



Modelling and strategies for the assessment and **Optimisation of Energy Usage** aspects of rail innovation

## Deliverable D 7.1 Outlook of Mainline, Regional and Urban Rail Energy Usage

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## Executive Summary

This report has been prepared as Deliverable D7.1 “Outlook of Mainline, Regional and Urban Rail Energy Usage” in the framework of the EU co-funded, specifically relating to WP7, Task 7.1 “Outlook of mainline and regional rail energy usage” and Task 7.2 “Outlook of urban rail energy usage”.

The aim is to provide an overview of energy consumption trends and energy efficiency improvement schemes from mainline and regional railway companies and urban railway companies.

An analysis of the final energy consumption provided by companies that pledged to the UIC Environment Strategy and Reporting System (ESRS) will be given. Compliance with the target can be appreciated. Drivers allowing energy efficiency improvement were explored.

An insight of urban railways development is also provided aside from the evolution of public transport services demand evolution.

A perspective of the upcoming improvement is shown by looking into undergoing development technologies.

## Abbreviations and acronyms

Abbreviation / Acronyms	Description
ADAS	Advanced-Driver-Assistance Systems
ATO	Automatic Train Operation
ATS	Automatic Train Stop
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
C-DAS	Connected Driver Advisory System
CO <sub>2</sub>	Carbon Dioxide
DAS	Driver Advisory System
EETC	Energy-efficient Train Control
EETT	Energy-efficient Train Timetabling
EDLC	Electric Double Layer Capacitors
ESRS	Environment Strategy Reporting System
ESS	Energy Storage System
FES	Flywheel Energy Storage
GWh	Gigawatt Hours, a million of Watt Hours
HST	High-Speed Train
HVAC	Heating, Ventilation and Air-Conditioning
IGBT	Insulated Gate Bipolar Transistor
IM	Infrastructure Manager
IoT	Internet of Things
KPI	Key Performance Indicator
kWh	Kilowatt Hours, a thousand of Watt Hours
LRT	Light Rail Transit
OCL	Overhead contact line
PHS	Pumped Hydro Storage
PKM	Passenger kilometre
RU	Railway Undertaking

SiC	Silicon Carbide
TKM	Tonne kilometre
TRL	Technology Readiness Level
TTW	Tank To Wheel
TWh	Terawatt Hours, a billion of Watt Hours
UIC	International Union of Railways, from the French “Union Internationale des Chemins de fer”
UITP	International Union of Public Transports, from the French “Union Internationale des Transports Publics”
UTO	Unattended Train Operation
V2V, V2I, V2X	Vehicle-to-Vehicle, Vehicle-to-Infrastructure, Vehicle-to-Everything
W, Wh, kWh, GWh, TWh	Watt, Watt Hour, Kilowatt Hours, Gigawatt Hours, Terawatt Hours
WTT, WTW	Well to Tank, Well to Wheel

## 1. Introduction

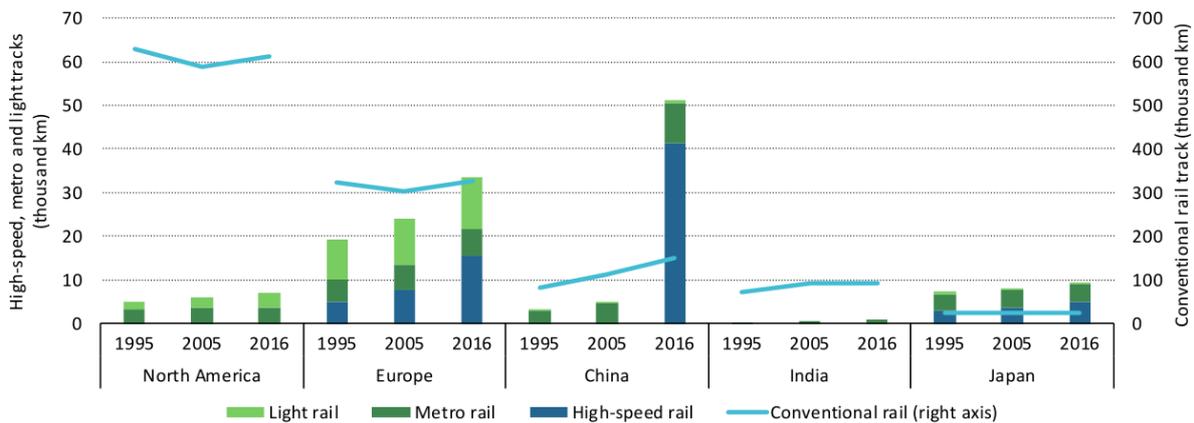
The present document constitutes the Deliverable D7.1 “Outlook of Mainline, Regional and Urban Rail Energy Usage” summarising energy usage requirements and trends evaluating their significance and influence globally at systems level. The document uses data from UITP and UIC’s internal databases to analyse energy usage trends allowing to establish an outlook of the energy consumption landscape in railway systems.

Section 2 provides an overview of railway systems energy usage data and requirements (mainline and urban) including those related to socio-political and environmental targets. Section 3 explores possible energy consumption trends including prospective technology developments, also briefly covering the role of automation in urban railways e.g. ATO as well as the main characteristics of smart management of rail network. Sections 4 and 5 summarise the findings of the deliverable, providing some conclusions.

## 2. Rail Systems Energy Usage Assessment and Requirements

This section provides an overview of the main aspects of energy usage at a system level and by type of service. It will also introduce a summary of key political, social, economic and environmental factors contributing to the system energy outlook.

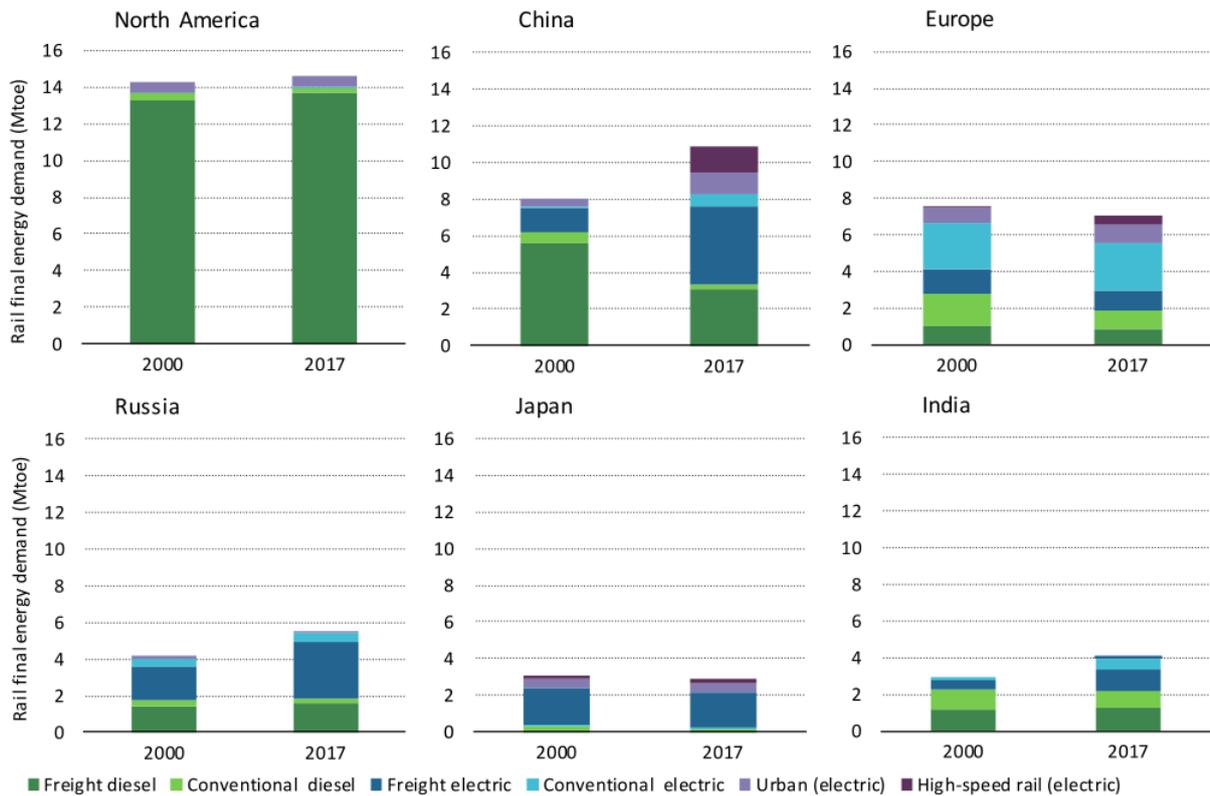
In the global context, Europe has the most extended railway network. Even if China’s High-Speed Rail system has been developing exponentially in the past years (Figure 1), Europe is maintaining and continuously enlarging the longest track assets. Therefore, energy efficiency improvements are mostly to be made on existing rolling stocks and networks according to their lifespan. High-Speed Rail is now developed in European countries as a substitute for short flights.



Note: Conventional rail includes infrastructure used both by conventional passenger and freight rail.

**Figure 1: Main regions' breakdown and evolution of track length by service type in thousand kilometres (IEA, UIC 2019).**

Europe has the most balanced mix of service type energy requirements: Figure 2 shows the final energy demand in million tonnes of oil equivalent (Mtoe) by traction and service type. While diesel represents a big share of American trains’ energy consumption, Chinese’s usage of fossil fuel-powered locomotives has greatly dropped thanks to the newly electrified routes. Japan’s efficiency seems quite stable while Europe managed to greatly reduce its overall consumption since 2000. This is confirmed by UIC’s results from its work with European train operating companies, as described in the next part.



**Figure 2: Rail final energy demand by service type over the world (IEA, UIC 2019)**

This first sub-section will give an overview of the latest energy usage trends at mainline and urban railways. According to the available data, main European railway companies’ consumption pattern can be established. A look into passenger dedicated and freight dedicated trains efficiency will be given. Drivers for energy efficiency improvements will be studied for each service type.

Urban rail state-of-the-art both for metro and light rail is provided in Section 2.2 supported by a summary of OPEUS D1.1 Urban rail system energy requirements in Europe.

## 2.1 Energy consumption at mainline railways

### 2.1.1 Political, social and environmental aspects of energy usage

#### 2.1.1.1 Social

Safety, cleanliness, comfort and convenience are related to passenger satisfaction and higher quality services typically come hand in hand with higher energy consumption. This includes the availability of real-time data, the inclusion of toilets or café services on intercity services and influences stations, particularly with lighting, escalators and smart services.

### 2.1.1.2 Political

On occasion of COP 21, many European railways signed the ‘Railway Climate Responsibility Pledge’ based on (UIC, 2014) committing to

- Reduce their specific energy consumption and CO<sub>2</sub> emissions, contributing to UIC’s “Low Carbon Rail Transport Challenge” targets.
- Stimulate modal shift
- Actively communicate climate-friendly initiatives to raise awareness, acceptance and recognition of the role of sustainable transport as a solution for climate change.
- Report their energy and CO<sub>2</sub> data on a regular basis.

The “Low Carbon Rail Transport Challenge” can be broken down into two sections to meet the 2-degree scenario (UIC, 2014).

Energy Consumption and Carbon Intensity (relative to a 1990 baseline):

- Reduction in specific final energy consumption from train operations:
  - 50% reduction by 2030;
  - 60% reduction by 2050;
- Reduction in specific average CO<sub>2</sub> emissions:
  - 50% reduction by 2030;
  - 75% reduction by 2050.

Modal Shift:

- Railway share of passenger transport (relative to a 2010 baseline):
  - 50% increase by 2030;
  - 100% increase by 2050;
- Railway share of freight land transport
  - Equal to road by 2030;
  - 50% greater than road by 2050.

### 2.1.1.3 Environmental

The environmental impacts of global warming and greenhouse gas emissions have been well documented. Globally railways cover 8% of passenger traffic and 7% of freight traffic, however, despite this, it only accounts for hardly 2% of transport energy demand and for less than 2% of GHG emissions. If railway traffic was replaced globally by road vehicles then global GHG emissions would increase by 1.9 Giga-tonnes (IEA-UIC, 2019). This is due to the economies of scale that railways provide along with widespread electrification.

While there is much discussion on electric cars recently, around 80% of European passenger rail traffic is already electrified, putting railways in a unique position to lead the coming renewable energy revolution. Railway Undertakings (RUs) are already taking advantage of this. Examples

include the Dutch Railways (NS) sourcing all of their traction electricity from windfarms in the Netherlands, Belgium and Scandinavia in 2017 (NS, 2017) while renewable energies made up 42% of Germany's (DB) traction energy mix with the goal of carbon-free operation before 2050 (DB, 2018). Some RUs even operate their own renewable sources for traction energy e.g. Swiss Railways (SBB) which sources 75% of their traction power from six hydroelectric plants which they own and operate (SBB Infrastructure, 2012).

## 2.1.2 Energy consumption by mainline operators

Main European Railway operators pledged to reduce their carbon footprint through the UIC CER Commitment. Based on this commitment, UIC is gathering energy consumption and Carbon Dioxide (CO<sub>2</sub>) emissions data via the Environmental Strategy Reporting System in the "Energy and Environmental Database", which is fed on a yearly basis since 2005.

European Railways have set, with UIC, targets<sup>1</sup> for 2030 in the fields of Climate Protection, Energy Efficiency, Exhaust Emissions and Noise & Vibration.

Energy efficiency target for 2030 and vision for 2050:

- By 2030 the European Railways will reduce their specific final energy consumption<sup>2</sup> from train operation by 30% compared to the base year 1990; measured per passenger-km (passenger service) and gross tonne-km (freight service).
- The European railways will strive towards halving their specific final energy consumption from train operation by 2050 compared to the base year 1990; measured per passenger-km (passenger service) and gross tonne-km (freight service).

Companies signatories of the UIC CER commitment represent, in 2016, 86.01% of the passenger traffic and 53.10% of the freight traffic<sup>3</sup> count from Eurostat (EUROSTAT 2017, EUROSTAT 2019).

The energy consumption mentioned here refers to the final energy consumption (i.e. Tank-to-Wheel energy usage, TTW) by the vehicle's power unit: It includes HVAC, onboard lighting and catering. It also includes shunting energy usage. Diesel consumption figures have been converted from tonnes of fuel consumed to Gigawatt Hours (GWh) and added to the electricity consumption figures.

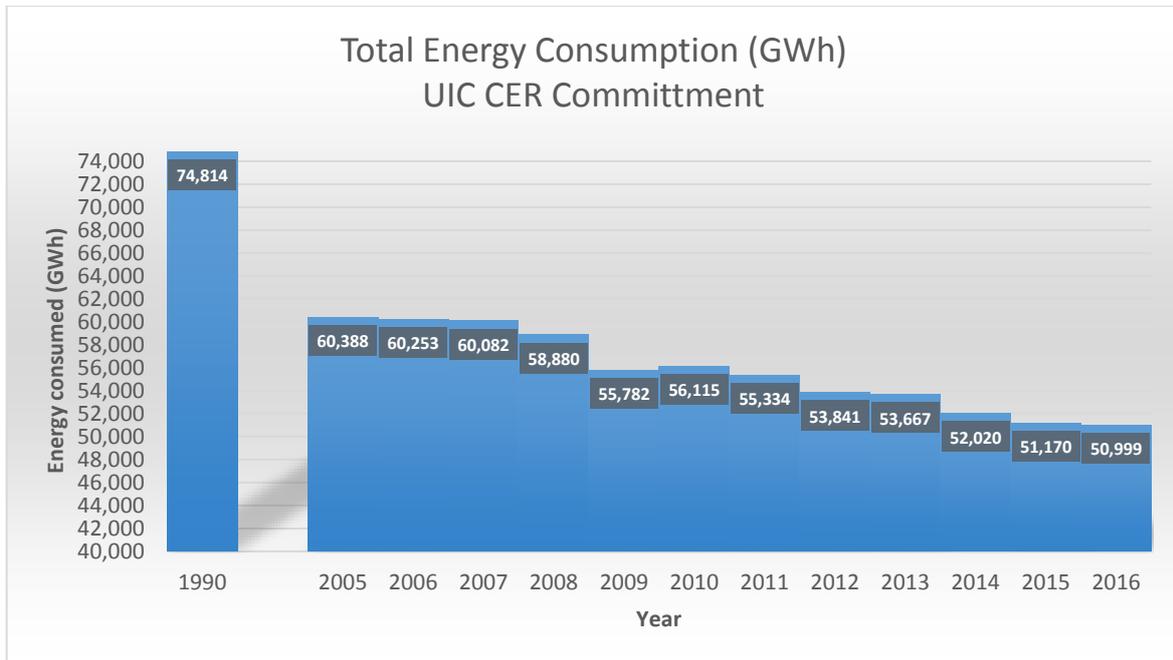
Figure 3 shows the total energy consumption in GWh in 1990 and over the whole collection period (2005 to 2016) regarding both Passenger and Freight activities. Data sets collected in year N refers to year N-2 activity (e.g. 2018 collected data concerns 2016 figures). The consumption has been

<sup>1</sup> Targets 2030 and Vision 2050 - UIC technical documents: "Moving towards Sustainable Mobility: European Rail Sector Strategy 2030 and beyond"

