FINE 2 Study for parallel operation of substations)
Comment	-

- https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=fine-2

5.3.4. Infrastructure manager information for railway undertakings: increase the operator awareness regarding more efficient driving and consumption at standstill

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium/high	High
Special note	Inventive solution		

Field	Collaboration/partnership between IMs and RUs to define measures
Solution	The solution concerns collaboration and information sharing from IMs to train operators. Given that IMs have useful information regarding consumption as they are more likely to have access to the energy meter data from plug sockets and any other stationary equipment.
Description	• Reporting driving issues due to tracks/infrastructure • Collaboration/cohesion for efficient power management • IM to provide TMS link for DAS
Objective	Energy saving, avoiding network collapse due to overconsumption
How to	This solution goes beyond an operator-only solution: • Collaboration between IMs & RUs regarding traction energy consumption patterns, anomalies, possible improvements • Collaboration for strategies on timing energy supply with traffic management and stabling/maintenance/operation times • Real-time information sent to drivers through automatic messages sent from TMS, and automatic or manual adjustment of traction unit power consumption (disruption management with C-DAS or other)
Costs and resources required	Best use of investment, better reliability, availability, maintainability, and safety (RAMS) of the system. No capital investment needed

Benefits Effects	Energy: According to identified saving potentials
Effects (CO_2)	Footprint: According to traction energy saved and energy mix behind
Ease of implementation	The number of operators involves more complexity but also more information
Constraints, challenges, or lessons learnt	Possible issues in terms of railway traffic management (implementation not possible due to traffic management/timetable constraints)
S/M/L term	Short-term implementation
Efficiency	(Cost over effect)
Maturity	-
Mentioned by	-
Experience	-
Comment	-

5.3.5. Smart control of power supply and on-demand supply

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Field	Smart control of power supply equipment
Solution	Automatic control of power supply: switching off of transformers to avoid inherent operational losses in the system
Description	Substations have transformers that consume reactive and active energy according to power demands. If the substation is not supplying any trains, inherent operational losses can be avoided with an active power electronic switchgear monitoring the presence of trains. This is possible thanks to a process bus communication taking substation control to a new level.
Objective	Energy saving and optimal equipment use (reduced losses & wear)
How to	The process bus transmits sampled values (SV: current and voltage), measured and digitised by merging units to the protection device. Leading to new control and protection functions. Coupled with a system that detects the presence of trains, a power switch turns the supply system on or off if there are no trains. The power switch which is triggered at specific times to avoid stress and energy losses in the equipment. The technology, almost state-of-the-art in the public energy supply, has not been used for railway power supply applications before. The challenge is with the individual peculiarities of the railway power supply resulting in different requirements and prerequisites.
Costs and resources required	SNCF: Cost of installation of a power switch/automated switch
Benefits Effects	• Considerable improvement of the railway system's energy efficiency

	• Positive impact on the lifespan of equipment. • Contribution to better plan investments and evaluation of the railway system's energy efficiency
Effects (CO2)	Related to electricity saved, depending on electricity production mix
Ease of implementation	New technology
Constraints, challenges, or lessons learnt	-
S/M/L term	Short term
Efficiency	It works well, with results present
Maturity	Mature (in use in the energy market) S2R: Solution ready. Besides laboratory testing and trial operation of the process bus technology in a 16,7 Hz railway power supply environment, the Shift2Rail IN2STEMPO project investigated the application in further railway power supply systems, the necessary homologation process to introduce the technology into the market and connections to further WPs. The tests have shown the overall applicability of process bus in an 16,7 Hz railway power supply environment. Furthermore, the IN2STEMPO project has highlighted necessary engineering tasks and limits of a single process bus network as well as used device.
Mentioned by	SNCF Réseau, 1,5kV DC, under study Shift2Rail IN2STEMPO project
Experience	SNCF: 3 years
Comment	Feasibility and advantages demonstrated. Large-scale use will decrease costs. Many possible applications (i.e., adaptation of the number of rectifiers in service in large substations according to real traffic volumes)

https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2stempo

5.3.6. Increased voltage for better transmission efficiency

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Low or High	High

Special note More sharing needed

Field	Electricity losses in the traction energy transmission system
Solution	Higher voltages to reduce transmission losses in the overhead contact line. • Bane NOR: Transport at double voltage, distribution to pantographs at TSI stipulated values through autotransformers

	• FS RFI: Increase the traction supply voltage in electrical substations in order to decrease energy loss (up to 3.9kV DC and 27.5kV AC)
Description	• Bane NOR: Approx. 2% of the energy in the electric traction power supply system is lost in the overhead catenary system (16GWh for Bane NOR every year). By changing the old 15kV to the new 30kV system, losses are estimated to go down by 60% for 25kV and 75% for 50kV
Objective	Reduce transmission losses
How to	The idea is to use the highest permanent suitable voltage system (e.g., 27.5kV) for the substation transformer: Increase the line voltage (e.g., at 3.9kV DC) instead of operating at a lower voltage, by acting on the tap changer of the traction transformer. This allows to reduce the catenary energy losses. Another method is to change the power supply infrastructure from a single-phase to a double phase system with autotransformer posts. This solution initially requires high investment, but reduces catenary energy losses while also increasing the power supply infrastructure's general performance. • Bane NOR's grid is using 15kV over 16.7Hz. A feeder line of -15kV is added to the 15 kV feeder allowing 30kV to be used. So the traction power supply system is 15 kV, and is known as 2x15 kV with autotransformers
Costs and resources required	• Bane NOR: A cost benefit analysis for each project in terms of train performance, CAPEX, OPEX, CO_2 emissions has to be carried out to make a choice between single 15 or 2x15 kV
Benefits Effects	Energy: Using an autotransformer system compared to the conventional system, can reduce transmission resistance by up to 30% • FS RFI: Expect a -5% due to this measure, combined with staff training for driving and energy saving on stabled trains
Effects (CO_2)	Footprint:
Ease of implementation	• Easy if possible by acting on the transformer • Expensive if changing power supply
Constraints, challenges, or lessons learnt	FS RFI: Possible issues related to overvoltages at the pantograph
S/M/L term	FS RFI: Short-term implementation
Efficiency	(Cost over effect)
Maturity	High maturity for 25kV, technology in use since the 1960s
Mentioned by	Bane NOR, DB, Trafikverket, SBB, FS
Experience	25kV since the 1960s, also implemented in Germany, Sweden , Switzerland (Luino) with 15kV
Comment	This is 2x15kV with autotransformers. 30 kV is difficult to implement, as is 50kV. Additionally, 30kV is not TSI compatible. Consistency with RST TSI and Energy, EN 50163 and 50388 required Also concerns 1.5kV UNIFE: The same approach could be implemented on all PS voltage systems (1.5kV DC, 15kV AC, 750V DC, etc.)

5.3.7. Flexible traction energy supply systems

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

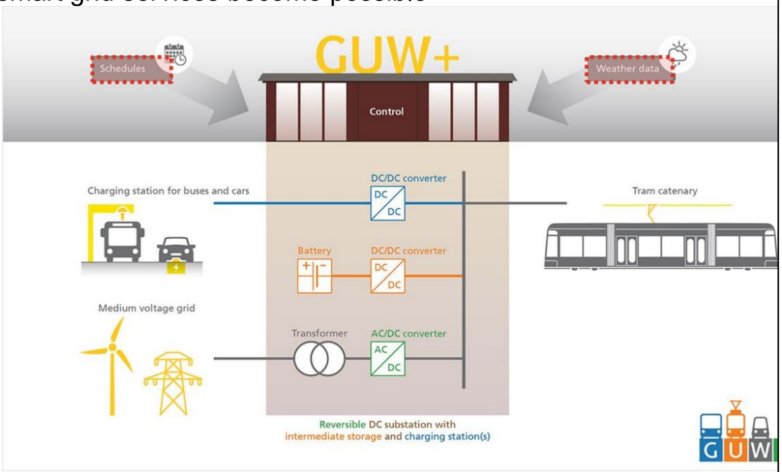
Field	Electricity losses in AC traction energy transmission systems
Solution	Smart traction power supply 50Hz AC (Shift2Rail In2stempo): Connect phase pairs: send energy back to the public grid Double-side feeding and power quality improvements by using flexible AC transmission systems (FACTS) Using different FACTS, e.g., SFC (static frequency converters) or SVC (static var compensators) for AC power supply systems (see below) SNCF Réseau: Balancers, voltage boosters
Description	Flexible AC Transmission System (FACTS): • Static var compensator (SVC): compensates reactive power to improve voltage levels (reduces losses, increases track capacity) (cheaper and easier to implement than SFC) Ready to use • Railway interline power flow converter (RIPFC): double-side feeding, (improving voltage levels, reducing losses and increasing track capacity), peak load reduction • Benefit: no need to change substations. This is a solution for the management of neutral sections (see *5.3.3 Supply structure/neutral sections*) Not implemented • Static frequency converter (SFC): used instead of a conventional substation to control flows Allows peak load reduction, voltage stabilisation, double-side feeding, power quality improvement, and the removal of neutral sections Ready to use
Objective	• Reduce transmission losses • Reduce power demand peaks • Improve voltage stability and power quality • Balance the connection to the public grid
How to	By replacing conventional transformer substations with SFC, double-side feeding can be enabled, and supply sections can be coupled This leads to improved voltage stability, reduced transmission losses, better energy exchange between trains, and power demand peak reduction SVC can be used to compensate reactive power and thereby improve the line's voltage stability Integrate with urban stakeholders (ESS + energy management systems)

	Examples: • The European MERLIN Project (mainline smart grid)
Costs and resources required	Depends on substation size and technology used
Benefits Effects	Energy: Depends on the specific train operation use case and the solution implemented, double-side feeding and voltage stabilisation can significantly reduce transmission losses
Effects (CO_2)	Footprint:
Ease of implementation	SVC and SFC are state-of-the-art
Constraints, challenges, or lessons learnt	These solutions need to be studied in conjunction with their impact on traction units and related functioning within the traction power supply facilities. To be included in EN50388. Impact on signalling systems shall also be verified
S/M/L term	Medium/long-term implementation (due to investment planning requirements)
Efficiency	(Cost over effect)
Maturity	Feasible, demos held as part of S2R/ERJU SFC and SVC are ready to use
Mentioned by	SNCF Réseau, Eurotunnel, NR, DB, Bane NOR, TRV, ÖBB, SBB
Experience	DB, SNCF, ÖBB and SBB since more than 20 years
Comment	-

5.3.8. Installing energy recovery systems on DC railway lines

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

Field	Using braking energy on DC electric traction powered networks
Solution	Inverter technologies to feed energy back to the supplying power networks
Description	○ Reversible substations within a DC power supply system contribute to a higher use of the energy regenerated by trains during brake applications, as most of the braking energy is captured, which can reduce energy consumption by between 7% and 15% depending on the line, the services, and the number of reversible substations on the line ○ Trackside energy storage (see solution *5.3.16 Trackside energy storage*)
Objective	To ensure that train braking energy is reused and not wasted in braking resistors
How to	Example: A smart traction substation, which has power supply cubicles for urban rail, charging units for electric road vehicles and an energy storage system as (such as from the GUW+ project for urban rail). This offers a unique synergy and operational advantages to

	the operator. Thanks to a bi-directional input converter, several smart grid services become possible 
Costs and resources required	-
Benefits Effects	-
Effects (CO_2)	-
Ease of implementation	Several manufacturers can offer this solution
Constraints, challenges, or lessons learnt	It is not always possible to feed regenerated energy back into the public network, due to constraints from the public DSO/TSOs. These devices should be designed after traffic analysis is carried out. It has been demonstrated that implementing these devices in very dense traffic areas has no major impact, as neighbouring trains consume the regenerative energy
S/M/L term	Medium/long-term implementation (due to investment planning requirements)
Efficiency	(Cost over effect)
Maturity	-
Mentioned by	FS SNCF Réseau (reversible substations) ADIF & RENFE (reversible substations and rolling stock regeneration capabilities), tram and metro operators
Experience	-
Comment	-

5.3.9. Recovered braking energy: optimal management

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	High	Medium

Field	Optimal use of recovered energy via electronic brakes
Solution	Ensuring that the energy recovered via the overhead contact line within an IMs network will be spent or stored instead of lost. As

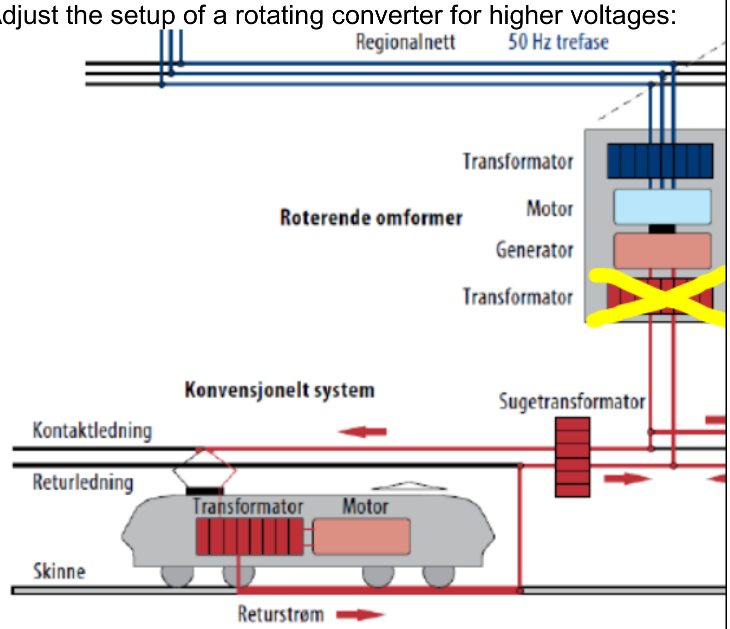
	suggested in the solution from *Operations, 5.2.7 Fine tuning train services* , timetabling can synchronise train acceleration and braking phases to ensure that energy is spent. However, energy can now also be stored in energy storage systems, or returned to the grid • Bane NOR: Synchronising recovered braking energy which is fed back to the grid with demand from the network or public grid
Description	• Bane NOR: Demand has to match the braking time. Connected to the public grid, Bane NOR ensures that the demand matches the surplus energy created by regenerative braking. This ultimately reduces the RU's overall energy consumption (recovery partially compensates consumption)
Objective	Maximise energy recovery via efficient (time/proximity) allocation
How to	-
Costs and resources required	-
Benefits Effects	Braking energy can be used by another train or by the public grid, which results in savings
Effects (CO_2)	-
Ease of implementation	-
Constraints, challenges, or lessons learnt	-
S/M/L term	-
Efficiency	-
Maturity	-
Mentioned by	- Bane NOR
Experience	-
Comment	-

5.3.10. Avoiding and reducing rotating converter losses (15kV, 16.67Hz systems)

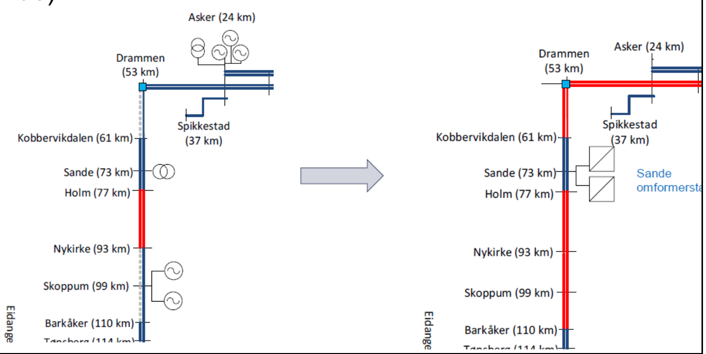
	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	High	High

Field	Electric losses in the traction energy transmission system
Solution	1. Redesigning rotating converters as high voltage converters to reduce losses, thereby increasing the functioning voltage of rotary converters 2. Replacing rotating converters with static converters to reduce losses, if the required energy output is moderate 3. Redesigning the feeder system via a set of static converters to replace a set of geographically spread-out rotary converters 4. Adapting the functioning point of a (set of) rotating converter(s) to fit the required load to reduce losses
Description	Rotating converters have a 20-30% loss ratio:

<table>
<tr>
<td></td>
<td>
1. By increasing the voltage of a rotary converter, the initial base losses due to operation at a specific voltage are avoided
2. Static converters have approx. 10% loss or less
Fewer static converters set to a proper functioning efficiency can replace more rotary converters spread across a route
3. The base losses of rotary converters are avoided by simply reducing the number of working components along the line
4. Regulators coupled with a set of rotating converters allows the load to each converter to be managed, to make sure they are working at their highest efficiency level
</td>
</tr>
<tr>
<td>Objective</td>
<td>
Increase converter efficiency, capacity, and avoid the need for a transformer
Increase converter efficiency by having them work at their optimal working point, adjusting the converters to the required load for optimal efficiency and capacity
</td>
</tr>
<tr>
<td>How to</td>
<td>
1. Adjust the setup of a rotating converter for higher voltages:



2. Remove rotating stations and transformers, replacing them with one bigger static station
E.g., 5 rotating stations (Asker & Skoppum) and 2 transformers (Asker & Sande) replaced by 2 static stations (Sande)



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	3. Analyse a segment's needs and accommodate this with the appropriate numbers of converters for operation at their highest efficiency level 4. Smart management of the rotating converter's operation can increase the efficiency according to the load. By adjusting the regulator to the rotary converters' optimal operating point (also meaning optimal efficiency levels (voltage)), the initial base losses are avoided (losses are higher at a lower operating point)
Costs and resources required	Note: Rotating converters are retrofitted as high voltage converters. The cost of a retrofit is low.