<sup>2</sup> As defined in the UIC Leaflet 330 - Railway specific environmental performance indicators – UIC 2008

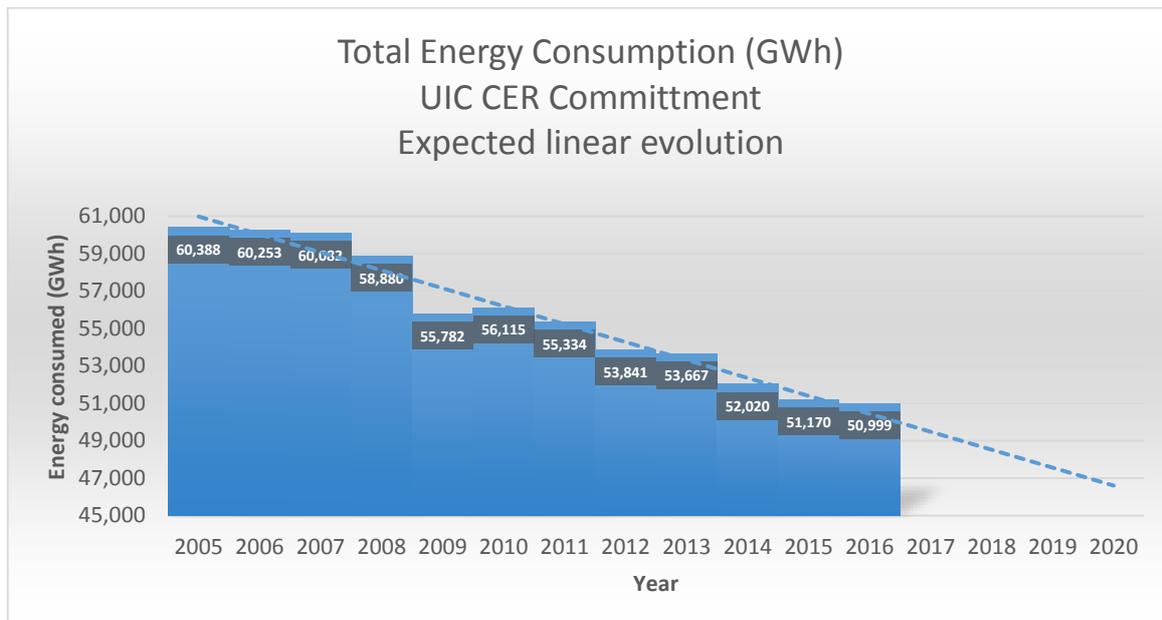
<sup>3</sup> Market evolutions tend to lower these figures until the new operators commit. Of course, UIC aims to be able to increase this data collection coverage, but the left share is split between many small operators in many countries.

reduced by 171 GWh between 2015 and 2016 which is a 0.33% decrease. It has been reduced by 23 815 GWh compared to 1990 which accounts for a reduction of about 32% over the entire period.



**Figure 3: Evolution of the total energy consumption per year over 2005 to 2016 compared to the baseline year value of 1990. UIC ESRS 2018**

Extrapolating the trend of the period 2005 - 2016 allows us to estimate what the following years' consumption could be (Figure 4). Thus in 2020, the consumption could be lower than 47 000 GWh, meaning a decrease of 37% compared to 1990 (Figure 4). Finally, a long-term expectation from this linear trend would be a reduction of 49% (about 37 000 GWh). This would mean that the "Vision 2050" objective (i.e. dividing energy consumption by 2) could be achieved in 2031.



**Figure 4: Evolution of the final energy consumption from 2005 to 2016 and expected linear trend until 2020. Data from UIC ESRS, 2018**

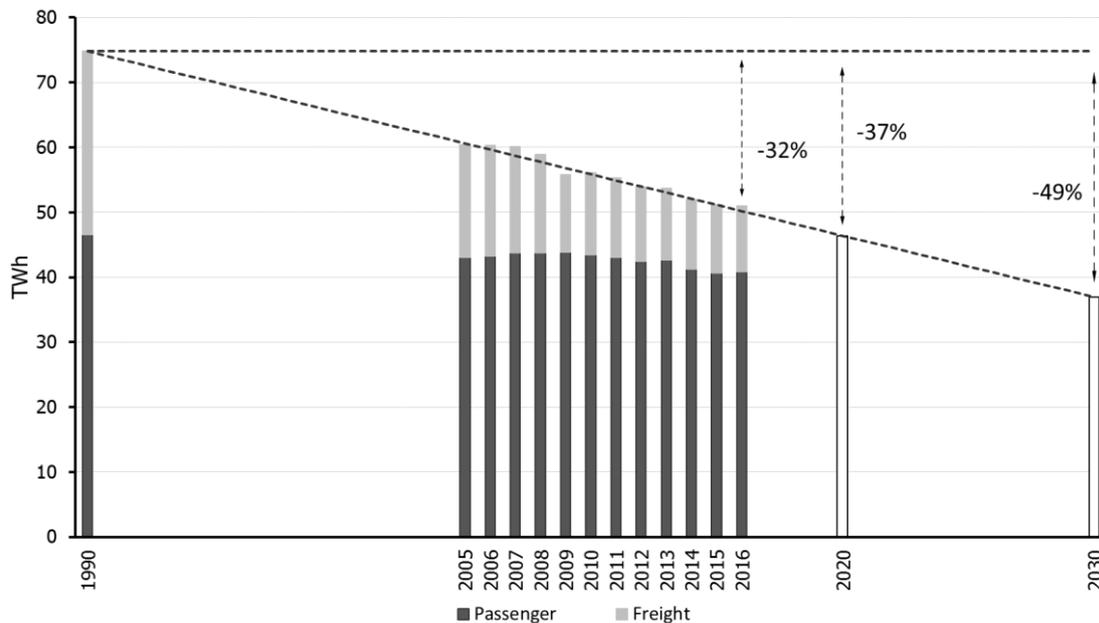
**Table 1** illustrates the split between energy consumed by passenger trains and freight trains.

Consumption share of \ in Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Passenger trains (%)	71,3	71,7	72,8	74,4	78,9	76,4	77,9	79,1	79,8	79,3	79,6	80,2
Freight trains (%)	28,7	28,3	27,2	25,6	21,1	23,6	22,1	20,9	20,2	20,7	20,4	19,8

**Table 1: Shares of final energy consumption by type of service (UIC ESRS, 2018)**

This trend would result in a potential decrease of 49% in consumed energy as illustrated in Figure 4. This prediction can be achieved if both passenger and freight services keep on improving although much potential for improvement is left in passenger trains. In this figure, final energy consumption is expressed in Terawatt Hours (TWh=1 000 GWh) with passenger trains consumption part (dark grey) and freight trains consumption part (light grey).

## Total Energy Consumption



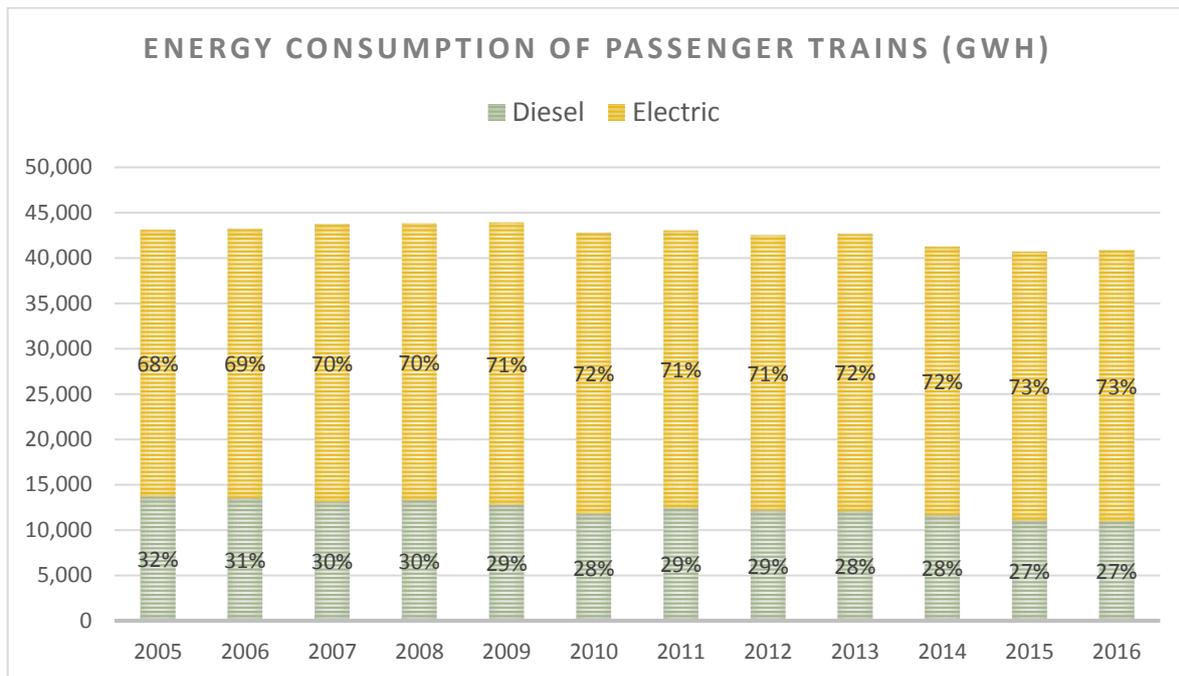
**Figure 5: Long-term trend prospect and reduction rates for 2020 and 2030. (source: UIC ESRS Report 2018)**

### 2.1.2.1 Focus on passenger trains

During the same period (2005 to 2016), the registered passenger activity kept on increasing overall. However, the energy consumption of passenger trains was not increasing accordingly.

Railway companies strive to reduce the use of diesel traction through electrifying or adding onboard energy storage and using natural gas (mostly LNG) and ultimately closing non-electrified lines.

The actual efficiency of these efforts is visible in Figure 6, showing the split between electric (yellow) and diesel (green) energy consumption. UIC stats also confirm a trend in increasing length of electrified track in Europe.



**Figure 6: Passenger trains' total energy consumption in GWh. Data from UIC ESRS, 2018**

Focusing on passenger trains' specific energy consumption (Figure 7) allows seeing both occupancy rates' influence and how trains performed. The decreased consumption can be either explained by (CER UIC 2014; UIC 2014):

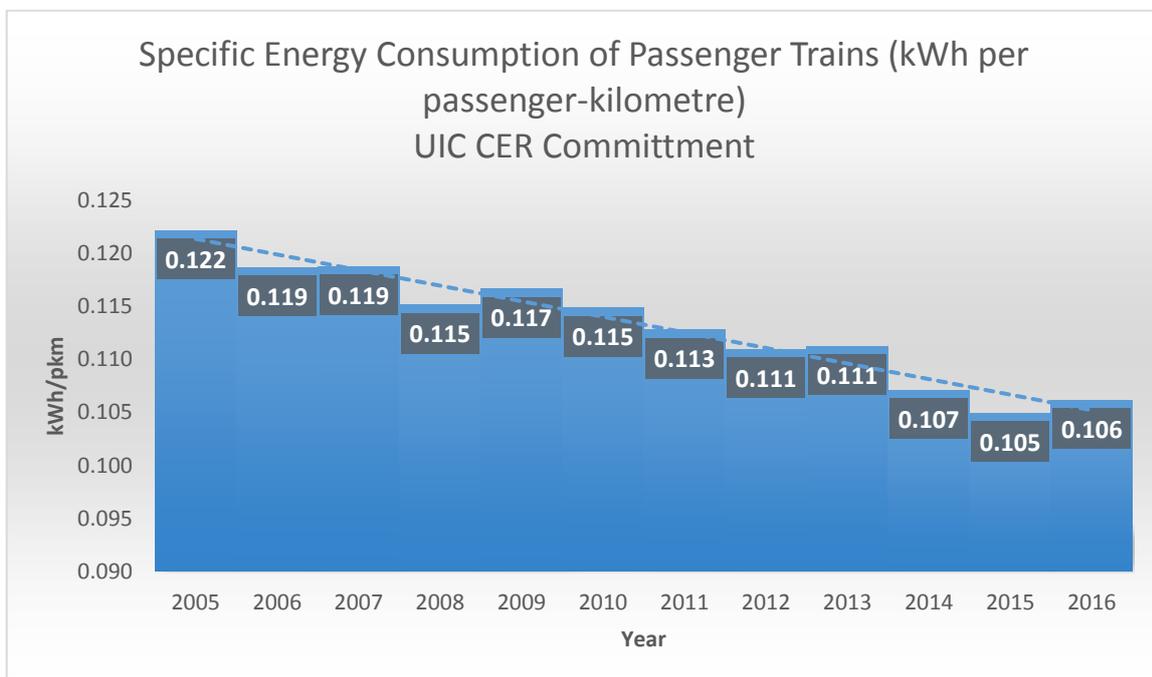
- i. Higher occupancy rates:
  - a. Empty runs management;
  - b. More efficient loading (Passenger information);
- ii. More efficient trains:
  - a. New rolling stock;
  - b. Traction type;
  - c. More efficient components (incl. Traction system parts, Heating, Ventilation and Air Conditioning (HVAC));
- iii. More efficient train runs:
  - a. Traffic management/Train control systems;
  - b. Driving Advisory Systems (DAS)/Automatic Train Operation (ATO);
  - c. Optimised stabling;
- iv. More efficient driving patterns (goes hand in hand with iii):
  - a. DAS/ATO;
  - b. Eco-driving;
- v. Energy input: Reduced transmissions losses (more efficient transmission systems/infrastructure);

- vi. Energy output: More efficient energy recovery from braking phases (Components or infrastructure efficiency, Eco-driving, DAS);
- vii. Better management of auxiliaries (incl. HVAC);
- viii. Other improvements (multiple reach/small improvements).

Timetabling strategies currently aim at optimising occupancy rates by adapting train sizes to passenger flow and optimising Connected DAS' algorithms for traffic adapted journey profiles.

The drastic change in efficiency can be due to rolling stock renewal and/or electronic braking implementation, allowing energy recovery up to 30% according to the transmissions technology used. The actual improvement methods will be introduced in part 2.1.2.3 Levers and targets.

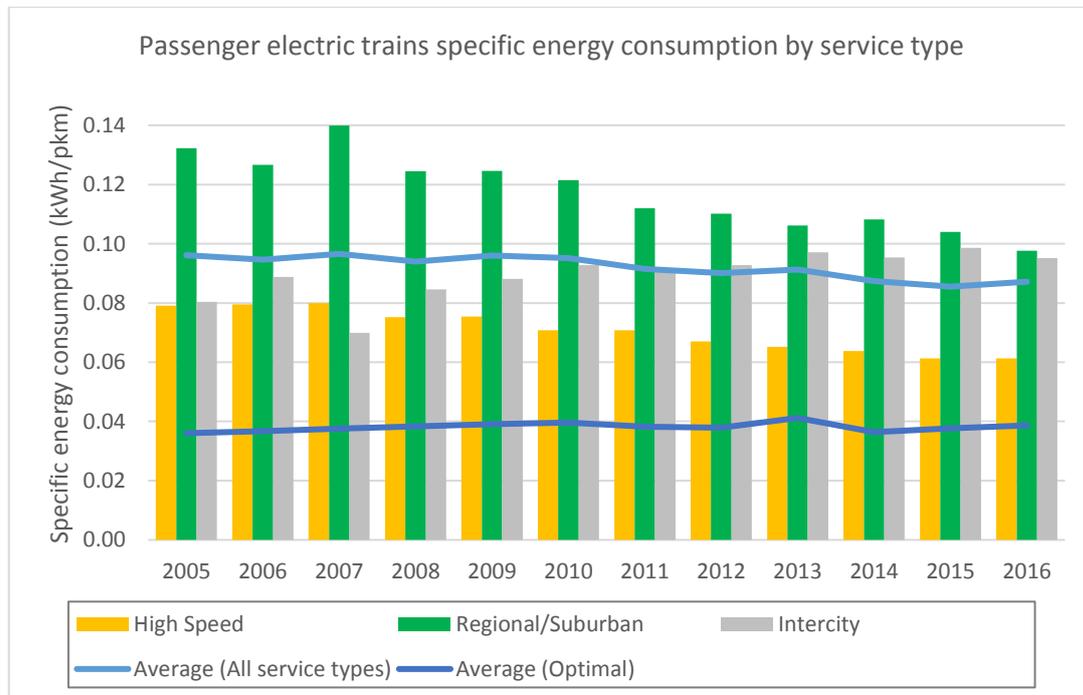
Efficiency of passenger trains covers a wide range of values due to the large differences in the performance of the rolling stock, as well as to operational aspects, such as speed and dependence to the traffic.



**Figure 7: Passenger trains' specific final energy consumption in kWh/pkm. UIC ESRs 2018**

Although data is hard to obtain completely and consistently by service type (and therefore not accurately representative), it can still be arranged in indicative averages over the same period (Figure 8: Passenger electric trains' specific energy consumption by service type in kWh/pkm). The figure shows the "Average (all service types)" as the average without differentiating the service type. "Average (Optimal)" illustrates the specific consumption of all service types if the trains were full (Occupancy rate = 100 %, consumption in kWh/seatkm). In Figure 8: Passenger electric trains' specific energy consumption by service type in kWh/pkm, only electric trains are considered due to data availability.

As expected, the specific energy consumption of trains of high frequency stopping service type will be higher. Nevertheless, regional/suburban trains' consumption seems to be decreasing faster. This could be mainly explained by the progressive implementation of electronic braking allowing energy recovery and efficient traffic management with Eco-driving/DAS/ATO as such trains would be able to achieve large energy savings due to the amount of acceleration and braking phases.



**Figure 8: Passenger electric trains' specific energy consumption by service type in kWh/pkm. UIC ESRS 2018**

Without differentiation of service types, a survey among the reporting UIC members was conducted in 2014 and has made possible to understand what were the triggers for their entire passenger and freight trains fleet efficiency improvement. It resulted (Figure 9) in showing that the most effective lever was in the improvement of rolling stock's efficiency. That is to say by the renewal or refurbishment of traction units or its components.

The punctual trend depicted in Figure 9 seems to be applicable to a longer period, as according to the study's estimation, the trend of development would be approximately the same for the past 15 years and the next coming 15 years (Figure 10) (CER UIC, 2014).

For passenger trains, the most efficient lever appears to be the renewal or refurbishment of the rolling stock. Energy efficiency improvement until 2012 is due, up to around 15%, to better braking energy recovery. The potential improvement, thanks to this technology, was expected to be slightly lower for the 15 years following 2012 as it would rely mostly on how infrastructure (power management and voltage frequency) and DAS algorithms could be adapted to enhance the amount of energy recovered.

Due to increasing passenger traffic and thanks to great potential for improvement, DAS systems have an important role to play in the future train management and train run.

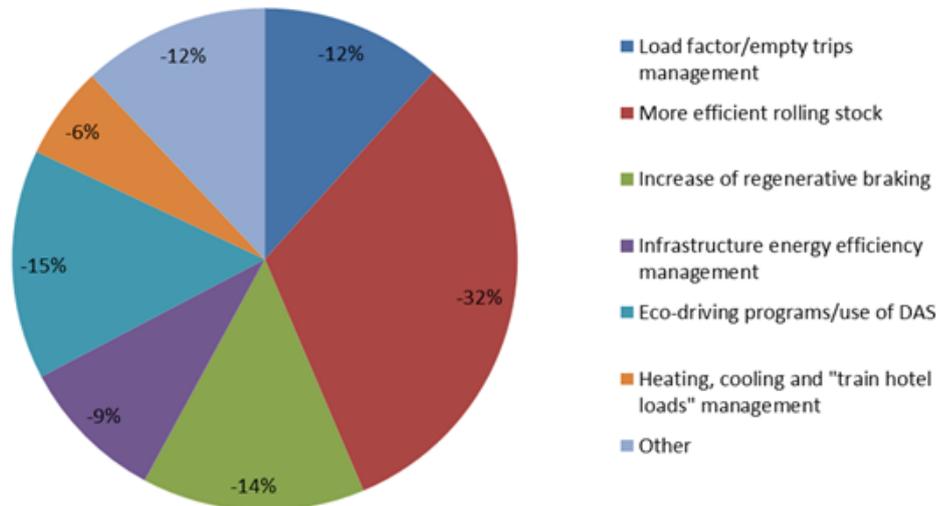
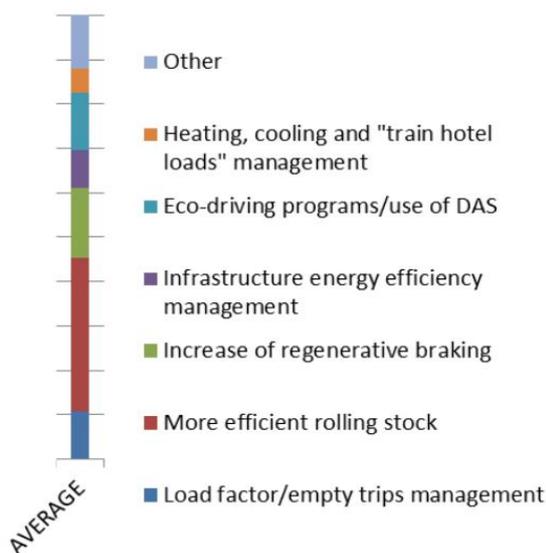


Figure 9: Energy efficiency triggers/action areas improvement factors and their shares in reducing passenger trains' specific energy consumption between 2011 and 2012 (CER - UIC, 2014)

### Last 15 Years



### Next 15 Years

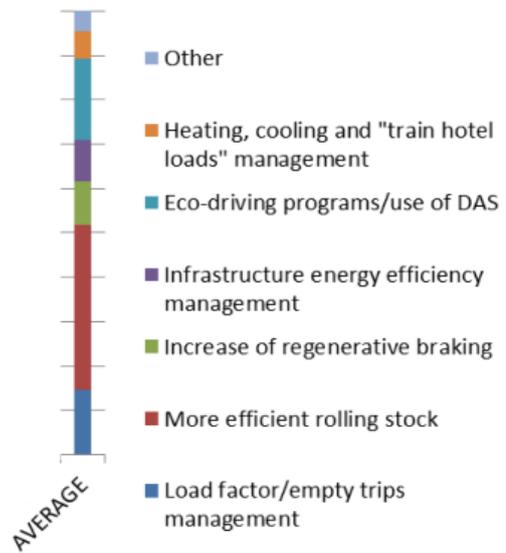


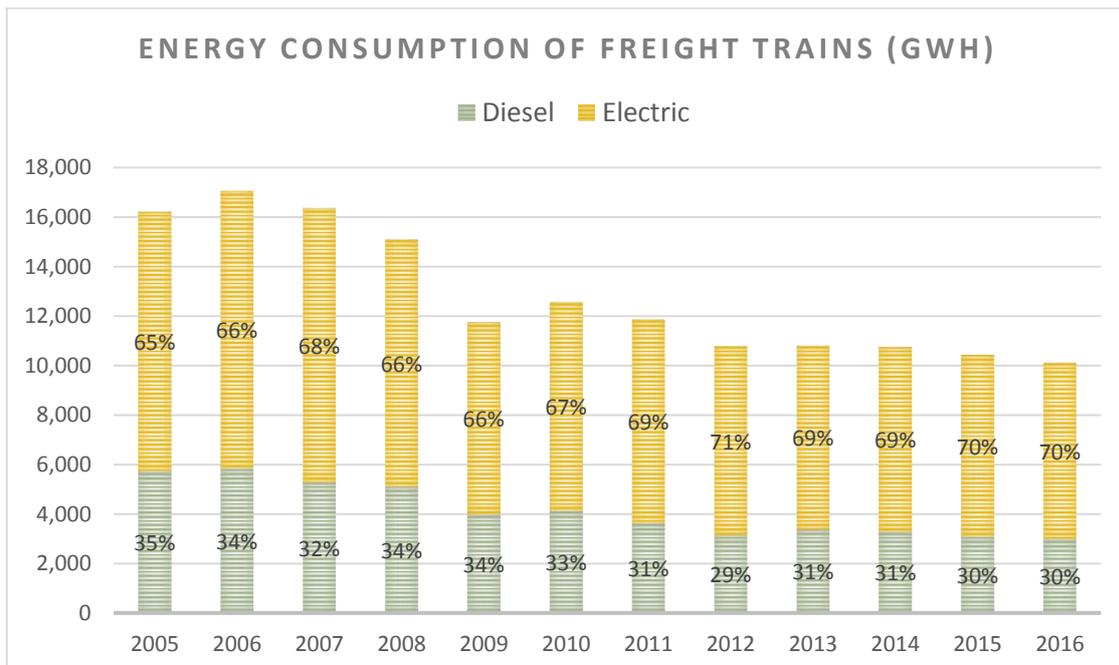
Figure 10: Energy efficiency triggers/action areas improvement factors during the 15 years before 2012 and expected levers to be activated in the next 15 years after 2012 for passenger trains (a segment is 10%) (CER - UIC 2014)

### 2.1.2.2 Focus on Freight trains

The overall freight activity measured, in net tonne-kilometres, is decreasing (UIC ESRS 2018). However It is increasing according to EUROSTAT figures (EUROSTAT, 2017). Therefore, the share of European companies' freight activity covered by the ESRS (Environment Strategy Reporting System) is decreasing compared to EUROSTAT reported activity.

Energy usage has been lowered by 6 000 GWh since 2006 and efforts to reduce the usage of diesel traction are visible over the whole period (Figure 11). The reduced share of diesel consumption can be either due to the decreased activity and efficiency improvements as freight trains consume less per tonne hauled (Figure 12). These improvements could be the result of:

- i. Decreased activity
- ii. Eco-driving, DAS;
- iii. More efficient engines and components;
- iv. Recovered energy from braking and engine idling thanks to onboard ESS;
- v. Improved load factor;
- vi. Closed lines.



**Figure 11: Freight trains' total energy consumption in GWh. UIC ESRS 2018**

Levers to improve freight services are less numerous than for passenger trains. As shown in Figure 13, management of the optimal loading was the most effective way to reduce energy consumption between 2011 and 2012, followed by rolling stock improvement and braking energy recovery optimisation. Note that these two levers can be triggered by the procurement of new rolling stock equipped with electronic brakes, such as new electric or hybrid trains.

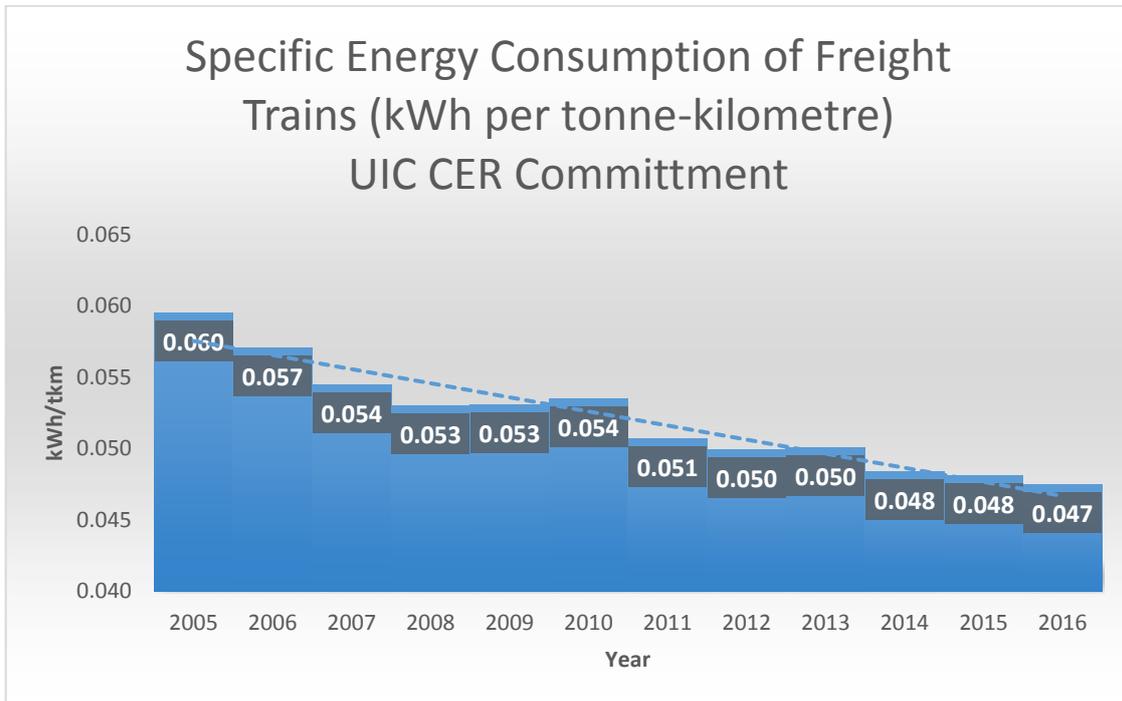


Figure 12: Specific final energy consumption of freight trains by net tonne-kilometre (kWh/tkm)

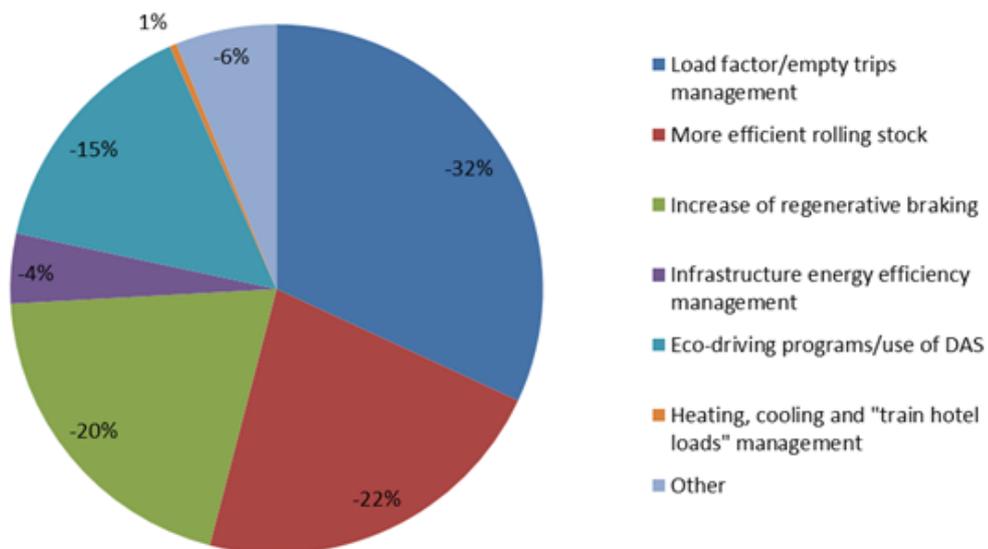


Figure 13: Energy efficiency triggers/action areas improvement factors and lever's share in reducing freight trains' specific energy consumption between 2011 and 2012 (CER - UIC, 2014)

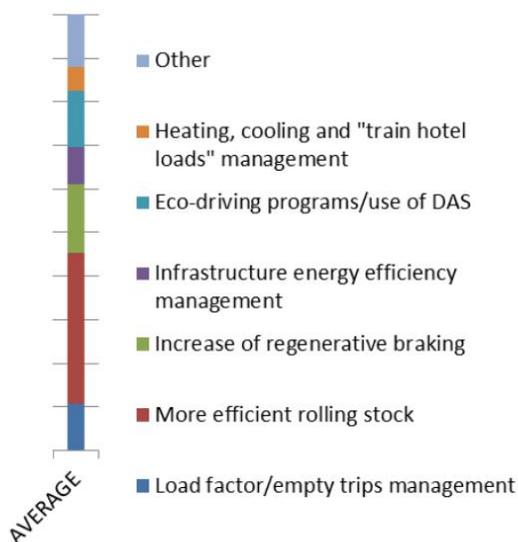
However, the drivers of improvement are on average different over a wider timeframe (Figure 14). The trigger "More efficient rolling stock" had the highest impact on energy efficiency before 2012, followed by the closely linked improvement of braking energy recovery.

As illustrated by 2012 results (Figure 14, CER - UIC 2014), increased load factor and better

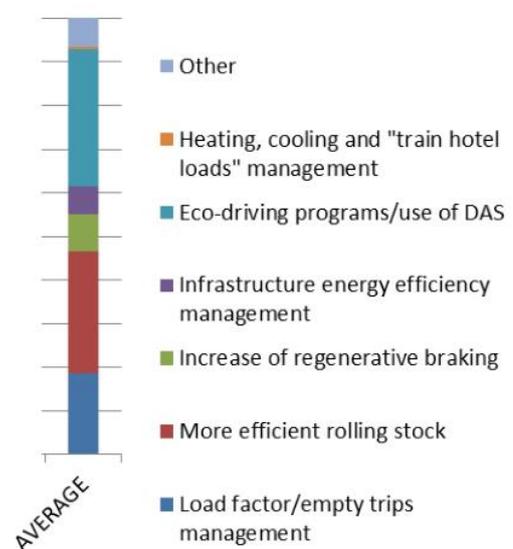
management of empty trips are expected to have a greater impact in the years following 2012. It can then partially explain the trend displayed in Figure 12 between 2013 and 2016 (as assumed in point v.).

The same remark can be made for improvements resulting from the use of DAS and eco-driving. It is useful to highlight that, DAS was expected to have enormous potential (around 30%) to reduce freight trains' consumption after 2012. Heavy loads of goods mean much more energy dissipated in brakes, thus, avoiding stops by adapting trains' speed can have a good impact on the resulting consumption.

### Last 15 Years



### Next 15 Years



**Figure 14: Energy efficiency triggers/action areas improvement factors during the 15 years before 2012 (left) and expected triggers in the next 15 years after 2012 (right) for freight trains (a segment is 10%) (CER - UIC 2014)**

### 2.1.2.3 Levers and targets

Companies involved in UIC's activities kept on seeking means for improvement. A timeline has been created (Table 2), based on UIC's activity and mentioning the topics.