Benefits Effects	• Increased converter efficiency
	• Avoid the need for a transformer before the grid
	• Reducing the number of working components reduces the number of potential failures
	For rotating to static:
	• Long-term benefits due to increased efficiency (40 years)
	• More stable given the reduced number of stations
	• Reducing the number of working components reduces the number of potential failures
	• Losses are reduced to approx. 1.5-2% per static station, compared to 10-15% per rotating station
	• Result in terms of energy:
	  ○ Rotating converters have a 20-30% loss
	  ○ Static converters have approx. 10% loss or less
	A smart management system helps to make the most out of a (set of) converter(s), and avoid the losses from multiple converters working at the same time if they are not needed. Increased efficiency of the converter(s) (in operation)
	Smart management also helps to reduce the number of components constantly in use, thus reducing the number of potential failures
	Energy: Avoiding the inherent losses from the converters which were removed

Effects (CO2)	Footprint: Relative to energy saving and the electricity mix in use Balanced use to save equipment from wear and tear (better lifecycle)
Ease of implementation	-
Constraints, challenges, or lessons learnt	-
S/M/L term	-
Efficiency	-
Maturity	-
Mentioned by	-
Experience	-
Comment	-

5.3.11. Lighting: efficiency and management

	Innovation	Ease/rapidity	Benefits
Level	Medium	High	Medium

Special note More sharing needed

Field	Avoid and reduce rail infrastructure specific lighting energy consumption
Solution	• Intelligent control (dimming and/or powering off) • Replace old lighting with more efficient (LED) lamps For general building lighting, see *5.4.6 Smart and efficient LED lighting*
Description	Lighting adapted to operational requirements: • Switched off when there is sufficient light • Automatic switch on when in operation in the dark • Automatic switch off when rolling stock is not in use • Automatic/manual switch on or off for different maintenance phases
Objective	Save energy through the moderated use of lighting
How to	-
Costs and resources required	-
Benefits Effects	Energy: LED lights would only require a few watts to illuminate, thus benefits are relative to the scale of deployment
Effects (CO_2)	-
Ease of implementation	-
Constraints, challenges, or lessons learnt	-
S/M/L term	-
Efficiency	-
Maturity	-
Mentioned by	-
Experience	-
Comment	-

UIC Non-traction energy study report 2012
https://uic.org/sustainability/energy-efficiency-and-co2-emissions/

5.3.12. Switch/turnout heating system management, optimisation and upgrading

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	High	High

Field	Power management for switch/point heating
Solution	Optimising switch heating controls to reduce energy consumption without affecting safety and availability. This commonly means

	upgrading to more efficient, automated and electric heating (avoiding unnecessary heating), and avoiding the use of gas System management scheduled according to weather forecasts to eliminate excess energy consumption from heating Energy efficiency for switch heating can be ensured through a proper power management of the electronic control cabinets/power units For non-automatic electric switch heating systems, increasing staff awareness regarding efficient and effective management is another solution to decrease energy use Proper heater insulation is crucial to avoid wasting heat. A combination of better insulation and power regulation significantly increases the heater energy efficiency (UIC-FFE, 2017) The heater technology itself can be switched to a more efficient/less critical energy source (e.g., gas to electric). Another solution is to use geothermal heat, wherever possible, as described in UIC-FFE 2017.
Description	Switching to electric and/or automatic switch heating has been RFI's solution. For SBB, weather stations along the track measure the outside temperature and precipitation. The updated software control logic now uses this information to optimise the switch-on and switch-off parameters, which can be optimised through longer test runs for gas heaters In 2013, railway switch heating represented 50% of Bane NOR's total energy consumption, and half of the electronic control cabinets/power units at that time did not have power management. The deployment of a power management system has increased this figure to 91.5% as of September 2023 (which this being at 80% in 2017). Now, Bane NOR is pushing the responsible parties to regulate the final ones according to temperature and weather
Objective	To reduce switch heating energy demand and to ensure that heating is not on when it is not needed
How to	Link functioning levels/schedule to temperature/weather forecasts for a smart predictive adjustment Upgrade to electric heating, thus avoiding the use of gas, and switching to more efficient heaters Upgrade to automatic heaters (to avoid unnecessary heating time) Through longer running tests, it is also possible to reduce the gas switch heating parameters from 14°C to 10°C (temperature sensors at the rail foot for switching burner tubes) Electronic control cabinets/power units can be replaced with new power managed units, which have temperature sensors in the air and on the tracks, and know when precipitation occurs. They are

	connected to a weather station, so they know the forecasted temperature
Costs and resources required	The price of the power management system and its installation
Benefits Effects	Automatically switching off heating saves energy that would be wasted when the weather conditions mean that heating is not required Heating times could be reduced by around 120 hours per year without any impact on the availability and safety of the switch heating systems The power management systems could cut non-traction energy losses for switch heating by up to 60%
Effects (CO_2)	Relative to the reduction in energy consumption
Ease of implementation	Easy, solutions already exist. For electronic control cabinets/power units, software allows them to be monitored
Constraints, challenges, or lessons learnt	Possible issues in terms of railway traffic management. Needs to be followed up continuously with someone to analyse the cost/benefit ratio of regulated switch heaters. If switch heaters are monitored at the same time and an anomaly is spotted, it is possible to adjust them during maintenance Bane NOR used to have a system from a producer to monitor switch heating and more (Genesis from Malthe Winje), but they have now built their own system to independently manage the data according to their needs and so that it work smoothly with each supplier that they choose to install
S/M/L term	Short-term implementation for electric/automatic switch heater installation Short-term implementation for staff management
Efficiency	Medium to high, since a lot of energy can be used for heating
Maturity	Mature
Mentioned by	Bane NOR has been using ProxII, Malthe Winje, and Pintsch regulation systems to implement the electronic control cabinet/power unit smart management solution
Experience	Bane NOR has reported that their experience with the electronic control cabinet/power unit smart management solution has been very good so far
Comment	-

5.3.13. Tunnels

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium	High

Field	Tunnel management
Solution	Fine tune tunnel lighting and ventilation to save energy
Description	• Tunnel ventilation can represent high energy use: adjusting ventilation to reflect exact needs can save energy

	Caution must be taken as lowering or increasing ventilation might influence traction energy consumption (e.g., pressure in long tunnels)
	• As for other buildings, tunnel lighting can be switched for a more efficient technology (LED)
	• Tunnel optimisation to reduce resistance from pressure (Niu et al., 2020):
	  ○ Lowered pressure
	  ○ Pressure recycling ducts
	  ○ Tunnel portals

Objective	Save traction energy, ventilation and lighting spent through and for tunnels
How to	Alternation to tunnel operational practices
Costs and resources required	-
Benefits Effects	-
Effects (CO_2)	Footprint:
Ease of implementation	-
Constraints, challenges, or lessons learnt	Safety restrictions in each country: • Switching off lighting may have safety implications • Fire safety for ventilation
S/M/L term	Short
Efficiency	(Cost over effect)
Maturity	-
Mentioned by	ProRail
Experience	-
Comment	-

5.3.14. Measurement equipment

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium	Medium
Special note	Inventive solution		

Field	Monitoring energy consumption
Solution	Monitoring the energy consumption of electrotechnical systems and subsystems
Description	Monitoring the energy consumption of electrotechnical systems and subsystems helps to: • Understand consumption patterns • Identify anomalies and areas with energy saving potentials • Show real savings due to improvements
Objective	Understand flows and units with high consumption in the electric traction power supply system to identify options for optimisation
How to	Different approaches to monitoring in substations, on trains, or locations within the system are possible. Pre-existing Supervisory Control And Data Acquisition systems (SCADA, a control system architecture comprising of computers, networked

	data communications and graphical user interfaces for high-level supervision) can be used for monitoring within substations. The more values and information gathered, the better the analysis is
Costs and resources required	Depending on the extent of monitoring
Benefits Effects	-
Effects (CO_2)	-
Ease of implementation	Monitoring equipment is available from many manufacturers
Constraints, challenges, or lessons learnt	Depending on the level and extent of monitoring, a lot of equipment is needed, and a high volume of data needs to be processed
S/M/L term	-
Efficiency	-
Maturity	Ready to be used
Mentioned by	-
Experience	-
Comment	-

5.3.15. Renewable energy supply

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Medium	High
Special note	Inventive solution		

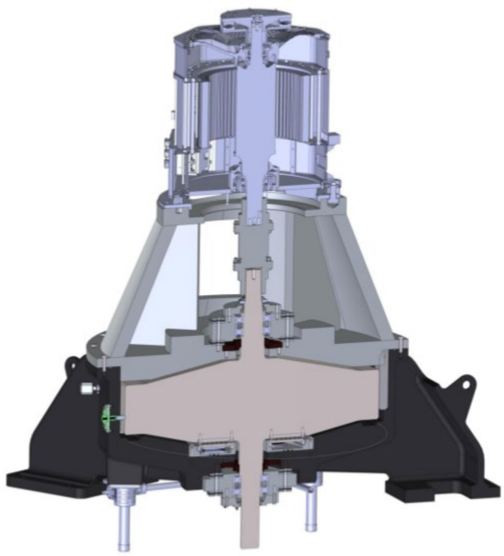
Field	Renewable energy supply
Solution	Increasing the share of renewable energy fed into systems to reduce dependency on the energy market (prices)
Description	Infrabel: Connecting photovoltaic (PV) power plants to supply the railway grid with green electricity
Objective	Reduce the carbon footprint, ensure that some of the electricity supply is at a fixed price
How to	Own investments or have an agreement with a third party (Power Purchase Agreement) and an agreed price over a defined timeframe (e.g. 20 years)
Costs and resources required	For own investment: approx. 1.5M€ for 1MW plant For third-party investment: limited investment costs (man-hours for tendering and connecting the supply to the railway grid only) and reasonable electricity prices
Benefits Effects	Energy: Green electricity, own dedicated production
Effects (CO_2)	Footprint: Footprint of installing the specific plant, emission free while operating, emission reduction if replacing a fossil fuel
Ease of implementation	Permits are needed for large PV plants (especially if not on roofs). For PV plants on sidings, it may come into conflict with the environmental value of the trackside

Constraints, challenges, or lessons learnt	Renewable sources can be intermittent and therefore not systematically usable for permanent consumption, such as for traction. Different ways of consuming this intermittent energy are to: - Send the energy flow to the traction substation and decrease the power use from the main grid. - Store it (batteries, chemical, flywheel, H2) for use at the best possible time (See *5.3.16 Trackside energy storage*) - Send it to the mains, which acts as a overall “reservoir” for electricity customers - Directly consume it onsite for stations, auxiliary installations, via a storage system
S/M/L term	Medium
Efficiency	High due to high benefits
Maturity	Very mature technology. Prices have dropped significantly in last decade
Mentioned by	Infrabel covered the protective roofing of HSL 4 at Peerdsbos with 3.5MW of solar power in 2011 (via a third party). Infrabel will also be investing in 2.7MW of solar power on a field next to the Avernas substation (HSL 2). Infrabel is investigating the building of substantial power generation (multiple MWs of solar power) on HSL 2 sidings.
Experience	See ease of implementation
Comment	-

5.3.16. Trackside energy storage

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

Field	Stationary energy storage systems
Solution	Large stationary hybrid super capacitors and battery storage • Infrabel: Flywheel (mechanical) • PKP: Hydrogen (chemical) • Battery, capacitors (chemical) • Water (mechanical) • Air (mechanical)
Description	Energy storage technologies are becoming more and more mature. The most common technology is the lithium battery, due to its high energy density per unit of mass or volume An energy storage system (ESS) allows “load shedding” for both production and demand on the grid (when paired with renewable energy and the traction grid) It is important to note that common lithium battery technology allows a moderate energy input and output, which is why pairing it with supercapacitors or electric double layer capacitors (EDLC) is important. EDLCs allow significant energy transmission, to maximise recovery efficiency (UIC 2019 Workshop)

	• Infrabel: Flywheel technical specifications o Energy: 26.1kWh (= 3MW for 31.32 seconds) o Power: 3MW o Rotation speed: 4000 rpm o Rotating part: 5 tons o Diameter: 1m50 o Noise: up to 120 dB(A) • PKP: Hydrogen production and storage via electrolysis from solar energy. It will allow up to 23kg of hydrogen to be stored at one time with the power output for individual components being 36kW for the electrolyser, 20kW for the fuel cell capacity, and approx..150kWp for the solar farm. Will be used to power a substation. In the future, traction energy for both electric and hydrogen trains (current and fuelling) may be provided[7]
Objective	• Avoid peak power charges by using stored energy • Improve braking energy recuperation/better line coverage for recuperation
How to	• Infrabel 
Costs and resources required	
Benefits Effects	The principle of using an ESS is to reduce energy demand during peak hours, and store excess power. This equalising role can also be achieved for connected renewable energy production plants. Thus, energy savings can be significant, depending on the imbalance between energy supply and demand. Avoiding peak power transmission allows reducing transmission stress (thus heat and losses) in general. Additionally, the energy storage system can help make sure regenerated energy will be stored and reused around the location.