**Table 2: Timeline of enhancements mentioned in UIC as a research topic and as applied to the railways. UIC's Energy & CO<sub>2</sub> Network Inputs (2009-2016)**

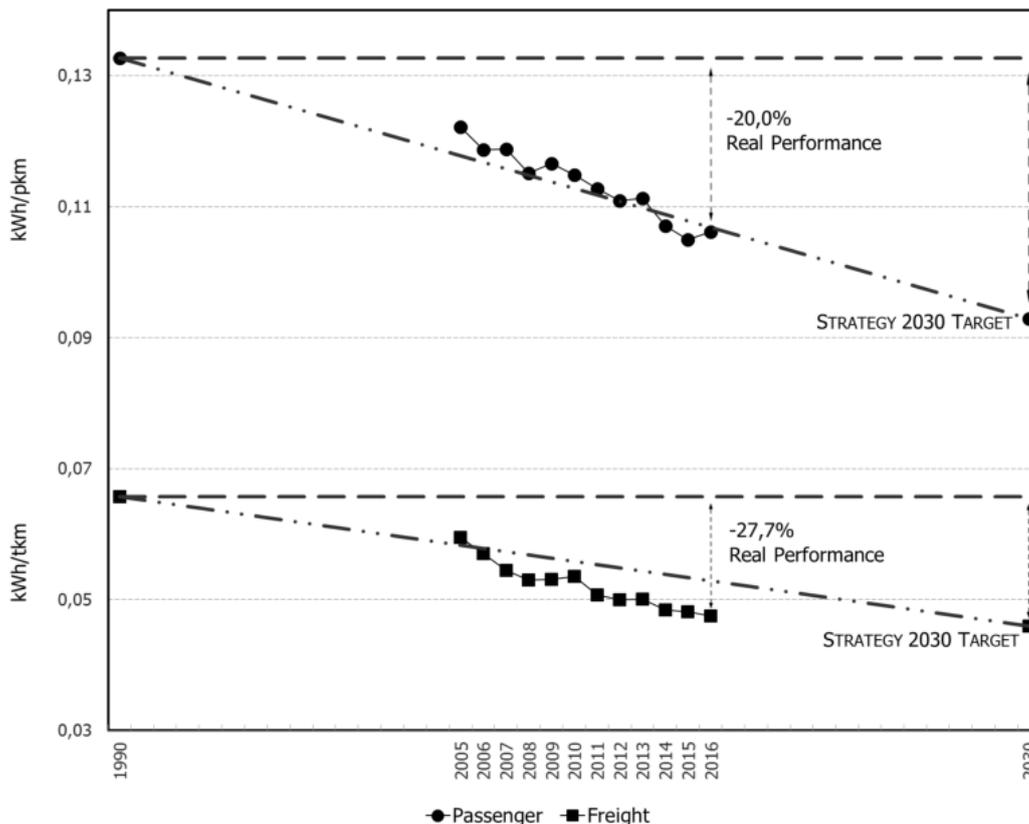
Year	Applied	Research topics
2009	<ul style="list-style-type: none"> <li>• Further electrification</li> <li>• Optimising occupancy rates/load factors</li> <li>• Optimised operation modes (Eco-driving and Traffic management)</li> <li>• Vehicles renewal</li> </ul>	<ul style="list-style-type: none"> <li>• Further electrification</li> </ul>
2010	-	-
2011	-	-
2012	<ul style="list-style-type: none"> <li>• Integrated energy management, avoidance of power demand peaks (reduced transmission losses)</li> <li>• Onboard energy metering deployment Directive 2012/27/EU, 25 Oct.2012</li> </ul>	<ul style="list-style-type: none"> <li>• Eco Driving</li> <li>• Eco Stabling</li> <li>• Adaptive train control for optimised train flows (reduced stops)</li> <li>• Rolling stock components optimisation</li> <li>• Energy metering</li> <li>• Energy settlement</li> <li>• Energy management system</li> </ul>
2013	<ul style="list-style-type: none"> <li>• Eco Driving</li> <li>• Adapting locomotives/coaches' setups</li> <li>• Improving efficiency of components</li> <li>• Stop HVAC when not running (stabling)</li> </ul>	<ul style="list-style-type: none"> <li>• Efficient operations</li> <li>• Energy Storage for renewable energy</li> <li>• Hybrid trains</li> <li>• Eco Driving</li> <li>• Driver Advisory system</li> <li>• Energy based timetabling</li> <li>• Insulation of rolling stock</li> <li>• LEDs in rolling stock</li> <li>• Energy metering systems</li> <li>• Reducing the energy consumption/loss in rotary converters</li> <li>• Aerodynamics for freight trains</li> <li>• Detailed energy metering</li> </ul>
2014	<ul style="list-style-type: none"> <li>• Optimising recovered energy by electronic braking (up to 30% achieved)</li> <li>• Adoption of metering systems</li> <li>• Enhanced driver training (in Eco Driving)</li> <li>• Incentives for driver to follow eco-driving rules (incl. braking methods for optimal recovery)</li> <li>• Energy saving stabling modes</li> </ul>	<ul style="list-style-type: none"> <li>• Assessing long term energy saving potentials (production of rolling stock, capacity, speed, traffic, technology)</li> <li>• Energy consumption modelling</li> <li>• Smart stations / Stations requirements assessment</li> <li>• Shift 2 Rail projects frame start</li> <li>• Smart LED lighting in rolling stock</li> </ul>
2015	<ul style="list-style-type: none"> <li>• Close to complete deployment of metering systems</li> <li>• Adaptive train control for optimised train flows (reduced stops)</li> <li>• Lighter rolling stock</li> </ul>	<ul style="list-style-type: none"> <li>• Onboard Batteries</li> <li>• Geothermal HVAC in stations</li> <li>• DAS algorithms</li> </ul>

- 2016**
- DAS deployment
  - Rolling stock modernisation, higher capacity rolling stock
  - Improved load factor for off-peak hours
  - Optimisation of train preparation and stabling
  - LEDs in rolling stock

Improvements applied according to Table 2 certainly had effects in trains' efficiency. It can be highlighted by comparing achieved reduction in energy consumed by kilometre over the corresponding and following years, as in Figure 15. For example, 2009 to 2015 witnessed a great progress in efficiency of passenger trains. While reduction is also consistent between 2010 and 2016 for freight trains.

Freight trains' specific energy consumption trend is good as the targeted reduction for 2030 is close to be achieved (Figure 15).

### Specific energy consumption



**Figure 15: Passenger and freight trains specific energy consumption and outlook to the 2030 target (-30%) (source: UIC ESRS Report 2018)**

This is, however, more challenging to passenger trains for which the quality of service is much more dependent on comfort (load factor/HVAC), punctuality (Traction) and, therefore, it is more difficult to ensure continuous improvement.

### 2.1.2.4 High Speed rail

The development of high-speed lines is now a major challenge as it allows more efficient train operations and is a good alternative to avoid aviation emissions. The fact that it is faster than usual lines can ensure revenue for companies.

Infrastructure is accurately conceived, trains are light, aerodynamically enhanced and more efficient.

As shown in Figure 16, all the consumption spots are favourable to High-Speed trains, except aerodynamic drags<sup>4</sup>.

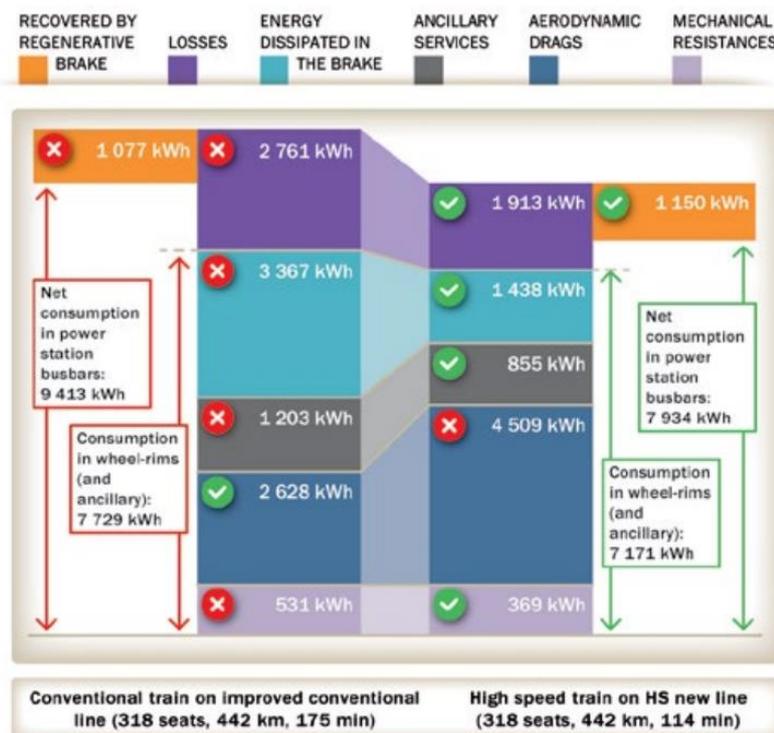


Figure 16: Example of energy consumption breakdown – High-speed train (right) compared to a conventional train (UIC Railway handbook 2015)

<sup>4</sup> Note: The study has been made in 2010, and the energy figures are not representative anymore of the current HSR (High-Speed Railways systems) efficiencies, the purpose is just to illustrate

### 2.1.2.5 DAS's potential

Deliverable D4.1 “DAS assessment” summarises the main functionalities and characteristics of standalone DAS (S-DAS) and connected DAS (C-DAS) and their suitability for energy management and optimisation of driving strategies. More specifically, this task is a comparative assessment of S-DAS and C-DAS and their relevance to the four operation scenarios: urban, regional, high speed and freight operations (OPEUS D3.1, 2017). D4.1. reviews and discusses the variation of optimisation algorithms, driving strategies and models which are the principle and fundamental methods of deriving optimal energy-efficient driving strategy/advice. It discusses the aspect of the energy-efficient train control (EETC) and energy-efficient train timetabling (EETT), including how different operation types influence energy optimisation.

Implementation of S-DAS (Standalone DAS) and C-DAS (Connected DAS) is a hot topic for main European railways. 12 IMs and RUs have gathered experts in the UIC SFERA (Smart communications For Efficient Railway Activities) to set up a standardised protocol dedicated to information exchange in DAS systems. The results should be published at the beginning of 2020. Depending on a company, S-DAS has already been implemented and C-DAS solutions are being implemented since 2018 in collaboration with Infrastructure Managers. C-DAS developments also open a shortcut to Automatic Train Operation (ATO) bypassing human factors to energy savings.

Savings from optimised DAS implementation and cross-border DAS compatibility have been assessed to reach 1.4% and 13.3% according to SBB's 2019 paper on energy savings. According to improvement already achieved by companies, the benefits can be much higher.

### 2.1.3 Transmission Losses

Deliverable D5.1 “Traction chain characterisation” presents a description of the traction system and auxiliaries parameter based on the vehicle architecture. The general defined vehicle architecture depends on the catenary voltage system, from which the specific architecture for each scenario (urban, regional, high-speed and freight) can be elaborated. A specific conventional tram architecture is used in that document as an example, where all traction components (converters, traction motors, etc.) are also defined and described. D5.1 proposes some topologies as well as some energy and management strategies in order to run simulations and to investigate possible measures for reduction of energy losses in D5.2. Nevertheless, this only applies to rolling stock and reporting losses can be a complicated task for operators according to the energy settlement system in the country.

Available data shows that around 7,5 % of the energy consumed by trains has been lost in 2016 during transmissions for European mainline railways according to a weighted average by consumption (ESRS 2016 figures).

### 2.1.3.1 Traction components efficiency

Regarding Alternative Current traction topologies, simulations thanks to the OPEUS-tool, introduced in OPEUS Deliverable D3.4, showed that improving traction components' efficiency (e.g., with Silicon Carbide (SiC) components) gave the most interesting results beside weight and gearbox improvements. As the improved efficiency also serves to increase the recovered energy from the brakes, the best results were simulated for the Regional service (with maximum speed: 140km/h) with 8.8% kWh saved for efficiency improvement of 3%. This level of savings is assumed to be possible because of the high frequency and time length of acceleration and braking phases.

### 2.1.3.2 Partial switch-off

Another strategy to avoid losses during low load operations is explained in OPEUS Deliverable D3.3 and consists in temporary switching-off traction components. This is a partial switch-off. The simulation resulted in substantial energy savings by switching off *some motors* while the train was cruising and *all motors* while coasting or standing still. Again, this method is the most efficient for numerous coasting phases and long-standing still time service type (See OPEUS deliverables D3.3 and D5.2 for simulation results by service type).

## 2.2 Urban energy usage requirements and trends in energy consumption – general overview

Urban rail are typically services delivered by tram LRT and metros. As of December 2018, there were 38 cities with a metro system and 187 cities with a tram/LRT system in the European Union. The details of the installed assets are shown below.

**Table 3: Number of metros and tram LRT in Europe**

	<b>Metros</b>	<b>Tram LRT</b>
<b># systems</b>	38	184
<b># lines</b>	151	1288
<b># line-km</b>	2606	8473
<b># stops</b>	2656	20621
<b>Av. Line length (km)</b>	17.2	6.6
<b>Av. dist. betw. Stops (m)</b>	981	411
<b>Fleet</b>	23 905 cars	18 473

Below, the key figures about the development of metros and tram LRTs are provided to better understand the importance of energy consumption issue for urban rail.

### 2.2.1 Metros

A majority of systems (28 out of 38) were opened in the 70s, 80s and in the first decade of this century (Figure 17).

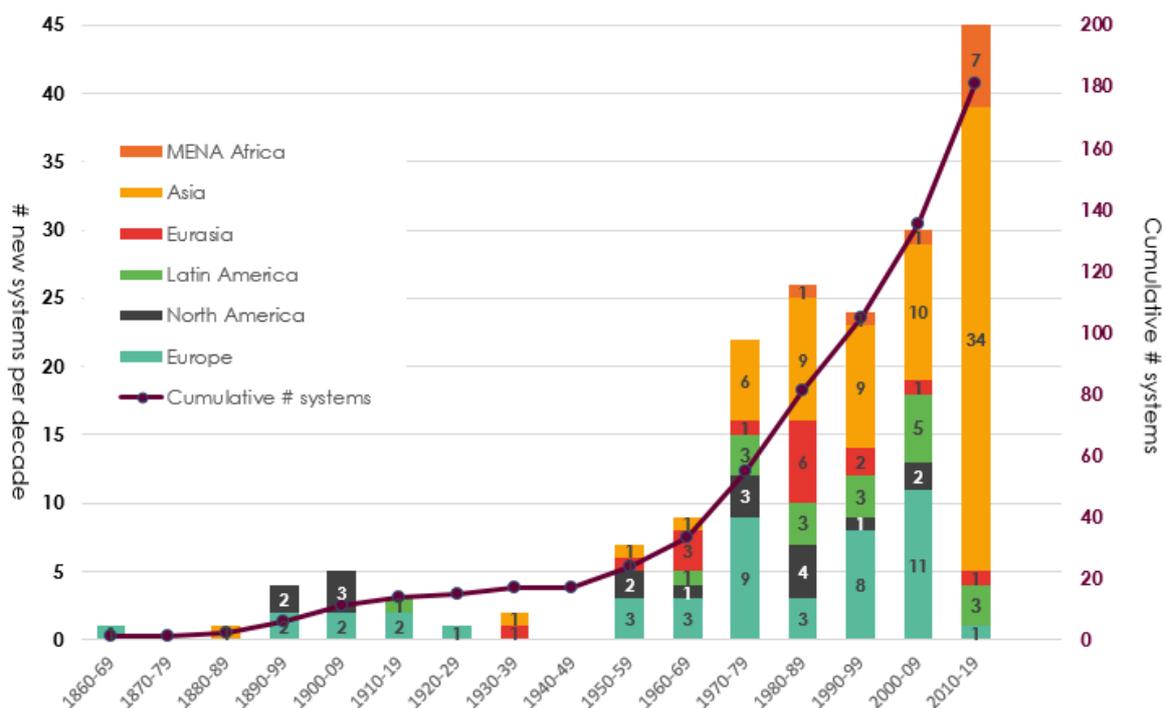
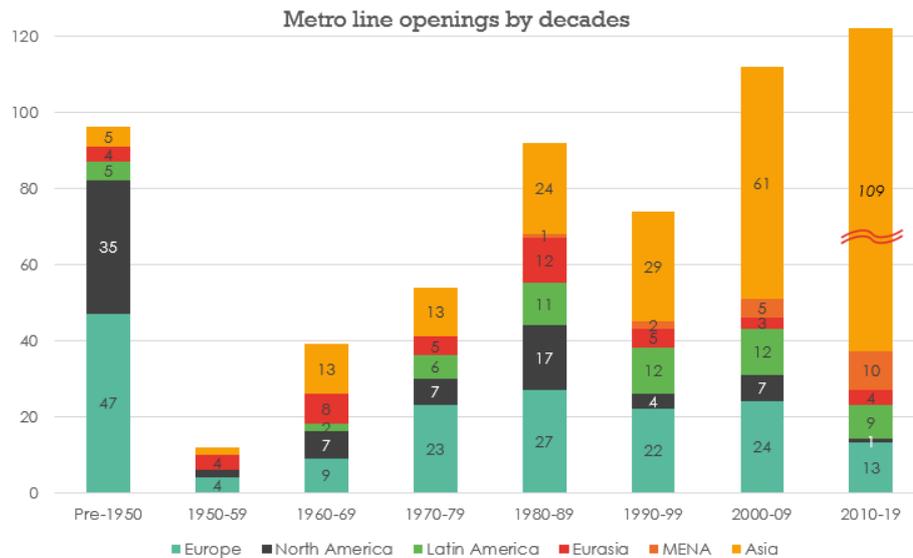


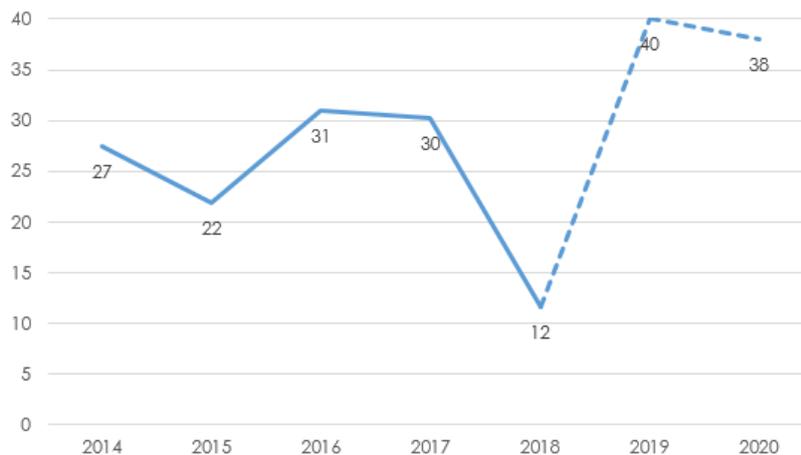
Figure 17: Metro system opening (per decade) 1860-2019. Source: UITP

A more detailed analysis of asset age base by line shows that 133 out of 151 lines were built more than 40 years ago, thus requiring massive brownfield re-investment in rolling stock and infrastructure, and an opportunity to improve the energy-efficiency of both mobile and fixed (traction and non-traction) equipment.