[7] https://transformercalculations.com/blog/pkp-energetyka-to-build-hydrogen-storage-at-traction-substation

	• Infabel:
	  ○ Short term: recuperation of braking energy + smoothing the power supply
	  5MW 100kWh 100 cycles per day
	  ○ Storage of produced energy
	  500kW 1000kWh 1 cycle per day
	  ○ UPS
	  100kW 1000kWh 1 test cycle per month
	  2kW 10kWh 1 test cycle per month
	  ○ Cons: Noise, wear with friction
	• Hydrogen allows long term energy storage, for example, to provide a rescue power supply

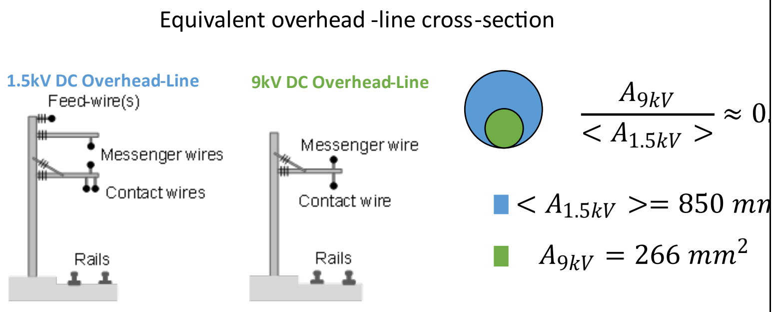
Effects (CO_2)	Related to avoided heat and losses, and retransmitted regenerated energy, according to electricity generation mix.
Ease of implementation	Since maturity is very variable between the technologies, it is a challenge to be an early adopter and get a successful pilot project.
Constraints, challenges, or lessons learnt	Risk of failure, obsolescence (technology maturity), limited capacities.
S/M/L term	According to technology. Water storage requires large infrastructure → Long term. Battery packs, containers are available on the market → Medium term.
Efficiency	According to power stress on grid, potential regenerated energy saved from waste.
Maturity	Pilot programmes for flywheels and hydrogen Battery and capacitors solutions are market-ready
Mentioned by	Infrabel, FS RFI, PKP, SBB, SNCF
Experience	-
Comment	-

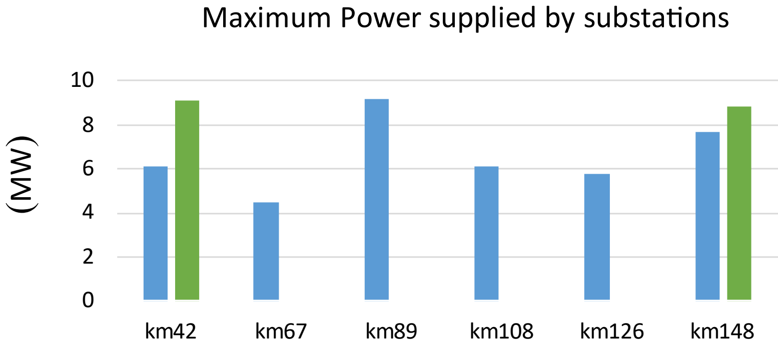
5.3.17. Medium voltage direct current electrification systems

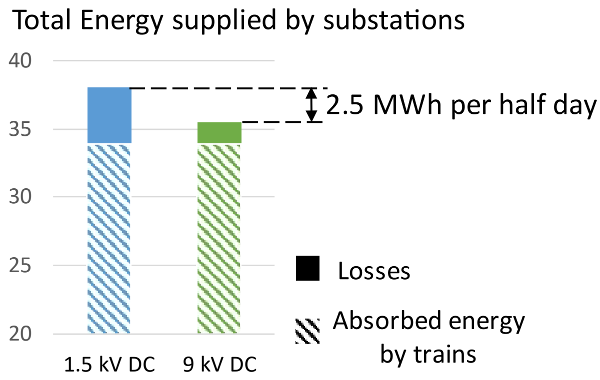
	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Low	High
Special note	Inventive solution		

Field	Traction power supply system efficiency
Solution	Using a Medium Voltage Direct Current (MVDC) electrification system to reduce transmission losses, copper use Increase the voltage at the overhead contact line.
Description	SNCF (also within the S2R FUNDRES project) tested a 9kV train supply to optimise the renewal of electrified lines, with interesting results (see below) (Hervé Caron at UIC *The role of IMs in the traction energy transition* Workshop 2019 & UIC OPEUS D7.1)
Objective	• Increase energy supply efficiency, • Reduce material & equipment use

<table>
<tr><td></td><td>• Deploy smart power management</td></tr>
<tr><td>How to</td><td>Case study: the Bordeaux-Hendaye line






</td></tr>
<tr><td>Costs and resources required</td><td>High
Industry to supply switchgear at the voltage (between 6 and 10kV)</td></tr>
<tr><td>Benefits Effects</td><td>Reducing the amount of copper in the overhead contact line (the cross-section is 70% smaller (than the 1.5kV DC), approx. 20M€ saved for 100km)
Fewer 9kV DC substations required than for 1.5kV DC (about 60% less installed power)
Increasing efficiency (approx. 6%)
Savings of 2GWh per year for 100km (about 150k€ per year). A light overhead contact line also prevents inductive voltage drops:
• The reduced line cross-section results in less copper used
• Improved efficiency/reduced transmission losses from 11% (1500 V) to 5% (9000 V)
• Reduced number of substations needed
• Power sharing and equalising between substations</td></tr>
</table>

	• Allows a three-phase power supply from the public grid • Lighter and simpler power converter onboard locomotives • Silicon Carbide power semiconductors enable compact Medium Voltage (MV) traction converter production • This system can also be a solution for countries currently without electrification • Allows easier integration of the MVDC smart grid concept
Effects (CO_2)	Linked to loss reduction. With a 9kV system, traction power supply system efficiency is the same a 2x25kV (more than 97%) Reduced operational footprint with reduced copper consumption However, the carbon footprint of building the new infrastructure and rolling stock would only be balanced out after a long time
Ease of implementation	Hard, see constraints and challenges
Constraints, challenges, or lessons learnt	Only possible for new lines. The rolling stock also needs to be 9kV capable (current rolling stock cannot operate with 9kV DC) Replacing both existing lines and rolling stock with a new system is costly The Energy TSI needs to be adapted
S/M/L term	Long term
Efficiency	High
Maturity	Attractive for countries that need to develop an electrified railway network A DC system which European railway companies can work towards in the long-term
Mentioned by	SNCF
Experience	Studies carried out in some countries: France, Russia
Comment	The first step is to enhance 1.5kV to 3kV, or use 2x1.5 or 3kV with electronic autotransformers

UIC « The role of IMs in traction energy transition" workshop: https://uic.org/events/the-role-of-infrastructure-managers-in-traction-energy-transition & UIC members access https://extranet.uic.org/en/node/90324?grp=297

5.4. Buildings

This section deals with railway buildings, including stations, offices and workshops. Measures in terms of efficient HVAC, lighting and good practice to avoid specific energy consumption are likely to be applicable to all of the abovementioned types of buildings.

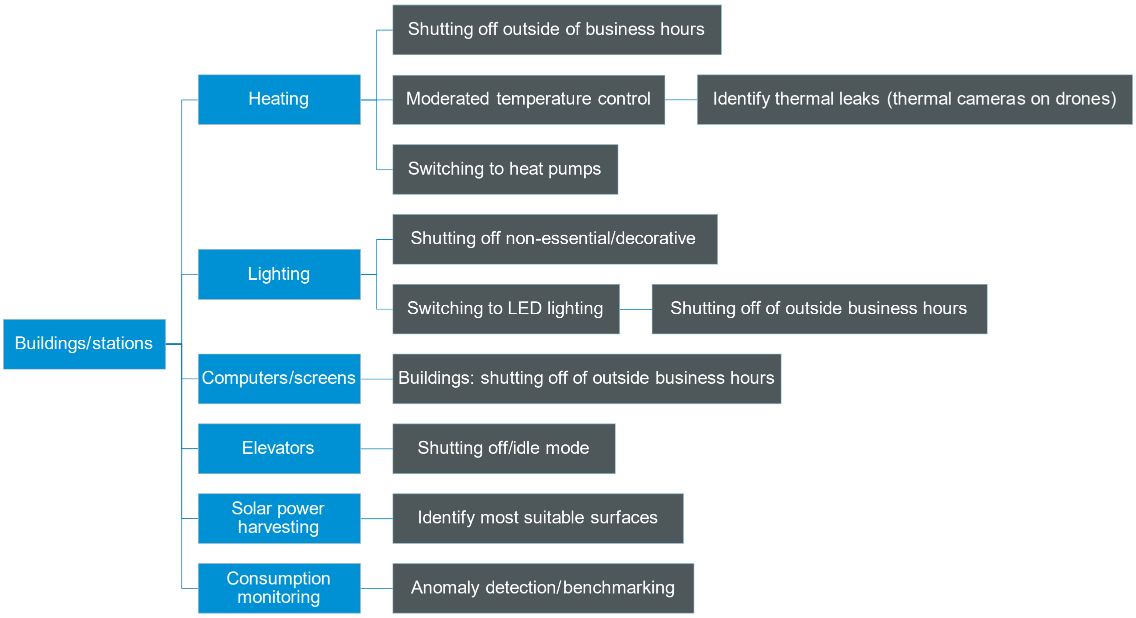


Figure 30: Building/station solutions map as proposed for the UIC workshop

5.4.1. HVAC: efficiency and management

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Field	HVAC energy management
Solution	• Using intelligent HVAC control for buildings: ○ According to weather data/forecasts ○ According to CO_2 levels • Setting lower heating/higher cooling temperatures (see detailed strategies in 5.4.3 Practices for saving energy in stations, buildings, and workshops • Upgrading equipment to a more efficient system (e.g. heat pumps)

	• Useful temperature control: find alternatives to heating and cooling lost large scale (e.g., heating jackets, portable coolers)
Description	• Comfort levels are crucial and temperature settings should be carefully reviewed • Optimising actual building designs based on a holistic approach followed by optimising the technical settings of cooling and heating systems • Improving the efficiency of the system itself by upgrading to heat pumps and avoiding refrigerants which can be leaked as greenhouse gases • Reducing energy losses by identifying and fixing leaks and improving insulation
Objective	Save energy on temperature control systems
How to	SNCF: For some workshops, heating can be inefficient. E.g., very large workshop with very few employees. Heating jackets were offered to staff, allowing to reduce heating energy use. The jackets are waterproof. It is fed by a battery and can offer three levels of heating. It can last up to 10 hours on the weakest mode.
Costs and resources required	SNCF: 50-150€ per jacket.
Benefits Effects	SNCF: Heating temperature could be lowered to 15°C thanks to the jackets, without problems on comfort of staff.
Effects (CO_2)	Footprint:
Ease of implementation	SNCF: Procurement and staff dialogue (see below)
Constraints, challenges, or lessons learnt	SNCF: The introduction of heated jackets must involve the staff and be agreed with social partners. The reluctance of some employees on safety or medical grounds must be alleviated: no risk of electrocution because voltage is extremely low, safety device to prevent overheating, no electromagnetic fields. Safety and care instructions (washing, storage, etc.) must be followed.
S/M/L term	SNCF: Jackets, short term
Efficiency	SNCF: Good
Maturity	SNCF: Good
Mentioned by	-
Experience	-
Comment	-

5.4.2. Harvesting solar power

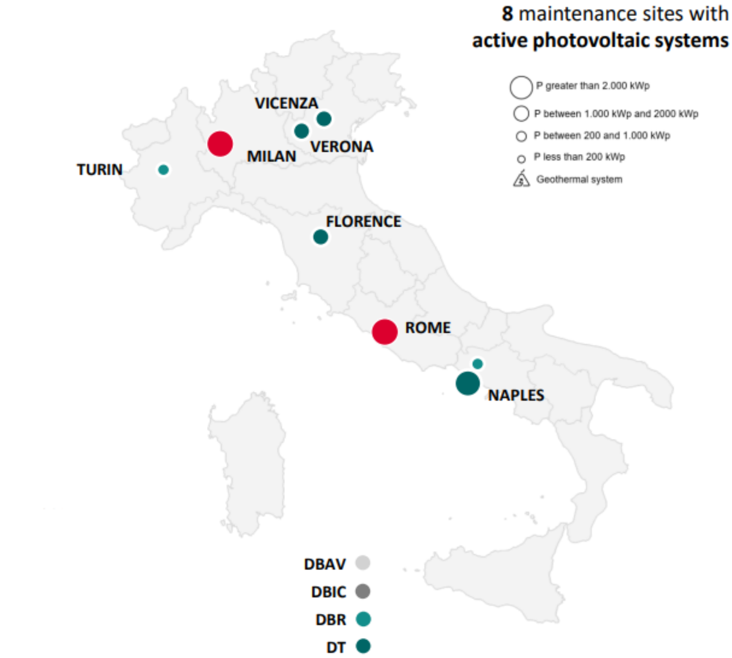
	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High

Field	Renewable energy supply/independent production
Solution	Install solar panels on the surfaces of buildings which have been identified as being suitable Trenitalia: Install solar panels on maintenance sites all over the country ProRail: Install solar panels on noise barriers

<table>
<tr>
<td>Description</td>
<td>

- RFI:
    - Installation of PV power plants in existing electrical substations in order to decrease traction energy consumption
    - Installation of PV power plants in railway stations to decrease the energy consumption of auxiliary equipment
- Bane NOR already has one switchgear building with solar panels installed on the roof. In 2025 the platform roofs at Drammen Station will be covered with solar panels

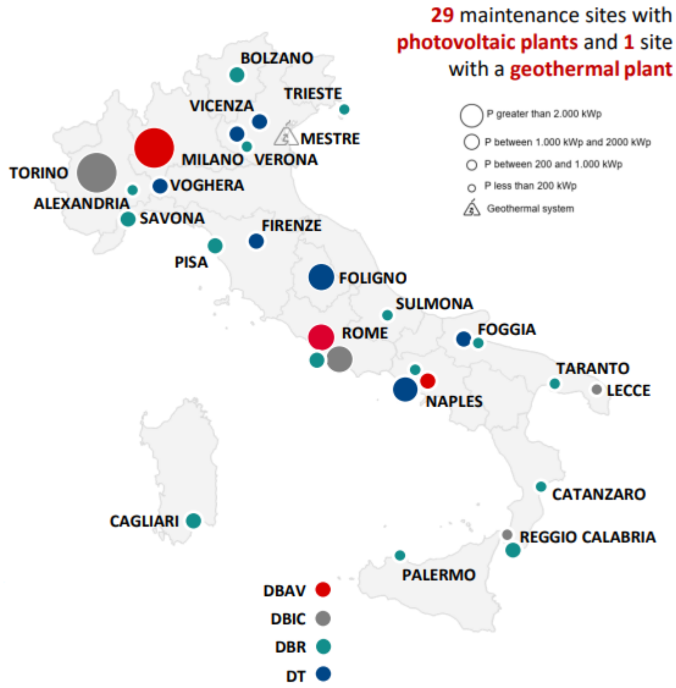
- Trenitalia: Currently has 8 maintenance sites with active photovoltaic systems, producing 6094kWp in total

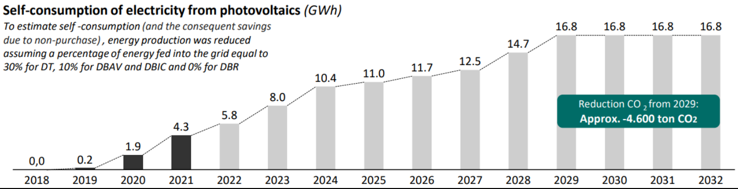


- CFL: Installation of solar panels, and identification of ultra-light solar panels for warehouses due to roofing constraints
- Infrabel: 7.35 MWp on buildings, upcoming installation of 8.65 MWp
- ProRail: Solar panels installed on noise barriers and on 14 buildings/stations, with more to be installed

</td>
</tr>
</table>

	• SNCF: SNCF Renouvelables was created to handle the development of renewable energy production on available and eligible assets:
	    ○ 15-20% of SNCF's electricity needs will be covered
	    ○ Reduced costs will fund railway line revitalisation in France, in line with the French government's plan to modernise the railways
	    ○ 10,000 hectares were identified for optimal solar production, 1000 of which will produce 1000MWp by 2030:
	    ○ Starting in 2030, they will consider using 7000km of trackside
	    ○ Since more than 80% of SNCF's trains run on electricity, it will greatly contribute to decarbonising their operations

Objective	Make the most of unused surfaces to produce energy within the infrastructure • Trenitalia: Increase the energy production to 16,625kWp by 2031
How to	Identify suitable locations, in terms of exposure to sun, surface and proximity to the grid or consumption point • Bane NOR: Working with regulatory authorities to find out ways to reduce the barriers to new solar projects. To be installed on stations, switchgears and then on buildings and other assets • Trenitalia: Increasing the number of photovoltaic plants to 29 and installing a geothermal plant 
Costs and resources required	Studies on suitable locations for solar panels Price of solar panels for a surface, the plant itself and connecting it to the grid or consumption point

<table>
<tr><td>Benefits
Effects</td><td>Energy: The energy produced by the newly introduced panels adds to the already available energy. It can avoid the necessity of purchasing energy for systems with low power requirement in stations or other assets.
Trenitalia: To reach a 16.8% rate of self-sufficiency from photovoltaics by 2029


</td></tr>
<tr><td>Effects (CO_2)</td><td>Footprint: Relative to the energy demand avoided (scope 2)
Trenitalia: An approximately 4600 tons of CO2 reduction for 2029 (see picture above)</td></tr>
<tr><td>Ease of implementation</td><td>Fairly easy for buildings and newly built stations
More complex for existing stations
Higher complexity for noise barriers</td></tr>
<tr><td>Constraints, challenges, or lessons learnt</td><td>Land space constraints and maintenance expertise</td></tr>
<tr><td>S/M/L term</td><td>RFI: Long-term implementation (~10 years)</td></tr>
<tr><td>Efficiency</td><td>(Cost over effect)</td></tr>
<tr><td>Maturity</td><td>Mature (solar panel technology)</td></tr>
<tr><td>Mentioned by</td><td>Bane NOR, CFL, FS, Infrabel, SNCB/NMBS, SNCF, SBB</td></tr>
<tr><td>Experience</td><td></td></tr>
<tr><td>Comment</td><td>An easy and quick solution to implement, and something every company should focus on
Solar systems have a typical 20-25-year warranty, 10 years for inverters and they last much longer and require very little maintenance</td></tr>
</table>

5.4.3. Practices for saving energy in stations, buildings, and workshops

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	High	High

Field	Energy consumption of buildings (stations, offices, workshops) Management and fine-tuning of the temperature and lighting Increase heating efficiency. Automated switch off/hibernation systems for lighting
Solution	Proper heating/cooling management and avoiding or reducing energy consumption for lighting, screens and equipment
Description	Measures to ensure a more efficient heating and lighting system inside and outside of the facilities Defining a set of best practices Deploying an internal communication operation
Objective	Reduce energy consumption
How to	• Moderate and automatic management of heating and cooling.

	• Switching off/automatic switching off of lighting, screens, equipment as vending machines, printers, etc. • SNCF: Staff best practices Recommendations such as: o 19°C for heating, turning off hot water, 26°C for cooling o Shutting down energy sources outside of business hours o Switching off screens outside of business hours Investments including: o Replacing lamps with LED lamps o Reducing light intensity o Having motion detector, o Renewing insulation o Having automated doors to limit heat exchange • Trenitalia: Decreasing temperatures to 12°C in sheds and 16°C in workshop environments. Concentrating processes in as few areas/rooms as possible. Detecting air leaks and only turning on air compressors when needed For efficient lighting: increasing the number of sensors which activate lighting on command and external security lighting only when necessary. In unused areas, lighting and machinery/equipment should be switched off • SBB: o Reduce lighting in the 30 largest stations. Applies to decorative lights such as facades or Christmas lighting. Basic lighting for health and safety is not reduced o Reduce the automatic light switch-off countdown time to for offices o Elevator controls are optimised to reduce the number of rides o Surplus fridges turned off o Hot water supply shut off o To save gas: switching from gas heating systems to oil-powered systems. Checking and optimising 116 buildings using gas powered heating o Replace lighting (switch to LED) o Renewal of amenities o Reduce heating/cooling requirements. Between 20°C and 26°C, office buildings are neither heated nor cooled
Costs and resources required	Definition of best practices Deployment of internal communication operations Cost of studies, tests, and deploying the changes
Benefits Effects	Energy: Trenitalia: Savings of up to 5 million euros per year for lighting and 300 thousand euros per year for air leaks SBB: For reduced station lighting: ~0.1-0.2MWh per day. For gas savings, a 15% reduction (~2-4GWh/a, 50% in 2023/24) due to switching the heating system in buildings. Optimising gas heating and operations resulted in a 2GWh energy saving

Effects (CO_2)	Related to reduced energy consumption
Ease of implementation	Easy
Constraints, challenges, or lessons learnt	Definition of a set of good practices adapted to the local situation Education of the staff Monitoring of the energy consumption
S/M/L term	Short-term
Efficiency	-
Maturity	
Mentioned by	SNCF FS Trenitalia SBB
Experience	-
Comment	

5.4.4. Drone use for solar panel performance inspections and HVAC loss detection

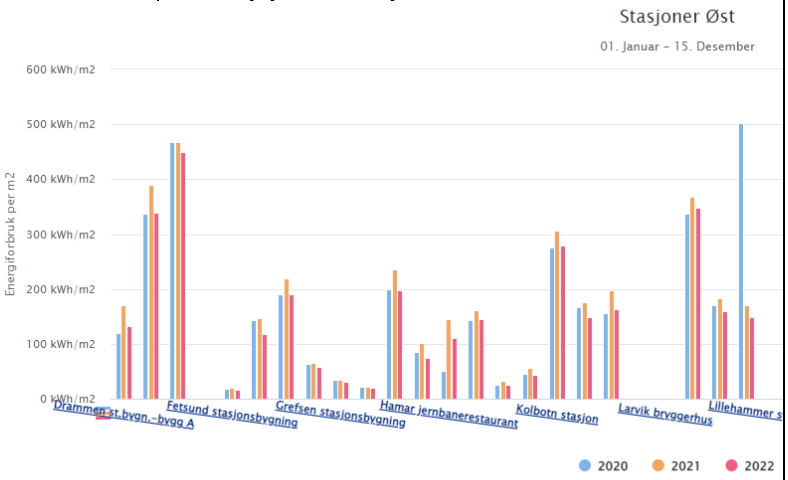
	Innovation	Ease/rapidity/aff.	Benefits
Level	High	High	High
Special note	Inventive solution		

Field	Heating losses and autonomous energy production
Solution	Drone use for solar panel inspections and heating loss detection
Description	NS Stations: Tests have been developed to inspect the satisfactory performance of solar panels in hard-to-reach areas. Broken cells may hinder the energy production of these panels and it is possible to detect them using cameras attached to the drone For heating losses, drones equipped with thermal cameras have been used to this end
Objective	Improve autonomous energy production by ensuring the best possible functioning of the solar panels and avoid heating losses
How to	Through the use of unmanned aerial vehicles (UAVs)
Costs and resources required	Pilot training and the cost of the unmanned aerial vehicles and sensors
Benefits Effects	Losses will be easily detected through the use of thermal cameras so it is clear where maintenance is needed
Effects (CO_2)	Related to reduced energy losses, thereby reducing consumption
Ease of implementation	Easy, it can also be subcontracted
Constraints, challenges, or lessons learnt	The main challenges will be related to drone flights over populated and/or confined areas, as regulation is very strict when flying over the former. Drones may be restricted to specific flight areas
S/M/L term	Short-term
Efficiency	High
Maturity	Mature

Mentioned by	NS Stations is currently using unmanned aerial vehicles for this purpose in stations
Experience	The reported experience from NS Stations is positive
Comment	

5.4.5. Monitoring and benchmarking energy consumption in buildings

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	Medium

Field	Real estate energy consumption
Solution	BaneNOR: Benchmarking buildings and asset energy consumption
Description	Within Bane NOR's Real Estate Division, the properties are equipped with an energy management system (EMS), which allows total and specific energy use to be tracked, with the use of district heating and water in the system also being followed-up. It also has ET-curve functionality which shows how much energy is used at different external temperatures. An ET-curve will therefore allow the performance of properties in different climates and time periods to be compared.
Objective	Reduce the energy consumption of properties and thereby save money
How to	Have an EMS where buildings based on kWh per square meter can be compared, to enable benchmarking on how different buildings perform. It should also have an ET-curve since energy usage for heating varies with the external temperature. This is to increase comparability year after year. 
Costs and resources required	Energy meters, software, development and follow-ups

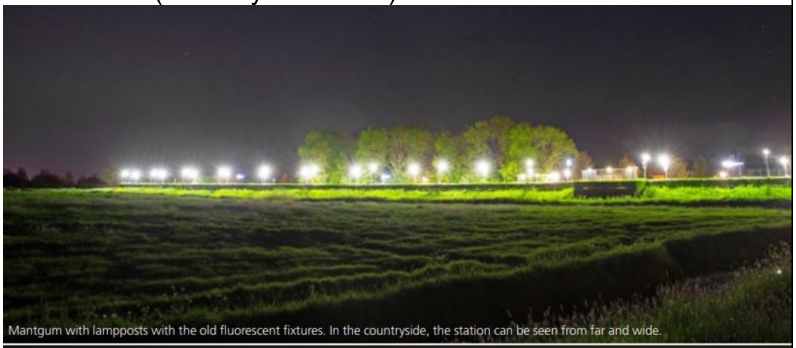
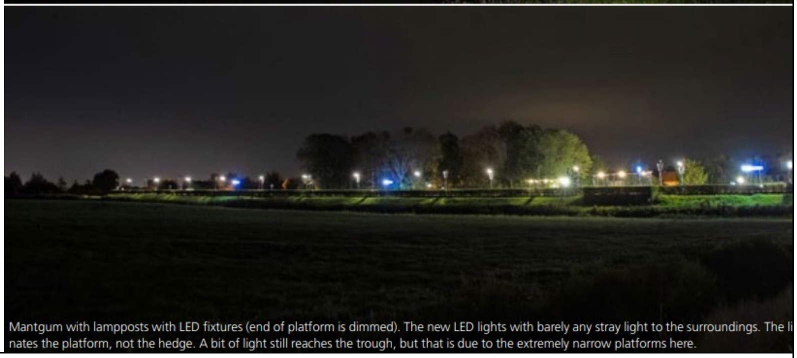
Benefits Effects	• Understand consumption
	  • Profile
	  • Patterns

	• Identify saving potential • Aware control of energy flows • Notice savings due to proper control • Set and reach [realistic] energy saving targets • Control to avoid grid congestion, improving distribution • Adapt power management to the evolving electrification. Higher levels of electrification require more visibility on consumption
Effects (CO_2)	Footprint: Relating to a reduction in energy use.
Ease of implementation	Most buildings already have automatic energy meters, so only requires software to be installed
Constraints, challenges, or lessons learnt	
S/M/L term	Medium/long-term
Efficiency	(Cost over effect)
Maturity	Mature
Mentioned by	Bane NOR (In Norway by Equinor, several Norwegian municipalities, Borregaard, Nortura, Agder Energy and many more)
Experience	
Comment	

5.4.6. Smart and efficient LED lighting

	Innovation	Ease/rapidity/aff.	Benefits
Level	High	Medium	High
Special note	Inventive solution		

Field	Lighting consumption management
Solution	• Upgrades to more efficient LED lighting to replace fluorescent/incandescent/ halogens/neon lighting • Use/install smart devices to control lighting
Description	LED lighting is a technology that has proven to be more energy efficient and has a longer lifespan than halogen and incandescent bulbs. According to ProRail, replacing traditional fluorescent lighting with LEDs saves around 50% (increased to 75% if dimmed in the absence of passengers). Smart and automatic management, coupled with efficient lighting, extends the potential savings whenever lighting is not required at particular intervals Example: motion sensors in railway stations which automatically trigger lighting when movement is detected and turns off lighting after a period of time without movement Dimming control, etc.
Objective	Reduce energy consumption related to artificial lighting by replacing bulbs with more efficient LED lights
How to	Replace halogen, fluorescent and incandescent bulbs with LED lights. However, it is important to purchase lights with a good lifespan, because earlier LED technology had flaws where bulbs turned yellow or purple or began flickering. Therefore, ProRail

	made sure to have a guaranteed lifespan requirement. The lighting's efficiency can be seen by its lowered light pollution and increased precision as shown by the Mantgum station in the Netherlands (courtesy of ProRail).  Mantgum with lampposts with the old fluorescent fixtures. In the countryside, the station can be seen from far and wide.  Mantgum with lampposts with LED fixtures (end of platform is dimmed). The new LED lights with barely any stray light to the surroundings. The li nates the platform, not the hedge. A bit of light still reaches the trough, but that is due to the extremely narrow platforms here.
Costs and resources required	Acquiring the lighting and replacing the old ones Retrofitting fixtures instead of replacing them increases savings. Gains in terms of sustainability principally come from reusing casings/shades
Benefits Effects	Energy: FS RFI: LED bulbs use around 80% less energy than incandescent bulbs and 40% less than halogen, therefore energy consumption is significantly decreased ProRail: Halved station lighting related energy consumption. Reported energy intensity ranges from 0.15 to 6 Watts per meter squared illuminated, according to each location's needs (e.g., 4 and 6 for the train hall and waiting room or enclosed platform respectively and around 0.15 to 3 for passengers crossing sections) 43% reduction (137,000kWh [TBD for one station]) due to dimming over the initial six months
Effects (CO_2)	Footprint: Related to reduced energy consumption and IT/NL's electricity mix
Ease of implementation	Easy. However, the setup has to be thought out and optimised for each station/building
Constraints, challenges, or lessons learnt	Avoiding lighting which is too strong, which decreases passenger comfort, as well as on the track, to avoid blinding drivers
S/M/L term	Medium/long-term implementation (due to the investment planning requirements)
Efficiency	Medium-high
Maturity	Mature
Mentioned by	FS

	ProRail: LED with dimming on almost all platforms
Experience	ProRail, NS (see report)
Comment	ProRail's Lighting programme report should be read for more details and for information on good practice: https://www.spoorbeeld.nl/sites/default/files/2023-07/Duurzaam%20licht%20op%20stations_enkele%20paginas_ENGELS_web.pdf

5.4.7. Escalator, elevator, and conveyor system efficiency

	Innovation	Ease/rapidity/aff.	Benefits
Level	Medium	Low	Medium

Field	Conveyor systems
Solution	Escalators equipped with Variable Speed Drives (VSD) Escalators and elevators equipped with regenerative systems
Description	These should be fitted or upgraded with energy efficient drives and should be intelligently controlled. Standardised solutions are available in the market, but there is substantial potential still to be exploited by the railways (UIC 2012)
Objective	-
How to	-
Costs and resources required	High SBB: Escalators with energy recovery do not save enough to justify the switch, before an escalator's end of life of (expensive)
Benefits Effects	-
Effects (CO2)	-
Ease of implementation	-
Constraints, challenges or lessons learnt	Consider in new or renewal of assets
S/M/L term	In line with asset renewal/new construction
Efficiency	-
Maturity	Standardised solutions are available in the market
Mentioned by	SBB, UIC
Experience	-
Comment	-

5.4.8. Contractual energy commitments and auditing for concessions/shops

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	Medium	Medium

Field	Value chain management

Solution	• Defining moderate energy use clauses in concessions/shops on leasing contracts • Sub-metering for accurate evaluation and billing
Description	Energy use should be billed based on real consumption using sub-metering. Efficiency benchmarking is possible with indicators for average energy consumption per m2 for different concession types (e.g., food shops, cafés/restaurants, non-food). Railway-owned shops could showcase the successful implementation of energy efficiency measures
Objective	Incentivise good energy practices in tenants
How to	Targets, incentives, and energy audits should be built into contracts.
Costs and resources required	No capital cost. May reduce negotiation power and reduce rental market
Benefits Effects	-
Effects (CO2)	-
Ease of implementation	Market dependant
Constraints, challenges or lessons learnt	Tenant capacity
S/M/L term	Short/medium depending on tenancy contract renewal and turnover
Efficiency	-
Maturity	-
Mentioned by	UIC
Experience	-
Comment	-

5.5. Processes

5.5.1. Staff: Communication, management, involving employees in energy saving behaviour

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	Medium	High

Field	Change management. Communication to staff Education of staff, steps by staff

Solution	• SNCF:
	  ○ Eco-driving and eco-stabling management: incentives, communication to staff, guides
	  ○ Deployment of an internal campaign to encourage energy saving behaviour
	• RFI: Staff training for the efficient management of manual switch heaters
	• Trenitalia:
	  ○ Driver training for eco-driving
	  ○ Define management requirements and limits for reducing the energy consumption of lighting, heating, and any other equipment
	  ○ Accelerate the installation programmes for water solar heating, LED lighting, and automated systems
	  ○ Synchronise all staff work hours
	  ○ Synchronise staff work hours in line with solar power production
	• SBB:
	  ○ Staff survey to assess potential energy saving measures
	  ○ Defining energy saving actions for operational staff on specific fleets
	• NR:
	  ○ Dialogue with operational staff, audits
	  ○ Implementation of energy saving measures by operational staff
	• Infrabel
	  ○ Workshop processes optimised for energy saving
	  ○ Raising awareness