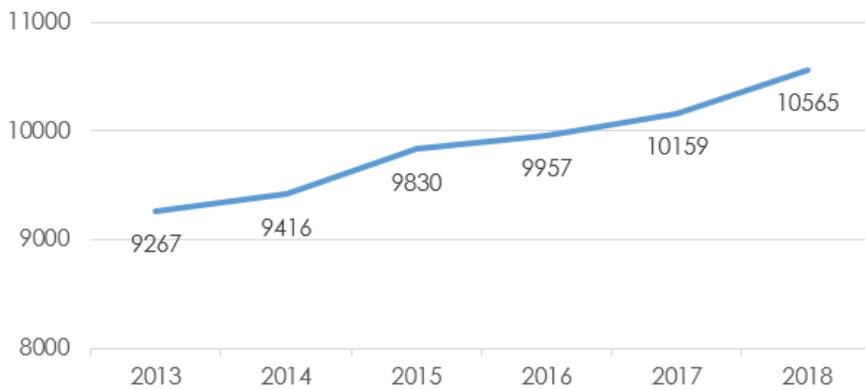
**Figure 18: Metro line openings (per decade). Source: UITP**

In last 4 years, fixed assets grew by 4.7% (+122 km) in Europe. However, this was nearly exclusively for existing system extensions. Only one new system was added in Brescia. The trend is expected to increase significantly in 2019 and 2020, especially due to opening of new lines (e.g. Copenhagen, Rennes, and Thessaloniki).



**Figure 19: Evolution of new metros in Europe (km). Source: UITP**

Over the same period, ridership has increased by 1298 million (+14%), i.e. an average annual increase of 2.8%. This means that the evolution of usage is faster than the evolution of assets and this translate into increased asset use intensity and better per capita energy efficiency KPI (energy consumed per pax).

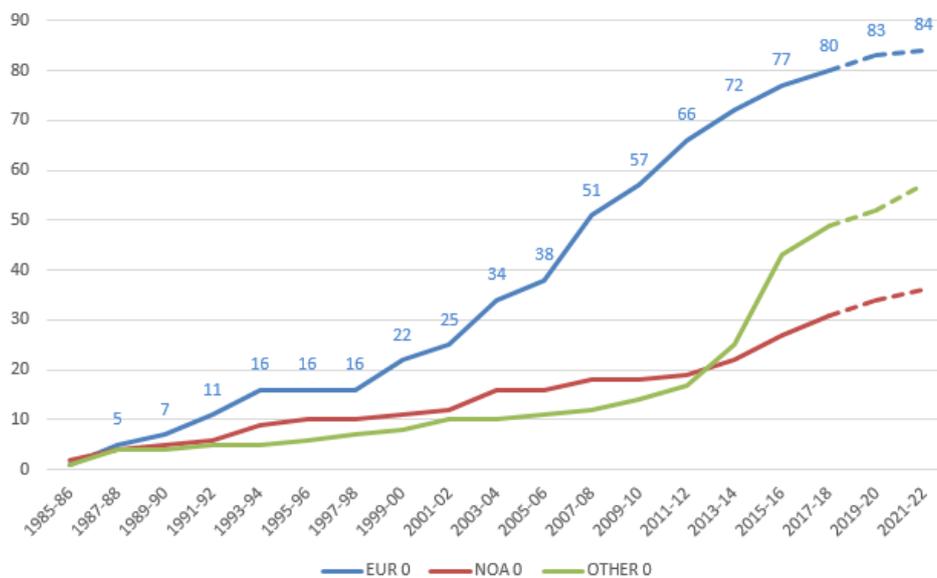


**Figure 20: Ridership in European metros (mln). Source: UITP**

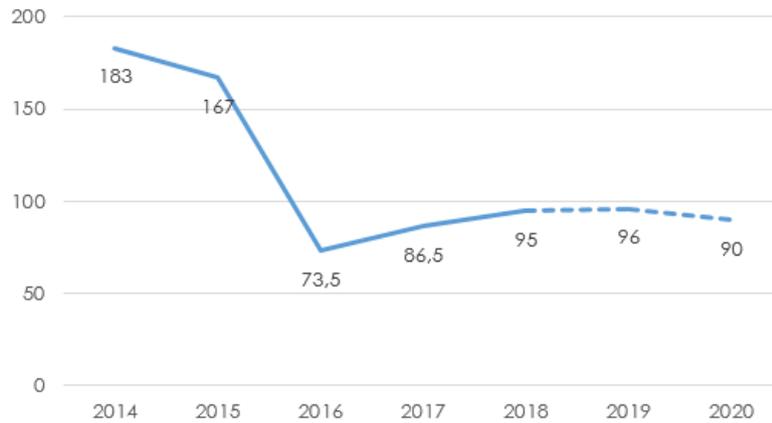
### 2.2.2 Tramway / Light Rail Transit

Tram systems commonly belonged to the street-scape of nearly all large and medium-sized European cities since the late 19th Century. After the 2<sup>nd</sup> World War, many of them scrapped their ageing and ailing trams to “modernise” their transport system and give space to cars, except in Central and Eastern Europe, Germany, Austria, Switzerland, Netherlands and Belgium where modernisation efforts led to the concept of Light Rail/Stadtbahn.

Since the mid-80s, LRT was successfully (re)introduced in 80 European cities for a total of 1475 km (Figure 21).



**Figure 21: New LRT system openings 1985-2018-2022. Source: UITP**



**Figure 22: Evolution of new LRT Europe (km)**

In **Error! Reference source not found.**, the updated numbers with estimated consumption for urban rail are presented. The initial data was presented in D1.1 Urban rail system energy requirements in Europe of OPEUS project (OPEUS, 2017). It has been updated with latest figures (Dec; 2018) and adapted to reflect only the EU (excl. Norway, Switzerland, Serbia, Bosnia and Turkey).

Table 4: Consumption estimation of urban rail

CONSUMPTION ESTIMATION OF URBAN RAIL IN THE EU (Jan 2019)		
	Metro	LRT
<b>INFRASTRUCTURE DATA</b>		
Cities #	38	187
Lines #	151	1.288
Km infra	2.606	8.473
Stops	2.656	20.621
Underground	70%	0,10%
<b>OPERATION DATA</b>		
Patronage (10 <sup>6</sup> . pax/y)	10.747	8.425
Passenger-km (10 <sup>6</sup> pkm/y)	64.482	33.700
<b>FLEET DATA</b>		
Fleet Coach	23.905	18.473
Coach-km (10 <sup>6</sup> ) /y	2.390,5	1.108,4
<b>ENERGY DATA</b>		
Rolling stock GWh / y	5.976,3	2.771,0
Station GWh / y	1.593,6	618,6
Total GWh / y	7.569,9	3.389,6

This consumption was computed on the basis of following expert assumption and UITP study results

- Average trip length in metro 6km and in LRT 4km
- Av. yearly mileage: Metro 100,000 km; LRV 60,000 km
- Av. metro consumption: 2,5 kWh/coach-km (UITP sample of 13 metros) idem for LRV (not coach); calculated on RATP 2011 data
- Av. metro station consumption: 0,6 GWh / year (UITP sample of 13 metros excl. tropical cities with AC-ed stations) --- 20 times less for LRT stations

### 2.2.3 Energy requirements for urban rail systems

D1.1 Urban rail system energy requirements in Europe of OPEUS project (OPEUS, 2017) describes the investigations into the social, political, economic, environmental and operational requirements related to the energy usage in urban rail systems. The key outputs of this deliverable are presented below in order to support the outlook of future energy consumption trends and definition of emerging technologies that may help to make urban railways more energy efficient.

Firstly, customer expectations are notably increasing. Customers expect better quality, higher comfort and new services (HVAC, real-time information, infotainment, amenities such as wi-fi connectivity in stations and trains, charging facilities for their mobiles etc.). It influences the overall energy consumption and requires more energy for urban rail operation, thereby offsetting improvements in energy efficiency for traction purposes.

Secondly, the existence of the problem of climate change and greenhouse gas emissions promotes the focus on clean energy and energy efficiency. Transport is a large contributor to energy usage, CO<sub>2</sub> emissions and PM and local pollutants, and the only sector seemingly unable to decrease its carbon footprint. That is why a lot of attention is paid to make transport more environmentally friendly. Moreover, EU policy becomes more oriented on green energy and sustainability. Roadmaps, white papers, agreements on global climate change position, investments in research and innovation, specific regulations – all these aspects influence the modernisation and replacement strategy in railways.

Thirdly, the main trends presented by the Commission in 2016 (EC, 2016) are still relevant: urbanisation and ageing population, collaborative economy, automation and connected vehicles, digitalisation and Mobility as a Service (MaaS), new materials, increasing security threats, etc. The first two trends influence the growing demand for public transport and require the increasing of urban rail capacity.

In addition, optimisation of expenses and increasing of the revenue is always a key point for discussion. New possibilities for reducing the operational costs and costs of ownership play an important role. For example, according to UITP statistics (2017), 15-20% of urban rail operational expenditures are related to energy consumption. Thus, reduction of energy consumption and energy optimisation is an important topic of research and innovation.

### 3. Introduction of Novel technologies

The future of energy consumption is influenced by many trends and emerging technologies. As a result of these trends above, urban rail industry is being focused on the innovations that improve the efficiency of traction systems and reduce the on-board energy consumption, such as efficiency of the components in traction system and optimisation of weight and dimensions of the rolling stock (Amsler, 2019).

The analysis done by Amsler (2019) shows that regarding traction system the following innovations can be highlighted:

New traction components and technologies:

- Synchronous motors with permanent magnet replacing induction motors
- Wideband electronic power semiconductors that can replace silicon-based components (insulated-gate bipolar transistor (IGBT));

Smart management of energy and energy savings:

- On-board energy management systems controlling automatically the use of individual equipment and components in order to optimize the performances and overall energy consumption of the vehicle;
- New methodologies for better lifetime estimate, improved design and validation processes of traction systems;
- On-board energy storage systems: batteries and supercapacitors as well as fuel cells and flying wheels;

Traffic management:

- Driving Advisory Systems (DAS) able to provide instructions to the driver as well as Automatic Train Operation/autonomous trams LRT;
- Fully automated train/metro operation (GOA4)

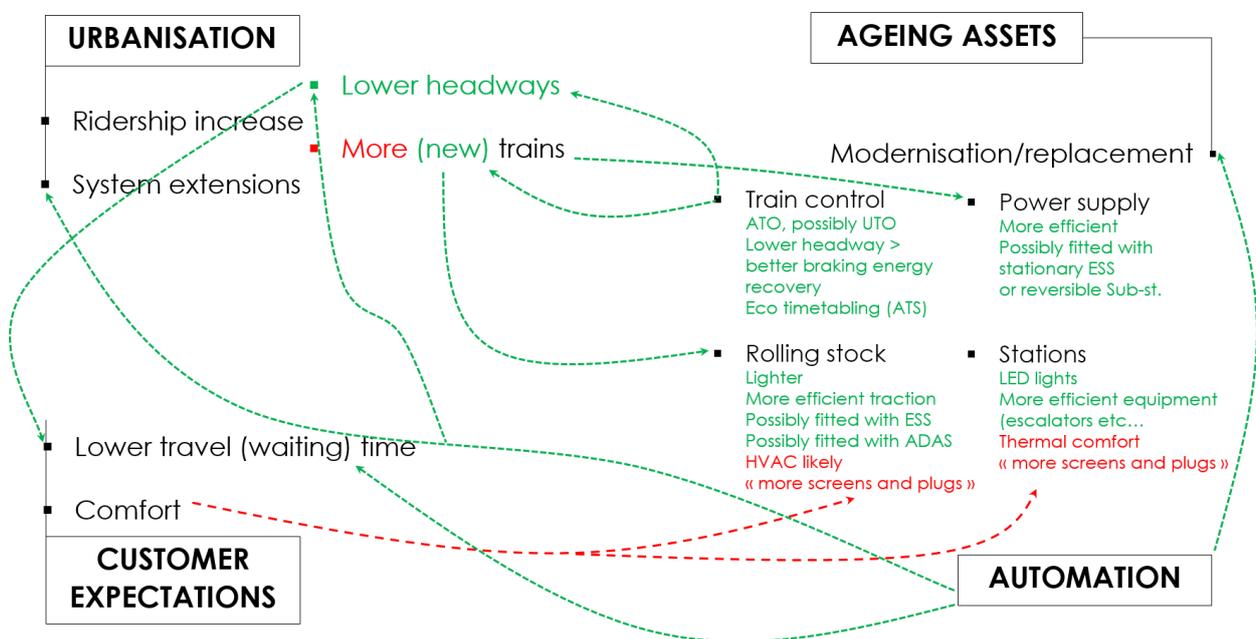
It is important to understand that these technologies should not be applied per se everywhere, but only following a careful appraisal of potential savings and analysis of the cost-efficiency. ESS systems, for instance, are generally not to be recommended in metros where the level of braking energy wasted is low (low headway, ATO-ATS (Automatic Train Stop) etc...). On branches with less dense traffic, stationary flywheels proved to be effective etc.

That list may be completed by more efficient HVAC that meet customers' requirements, smart energy management within the cities (introducing of "smart grid" approach and wide usage of regenerative braking concept) and digitalisation and interconnectivity (V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), V2X (Vehicle-to-Everything), IoT (Internet of Things)).

### 3.1 Future energy consumption trend outlook and interaction matrix

Energy consumption factors matrix (Figure 23) aims at highlighting the set of mutual and intertwined influence factors on energy consumption for the coming years, starting from 4 major trends:

- Increased urbanisation that causes ridership increase, system extensions, and needs lower headways and greater number of trains both in the case for urban and mainline services;
- Aging asset base of existing rail systems that leads to the increased level of modernisation and replacement of a train fleet, train control systems, power supply systems and systems at the stations;
- Increased automation of transport and rail in particular;
- More demanding customer expectations (e.g., comfort, lower travel time).



**Figure 23: Energy consumption factors matrix**

In green, factors are mentioned that likely increase energy efficiency and favourably affect the perception of rail transport:

- Lower headways maximise (i) braking energy recuperation by increasing the receptivity, (ii) contributes to lower travel time of passengers and (iii) to development of automatic train operation;
- New trains (new assets or fleet renewal) will improve energy efficiency;
- Technologies such as ESS, ATO or automation reduce energy waste and enable more eco-operation;
- New equipment for stations is also focused on optimisation of energy consumption.

In red are factors likely to lead to energy consumption increase:

- Additional trains required by increased ridership lead to absolute energy demand increase of rail transport (but reduced overall demand for energy for mobility – modal shift)
- Comfort features will lead to increased energy consumption.

## 3.2 Technologies for regenerative braking

### 3.2.1 Description

The produced kinetic energy while the train is breaking is transformed into electrical energy. This electrical energy is directly consumed by the train and the remaining energy is sent back to the feeder (3rd rail or catenary in AC systems). If there is a train accelerating in the same power supply section as the braking train, part of the energy needed for the accelerating train is provided by the braking train. Otherwise, the voltage increases and the braking energy of the decelerating train is dissipated in the braking rheostats in the form of heat (Amsler, 2019). The scheme with principles of energy recovery is shown in Figure 24.