Description	• Trenitalia: Specific driving courses for instructors to make drivers aware of economic driving, and (for runs without real meters or eco-driving systems) the use of electric braking approaching stations on all services and in particular on services running on the 3kV network, in order to make drivers aware of economic driving and the use of electric braking approaching the station

Objective	Decrease energy consumption by enhancing communication, training staff and encouraging members of the organisations to suggest new solutions
How to	Increase communication and information through the different organisation's departments Make staff from different departments proactive by encouraging them to propose areas/activities in which they have spotted potential energy saving solutions
Costs and resources required	Low - The main costs would be related to staff training, if any
Benefits Effects	• Trenitalia: expected benefits from 2024, potential savings ~1%, according to data from literature
Effects (CO2)	Related to reduced energy consumption
Ease of implementation	high
Constraints, challenges, or lessons learnt	Behavioural change and potential staff resistance
S/M/L term	Short-term
Efficiency	High
Maturity	Mature
Mentioned by	SNCF, RFI, Trenitalia, SBB, Network Rail, and Infrabel are some of the members who have reported solutions related to staff engagement
Experience	Very good – benefit of staff engagement and satisfaction
Comment	-

5.5.2. Management activities – cleaning

	Innovation	Ease/rapidity/aff.	Benefits
Level	Low	High	Medium

Field	Increase efficiency
Solution	• Cleaning skylights/normal windows for savings in lighting and heating • Cleaning solar panels for optimal efficiency
Description	Dirty skylight or windows may reduce the amount of natural light inside facilities Additionally, dirty solar panels produce less energy than those that are clean
Objective	Increase efficiency through regular cleaning
How to	Cleaning skylights/normal windows in facilities/stations and solar panels on roofs or in photovoltaic power plants
Costs and resources required	Subcontracting costs for cleaning services
Benefits Effects	The need for artificial lighting will decrease alongside the associated energy consumption. For solar panels, efficiency is increased when they are clean, subsequently increasing energy production
Effects (CO_2)	Related to reduced energy consumption

Ease of implementation	Very easy
Constraints, challenges, or lessons learnt	
S/M/L term	Short-term
Efficiency	High
Maturity	Mature
Mentioned by	FS Trenitalia
Experience	Good
Comment	

6. European research and innovation project solutions

Several recent European rail research and innovation projects under the Horizon 2020 European Research Framework Programme, and included in the Shiftt2Rail Joint Undertaking Work Programme, have focused on energy saving solutions for the rail transport system and arrived at important conclusions for ways to save energy in rail.

Similarly, the ongoing Europe's Rail Flagship Project 4 RAIL4EARTH (https://projects.rail-research.europa.eu/eurail-fp4/), that started in December 2022, aims at improving current railway performance in terms of sustainability, to build a more attractive and resilient transport mode and to contribute towards the objectives of a climate neutral Europe for 2050. The activities of this project cover rolling stock, infrastructure, stations, and all of their related subsystems (traction, bogies, brakes, energy storage systems, HVAC, etc.).

6.1. Shift2Rail

The most relevant Shift2Rail projects dealing with energy savings solutions are:

- FINE 1 project - Future Improvement for Energy and Noise https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=FINE%201,
- FINE 2 project - Furthering Improvements in Integrated Mobility Management (I2M), Noise and Vibration and Energy in Shift2Rail https://projects.shift2rail.org/s2r_ipcc_n.aspx?p=fine-2,
- IN2RAIL project - Innovative Intelligent Rail http://www.in2rail.eu/
- IN2STEMPO project – Innovative Solutions in Future Stations, Energy Metering and Power Supply https://projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2stempo,
- OPEUS project – Modelling and strategies for the assessment and Optimisation of Energy Usage aspects of rail innovation OPEUS (shift2rail.org)
- RECET4RAIL project – Reliable Energy and Cost-Efficient Traction system for Railway https://recet4rail.eu/

Other Shift2Rail projects have also contributed to the development of energy saving solutions and are identified in the catalogue of solutions (see 0

Energy saving measures).

The (non-exhaustive) list below presents some of the main conclusions of these projects regarding energy saving in rail, these being to:

- Encourage rail operators to produce and/or use certified zero-carbon renewable energy
- Pair power network management and railway grids to avoid the superfluous creation of infrastructure and reduce transmission losses
- Create direct links between renewable energy suppliers, consumers, and energy storage systems on the network (railways can have both roles) to avoid overproduction and therefore reduce energy wastage
- Optimise regular traffic flows by avoiding unnecessary stops through the use of connected traffic management systems
- Continue developing intelligent resources and management based on the principles of a circular economy
- Provide reinforced eco-drive training and in-cab driver energy consumption advisory systems

The following table also shows a specific set of solutions for implementing new technology, such as Silicon Carbide and composite materials for rolling stock:

FINE1 S2R selected energy related activities

TD	Topic	Future (S2R) technology	Application field
TD 1.1 Traction	Transformer	Medium frequency transformer with electronic convert	Regional
	SiC traction converter	Silicium Carbid (SiC) converter	All segments
	PM synchronous motor / Independently rotating motor-wheel-system	Indipendently rotating wheel with gearless synchronous motor with permanent magnets	High speed
	Parking Mode	Noise and energy reduction means in parking mode	Regional
	Energy storage	Battery drive for non-electrified lines	Regional
TD 1.3 Car body shell	Car body shell	Composite carbody shell with fiber reinforced plastic	
TD 1.4 Runninggear	Running gear	Lightweight running gear with new materials and concepts	All segments
TD 3.9 Smart Power Supply	Double fed power supply for 50Hz overhead lines	Double fed power supply for 50Hz overhead lines with increased substation distance and no switches for separaration of overhead line sections	All segments
	Track-side energy storage		
TD 5.3 Waggon design	High speed freightwaggon	High speed freightwaggon (120 - 160 km/h) with reduced weight, improved aerodynamic, electrification and automatic coupling	Freight mainline
TD 5.4 Novel Terminal, Hubs, Marshallingyards, Sidings	Refit andhybridisation of diesel shunting locomotive	Hybrid shunting locomotive with small diesel engine an Li-Ion traction batteries	Freight shunting
TD 5.5 New freight propulsion concep	New powerful freight locomotives with flexible an network independent operation	Electric mainline locomotive with powerful diesel and Li Ion battery	Freight mainline
	Electrical freight locomotive with Li-Ion batteries for last mile	Electric mainline locomotive with Li-Ion battery for last mile	Freight mainline
	Driver assistance system (DAS)	Connected DAS considering real time traffic informatic	Freight mainline
TD 5.6 Autonomous train operation	Automatic train operation (ATO)	Automatic train operation (ATO)	Freight

Figure 31: Set of innovative solutions by field, as identified for the FINE1 project's technical demonstrators (TDs), and rail service it would apply to

Additionally, S2R created a catalogue of solutions resulting from the research and innovation across all its innovation programmes (IPs). The solutions are listed in Table 6 below, and further details for each solutions can be found in the published catalogue.

Moreover the solutions of the Shift2Rail catalogue of solutions have been assessed and the ones having a higher potential in terms of energy savings have been included in the part *0*

Energy saving measures of this report.

Table 6: Shift2Rail: Catalogue of solutions by category (Shift2Rail, 2022)

IP1 **Passenger trains**
Cost-efficient and reliable trains, including high-capacitytrains and high-speed trains

Traction systems
- **Solution 1.** Master Silicon Carbide (SiC) semiconductors
- **Solution 2.** High Speed Motor on wheel

Traffic Control Management System (TCMS)
- **Solution 3.** Next Generation TCMS - New Vehicle Control Unit

Communication systems
- **Solution 4.** Standardised train-to-ground communication system

Light structures
- **Solution 5.** Light car bodies
- **Solution 6.** Door leaves
- **Solution 7.** Composite door leaves
- **Solution 8.** New door functions towards autonomous doors
- **Solution 9.** Boarding aid
- **Solution 10.** Lightweight Antenna Supporting Element

Light running gear
- **Solution 11.** Lightweight axle
- **Solution 12.** Austempered Ductile Iron (ADI) spoke wheel
- **Solution 13.** Light Running Gear frame

Condition based maintenance
- **Solution 14.** Health Monitoring Systems for Condition-Based Maintenance (bogie and track)

Braking systems
- **Solution 15.** Electromechanical brake System (EMB)
- **Solution 16.** Adhesion management solutions
- **Solution 17.** Adhesion management advanced solutions
- **Solution 18.** High-SIL brake control
- **Solution 19.** Innovative friction pair

Interiors
- **Solution 20.** Passengers' room adapted to their needs
- **Solution 21.** Driver's Cabin

Eco-friendly HVAC
- **Solution 22.** Eco-friendly air conditioning with natural refrigerant

IP2 **Traffic management**
Advanced Traffic Management and Control Systems' Solutions

ERTMS Next Generation
- **Solution 23.** Automatic Train Operation (up to GoA4)
- **Solution 24.** Moving Block
- **Solution 25.** Fail-Safe Train Positioning
- **Solution 26.** Adaptable communication system
- **Solution 27.** Integrated Mobility Management (I2M + TMS)
- **Solution 28.** Onboard train integrity

IP3 **Optimised Infrastructure**
Intelligent Asset Management and High Capacity Infrastructure

Long performing structures
- **Solution 29.** Low-cost high-speed bridges
- **Solution 30.** Long performing structures

Track system
- **Solution 31.** Enhanced switches and crossings
- **Solution 32.** High performance wheel-rail interaction

Maintenance
- **Solution 34.** Data for Track Circuit Maintenance
- **Solution 35.** Data & Positioning: Lean Tamping
- **Solution 36.** Automation: Robot platform
- **Solution 37.** Integrated measuring system
- **Solution 38.** Decision making planning
- **Solution 39.** Modular multitasking powered exoskeleton (MMPE) for rail workers

Energy

Solution 40. Smart Energy Metering
Solution 41. Automation: Robot platform
Solution 42. Smart control of rail power supply

IP4 **Digital services**
Towards "mobility as a service" engineered by railway

Multimodal eco-system
Solution 43. "One stop shop"
Travel experience
Solution 44. Travel Companion
Travel provider tool
Solution 45. Interoperability framework for TSPs
Solution 46. Contractual management marketplace
Solution 47. Business analytics for transportation
Solution 48. Crowd management
Solution 49. Software as a service (SaaS) solution

IP5 **European Railway Freight**
Technologies for sustainable and attractive European Rail Freight

Automation and digital operation
Solution 50. ATO GoA 2 for existing fleet
Solution 51. Freight digital automatic coupler (DAC)
Solution 52. Connected heterogeneous multiprocessing architecture for digitalisation of freight applications
Solution 53. Yard and network management
Solution 54. Intelligent video gate
Solution 55. Digital brake test
Maintenance
Solution 56. Condition based and predictive maintenance
Traction power
Solution 57. Distributed Power for long trains
Solution 58. Full Electric Last Mile Propulsion
Solution 59. Battery module
Wheels and axles
Solution 60. Light thermostable wheel
Solution 61. Silent wheelset
Solution 62. Axle mounted power harvester
Wagon
Solution 63. Extended market wagon
Solution 64. Core market wagon

CCA **Horizontal Innovative Solutions for Railway**
Cross-cutting activities

Solution 66. Simulation Model for large networks
Solution 67. Energy labelling of rail vehicles
Solution 68. KPI model for impact assessment
Solution 69. Modal shift evaluation model for impact assessment
Solution 70. Energy simulation tool

6.2. Europe's Rail – RAIL4EARTH project

To achieve the target operational outcomes in Europe's Rail, several technical improvements were identified by the RAIL4EARTH project.

To develop flagship demonstrations for each enabler, some functions must be delivered with enough maturity, with a target technology readiness level (TRL) as given below.

Enabler 1	Trains with on-board Energy Storage Systems. High performance and high-efficient Battery Electric Multiple Unit (BEMU) trains with long

	autonomy (80km baseline and over 200km target) and suburban catenary trains with high levels of braking energy recuperation and energy autonomy (TRL6/7 to be achieved in 2026).
Enabler 2	Hybrid hydrogen trains – infrastructure inspections/maintenance of heavy-duty vehicles and locomotives for freight/passengers at TRL5/6 (powered with H2 gas or liquid H2).
Enabler 3	The application of solutions for the production, storage and refuelling of hydrogen for railway vehicles using the example of a prototype refuelling station. Development of a standard refuelling interface using algorithms to ensure the optimum time and safety of the process, as well as provide scalability and future growth for the refuelling station, depending on the demand for hydrogen (TRL6 target for 2025).
Enabler 4	Integrate various sources in different systems (e.g., 25kV AC, 1.5/3kV DC), including renewable energy, energy harvesting technologies, superconducting, braking energy recuperation, etc, as well as the integration of energy storage (TRL6 target for 2025).
Enabler 5	Solutions for optimal energy management in the whole power system, covering traction and non-traction demand, including stations being used as energy hubs and integrated in a smart grid according to the market rules (TRL5 target for 2025).
Enabler 6	Increase adaptation to climate change with the development of a tool on European climate variables, which is usable for railway assets, considering risk assessment reports and the benchmarking of existing solutions to accelerate a reduction in the environmental impact had (TRL5 for 2025 to implement adaptation strategies).
Enabler 7	Develop noise indicators, simulation tools, optimised components and optimised maintenance regimes for noise and vibrations, also taking different climates within the EU into account (TRL6 target for 2025).
Enabler 8	Methodologies and guidelines for an optimised redesign/rehabilitation of station layouts, including modularity oriented towards carbon footprint reduction (TRL5/6 in 2025).
Enabler 9	Develop tools and indicators to promote sustainable designs, assess improvements in environmental performance and ensure the standardised reporting of the rail sector's environmental impacts (TRL5 in 2025).
Enabler 10	Develop and introduce electro-mechanical braking systems, pantographs, and suspension to the market, while targeting energy

	savings on the relevant subsystems and reduce associated maintenance costs by reaching TRL6 for 2025 and preparing for later developments.
Enabler 11	Introduce optimised motors and gearboxes, high performance bogies, suspension and new materials following the principles of a circular economy (reaching TRL6 in 2025).
Enabler 12	Deliver alternative technologies to replace HVAC system hydrofluorocarbon refrigerants with green refrigerants or new cooling technologies with reduced energy consumption (TRL6 target for 2025).
Enabler 13	Introduce enhanced experimental and numerical methodologies on aerodynamic certifications (TRL6 by 2025).
Enabler 14	Demonstrate a healthier environment within rail vehicles (TRL7 target for 2025).
Enabler 15	Reinforce appeal via on-demand comfort for users such as improved access, lighting, thermal and acoustic conditions, as well as with new architecture to increase passenger capacity (TRL5/6 target for 2025). Enabler 15 deals with light interiors that could lead to increased capacity, while the new modular interior will also balance passenger-oriented customisation with current standards, in order to increase on-demand passenger comfort.
Enabler 16	Reinforce the ability to adapt rolling stock interiors to support the rolling stock capacity increases (TRL5/6 target for 2025).

6.3. Energy saving measures identified vs European R&I activities

The table below presents an analysis of the solutions introduced in section 5 of this report alongside solutions developed in the Shift2Rail projects or currently under development in Europe's Rail Flagship Project 4 RAIL4EARTH.