#### Principles of Energy Recovery

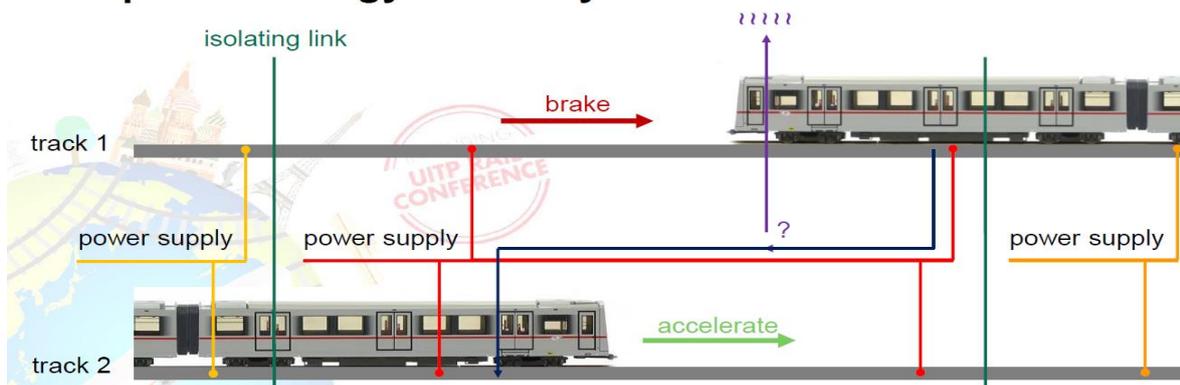


Figure 24: Regenerative Braking in Metros. Source: Steinbauer, 2018

### 3.2.2 Maturity of the technology

The principle of this type of technology is the following:

During braking, the motors of a train act as generators, converting mechanical energy to electrical energy. It can be reused to supply on board auxiliary loads while the exceeded energy is fed back to the third rail. This energy can be directed to a neighbouring train that might be accelerating within the same power supply section as the braking one. However, it requires planning accuracy of the timetables, and even in this case, a certain level of uncertainty exists as the time and location of the accelerating train cannot be guaranteed. So, it will increase the voltage of the third rail, therefore, the braking train dissipates the energy in the braking rheostats (Khodaparastan et al., 2019).

To cover the previous gap and minimize energy waste, several options and technologies integrated with regenerative braking appeared:

### 1. Train timetable optimisation (Technology Readiness Level 6 (TRL 6<sup>5</sup>))

Synchronisation of train operation and timetables so that while a train is braking and feeding regenerative energy back to the third rail another train is simultaneously accelerating and absorbing energy from the third rail or catenary AC systems. However, the timetable optimisation may limit the simultaneous acceleration of too many vehicles which could reduce maximum traction power (OPEUS, 2017).

This can be achieved through:

- Time-tabling optimisation (operation planning stage)
- Eco-driving or implementation of ATO-ATS systems (operation execution stage)

### 2. Energy storage systems (ESS) (TRL 3 to 6)

When it is not possible to consume directly the regenerative energy and to avoid its wasting through the above described operational measures, the recovered braking energy can be stored stationary (electric railway infrastructure) or on-board in the train itself and used later on which will reduce the energy consumption, operating and maintenance costs of railway system, such as supercapacitor, battery and flywheel, and released to the third rail/catenary when demanded. More detailed in Section 5.2.

The critical step is to identify a location on the network where enough energy can be stored and saved in a cost-effective way. ESS systems, which might be used in DC or AC systems, but mostly focused in DC catenary systems, being mobile or stationary are not always justifiable.

### 3. Smart grid 6 (TRL6)

With new communication technologies, smart grid's intelligence level of energy distribution will increase which will optimise the management of new renewable energy sources, loads, storage

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<sup>5</sup> Where a topic description refers to a TRL, the following definitions apply:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

<sup>6</sup> Intelligent distribution and storage of energy within the railway system (comprising rolling stock, infrastructure, real estate etc.) with a potential interface to the public grid and the ability of timely balancing the energy flow

systems and the grid. Also, smart grids technologies will make the recovery of the braking energy of the trains more optimised by integrating local renewable energy production and storage systems to ensure high quality of train supply, increase globally the energy efficiency and reduce the energy cost (Gazaignes, 2017).

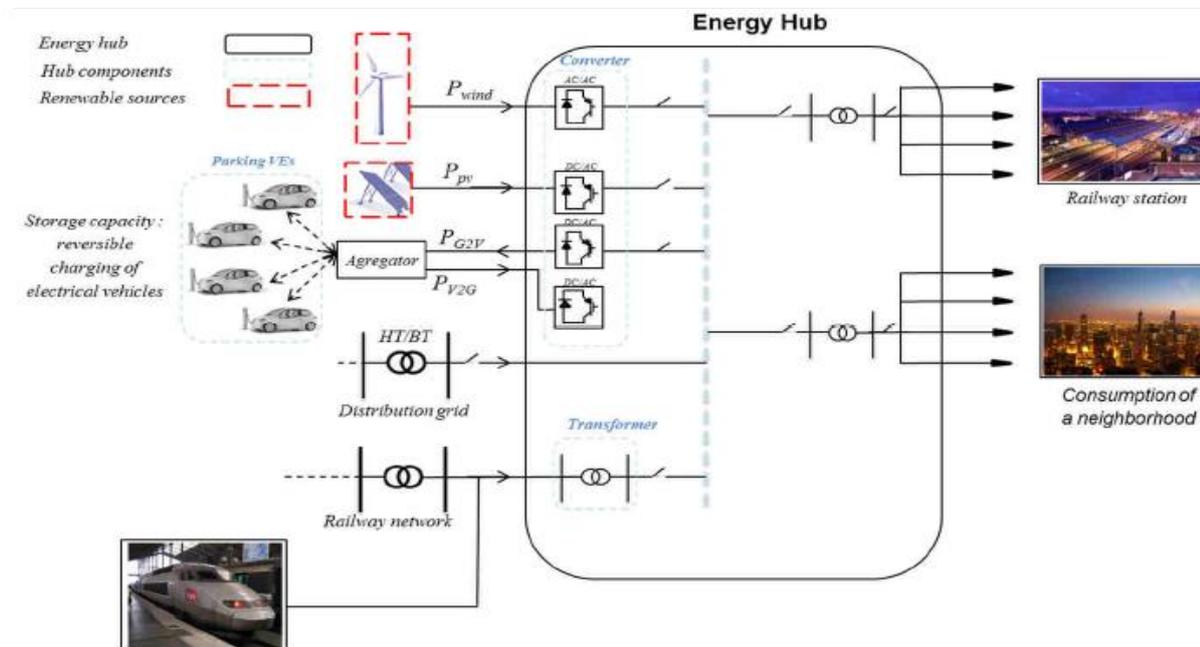


Figure 25: illustration of smart grid working. Source: Gazaignes, 2017

### 3.2.3 Roadmaps of Technology Developments

Table 5: ERRAC<sup>7</sup> Roadmap (from vision to action)

Vision & Need	Type of activity	Technical Maturity	Priority
Re-use of kinetic energy by: <ul style="list-style-type: none"> <li>Improvement of technologies with basic systems.</li> <li>Link to smart grids</li> <li>Prove reliability</li> </ul>	Research	2020	High Priority
Smart Grids and the multiplication of energy sources: Development of techniques based on an economical potential assessment	Research and Development	2030 Continuous research efforts required	High Priority

<sup>7</sup> The European Rail Research Advisory Council ([www.errac.org](http://www.errac.org))  
 GA 730827

### 3.2.4 Pilots

Train2car is a pilot project conducted in Madrid between 2011 and 2014 aims to charge electric vehicles with green energy through regenerative braking of metro trains. This project is funded by (MINECO)<sup>8</sup> and the participants are Metro de Madrid as project coordinator, SICA, ICAI<sup>9</sup> and CIEMAT with other key collaborators like SIEMENS (sub-contracted) and CITROËN.

The main objective in the project is to use the exceeding regenerative braking energy of the metros trains to charge the batteries of the electric vehicles through innovative and smart management of the DC grid and other electrical devices (traction substations, fixed accumulators, batteries...) of these metropolitan transportation systems. That maximizes the utility of the energy regenerated during the braking and the global efficiency of the system and the project results were positive as it successes in all tests (de Santiago Laporte, 2015).

“Hedgehog Applications” won a UIC digital award in 2018 for their concept of using recovered braking energy to feed a smart grid (with an ESS) connected to other renewable energy power plants and a bus fleet that could then run emissions-free. They plan to test this system by a pilot test in Apeldoorn during 2020 (Railtech, 2019).

## 3.3 Energy Storage Systems

As detailed in deliverable D6.1, ESSs can be very helpful in energy management for electric vehicles, especially when DC systems are used for supplying to tracks. It allows recovering energy from electronic braking, especially if its direct usage is not possible. It also helps in reducing total energy consumption, power demand peak reduction (peak shaving), voltage regulation and allowing vehicles to run on non-electrified lines.

### 3.3.1 Description

The growth of rail operation and energy consumption are the reason behind energy recovery projects. Energy recovery projects have significant impact on the environmental and other aspects as they can reduce energy consumption, costs, emissions, noise and tunnel temperature<sup>10</sup>. Also, the positive results in voltage regulation cannot be ignored. The principle of energy storage system is that it absorbs regenerative energy from train braking and reuse it for train’s acceleration instead of being wasted in the form of heat and noise (Steinbauer, 2018).

For both urban and mainline railways, ESSs are good alternatives to routes’ electrification, which is not always worth the cost, for example, in the case of low patronage routes (rural) or short urban lines with reduced space environments available and suitable for the needed infrastructures

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<sup>8</sup> Ministerio de Economía y Competitividad

<sup>9</sup> Instituto Investigación Tecnológica

<sup>10</sup> If the natural exchange of regenerated energy between vehicles didn’t happen as there is no accelerating train simultaneously with a braking train, voltage increases and the braking energy of the decelerating train is dissipated in the braking rheostats in the form of heat which will rise tunnel temperature.

(cities). For example, infrastructure managers can find a good balance between ESSs capacity and electricity supply points so that partially electrified lines can accompany the charge of the onboard ESS along the line or at stations (Nice's Tram). Onboard solutions can also help in reducing diesel consumption when it is not possible to implement electric supply. Onboard systems allow diesel engines to idle during braking and acceleration phases, therefore lowering consumption and noise level around the stations.

The main goal of such projects has been improving energy recovery system to a point where energy lost is almost zero. The aim is now also to enhance power management, allowing peak energy demand shaving, and storing overproduced energy from dedicated renewable energy plants. As railways committed to decarbonising their electricity supply, the share of renewable energy directly feeding the railway grid is constantly increasing. Coupled with ESSs, these renewable energy plants can act as buffers for both the railway grid and plants overflows.

The most commonly used technologies for onboard and offboard energy storage are now:

- Flywheels (Mechanical energy storage);
- Batteries (Chemical)
- Supercapacitors / double-layer capacitors. (Chemical, Electromagnetic)

Fuel cells (chemical) are appearing now on a limited scale, but they'll probably get a bigger share in the near future.

### 3.3.2 Maturity of the technology

The energy savings are growing rapidly focusing on renewable energy technologies to face the growing demand for energy and environmental challenges. Energy storage systems will be the key of transforming power and transportation systems to renewable energy sources in the future. Energy storage systems that are used to store various forms of energy will play a major role in the future for residential, commercial and industrial sectors, and will lead to a transformation of both the power and the transportation sectors (Swain & Shyamaprasad, 2019).

Energy storage systems can be broadly categorised to mechanical, electromagnetic, chemical and thermal storage systems (Figure 26: Pictorial view of the energy storage systems and generation. Source: Swain & Shyamaprasad, 2019

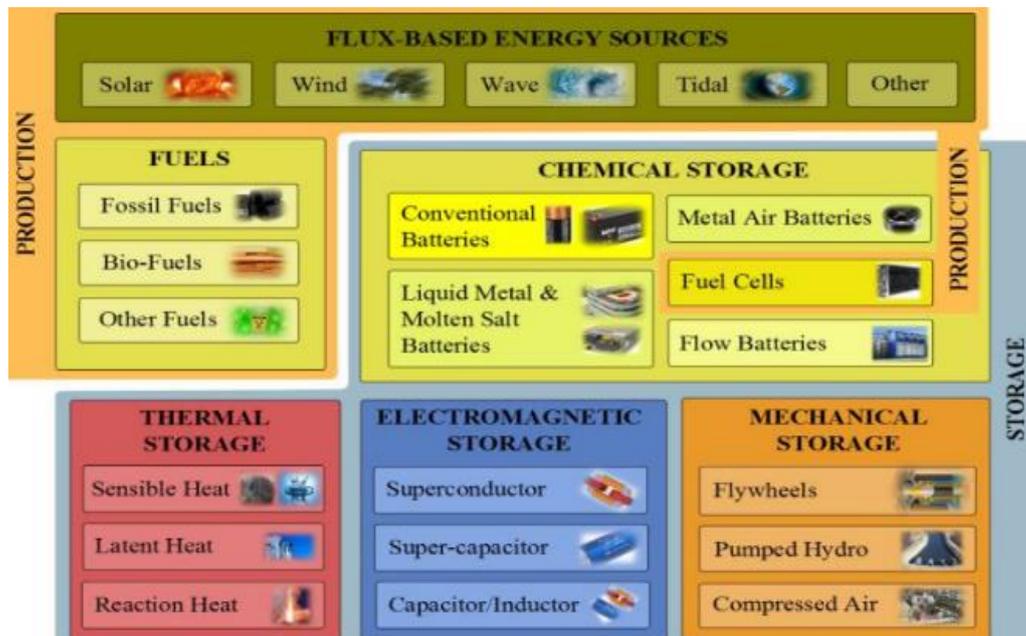


Figure 26: Pictorial view of the energy storage systems and generation. Source: Swain & Shyamaprasad, 2019

Hydraulic Energy Storage based systems (such as the ones created under the PowerTrain RSSB projects for the UK or the ARETEMIS initiative) are useful also when used in infrastructure sections without catenary.

### 3.3.3 Mechanical energy storage system

Amongst all the storage technologies, mechanical energy storage has the highest share. There are different kinds of mechanical storages, such as pumped hydro storage (PHS), flywheels (FES) and compressed air energy storage (CAES). On the one hand, these systems that widely used have a huge potential to grow, pertaining to its various beneficial factors, such as technical maturity, regulation of power and frequency, relatively lower environmental impact and high energy/power densities (Deane et al., 2010). On the other hand, high capital costs, safety issues and development of modern technologies can be obstacles facing the growth of mechanical energy market (Swain & Shyamaprasad, 2019).

Table 6: Comparison between different mechanical energy storage technology. Source: Swain & Shyamaprasad, 2019

Parametric	PHS	CAES	FES
Scale/ Application	Large/ Energy management	Large/ Energy management	Medium/ Power quality
Technical maturity	Mature/ Fully commercialised	Proven/ Commercialising	Mature/ Commercialising

Environmental Impact	High/medium	Medium/low	Low
Specific Energy (Wh/kg)	0.3-1.5	3.2-60.0	5.0-200.0
Energy Density (kWh/m <sup>3</sup> )	0.5-1.5	0.4-20.0	0.25-424.00
Specific Power (W/kg)	0.01-0.12	2.20-24.0	400-30,000
Power Density (kW/m <sup>3</sup> )	0.01-0.12	0.04-10	400-2000
Efficiency (%)	65-87	57-89	70-96
Cycle Life (cycles)	10k-60k	8k-30k	10k-100k
Energy Cost (USD/kWh)	1-291.20	1-140	200-150k
Power Cost (USD/kW)	300-5288	400-2250	30.28-700

Flywheels can pretend to a good lifespan and higher efficiency than electrochemical storage solutions. However, it is more expensive, produces a high level of noise (120 dB(A)) and discharges fast (Infrabel, Eaton, UIC Workshop 2019).

### 3.3.4 Chemical energy storage system

Chemical storage systems are highly varied in terms of energy storage products that are commercialised presently includes:

- Traditional batteries;
- Molten salt/liquid metal batteries<sup>11</sup>;
- Metal air batteries<sup>12</sup>;
- Fuel cells<sup>13</sup> and flow batteries<sup>14</sup>.

There are different kind of batteries in the market with various maturity level. For example, lead-acid batteries reached to the highest level of development and no significant improvement in

<sup>11</sup> Molten salt (Sodium Sulphur-NaS and Sodium Nickel Chloride-NaNiCl) and liquid metal are the typical class of high temperature chemical batteries which use molten salts and liquid metals which acts as electrolyte as well as the electrodes

<sup>12</sup> Metal air batteries (Zinc Air and Iron Air) are the cross-over of fuel cells and traditional chemical batteries, having one anode electrode and other as oxygen electrode (catalyzes the production of hydroxyl ions)

<sup>13</sup> Flow batteries are very much similar in operation to fuel cell systems. To generate electricity, the electrolytes containing dissolved active material flow through the fuel cell

<sup>14</sup> Fuel cells (FC) are generally used now as energy generation devices rather energy storage devices, which takes hydrogen and oxygen as input and produces electricity and water as output. The fuel is oxidized at anode and reduced at the cathode

terms of capacity can be done but it is a big part of today’s technology system due to the cost-effectiveness of lead-acid batteries.