Solutions introduced in section 5	**Shift2Rail – Europe's Rail**
Rolling Stock	

1. Maximise braking energy recuperation by optimising the braking system 2. Heat pumps for enhanced HVAC efficiency 3. Dry transformers 4. Hydro-elastomeric axle-guide bearings 5. Optimised traction inverters 6. Renew rolling stock equipment 7. Thermal efficiency and insulation of rolling stock 8. Aerodynamic efficiency of rolling stock 9. Rolling stock refurbishment and fleet renewal	**Shift2Rail projects** • Substitute diesel trains with electrical, battery or hydrogen trains (regional, high-speed and freight locomotives) • Retrofit diesel trains as battery or hydrogen trains • Silicon Carbide converters • Extended freight market with improved aerodynamics • Optimised container sequences for intermodal freight trains **Further developments in Europe's Rail** • Development of long-range batteries • Airless trains • HVAC solutions using an alternative natural refrigerant with higher Coefficient of Performance (FP4)

Operations	

1. Use the most efficient trains for operations
2. Eco-driving – saving traction energy
3. Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO)
4. Partial equipment ue: adapt equipment use to the required load/needs
5. Interval operation of traction coolant pumps in parking mode
6. Fleet-specific temperature management
7. Weather-forecast-linked predictive HVAC management
8. Eco-stabling, eco-parking, reducing stabled train consumption
	Shift2Rail projects
	• Optimised Driving
	  ○ Connected to DAS
	  ○ Automatic Train Operation
	  ○ Traffic management
	
	Further developments in Europe's Rail
	• Energy management of battery and hydrogen trains

9. Timetable-based maintenance	

<table>
<tr><th colspan="2"><u>Infrastructure</u></th></tr>
<tr>
<td>
1. Optimise switch/point heating systems
2. Redesign rotating converters as high voltage converters to reduce losses
3. Replace rotating converters with static converters to reduce losses
4. Redesign supply stations to reduce energy losses
5. Smart management of rotating converters to reduce losses
6. Upgrade to automatic electric switch/point heaters
7. Staff training on efficiently managing manual switch heaters
8. Upgrade to automatic electric switch/point heaters
9. Implement a more efficient uninterruptible power supply system for signalling
10. Switch to a 30kV supply instead of 15kV
11. Power management of switch heating
12. Infrastructure manager information to railway undertakings: increase the awareness of operators regarding more efficient driving and a reduction in consumption when stabled
13. Meteorology linked predictive and automatic switch/point heating management
14. Reduce energy losses in overhead contact lines with increased voltage levels
15. Install energy recovery systems in 3kV DC railway lines
16. Trackside flywheel energy storage
</td>
<td>
<u>Shift2Rail projects</u>
• Electrical energy supply from renewable resources
• Further electrification of railway lines
• Infrastructure for battery and hydrogen trains
  ○ Charging stations
  ○ External energy for stations and platforms
  ○ Hydrogen refuelling stations

<u>Further developments in Europe's Rail</u>
• Standardisation of interfaces for battery and hydrogen trains
</td>
</tr>
</table>

7. Regulations: Constraints and challenges

This report has given and assessed the potential energy saving measures according to their estimated cost in terms of time, money, and effort weighted against the benefits they offer.

This section deals with the potential impact of these saving measures on the EU TSI regulations.

- ENE: Energy
- INF: Infrastructure
- LOC & PAS: Rolling stock, locomotives, and passengers
- WAG Wagons
- NOI: Noise
- SRT: Safety in railway tunnels
- CCS: Control command and signalling
- PRM: Persons with disabilities and with reduced mobility
- OPE: Operation and traffic management
- TAP: Telematic applications for passenger service
- TAF: Telematic applications for freight service

It then explains the necessity for the System Pillar Task 1 (aiming to select improvements to be implemented for standardising specifications) to provide information in a future deliverable on the impact of these solutions on the future railway system architecture.

The UIC Taskforce members also highlighted the challenges in terms of energy supply and purchase policies, as discussed during the workshop (see the introduction of the catalogue 5 Energy saving measures), which are summarised in section 7.1 Energy supply and purchase.

Potential impact on the EU TSI regulations

The concepts and issues discussed in this document mainly concern four subsystems:

- Locomotive and passenger (rolling stock)
- Energy in infrastructure
- Operation
- Buildings

If we consider the traction power supply system and its interface traction units, the European technical regulation/standardisation framework shall be adhered to using the following documents (at a minimum) in terms of methodology and requirements:

- TSIs

- EN 50367[8], EN 50388[9], EN 50163[10], EN 50463[11]

The compatibility of the different innovative solutions identified in section *0*

8 EN 50367: Fixed installations and rolling stock - Criteria to achieve technical compatibility between pantographs and overhead contact line

9 EN 50388: Power supply and rolling stock - Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability

10 EN 50163: Supply voltages of traction systems

11 EN 50463; Energy measurement on board trains - Part 2: Energy measuring

Energy saving measures for each subsystem (Rolling Stock, Operation, Infrastructure, Buildings) with the TSIs and European standards was analysed. The main aim was to identify if the current technical regulatory framework defined by the TSIs and European standards would prevent the implementation of an innovative solution:

- Would the innovative solution require a change or more specifications in the TSI(s)?
- Are the TSIs preventing any of their implementation or explicitly allowing it?

Rolling Stock: See appendix 3-1 with constraints and challenges on energy saving measures
Operation: See appendix 3-2 with constraints and challenges on energy saving measures
Infrastructure: See appendix 3-3 with constraints and challenges on energy saving measures
Buildings: See appendix 3.4 with constraints and challenges on energy saving measures.

In a nutshell, only four of the given solutions would have an impact on a TSI (from the Infrastructure subgroup), meaning that the current TSI would not facilitate their deployment:

- 5.3.3 Supply structure/neutral sections; TSI ENE,
- 5.3.4 Infrastructure manager information for railway undertakings: increase the operator awareness regarding more efficient driving and consumption at standstill; TSI ENE and TSI LOC&PAS,

5.3.9 Recovered braking energy: optimal management5.3.17 Medium voltage direct current electrification systems

For these four innovative solutions, research and development can result in the establishment of different and new parameters and values. As soon as a new concept is approved, the interoperability directive and related TSIs explain how to proceed via a procedure named "innovative solutions", which needs a "request for technical opinion" (i.e. article 10 of TSI Energy).

Once this process has been followed, and the technical request approved, the new concept is declared interoperable. For serious changes or evolutions, such as a new voltage system, a change request shall be drafted. This Change Request will be then addressed and assessed within the respective Topical Working Groups of the European Union Agency for Railways (ERA). Depending on the outcome of the working group, the change could be implemented in the next TSIs revision, and the subject shall be worked on within ERA's working groups.

It means that everything is possible provided that the concept is validated against the six essential requirements and cost-benefit analysis.

Impact on the future railway system architecture

The implementation of certain solutions given in this report may have an effect on some EU TSI regulations. In addition, as some TSI regulations interface with one another (see Figure 32), data exchange between the various subsystems of the railway system architecture could be impacted, which is why the System Pillar Task 1 will assess this influence on the future architecture in an upcoming deliverable.

Nevertheless, these innovations will have a benefit on the performance of the future railway system architecture.

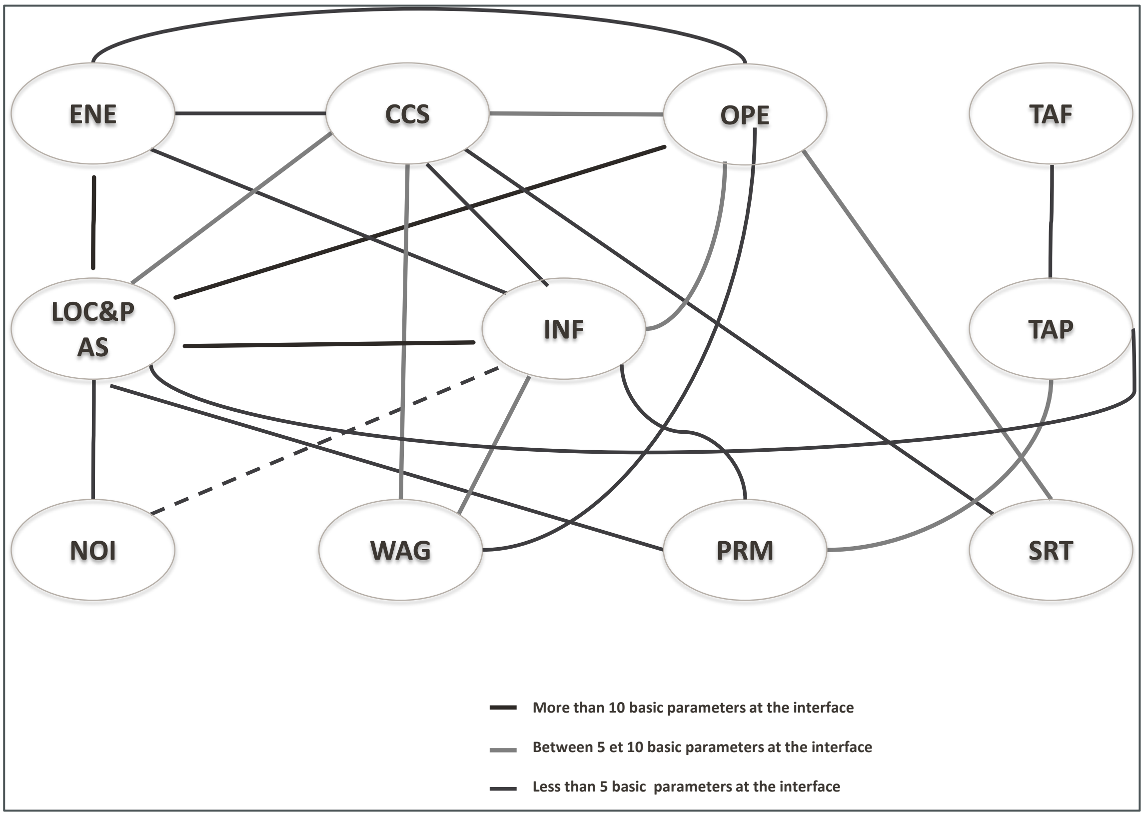


Figure 32: TSI interface map

7.1. Energy supply and purchase

Energy contract management, as explained from the workshop when introducing 5

Energy saving measures, varies from country to country.

Regulations should allow setups where energy procurement is taken care of by the railway operators themselves. In Spain, the procurement role is being shifted from IMs to the different operators.

When it comes to integrating renewable energy, it was highlighted that individual member states may interpret Article 38 of Directive (EU) 2019/944 differently.

The implications of this varying interpretation on the possibility of integrating renewable energy production and energy storage facilities into the traction grid are that the electricity grid of an IM (including the overhead contact lines) must be considered to be a closed distribution system (CDS) (Article 38 of Directive (EU) 2019/944 amending Directive 2012/27/EU).

Member states are interpreting this article differently. In some countries the IM is considered to be a CDS, in other countries the IM has a specific status, and in other member states again Directive 2019/944 is not considered to be applicable to IMs.

If an IM is considered to be a CDS, then the regulator within the member state must exempt the IM from a number of requirements that prohibit activity development, such as:

- Flexibility services
- Recharging points for electric vehicles
- Energy storage facilities

If an IM is considered to be a distribution system operator (which includes CDS status), then the IM is considered to be a vertical integrated undertaking. In this case, the member state can decide not to apply certain obligations (Article 35). However, not all member states have used this application.

It is not clear if an IM can sell this electricity to railway undertakings, which is important as an IM has a more limited electricity consumption than a railway undertaking. A long-term agreement between an IM and railway undertaking is also necessary, as an investment in a renewable energy installation requires 10 to 15 years to be profitable.

7.2. International traffic

Increasing seamless international operations is a sought goal by railways. Since traction energy represents high amounts, a specific challenge is the harmonisation of energy settlement processes between operators and infrastructure managers, using both estimations and energy measurement data. The more efficient and transparent this process will be, the more international services will be delivered (see *5.2.6*

Using energy measurement data). Implementation of energy measurement systems in undergoing across European operators. Energy measurement data will more and more be collected by the settlement services of each settlement area, and it will enable more efficient energy consumption benchmarking and international operation (More information in the sector declaration https://www.cer.be/cer-agreements-resolutions/eu-rail-sector-declaration-on-traction-energy-metering-and-settlement)

7.3. Deployment and evolution of DAS towards ATO

The standards for a clear interface between Driving Advisory Systems (DAS) and Automatic Train Operation (ATO)

The railways are in the process of rolling out Full Supervision ETCS, which will enable ERTMS/ATO. This is a game changer for railways, as it will increase capacity, punctuality, energy efficiency and safety. This is a (very) long-term work (forecast to implement is 2030 and later for some countries). In the meantime, railways need to improve efficiency of operation and timetabling with available ERTMS/ATO features.

Plus, onboard ETCS equipment must be updated. One major challenge for the railways is to understand how to develop, implement, and benefit from DAS (see *5.2.3 Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO)*), as the first step towards having ATO, without losing what was built for DAS, as ATO specifications are released.

One important challenge is that there is often more than one operator and IM by country and substantial cross-border traffic. Therefore, to enable a unified and efficient connection of the multiple DAS to multiple traffic management (with connected DAS, also cross-border), and getting the benefits of real-time traffic management, it is important that an operator can seamlessly switch from one IM DAS service to another (also in a cost-effective way short-term).

8. Discussion on the incentives and challenges for implementation

This section addresses the challenges and support needed for railways to implement and accelerate energy saving solutions.

The implementation of energy efficient and energy saving measures is especially driven by current electricity costs and risk regarding future energy scarcity. However, the EU Directives and national regulation on decarbonisation can significantly constrain railways when they are faced with uncertainty in terms of profitability.

Information and metering

As not all consumption points or traction units are covered by energy meters, and therefore, energy usage information is regularly based on aggregated levels from models and assumptions. Through better data and information systems, data sharing and sub-metering, the energy use and loses could be better understood and efficiency opportunities easier identified.

Industry structure challenges

Due to the business model and organisational structure of many railways, the investment costs and benefits from energy efficiency are not always clear. In some instances, the entity that must make the investment, may not be the same entity that will enjoy the energy saving. For example, there is extensive costs to an Infrastructure manager to straighten or adjusting track curves but the energy saving cost reduction will be a benefit of the train operators. The same is the case for providing C-DAS data. There would need to be a particular incentive or funding available for an infrastructure manager to make this investment for the benefit of the wider rail industry.

The pay-back period, uncertainty and change

A barrier identified is a focus on moderate initial investment and a preference for short payback times. Larger capital investments with long term pay back periods are difficult to build a business case for despite significant energy savings that can be achieved taking a longer time for return on investment. Some of the advanced energy saving technology solutions have a high capital cost.

Adopting new technology (often on a large scale for railways) can also be challenging due to uncertainty surrounding return on investment, which is why support from governments and European funds and policies is so important. On a more detailed level, each solution from this report could have an impact on operations which may pose a challenge. The impact can range from being very limited, as it deals with a very specific part/piece of equipment, to being very large, e.g., in terms of timetabling because it requires other changes in the rail operations.

Aside from the impact of work to implement a change, there is also the impact of the change itself, as it may influence the way customers choose to organise and use train services. Timetabling is one of the main concerns that conflicts with the most efficient use of energy.

Human resources and factors

A known constraint is the lack of internal human resources and expertise to coordinate energy saving projects.   Building the business case for such an investment can be resource demanding and the processes can take significant periods of time before decisions can be made. There is a constraint also on the expertise needed to implement the projects. Retraining and capacity building requirements demand time from railways staff, which is particularly challenging for those rostered and operational critical such as drivers.

Since train traction has the highest consumption, it is important to highlight that the human factor remains a central challenge to achieving savings on traction through eco-driving and advisory systems. Much of the time, this issue applies to any energy savings that require manual interaction (i.e., whenever system is not automatic). Behavioural change programmes can be difficult to negotiate and implement and require the engagement and acceptance of the workforce.

Customer comfort

Meeting customer comfort and convenience is central for passenger services, and this can conflict with energy saving on topics such as heating, cooling, ventilation, and timetabling. Automated systems may offer a solution, but upgrades of these systems can be expensive and prevent the railways from making the most out of the equipment's lifespan.

Customer information and advertising can help to explain changes in the train temperatures and prevent complaint.

Equipment lifespan

The long lifespan of railway assets is strength for railways to be more sustainable and resource efficiency, but this can also be a challenge when it comes to introducing state-of-the-art or innovative technology. As rolling stock has a life span of more than 30 years, the renewal and replacement with modern energy efficient systems is a slow transition.

Energy production

Partnering with distribution and transmission operators (DSO/TSO) with a given country is beneficial, given the scale of the electricity network needed for rail. Renewable and recuperated energy from train brakes gives railways, DSOs, and TSOs are a further reason to work together for an efficient management of transmission infrastructure. This should consider demand/load management, including smart management with energy storage systems, enabling reduced use of fossil-based electricity production in the long run.

In this sense, it is also important for a railway company to understand to what extent it can and should be an energy supplier or partner with energy sector players. In Europe, there is a good range of examples where the railways and energy production that are entirely separate, and equally, where railway companies also play a very important role in energy generation. Thus, it is useful for policies to properly consider this ability, and incentivise, and foster it to help the energy market to decarbonise and extend capacity, while in parallel moving to smarter grids.

Decarbonisation and phasing out fossil fuels

Decarbonisation will only be achieved by phasing out diesel traction, which can also impact profitability, as alternative technology may not yet be able to offer the same ranges for operation and may have higher costs. Additionally, there is a high risk for rail when implementing innovative (and not entirely mature) solutions (e.g. hydrogen), even on a small scale (lifespan, operational constraints). Therefore, it would require incentives, partnerships, or public funding to mitigate unexpected failures or additional expenses which would have a widespread impact on operations.

Where could European rail activities and research be strengthened?

The availability of a railway line has been demonstrated to stimulate economic growth and avoid greenhouse gas emissions from road use. Therefore, it is a benefit to society for railways to provide services when profitability is not their principal concern. Rail should have state-of-the-art operation efficiency, and circular economy practices. For this reason, some companies across Europe have been considering reopening smaller parts of their network, as they can be covered by small battery trains and are a good step to more efficient operations and to decarbonisation.

Given the lifespan of rail equipment, it is important that all research and innovation is carried out with regard to the long-term and large-scale needs of railways, meaning that upgrades should be developed that initially do not require equipment changes, with subsequent innovation that:

- Is future-proof (long-term maturity)
- Can be quickly implemented at a moderate cost
- Is convenient for a large-scale deployment

Whenever planning is possible, and when railways adopt environmentally friendly (efficient or emission-free) systems, this should be acknowledged and supported via subsidies and green investments. Railways should be eligible for carbon credit grants for decarbonisation and avoided emissions from modal shift.

Priorities for implementation/deployment programmes

Current priorities for European train operators are to:

- Save traction energy by rapid implementation of eco-driving, eco-parking, and driving tools
- Deploy energy measurement systems in trains for accurate information and settlement (including cross-border)
- Phase out diesel traction by using alternative traction systems. As stated above, rolling stock has a long lifespan, therefore, the strategy is to:
  1. Retrofit internal combustion engines to use renewable fuels, or fuels with a lower impact as a transitional solution
  2. Upgrade rolling stock and deploy:
     - 2.1. Hybrid battery/combustion engine trains (usually also with a pantograph) as a transition step, fully electric battery trains, with a proper balance between battery size and electric infrastructure
     - 2.2. Whenever batteries are not a solution due to a line's length (e.g., more than 100km without charging capabilities), hydrogen traction should be explored

Nevertheless, these pose new challenges and research questions:

For 1: The proper definition of "renewable" for fuels. Which synthetic fuels can be considered renewable? And what is their availability for operation?

For 2.1: Knowing the proper battery technology for efficiency, safety, energy density and sustainability (controversial materials and production footprint), where proper sustainability assessments like Life Cycle Analysis (LCA) would help railways in their decision making.

For 2.2: Green hydrogen sourcing, efficiency of the electrolysis, storage, and supply.

On the other hand, Infrastructure Managers focus on:

- Having the most efficient timetabling, peak power demand management and reduced transmission losses. As illustrated by the solutions, the is also linked to effective timetable management (use of recovered energy, asynchronous traction efforts, etc)
- Offering an efficient settlement system according to the requirements described in the Sector Declaration[12]

[12] https://www.cer.be/cer-agreements-resolutions/eu-rail-sector-declaration-on-traction-energy-metering-and-settlement

- Extending in-house power generation with renewable energy on assets, stations, and buildings
- Phasing out gas or fossil fuel dependent systems, such as large heaters, switch heaters, etc. Making the most efficient use of energy-intensive electric systems with automated management

This extensive set of priorities makes it understandable that human resources might be an issue for railways in terms of improving core business and may push them to consider solutions that are not state-of-the-art.

9. Conclusion

Railways have an important role as a collective mode of transport. Energy consumption will always be high and is expected to grow with European targets to grow the market share of rail and increase electrification on the network to phase out the use of fossil fuels. As a consequence, railways have the responsibility to operate with optimal energy efficiency.

This report presents different approaches for a comprehensive energy saving strategy and at the same time demonstrates the efforts railways are putting in to keep energy efficiency at its optimal level. Some of the greatest savings can be found in traction energy and rolling stock including driving behaviours and optimal acceleration ad breaking patterns.

As highlighted, the railways need reasonable support from governments and within policy to achieve their highest level of efficiency including investments to make longer term savings.

Improvement made by railways is beneficial to many parties and people, and as projects are often long-term, this report highlights some of the simple solutions that can be quickly applied or have been taken from other domains (buildings, ICT, etc…).

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Appendix 1

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CFL Multimodal
Chennai Metro Rail Limited
Crossrail Benelux NV
CRRC-ZIC
DSB
East Japan Railway Company
EUSKAL TRENBIDE SAREA
Ferrocarrils de la Generalitat de Catalunya
FS ITALIANE S.p.A.
Infrabel
Infraestruturas de Portugal SA
Infrastructure of Serbian Railways“ JSC
Jernhusen
KORAIL
MERCITALIA Logistics S.p.A.
Network Rail
NMBS
NS
ÖBB-Infrastruktur AG
ONCF
PGE (PKP Energetyka)
ProRail
RENFE Operadora
RFI S.p.A.
RSSB
RTE
SBB AG
SCR" CJSC
Siemens Mobility GmbH
SNCF
SNTFM "CFR Marfa" SA
SPF Mobilités et Transports
SZ d.o.o. - Slowenian railways
THI Factory (Thalys)
Trenitalia SpA (FS Group - Italy)
UIC
UNIFE
VIA Rail
VR Group

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Survey details

Table 7: Items in the survey covering railway system consumption

Item	Sub-level	Sub-level	Sub-level
Infrastructure			
	Public accessibility		
		Passenger information systems	
		Heating, cooling, ventilation (aside from station energy consumption)	
		Fuel-powered heating, cooling, ventilation (aside from station energy consumption)	
		Conveyor systems (escalators, elevators, conveyor belts)	
		Lighting	
			Platform access lighting
			Track lighting (e.g., level crossings)
	Train control systems		
		Signalling	
		Switch/point heating	
		Fuel (gas)-powered switch heating	
	Telecommunications		
		Power supply systems	
		Railway communication	
			Critical telecoms (redundant/essential apps)
			Non-critical telecoms
		ICT/data	
		Business/staff communication	
	Tracks and technical centres		
		Tracks (e.g., lighting for staff)	
		Tunnels	
		Power for power plants	
		Power for electrotechnical subsystems	
			Frequency converters
			Substations
		Depots/sidings (outside maintenance workshops)	
		Other technical equipment	
Real estate			
	Large stations		
	Medium and small stations		
	Operational buildings		
	Offices		
Passenger transport			
	Electric traction power		
	Distribution losses		

	Fuel-powered traction power
	Fuel provision for traction
	Maintenance workshops
	Service facilities
	Ticket vending machines
Freight	
	Goods management
	Electric traction power
	Distribution losses
	Fuel-powered traction energy
	Fuel provision for traction
	Maintenance workshops
TOTAL	

Table 8: Items in the survey covering traction system energy consumption

Item	Sub-level	Sub-level	Sub-level	Sub-level
[Freight] Goods management/shunting				
[Diesel] Fuel provision/distribution (energy lost for supplying)				
Traction energy input				
	Losses at substations			
	Energy lost through transmission			
	Traction power			
		Train movement		
			Friction/rolling resistance	
				Wheels/track
				Other
			Aerodynamic/air resistance	
				Train profile
				Bogies/underbody elements
		Losses in traction systems		
			Choppers/inverters	
				Fans
			Motors	
				Fans
			Motor to axle/gearbox	
		Auxiliary systems		
			Lighting	

			Heating, ventilation and air conditioning	
			Air Compressors	
			AC/DC - DC/DC auxiliary converters	
			Plugs/screens	
		Recuperation from brakes		
	Recuperation from brakes (after use and losses from the train)			
Recuperated energy (after losses from the train and trackside supply system)				

Appendix 2

MÁV data

Item	*Sub-item*	*Sub-item*	*Sub-item*	*GWh/a*	*Share (%)*
Infrastructure				76.31	4.0%
	Public accessibility			39.1	51.2%
	Public accessibility	Passenger information systems		N/A*	-
	Public accessibility	Heating, cooling, ventilation (beside the consumption of stations in real estate)		N/A**	-
	Public accessibility	Fuel-powered Heating, cooling, ventilation (beside the consumption of stations in real estate)		N/A**	-
	Public accessibility	Conveyor systems (escalators, elevators, conveyor belts)		N/A**	-
	Public accessibility	Lighting		39.1	100.0%
	Public accessibility	Lighting	Platform access lighting	37.15	95.0%
	Public accessibility	Lighting	Track lighting (eg: level crossing)	1.95	5.0%
	Train control systems			19.28	25.3%
	Train control systems	Signalling		8.35	43.3%
	Train control systems	Point heating		10.85	56.3%
	Train control systems	Fuel (gas)-powered Point heating		0.08	0.4%
	Telecommunication			8.77	11.5%
	Telecommunication	Power supply system		2.63	30.0%
	Telecommunication	Railway communication		4.64	52.9%
	Telecommunication	Railway communication	Critical telecom (redundant/essential apps)	3.712	80.0%
	Telecommunication	Railway communication	Non-critical telecom	0.928	20.0%
	Telecommunication	ICT / Data		1.5	17.1%
		Business / Staff communication		N/A**	0.0%
	Tracks & Technical centres			9.16	12.0%
	Tracks & Technical centres	Tracks (eg: lighting for staff)		4.63	50.5%
	Tracks & Technical centres	Tunnels		0	0.0%
	Tracks & Technical centres	Power for power plants		0	0.0%

	Tracks & Technical centres	Power for electrotechnical subsystems		2.63	28.7%
	Tracks & Technical centres	Power for electrotechnical subsystems	Frequency converters	0	0.0%
	Tracks & Technical centres	Power for electrotechnical subsystems	Substations	2.63	100.0%
	Tracks & Technical centres	Depots / sidetrack (outside maintenance workshops)		0	0
	Tracks & Technical centres	Other technical equipment		1.9	20.7%
Real estate				220.256	11.5%
	Large stations			50.66	23.0%
	Medium and small stations			101.316	46.0%
	Operational buildings			11.01	5.0%
	Offices			57.27	26.0%
Passenger transport				1202.312	62.7%
	Electric traction power			546.81	45.5%
	Distribution losses			45.42	3.8%
	Fuel-powered traction power			293.982	
	Fuel provision for traction			316.1	26.3%
	Maintenance workshops			N/A**	-
	Service facilities			N/A**	-
	Ticket vending machines			N/A**	-
Freight				419.9	21.9%
	Goods management			0	0
	Electric traction power			308.53	0.735
	Distribution losses			21	0.05
	Fuel-powered traction energy			90.37	0.215
	Fuel provision for traction			0	0
	Maintenance workshops			N/A**	-
TOTAL				888.80	100.00%

					Commuter/ regional AC			**Commuter/ regional DC**			**Electric average**		**Commuter/ regional Diesel**			**Freight diesel**	
Item	***Sub-level***				***GWh/a***	***Share (%)***		***GWh/a***	***Share (%)***		***Share (%)***		***GWh/a***	***Share (%)***		***GWh/a***	***Share (%)***

Traction power				611.49	100.0%		1.45	100.0%		100.0%		239.36	100.0%		61.80	100.0%
	Train movement			477.39	78.1%		1.16	80.0%		79.0%		160.09	66.9%		44.49	72.0%
		Friction/rolling resistance		29.29	6.1%		0.05	4.0%		5.1%		12.92	8.1%			
			Wheels/tracks	9.96	34.0%		0.02	50.0%		42.0%		5.84	45.2%		1.85	4.1%
			Other	19.33	66.0%		0.02	50.0%		58.0%		7.08	54.8%		2.03	4.6%
		Aerodynamic/ air resistance		77.88	16.3%		0.15	13.0%		14.7%		31.29	19.5%			
			Train profile	57.01	73.2%		0.12	76.9%		75.1%		15.96	51.0%		4.07	9.2%
			Bogies/ underbody elem.	20.87	26.8%		0.03	23.1%		24.9%		15.33	49.0%		4.29	9.6%
	Losses in the traction system			77.54	12.7%		0.04	3.0%		7.8%		15.53	6.5%		4.90	7.9%
		Choppers/inverters		40.78	52.6%		0.01	25.0%		38.8%		7.54	48.6%		1.20	24.4%
			Fans	9.35	22.9%		0.00	2.0%		12.5%		1.80	23.9%		0.48	40.1%
		Motors		17.33	22.4%		0.01	25.0%		23.7%		0.10	0.7%		1.46	29.9%
			Fans	3.38	19.5%		0.00	10.0%		14.7%		0.02	21.5%		0.39	26.3%
		Motor to axle/gearbox		19.43	25.1%		0.02	50.0%		37.5%		7.88	50.8%		2.24	45.7%
	Auxiliary systems			56.56	9.3%		0.25	17.0%		13.1%		63.75	26.6%		12.41	20.1%
		Lighting		7.49	13.2%		0.04	15.0%		14.1%		7.29	11.4%		1.85	14.9%
		Heating, ventilation and air conditioning		26.14	46.2%		0.16	65.0%		55.6%		29.85	46.8%		3.94	31.8%
		Air compressors		15.05	26.6%		0.02	10.0%		18.3%		10.30	16.2%		5.79	46.6%
		AC/DC - DC/DC auxiliary converters		4.04	7.1%		0.01	5.0%		6.1%		15.12	23.7%		0.69	5.6%
		Plugs/screens		3.84	6.8%		0.01	5.0%		5.9%		1.18	1.8%		0.14	1.1%
	Recuperation from brakes			-49.99	-8.2%		-0.27	-18.4%		-13.3%			0.0%			
Recuperation from brakes (after use and losses from the train)				-43.10	-7.0%		-0.23	-16.0%		-11.5%			0.0%			

Appendix 3

Detailed analysis of innovative solutions and TSI compatibility

Appendix 3.1: Rolling Stock

	ENERGY SAVING MEASURE	CONSTRAINTS, CHALLENGES, OR LESSONS LEARNT	IMPACT ON TSI REGULATIONS (X = TO BE ASSESSED Y = IMPACT ON TSI N= NO IMPACT ON TSI)											COMMENTS
			ENE	INF	LOC & PAS	WAG	NOI	SRT	CCS	PRM	OPE	TAP	TAF	

		Key: **X: additional information is needed** **Y (Yes): this innovative solution could have an impact on a TSI. An explanation is given in column P.** **N (No): the innovative solution has no impact on a TSI. The TSI does not prohibit the solution, or the TSI explicitly allows the solution to be implemented. An explanation is given in the last column.** **A blank box means N/A**												
ROLLING STOCK														
5.1.2	**Insulated gate bipolar transistor (IGBT) traction** Wideband electronic power semiconductors that can replace	Hardware upgrade: Can have an impact on other systems like odometry, train protection			X				X					

	silicon-based components (insulated-gate bipolar transistor (IGBT)	systems, accreditation												
5.1.4	**Maximise braking energy recovery** Prioritise regenerative braking over other braking systems, and give haptic feedback regarding maximum braking efficiency to drivers	Sole use of regenerative braking and the possibility of feeding back the regenerated energy into the grid may be limited in some countries	N		N	X		X	X		X			The ENE and LOC&PAS TSIs ask for regenerative braking. Infra has to accept this energy and use it by any means possible. Exception if the power supplier refuses it