The second example is the lithium-ion batteries. Those batteries are suitable for storing large amounts of energy and having high energy density (80-300Wh/kg). Lithium-ion batteries have the huge potential and can become the future of energy storage systems and very promising for the near future in transportation applications due to the climate change and the clean environment policies, the EU countries have the agreements to cut their CO2 emissions by 80% in 2050 and to less dependent from oil (More details about lithium-ion batteries in OPEUS DEL 6.1 SECTION 2.2.2.4.). Commercial use is targeted somewhere between 2020 and 2030 as there are still a lot of obstacles to overcome (More details about batteries in OPEUS DEL 6.1 SECTION 2.2.2). Moreover, in Table 7 more comparison between different chemical storage systems in terms of maturity level and other patterns (Oberhofer, 2012).

**Table 7: Comparison of different chemical energy storage technologies based upon listed parameters. Source: Swain & Shyamaprasad, 2019**

Parameters	Nickel Metal Hydride (Ni-MH)	Nickel Cadmium (Ni-Cd)	Nickel-Iron (Ni-Fe)	Nickel Zinc (Ni-Zn)
Scale/ Application	Small /Energy management	Small, medium /Energy management	Small, medium /Energy management	Small /Energy management
Technology maturity	Mature/Fully commercialized	Mature/Fully commercialized	Mature/Limited development	Mature/Limited development
Environmental Impact	High	High	Low	Low

Regarding new applications, Container-sized ESSs were introduced to be a flexible replacement solution for a temporary reversible substation (Super-B, UIC Workshop 2019).

SBB launched in mid-2014 a pilot project to replace its heavy onboard lead-acid batteries. After a few years (mid-2018), it resulted in a lithium-ion phosphate battery (LiFePO<sub>4</sub>) prototype. As described in deliverable D6.1, it is safer than the other Li-ion technologies. The counterpart is lower power density and a shorter life. However, the load is now 110 kg instead of 334 kg and is expected to last at least 12 years thanks to a battery management system. Due to the very punctual usage needs (during shunting or maximum 3h emergency operation), the battery is well suited for the job that requires resistance to vibrations and low temperatures. (IRJ, 2018)

Moreover, according to the latest SBB presentation in the 2019 UIC workshop, the company is testing a hybrid construction train equipped with a Sodium-Nickel battery which is 100% recyclable, not subject to fire and explosion risks and insensitive to low (as low as -25°C) and high (up to +60°C) temperatures. Its stability would allow a 20 years lifetime.

### 3.3.5 Electromagnetic Storage

This category consists of inductors (magnetic field) and conductors (electric field) with advancement in the technologies, this has been extended to superconductors and supercapacitors (Electric double-layer capacitors (EDLC)) (Swain & Shyamaprasad, 2019).

EDLC is also known as electrochemical double-layer capacitors which were originally named “supercapacitors” by Nippon Electric Company, or “ultra-capacitors” by Pinnacle Research Institute. EDLC represent two main physics: energy storage in an electrochemical double-layer and the ions transfer as the results of electrochemical redox reactions (OPEUS, 2017).

Energy storage system exists in many levels of maturity from the early level of research and development to mature deployed technology<sup>15</sup>. In Figure 27: Maturity of energy storage technologies, the graph is showing energy storage technologies with respect to their associated initial capital investment requirements and technology risk versus their current phase of development (i.e. R&D, demonstration and deployment, or commercialisation phases).

Hybrid supercapacitors/Li-ion ESS is a new possibility to improve braking energy recovery efficiency (Eaton, UIC Workshop 2019). The ability of supercapacitors to manage high power inputs can be used as a buffer to optimise the charging/discharging efficiency of the Li-ion part. Enhancing both energy transmission efficiency, energy savings and ESSs’ lifespan.

SNCF’s experience proves supercapacitors to be compact (more compact substations), and maintenance free.

Applications of supercapacitors should also be very useful to suburban and metro lines as the time length between the braking phase and the acceleration phase is lower, thus more adapted to supercapacitors high power and fast charge/discharge capacities.

### 3.3.6 Thermal storage

Thermal storage systems (TES) are used in mainly thermal power plants (industry scale). However, it’s not widely used in the rail sector.

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<sup>15</sup> This development spectrum is roughly equivalent to the concepts of “Technology Readiness Levels” (TRLs).

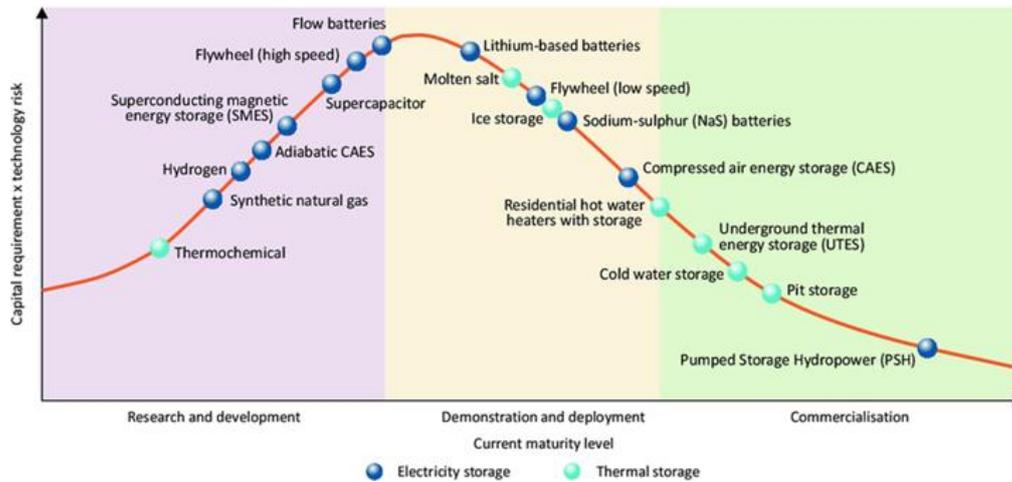


Figure 27: Maturity of energy storage technologies. Source: “Technology Roadmap Energy storage”, 2014

### 3.3.7 Roadmaps of Technology Developments

Table 8: Roadmap of technology development for EES

Vision & Need	Type of activity	Technical Maturity	Priority
Hybrid Traction 1. Multiple power sources for traction in due consideration of reliability, availability, maintenance, safety aspects for diesel applications. 2. Development of prototypes. 3. Energy Storage on-board. 4. Technologies to be carried out. 5. Engine stop at station.	Concluding research activities required followed by development.	2020 - 2030	High Priority
Next generation of power semi-conductor 1. Improvement of efficiency, weight, volume among others. 2. Standardisation (Common expressed request by the railway sector to the semiconductor industry)	Research	2020 - 2030	Medium Priority

Infrastructure Sections without catenary Railway lines without catenary operated with particular adapted rolling stock (traction energy supply by pantograph and energy storage on board)	Research	2050	Medium Priority
Energy Storage in the infrastructure	Development	2020	Low Priority

Source: ERRAC<sup>16</sup>

### 3.3.8 Pilots

In 2007, supercapacitor energy storage devices were installed in 4 substations in Beijing subway, line 5 where they were used to absorb regenerative energy in order to prevent regeneration failure and mitigate fluctuations of power supply voltage (Yang et al., 2014).

A pilot project in India launched by TERI<sup>17</sup> to support the implementation of Battery Energy Storage Systems (BESSs) at energy distribution level in Kolkata. The project aimed to integrate BESSs at distribution level. The Indian power sector targeted to achieve 175 GW of renewables by 2022 and 275 GW by 2027. Increasing penetration of renewable energy, as well as deployment of low-emission vehicles, by 2030 is critical for adoption of low-carbon pathways in the country. However, these initiatives can provide synergistic opportunities for applications of BESS to be an enabler of a secure electricity grid by managing variability of Renewable Energy (RE) generation (TERI, 2018).

In Tokyo metro a pilot project was conducted in 2013 to study the possibility of running the metro with an onboard battery in emergency situation like earth quake. Generally, when a train stops between stations during power failure caused by earth quakes, etc. It is operated up to the nearest station to bring passengers to the nearest station. However, when the train is not able to operate, station personnel come to rescue and assist in evacuating passengers to safety by walking through the tunnels to the nearest station (UITP, 2018).

## 3.4 Alternative Fuels

Railways now aim at ending the use of fossil fuels. As shown before, diesel traction is still representing close to a third of the energy consumed by operators (UIC ESRS, 2018). A few solutions are now empowered by this transition.

<sup>16</sup> The European Rail Research Advisory Council ([www.errac.org](http://www.errac.org))

<sup>17</sup> The Energy and Resources Institute (TERI) is a leading think tank dedicated to conducting research for sustainable development of India and the Global South. Established in 1974, TERI has become the pre-eminent institution for research, discussion and thought leadership on environmental governance and sustainable development.

### 3.4.1 Hydrogen

Hydrogen is interesting for railways, as it allows net zero emissions operation if produced by renewable energy and offers another solution than the full electrification of a line. Its power density allows relatively high transport autonomy (around 800km with one filling, UIC Workshop, 2019)

However, investment in this technology are only made by early adopters (Alstom's Coradia iLint now operates after finishing test running in Germany)

Investing in a Hydrogen powered system for a new line is more likely, because it would otherwise mean entirely switching the fuelling system. The hydrogen supply chain is not developed yet. And finally, the efficiency of water electrolysis seems to stall, meaning that is it more efficient to simply feed RE into the grid and ESSs.

### 3.4.2 Natural Gas (LNG)

RZD shows reduced air pollutant emissions thanks to natural gas locomotives trials.

Biofuels from residues and waste (UIC Workshop 2017). Also, RENFE has used LNG as supply systems in prototypes for their metric gauge lines in the north of Spain (2018).

### 3.4.3 Hybrid Systems

Hybrid systems are now a reliable solution to access braking energy recovery without infrastructure. A significant amount of research and development has gone into this approach in recent times. For instance, the combination of double-layer capacitors and Lithium-ion batteries have the highest potential to be successfully integrated into vehicle system architectures. Combining these two energy storage technologies into a single hybridisation package is a highly promising design that draws on their strengths without any significant drawbacks (Meinert M et al, 2015).

## 3.5 Other Solutions

Technologies not directly linked to the traction system can also be introduced as energy efficiency optimisation drivers.

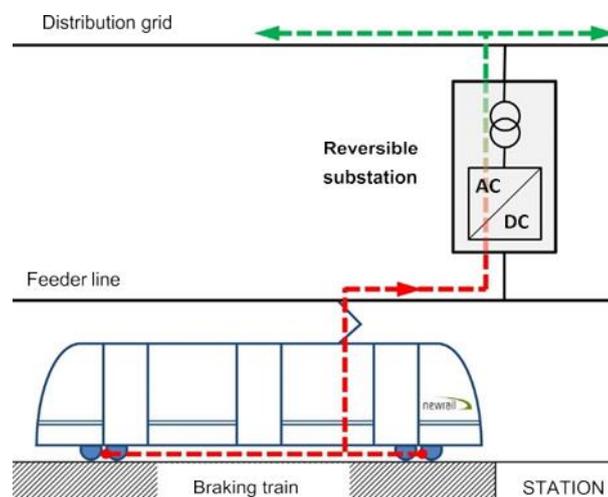
### 3.5.1 Dual inverter, Reversible Substations & off board ESS

Reversible substations have an embedded power inverter, allowing it to deliver energy into the railway grid and supply energy back into the electricity grid or into a coupled ESS. It is a great opportunity for the electricity grid responsible to consider railways as an energy producer so that the output from railways are correctly managed and not wasted. SNCF Research has dedicated a

study about the good integration of such substations into a smart electricity grid (Guillaume Escamez, UIC Workshop 2019).

Substations are typically able to provide electrical current to train only and are not able to drive generated electricity back to the upstream network (DC networks) because conventional substations use diode rectifiers that only permit unidirectional flow of power, while reversible substations can drive electricity in both ways due to an inverter enabling a bidirectional operation, see Figure 28. It allows using regenerated braking energy in the operator’s network (lighting, escalators, offices, etc.) or to sell it back to the energy provider. Reversible substations can provide electric current in two ways (Khodaparastan et al., 2019):

- By using a DC/AC converter in combination with a diode rectifier; and
- By using a reversible thyristor-controlled rectifier (RTCR).



**Figure 28: Schematic of reversible substations in urban rail. Source: González-Gil, Palacin, & Batty, 2013a**

The primary objective of reversible substations is to maximise the braking energy feedback to the upstream network. However, the priority should be given to the natural exchange of regenerated energy between vehicles. Moreover, minimising the level of harmonic is required by substations to ensure a good quality of power supply in both AC and DC sides (González-Gil et al., 2013).

When reversible substations compared with ESSs significant advantages of reversible substations over ESSs can be found as they call for reduced space, they have lower safety constraints and no exhaustive maintenance is required. Besides, the implementation, maintenance and repair do not affect operations in the rail system. On the contrary, inverting substations do not permit catenary-free operation of vehicles and cannot be used for voltage stabilization or peak reduction purposes.

On the other hand, one of the obstacles that the implementation of reversible substations in both urban and mainline rail systems is facing may be the high investment costs associated with their installation. As a way to reduce the payback period, the energy sent back to the grid could be maximised by minimising the interchange of regenerated energy between trains. However, this

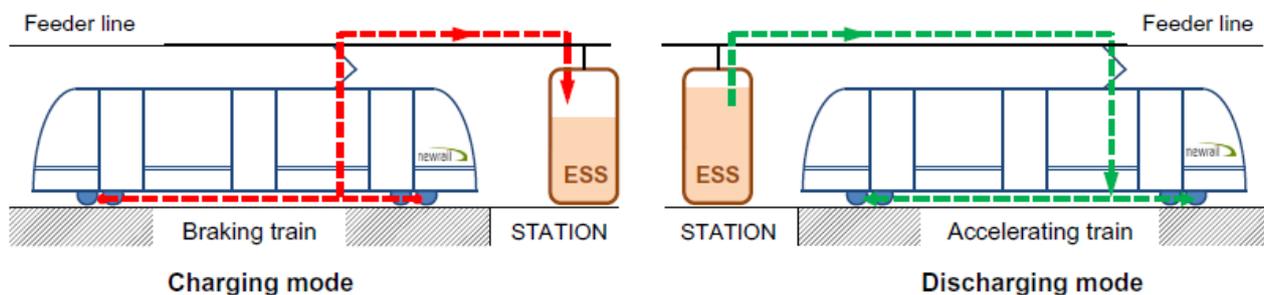
would require an in-depth economic study considering not only the energy prices set by public network operators but also the increase of power consumption due to less energy exchange between vehicles.

Different technologies, such as thyristor inverters in substations of DC systems recovering energy during braking processes were either simulated (D. Buscema et al., 2010) or tested (UIC, 2003) in the past.

UIC project REVSUB has progressed on the question on this question helping also the INVERFER project (Adif, 2011) through the development of a complete demonstrator comprising a functional reversible substation for 3000 V DC current, near Malaga in La Comba for a commuter’s active railway line (Malaga to Fuengirola) with successful results .

### Off board ESS (Wayside energy storage systems)

The wayside ESSs capture the regenerated braking energy that cannot be exchanged naturally between vehicles. The storage system can deliver energy to vehicles when acceleration is required and this will need a controller to manage the charge and discharge processes which works as a function of the voltage on the line<sup>18</sup>. Wayside ESSs are usually installed in existing substations or in specific places where the contact line voltage variations are more significant, for instance near to stations. Besides reducing energy consumption wayside ESSs can also stabilise the network voltage at weak points of the network, which is a major advantage over reversible substations. Also, wayside systems have fewer restrictions in terms of weight and required space in comparison with on-board devices. Moreover, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. However, transmission losses in the network make wayside systems less efficient (González-Gil et al., 2013b).



**Figure 29: Schematic of wayside ESSs operation in urban rail. Source: González-Gil et al., 2013b**

<sup>18</sup> When an overvoltage occurs due to braking process, ESSs absorb the excess of regenerated energy on the line (Charging mode, while when a voltage drop is detected, ESSs deliver the stored energy in order to keep the threshold value on the network).

## Maturity of the technology

Inverter-enhanced substations (reversible substation) are a mature technology that is already in use in some local DC systems, e.g. an inverter unit is run by Kölner Verkehrs-Betriebe AG (KVB), Cologne, Germany, in one of its substations.

From the UIC REVSUB and INVERFER demo projects, twelve other sites to build DC reversible substations have begun construction in Spain, that will approximately save 19 GWh per year, and also a total yearly emissions reduction of about 4.400 CO<sub>2</sub> tonnes.

On the other hand, also commercial solutions explore these possibilities for substations using regenerative braking, such as the HESOP system, created by Alstom.

## Roadmaps of Technology Developments

**Table 9: ERRAC Roadmap (from vision to action). Source: ERRAC<sup>19</sup>**

Vision & Need	Type of activity	Technical Maturity	Priority
Smart Grids and the multiplication of energy sources: Development of techniques based on an economical potential assessment	Research and Development	2030 Continuous research efforts required	High Priority
Energy Storage in the infrastructure	Development	2020	Low priority

## Pilots

The South-Eastern Pennsylvania Transportation Authority (SEPTA<sup>20</sup>) led a pilot project that proposed for the first time a combination of energy storage and energy return to the main grid. This project represents an integration between wayside ESS and smart grid technology. The main objective of this project is to reduce the overall consumption by more than 10% (1200 MWh per year) (González-Gil et al., 2013).