5.1.5	**Dry transformers**		N		N									Product standard to be applied. Generally, voluntary domain, for infra, dry type transformers in 25kV 50Hz have a higher impedance. Has this been studied?
5.1.6	**Heat pumps for enhanced HVAC efficiency** Replacing heating with the most efficient heating system: heat pumps	The complexity HVAC systems makes it hard to implement for rolling stock	N		N									

5.1.7	**Smart/automated heating, cooling and ventilation (HVAC)** • Automatic HVAC adjustment to coach CO2 levels • Automatic HVAC adjustment to coach thermostats • Automatic HVAC adjustment to weather data and forecasts	Education of staff	N		X									Check in LOC&PAS TSI if passenger and driver comfort requirements are fulfilled
5.1.8	**Lighting system upgrades** Implement LEDs in carriages/coaches		N		N									
5.1.9	**Aerodynamic efficiency of rolling stock** Improve high-speed train fairings to facilitate airflow	In the equation F= a+bv+cv2, where c (drag coefficient) increases with the squared	N		N									This solution reduces energy consumption

	in order to reduce the impact of air resistance on rolling stock	velocity (v) is a priority to be worked on In terms of air penetration, the aerodynamic wake of the train is an important issue (the Davis coefficients, a, b, c are constants that are found by analysing the train dynamics, and relate to the static resistance, rolling resistance and aerodynamic resistances respectively)												
5.1.10	**Hydro-elastomeric axle-guide bearings**	Used in most long-distance railway coaches			X									Potentially no impact on TSIs, to

	Hydro-elastomeric axle-guide bearings for double-sided use in axle-guide bearings of rail vehicles	in Switzerland, that don't have active axle-guiding systems. Even regional EMUs are being fitted with this technology, due to the benefit of having a lower "train-path price"												check in LOC&PAS TSI on the chapter dedicated to wheels/axles
5.1.11	**Thermal efficiency and insulation of rolling stock** Improving the capacity of rolling stock to retain heat or cold generated by HVAC systems	Windows of rolling stock have to be replaced, the insulation needs to be adapted and fitted to existing stock. Both can be carried out during maintenance work			X									Potentially no impact on TSIs, to check in LOC&PAS TSI on the chapter dedicated to passenger comfort

5.1.12	**Weight and capacity of rolling stock** Higher capacity and lighter rolling stock (via procurement whenever the refurbishment cost/benefit ratio is low	New vehicle authorisation needed			N									Unless the max weight per axle is not reached, which is the case here

Appendix 3.2: Operations

	ENERGY SAVING MEASURE	CONSTRAINTS, CHALLENGES, OR LESSONS LEARNT	IMPACTS ON TSI REGULATIONS (X = TO BE ASSESSED Y = IMPACTS ON TSI N= NO IMPACT ON TSI)											COMMENTS
			ENE	INF	LOC & PAS	WAG	NOI	SRT	CCS	PRM	OPE	TAP	TAF	

		Key: **X: additional information is needed** **Y (Yes): this innovative solution could have an impact on a TSI. An explanation is given in column P.** **N (No): the innovative solution has no impact on a TSI. The TSI does not prohibit the solution, or the TSI explicitly allows the solution to be implemented. An explanation is given in the last column.** **A blank box means N/A**											
OPERATIONS													
5.2.1	**Using the most efficient trains for operations** Favouring the use of rolling stock with lower consumption	The decision to pick one type of rolling stock over another can be based on: • Traction type (known	N		N								This is a general table. Naturally, new trains are more efficient Refurbishing

	and/or lower total mass	inherent efficiency) according to the infrastructure • Known efficiency of a specific electric rolling stock (energy consumption data, see 5.2.6)												and using older trains allows a train's lifespan to be increased Allowed by the TSI unless their requirements are fulfilled
5.2.2	**Eco-driving – saving traction energy** - Reducing the energy used for the train traction by giving appropriate instructions to drivers - Drivers training to eco-drive with specific driving courses	• Education of train drivers • Adapted timetables • Connected DAS (Driver Advisory System)	N	X	N				X		X			The impacts on the TSI regulations concern Connected-DAS From the ENE TSI's point of view: excellent

	- Reducing train speed in tunnels													
5.2.3	**Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO)** Deployment and implementation of DAS/ATO delivering driving advice to drivers or automated train control: • The first phase is Standalone DAS/ATO without connection to		N		N									Seen from ENE point of view: excellent

	Traffic Management Systems													
5.2.3	**Driving assistance tools, Driving Advisory Systems (DAS) and Automatic Train Operation (ERTMS/ATO)** Deployment and implementation of DAS/ATO delivering driving advice to drivers or automated train control: • Then Connected DAS/ATO (C-DAS, C-ATO), which manage conflicts and	Implementation of C-DAS is dependent on a Member State Infrastructure Manager's ability to handle the IM-side delivery of harmonised C-DAS messages to operators	X		X				X		X			• Potential interaction on Traffic Management System • Could facilitate real-time rescheduling - ENE: check that this traffic management does not create any voltage disturbances (clause 8 EN 50388-1 and EN 50163), but this idea goes in the

	harmonise traffic flows at a system level and to be built into system-wide train schedules													right direction
5.2.4	**Partial equipment usage: adaptation of equipment use according to load/needs** Partial use of traction engines according to load (partial switch-off when coasting)		N		X									ENE: excellent, but avoid numerous sudden changes which could affect voltage stability LOC&PAS: check the chapter on power consumption

5.2.5.	**Optimisation of power electronics** Fine-tune parameters for the maximum efficiency, such as the DC link voltage or magnetic flux		N		X									LOC&PAS: check that these measures will not lead to harmonic generation and voltage disturbance or instability
5.2.6.	**Using energy measurement data** The data output from an EMS is valuable for analysing a train run's driving efficiency. Whether it is to improve the eco-driving strategy (specific to a route or not), or		N		N				X		X			• Potential interaction with Traffic Management System for enhanced paths fitted with energy savings - ENE: no influence on energy metering shall be verified

	enhance driving advice for a DAS. Exact optimal energy consumption and punctuality can be found by analysing data from multiple train runs.													
5.2.7.	**Fine tuning train services** Adjusting and reducing train services in a way that is hardly felt by passengers: • ATO and DAS for the most efficient traction energy use, avoid train stops using information from traffic management		N		N				X		X			• Potential interaction with Traffic Management System for enhanced paths fitted with energy savings

	See Driving assistance tools (DAS & ATO) • Adjust the number of coaches/wagons during off-peak hours to the expected attendance/load • Reduce the number of stops, by skipping (low attendance) stations for frequently stopping trains • Develop a “stop on request” system (DE: Halt auf Verlangen); FR: arrêt à la demande) • Asynchronous train													

	acceleration to avoid energy use during peak hours and reduce losses (timetabling, power management) • A train's acceleration synchronised with another train's braking (timetabling, power management)													
5.2.8	**Efficient heating, ventilation, and air conditioning (HVAC) management** ● •Schedule and adapt HVAC													• Potential interaction with Traffic Management System

	strength to weather condition data/forecasts and to timetabling (e.g., eco-stabling)													
5.2.9.	**5.2.9. Eco-stabling, eco-parking**	• Education of the drivers • Time required to ready a train should not be underestimated, especially when a train is in hibernation mode or energy-optimised stabling. Some systems which were off need to start/reboot and carry out a test (ETCS, BRAKE, NBU etc.).The	N		N									ENE and LOC&PAS: positive aspects, no constraints from the TSIs

		planned parking length first needs to be assessed before the train is eco-parked												
5.2.10	**Interval operation of traction coolant pumps during stabling** Turn off traction converter coolant pumps and ventilation during stabling.		N		X									LOC&PAS: to be checked if the RAMS parameters of the train will remain fulfilled ENE: positive, check that harmonic emission level while stabling will stay fulfilled

Appendix 3.3: Infrastructure

	ENERGY SAVING MEASURES	CONSTRAINTS, CHALLENGES OR LESSONS LEARNT	IMPACTS ON TSI REGULATIONS (X = TO BE ASSESSED Y = IMPACTS ON TSI N= NO IMPACT ON TSI)											COMMENTS
			ENE	INF	LOC & PAS	WAG	NOI	SRT	CCS	PRM	OPE	TAP	TAF	
		Key: **X: additional information is needed** **Y (Yes): this innovative solution could have an impact on a TSI. An explanation is given in column P.** **N (No): the innovative solution has no impact on a TSI. The TSI does not prohibit the solution, or the**												

		TSI explicitly allows the solution to be implemented. An explanation is given in the last column. **A blank box means N/A**												
ENERGY on Infrastructure														
5.3.1	**Railway layout and infrastructure performance** Track curves adjustments to reduce friction and maintain speed			X										
5.3.2	**Electrification:** increased efficiency, renewable energy integration and smart management													See also Renewable energy supply (5.3.15)

5.3.3	**Supply structure/ Neutral sections**		Y											ENE: any new neutral section design shall be assessed against the ENE TSI and EN 50388-1 and 50367
5.3.4	**Infrastructure manager information for railway undertakings: increase the operator awareness regarding more efficient driving and consumption at a standstill** Data and information sharing between IMs and RUs on: • Energy consumption patterns, anomalies, potential improvements		Y		Y				X		X			

	• Cooperation for strategies on timing energy supply with traffic management and stabling/maintenance/operation times • CDAS													
5.3.5	**Smart control of power supply and on-demand supply** (Automatic) switching off of transformers to avoid losses, when no train is present on feeding the section		N		N									Fully compatible with the ENE and LOC&PAS TSIs
5.3.6	**Increased voltage for better transmission efficiency** Higher voltages to reduce transmission losses in the overhead contact line	Used in Japan and France since the 70's: high maturity	N		N									ENE: already in service and TSI compliant LOC&PAS: the traction unit is not influenced by this

5.3.7	**Flexible Traction Energy Supply** • Reduce transmission losses • Reduce peak powers • Improve voltage stability and power quality By replacing the conventional transformer substation and through integration with urban stakeholders (ESS + reversible substations + Energy Management system logic)	These solutions need to be studied in conjunction with the impact on traction units and related functioning within the traction power supply facilities. Impact on signalling systems shall also be verified	N		N				X					ENE: all these systems are TSI compliant unless they allow to remain within EN 50163 voltage boundaries and that voltage stability is not affected (EN 50388-2)
5.3.8	**Installing energy recovery systems on DC railway lines** o Reversible substations within a DC power supply system contribute to a higher use of the energy		N											• Potential interaction with Traffic Management System for enhanced paths fitted with energy savings

	regenerated by trains during brake applications, as most of the braking energy is captured, which can reduce energy consumption by between 7% and 15% depending on the line, the services, and the number of reversible substations on the line o Trackside energy storage (see solution “Trackside energy storage”)													- ENE TSI suggests it. Compliance with ENE TSI

5.3.9	**Recovered braking energy: optimal management** Synchronisation of braking energy returned to the grid with the grid or with public grid demand.		Y		X				X		X			• Potential interaction with Traffic Management System for enhanced paths fitted with energy savings -ENE: not very clear, care to be taken with the conditions needed to brake by regenerative braking -LOC&PAS: this shall be compatible with the control command of the traction unit.

5.3.10	**Avoiding and reducing rotating converters losses** Rotating converters have a 20-30% loss ratio. By increasing the voltage of a rotary converter, the initial base losses due to operation at a specific voltage are avoided		N		N									These components are not covered by the ENE, nor the LOC&PAS TSI
5.3.11	**Lighting: efficiency and management** ● Intelligent control • Replace old lighting with low-pressure sodium or LED lamps		N											

5.3.12	**Switch/point heating system management, optimisation and upgrading** • Optimising switch heating controls to reduce energy consumption without affecting safety and availability. This commonly means upgrading to more efficient, automated and electric heating (avoiding unnecessary heating), and avoiding the use of gas • System management scheduled according to weather forecasts to eliminate excess energy consumption from heating • Energy efficiency for switch heating can be ensured through a		N											• Potential interaction with Traffic Management System Not within the scope of ENE unless these devices do not generate harmonics or disturbances on catenary voltage

	proper power management of the electronic control cabinets/power units													
5.3.13	**Tunnels**							X						To be assessed with TSI Safety In Railway Tunnels
5.3.14	**Measurement equipment** Monitoring the energy consumption of electrotechnical systems and subsystems to understand consumption patterns, identify anomalies and areas		N											Not within the scope of the ENE TSI

	with energy saving potential													
5.3.15	**Renewable energy supply** Increasing the share of renewable energy fed into systems to reduce dependency to the energy market (prices). Renewable sources can be intermittent and therefore not systematically usable for permanent consumption, such as for traction. Different ways of consuming this intermittent energy are to: - Send the energy flow to the traction substation and decrease		N											ENE: unless the power input does not interact with the trains, it is not a matter of interoperability. But, check that the provisions against electric shocks, the detection of faults etc, are correctly fulfilled Also check that the voltage limits described in the EN 50163 are followed

	the power use from the main grid. This is possible if traction units consume - Store it (batteries, chemical, flywheel, H2) for use at the best possible time (see above) - Send it to the mains, which acts as a overall "reservoir" for electricity customers - Directly consume it onsite for stations, auxiliary installations, via a storage system													

5.3.16	**Trackside energy storage** Stationary energy storage systems		N											ENE: it depends on the way the energy is used or how it is connected to the catenary, for whether it is the case or not

5.3.17	**Medium Voltage Direct Current electrification system** • Medium voltage direct current (MVDC) electrification system to reduce transmission losses, copper use • Increase OCL voltage	The ENE TSI does not yet accept 9kV DC	Y											Currently not accepted by the TSIs and standards. It would require an innovative solution process after a proof of concept has been approved. If experiences and initial assessments are good, then a new electrification system could be integrated into the standards. Research and development to be carried out with a systemic view, RST and ENE

Appendix 3.4: Buildings

	ENERGY SAVING MEASURE	CONSTRAINTS, CHALLENGES, OR LESSONS LEARNT	IMPACTS ON TSI REGULATIONS (X = TO BE ASSESSED Y = IMPACTS ON TSI N= NO IMPACT ON TSI)											COMMENTS
			ENE	INF	LOC & PAS	WAG	NOI	SRT	CCS	PRM	OPE	TAP	TAF	
		Key: **X means that additional information is necessary** **Y (Yes) means that this innovative solution could have an impact on the TSI. Explanation is given in column P.** **N (No) means that the innnovative solution has no impact on the TSI: the TSI requirement does not forbid the innovation, or the STI explicitly allows the implementation**												

		of the innovation. Explanation is given in last column. Blank box means N/A												
BUILDINGS														
5.4.1	**HVAC: efficiency and management** ● Using intelligent HVAC control for buildings • Setting lower heating/higher cooling temperatures • Upgrading equipment to a more efficient system (heat pumps)													

5.4. 2	**Harvesting solar power** Install solar panels on suitable building surfaces													
5.4. 3	**Practices for saving energy in stations, buildings, and workshops** • Management and fine-tuning of the temperature and lighting • Increase heating efficiency • Automated switch off/hibernation systems for lighting													
5.4. 4	**Drone use for solar panel performance inspections and**													To be considered in conjunction with the UIC's

	HVAC loss detection												current work on national and European drone regulatory frameworks
5.4.5	**Monitoring and benchmarking energy consumption in buildings**												
5.4.6	**Switching to LED lighting**												
5.4.7	**Escalator, elevator, and conveyor system efficiency** To be fitted or upgraded with energy efficient drives and be												

	intelligently controlled													
5.4.8	**Contractual energy commitments and auditing for concessions/shops**													