A UIC project on methods of energy storage for railway systems will begin next year 2020, and it will cover:

- The development of a decision software tool:
  - o with inputs on information about braking energy in each type of station depending on type of trains, train kinematic parameters, layout of the station and number of daily Trains

<sup>19</sup> The European Rail Research Advisory Council ([www.errac.org](http://www.errac.org))

<sup>20</sup> <http://www.septa.org/>

- o and outputs on a first feasibility plan to analyse the possibilities of each type of station (energy saving estimations, how can we storage the energy, what is the best technology, how much does it cost, how much space I need) and suggestions for implementation of these systems

The development of a new UIC International Railway Solution (IRS) on the implementation of the ESSs in stations will be made from this project.

### 3.5.2 Medium Voltage Direct Current Electrification System

SNCF tested 9 kV train supply to optimise the renewal of electrified lines. It resulted in many interesting benefits:

- The light overhead line prevents inductive voltage drops
- The reduced cross-section of the line results in a lower copper usage
- Improved efficiency/reduced transmission losses from 11% (1 500 V) to 5 % (9 000 V)
- Reduced amount of substation needed
- Power sharing and balancing between substations
- Allowing three-phase power supply from public grid
- Lighter and simpler locomotive on-board power converter
- Silicon Carbide power semi-conductors enable the realisation of compact Medium Voltage (MV) traction converters

This system can also be a solution for countries not yet electrified. It allows easier integration of the MVDC smart grid concept (Hervé Caron, UIC Workshop 2019)

### 3.5.3 Superconducting cables

Superconductors are material that, when brought down under a critical temperature, can transport electricity without any resistance thus avoiding transmission losses/increasing transmission efficiency. The cables are cooled down thanks to liquid nitrogen.

The reduced size of these cables can reduce installation expenses. (Guillaume Escamez, UIC workshop 2016)

### 3.5.4 Auxiliary Energy Efficiency

The technical auxiliary systems in the vehicles are essential for the regular productiveness of the cars (fan engines, compressors, etc.). Moreover, the commercial auxiliary systems are critical to the comfort of the travellers or the conservation of the load (heating systems, cooling systems, lighting, etc.). Before these services used to be reduced, but the demand in the comfort requirements on board trains has made this consumption relevant (UIC, 2016).

As detailed in WP 2 section 2.5.11 there exists energy consumption not related to the actual movement of the train. This includes pumps, fans and HVAC systems as well as control units,

lighting and passenger electricity consumption (if jacks exist on board the train). These typically have a constant consumption throughout the day along with a cooling power which depends on the current traction power.

## HVAC

Better insulation, e.g., between the body-shell and internal panels reduce noise as well as heat loss during the winter and heat gain in summer. This is commonly implemented. However, improvements can only be done through new train purchase or major refurbishment. Greatest benefits are in insulating vehicles in the coldest areas of Europe, however the benefits of insulating against heat gain should not be forgotten. Vehicle livery, and colour of surface coatings have a significant effect on heat transferred by the sun: painting the roof in white in hotter countries will reduce internal temperatures while in full sun.

Window films can reduce both heat loss and thermal gain by fitting a transparent film to windows. Provide significant savings and likely to have short payback times.

There are various renewable energy sources that may be used to fulfil part of the energy needs of HVAC for a railway system, like:

- Photovoltaic panels and wind generators can be used to provide the railway with the energy facilities such as stations and depots. Moreover, lighting and HVAC systems can be equipped with renewable energy systems to power auxiliary needs. The goal of both means is to power contraction loads with clean energy and as a result of this decrease CO<sub>2</sub> emissions.
- HVAC systems have tremendous energy consuming and have the most critical influence on the overall train power consumption of all non-traction loads (UIC, 2016). There is ongoing research being carried out by manufacturers to increase the efficiency of their products. The following measures are proposed to reduce the energy consumed by HVAC systems:
  - New refrigerants: most HVAC systems are full with a refrigerant liquid that goes through the heat cycle and helps to transfer heat from hot to cold sections.
  - Smart HVAC management: CO<sub>2</sub> control tends to help to decrease energy costs by cutting off-peak heating and cooling loads. By setting CO<sub>2</sub> 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 and regulates temperature accurately ergo to passenger requirements, therefore reducing power consumption.

## Low-energy lighting

High power white LED technology has led to a wide range of improvements in energy consumption but also appearance and maintenance costs. Gives potential to vary lighting levels and use 'half' lighting options during the daytime.

Using new technologies that replace traditional lighting systems such as LED lamps and smart chart designs and devices, can lead to the reduction of the energy consumption by 40% and increase the life cycle of the total system, decreasing the associated CO<sub>2</sub> emissions simultaneously. The goal of establishing LED technology on board trains is to achieve advantages related to conventional lighting systems that are mentioned below:

- Lower power consumption;
- Elimination of flickering;
- No emission of ultraviolet rays;
- Reduction in life cycle costs.

### High-Speed

It is worth noting that auxiliaries' dedicated energy consumption is proportional to the time spent for the journey, therefore, High-speed trains will require less energy than a conventional train for a similar energy consumption pattern in comfort and other auxiliaries.

However, traction energy is substantially used against aerodynamic drags and according to OPEUS D5.2 simulations, coasting and partial switch-off of motors strategies have limited impact for energy savings.

### Roadmaps of Technology Developments

**Table 10: ERRAC Roadmap (from vision to action). Source: ERRAC<sup>21</sup>**

Vision & Need	Type of activity	Technical Maturity	Priority
<b>Energy-efficient Auxiliaries</b> Optimisation and development of intelligent management of auxiliaries (e.g. powering auxiliaries with kinetic energy)	Research	2020	Medium Priority

### Pilots

**Table 11: Real applications. Demonstrator**

Author	Explanation	Benefits
Berlin City Transport Operator (BVG) Liebherr-Transportation Systems	Liebherr will equip one of Berlin trams with an experimental occupancy dependant fresh air control based on CO <sub>2</sub> sensors that estimate the number of passengers and regulate the intake of fresh air.	This new system is expected to reduce HVAC energy consumption by 13%.

<sup>21</sup> The European Rail Research Advisory Council ([www.errac.org](http://www.errac.org))

Osaka Municipal Subway Midosuji Line (Tokyo) (Ishii, I. et al., 2012)	About 30,000 railway vehicles are scheduled to go into operation in the fall of 2016 with Kawasaki’s newly developed LED lighting and air purification system.	The new LED lighting system achieves outstanding energy efficiency and passenger comfort. It will be the first to adopt a cherry blossom-light on a railway vehicle. The pale-pink light has the effect of reducing stress caused by being exposed to artificial light, as well as providing a sense of healing and being easy on the eyes.
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### 3.6 From Driver Advisory Systems to unattended train operation (UTO)

The reduction of energy consumption is one of the main priorities for metro line and commuter rail systems operators nowadays due to the environmental impact and economic cost. Traffic operation strategies can be one of the ways to reduce energy consumption. In automated railways systems (mostly now, metros), those operations are controlled by the ATO system instead of being controlled by auxiliaries. According to UITP, there are various grades of automation based on which essential functions of train operation are the responsibility of staff, and which the responsibility of the system itself are as shown in Table 12.

**Table 12: Grade of automation. Source: UITP, 2012**

Grade of automation	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of disruption
GoA0	Driver	Driver	Driver	Driver	Driver
GoA1	ATP with driver	Driver	Driver	Driver	Driver
GoA2	ATP & ATO with driver	Automatic	Automatic	Driver	Driver
GoA3	Driverless	Automatic	Automatic	Train Attendant	Train Attendant
GoA4	UTO	Automatic	Automatic	Automatic	Automatic

Energy-efficient optimal driving strategies can reduce operating costs by reducing energy consumption. This is achieved both through the driving strategy and timetable. These strategies reduce maintenance costs due to a smoother driving technique, reducing friction between steel wheels and rails. The algorithms and models used to compute energy-efficient train control could be used in real-time Driving Advisory Systems (DAS) or Automatic Train Operation (ATO) systems. These have been further detailed in Deliverable 4.1.

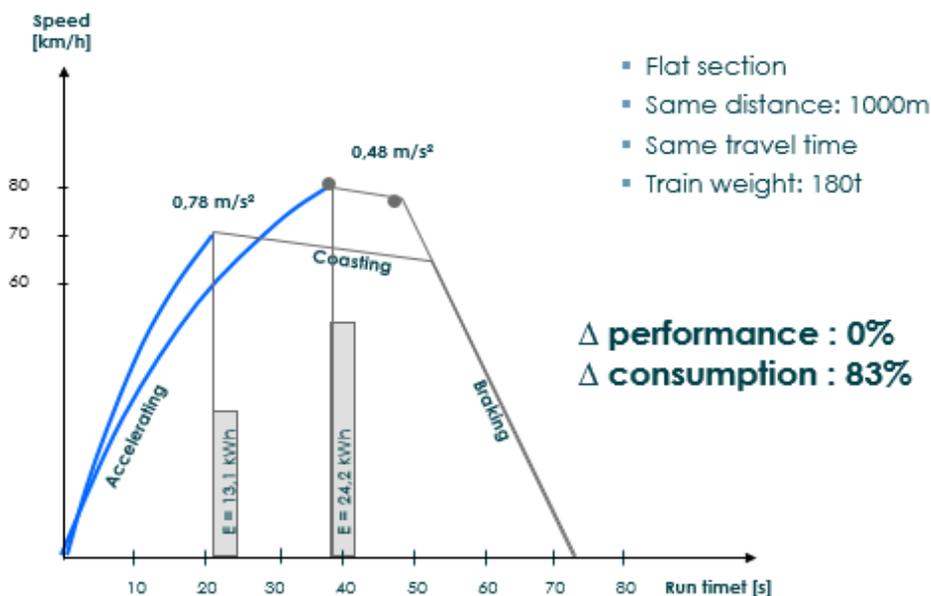
Due to the technical development train control systems have the ability to supervise, operating and controlling the entire operational process. The critical elements for this are:

- Automatic Train Protection (ATP) is the system and all equipment responsible for basic safety; it avoids collisions, red signal overrunning and exceeding speed limits by applying brakes automatically. A line equipped with ATP corresponds (at least) to a GoA1.
- Automatic Train Operation (ATO) ensures partial or complete automatic train piloting and driverless functionalities. The ATO system performs all the functions of the driver, except for door closing. The driver only needs to close the doors, and if the way is clear, the train will automatically proceed to the next station. This corresponds to a GoA2. Many newer systems are entirely computer-controlled; most systems still elect to maintain a driver, or a train attendant of some kind, to mitigate risks associated with failures or emergencies. This corresponds to a GoA3.
- Automatic Train Control (ATC) performs automatically normal signaller operations such as route setting and train regulation. The ATO and the ATC systems work together to maintain a train within a defined tolerance of its timetable. The combined operation will marginally adjust operating parameters such as the ratio of power to coast when moving and station dwell time, to bring the train back to the timetable slot defined for it. There is no driver, and no staff assigned to accompany the train, corresponding to a GoA4 or Unattended Train Operation (UTO), where starting and stopping, operation of doors and handling of emergencies are fully automated without any need for on-board staff.

Automated lines come ahead of conventional lines when it comes to operational costs. Staff costs are significantly reduced thanks to the abolition of the drivers' function, even in cases of line conversion, when staff is likely to be retrained and deployed to other features or speed profile. Acceleration and deceleration patterns can be adjusted to reduce energy consumption and maximise energy recovery, thus, significantly reducing energy costs. The beauty of ATO is that the train will always and continuously run the pre-defined optimal speed profile and run the most energy-efficiently while train in GOA1 or GOA0 where the driver is in charge, will never be able to stick so firmly and so steadily to the optimum profile. Some studies indicate a halving in operational costs depending on the used function. The graph in Figure 30 is comparing between two eco-driving modes under the same circumstances, the following points were observed:

- The coasting period of the train with higher acceleration was longer
- The energy consumption of the train higher acceleration was almost half of the other train.

## Eco-driving mode and braking energy recovery Optimised running diagram and energy consumption



**Figure 30: Eco-driving mode. Source: UITP, 2012**

There are two variants of DAS, Standalone DAS (S-DAS) and Connected DAS (C-DAS) which have been defined in (RSSB, 2012) and (Network Rail, 2015). S-DAS Systems have all data downloaded to the train before the journey begins and provides drivers with a train speed determined by the trains progress compared with predefined geography and schedule data, allowing for optimisation of energy usage but also improved safety, reduced wear and tear and improved delay attribution data. They were originally developed for long-distance freight services in USA and Australia and have recently started being adapted to passenger services (Network Rail, 2015).

C-DAS systems provide a train speed determined by the real-time, dynamic update of schedule information through a telecommunications link to a control centre monitoring many trains in an area of a network. It can optimise energy, capacity or network performance and have developed out of S-DASs linked to traffic management systems. By receiving schedule updates and providing train position to traffic regulation centres C-DAS provides improved recovery from disruption and regulation to a revised schedule along with improved conflict resolution. In the future, both variants may be able to optimise power consumption based on the local power supply or price.

## Roadmaps of Technology Developments

One of the Technical Demonstrators in Innovation Programme 2 of Shift2Rail<sup>22</sup> is to develop and validate a standard ATO up to GoA3/4 over ETCS, where applicable, for all railway market segments (mainline/high speed, urban/suburban, regional and freight lines).

### Pilots

An agreement was signed by German Rail (DB), Siemens and the city of Hamburg to develop a fully automated S-Bahn line in Hamburg by 2021. The agreement calls for the conversion of the 23km eastern section of Line S21 between Berliner Tor and Aumühle for fully automatic operation, and to equip four trains with the required technology to operate on it. Trains will operate on the future European Automatic Train Operation (ATO) standard in combination with the European Train Control System (ETCS) Level 2. While drivers will continue to be on board for operation outside the automated area, they will only intervene when required along the automated section of track (Burroughs, 2018).

## 3.7 Smart Management of Rail Network

The smart management of a rail network needs a greater and wider availability of communications solutions to support the data flows (Merlin D7.5, 2015). At first, this can result in higher energy needs for devices and data centres.

Railway grid equipped with reversible substations and linked to the electricity network can now play an important role in buffering energy demand peaks or production overloads from renewable energy when coupled to the energy market:

- Railways can deliver exceeding electricity produced by braking trains to the electricity grid through reversible substations. Although it can be stored, thanks to possibly installed trackside/in station ESSs, it is more efficient to immediately use it by feeding other trains or any consumer around.
- Railways can consume or store (Offboard ESSs) exceeding renewable energy production. In a larger perspective, every single BEV or stationery ESS will be able to act as a buffer to reduce energy lost in transmission or wasted because not used.
- Railway grid can be the link between renewable energy plants and the electricity grid (Alliander, UIC Workshop 2019).
- Railways can supply the electricity grid: Railways IMs are now working on having dedicated renewable energy plants to feed the trains or stations. When exceeding energy is produced, it can be fed to the general network for direct usage.

According to UIC, 2016, implementing the Railway Energy Management System (REM-S) can result in cutting expenses related to energy by 11,48%.

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<sup>22</sup> <https://shift2rail.org/research-development/ip2/>

## 4. Success factors for implementing new technologies, products and innovative concepts and strategies into a present value chain

### Main drivers:

High sustainability of rail systems compared to other transport modes and the strong political commitment of the European Union, of the Member States and of most cities in Europe (and worldwide) towards a better management of energy to face the climate and environmental challenges of the next decades and to improve the quality of life of their citizens (Amsler, 2019).

### Barriers:

The main barriers are:

- Cost of rail systems;
- Need for financial support from public authorities for the creation or extension or upgrade of rail systems;
- Incomplete harmonised validation and certification processes for placing products on the market, especially for urban rail applications;
- In the case of short distances (urban, mainline commuter and regional) rail market, its complexity involving a very large number of decision-makers for the development or improvement of rail networks which are always depending on local conditions for optimising the decisions made.

Europe has a very dynamic rail sector and has all the required technologies, applications and expertise (Amsler, 2019). However, manufacturers need to collaborate with infrastructure managers and railway operators/undertakings on the following goals:

- The exchange of experience on demonstrations and experimentations in real applications, certification processes, offering opportunities for benchmarking to operators and public authorities;
- The harmonization of specifications and certification of products/ tools/ methods/ processes largely shared among the various networks.

Identifying the responsibility of each actor to be involved in each implementation process is a challenge for the railway market.

The question of the good timing for adoption is also relevant: as railway assets life cycle is relatively long compared to light transport modes, should railways be early adopters of the new technologies? Or should they be the leader of innovators in this field?



## 5. Conclusions

It has been highlighted that many triggers can be used at the same time to improve energy efficiency. The goal is to activate them both considering feasibility and costs.

The increasing demand for passenger services either for urban transports and railways oppose a great challenge to find energy-efficient solutions with decreasing resulting benefits.

Hydrogen coupled to renewable energy breakthrough would be a good step towards emissions-free mobility.

The ESRS database profit as a benchmark for railway companies to understand the potential of and achieve energy efficiency improvements. UIC's short term goal is to update the commitments and enlarge the circle of reporting companies.

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