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Sustainable urban rail systems: strategies and technologies for optimal management of regenerative braking energy

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ABSTRACT

In a society characterised by increasing rates of urbanisation and growing concerns about environmental issues like climate change, urban rail transport plays a key role in contributing to sustainable development. However, in order to retain its inherent advantages in terms of energy consumption per transport capacity and to address the rising costs of energy, important energy efficiency measures have to be implemented. Given that numerous and frequent stops are a significant characteristic of urban rail, recuperation of braking energy offers a great potential to reduce energy consumption in urban rail systems. This paper presents a comprehensive overview of the currently available strategies and technologies for recovery and management of braking energy in urban rail, covering timetable optimisation, on-board and wayside Energy Storage Systems (ESSs) and reversible substations. For each measure, an assessment of their main advantages and disadvantages is provided alongside a list of the most relevant scientific studies and demonstration projects. This study concludes that optimising timetables is a preferential measure to increase the benefits of regenerative braking in any urban rail system. Likewise, it has been observed that ESSs are a viable solution to reuse regenerative energy with voltage stabilisation and energy saving purposes. Electrochemical Double Layer Capacitors has been identified as the most suitable technology for ESSs in general, although high specific power batteries such as Li-ion may become a

practical option for on-board applications in the near future. Furthermore, it has been demonstrated that reversible substations are a feasible and commercially available technology, although their economic viability strongly depends on the ability to sell the excess regenerated energy to the public network operators for an appropriate price. Finally, it has been concluded that a transfer of knowledge at international level between operators, manufacturers and other stakeholders is essential to achieve the great potential offered by regenerative braking, both in terms of energy efficiency, emissions reduction and system reliability.

Keywords: urban rail; regenerative braking; energy savings; energy storage; reversible substation; timetable optimization.

1. Introduction

Urban rail systems play a key role in the sustainable development of metropolitan areas for many reasons, but mainly because of their relatively low ratio between energy consumption and transport capacity. Nonetheless, in order to retain their environmental advantages over other transportation modes in an environment characterised by growing capacity demands and energy costs, significant improvements in energy efficiency must be achieved.

The conversion of kinetic energy into electricity, commonly known as *dynamic braking*, is based on the capacity of electric motors to also act as generators. The use of this kind of braking is widely spread in railway transport as, in contrast to friction braking, it does not generate wear and tear, dust, smell, heat or sound, [1]. In dynamic braking, the regenerated electricity may either be dissipated in banks of variable resistors (*rheostatic braking*) or may be reused within the transport network itself (*regenerative braking*). Before the outstanding development of power electronics in the last decades, rheostatic braking was the only available option. But with current technology regenerative braking appears to be a very

promising solution to reduce energy consumption in electrified urban transport networks.

Note that recuperation of braking energy in these kinds of systems is remarkably interesting as they are characterised by numerous and frequent phases of acceleration and deceleration.

Typically in regenerative braking, the recovered energy is primarily used to supply the auxiliary and comfort functions of the vehicle itself. Then, the energy surplus may be returned into the power supply line for use of other vehicles within the same network.

However, DC distribution networks, which are the most commonly used in urban rail systems, are not always receptive; i.e. they are not always able to admit the recovered braking energy. Generally speaking, the recovered excess energy can only be sent back to the supply network when a simultaneous consumption takes place, for instance when another train is accelerating in the same electric section. To dissipate the regenerated energy that cannot be used within the system, vehicles are typically equipped with on-board resistors implying not only additional weight and costs, but also a potential risk of fire.

In order to maximise the use of the recovered energy and consequently minimise the need of on-board resistors, two major alternatives have been studied in the literature. The first one consists in equipping vehicles with energy storage systems (ESSs) that temporarily accumulate the excess regenerated energy and release it for the next acceleration phase, [2] – [21]. The second option consists in improving the receptivity of the network. This implies introducing additional loads in the system demanding energy at the same time that the braking process takes place. For that, some investigations have suggested optimising scheduled timetables so as to synchronise acceleration and deceleration of trains as far as possible, [22] – [26]. Moreover, the installation of storage devices in substations or along the track (stationary or wayside ESS) could absorb the surplus regenerated energy, delivering it when required for other vehicles' acceleration, [3], [27] – [41]. Another option to improve the receptivity of the line is to equip substations with DC/AC inverters (reversible or active

substations) so that the regenerated energy can be fed back to the medium voltage distribution network, which is naturally receptive, [42] – [46].

Several studies have shown that application of regenerative braking in urban rail systems could potentially reduce their net energy consumption between 10% and 45%, depending on the characteristics of each system, [47] – [53] (note that track gradients have a notable influence on the amount of energy that can be recovered). Additionally, regenerative braking may mitigate some problems typically associated with electrified transport systems such as voltage drops at the feeder lines or high power peak consumptions, [7], [33]. Interestingly, in underground applications such as metro systems, regenerative braking might contribute also to reduce energy consumption in HVAC by lowering the thermal loads in tunnels and stations, [54], [55].

However, despite all the aforementioned advantages of regenerative braking, nowadays recovered braking energy is mainly dissipated in electrical resistors and only a small portion of it is used to supply the auxiliary systems of vehicles or returned to the feeder line. One of the possible reasons for that might be that technologies enabling an efficient management of regenerative braking in urban rail have only been available recently. The lack of experience feedback may be hindering operators and local authorities from investing in regenerative energy braking systems as a measure to increase energy efficiency in urban rail.

With the aim of covering a lack found in the literature, this paper presents a comprehensive overview of the options currently available for an optimal management of braking energy in urban rail systems. Firstly, it shows different strategies and methodologies developed in the literature to increase the interchange of regenerated energy between vehicles in the same system. Secondly, the paper introduces and compares the storage technologies suitable for railway applications, pointing out the most recent advances in the area. Thirdly, it discusses the advantages and drawbacks of stationary and on-board ESSs, underlining the key points to

be considered in the design stage. Lastly, this work analyses reversible substations as a means to return the recovered energy into the main distribution network. In order to demonstrate the applicability of the analysed technologies and emphasise their potential benefits, the study is completed with a list of the most recent and relevant cases of application in urban rail systems. The final objective of this paper is to provide an extensive state-of-the-art review on regenerative braking technologies that can help all the stakeholders to improve the energy efficiency of urban rail systems.

2. Maximising the regenerative energy exchange between vehicles

According to [3], the network receptivity can be defined as the ratio of the total energy returned back to the line over the potential energy that could be regenerated in the braking process (kinetic and potential energy). Considering that the potential energy recovery mainly depends on the track profile and the frequency of stops, and consequently it is fixed for every single system, a straightforward way to improve the line receptivity is to increase the number of trains accelerating and braking simultaneously. Note that as introduced before, if a vehicle decelerates while another accelerates in the same electric section, the regenerated energy can be directly transferred between both trains through the power supply line, as illustrated in Figure 1. A careful design of the operation schedule of trains may therefore lead to significant energy savings in the whole system. In addition to that, timetable optimisation may limit the simultaneous acceleration of too many vehicles, thus reducing maximum traction power (consumption peaks) and consequently investment and operational costs, [22], [23].

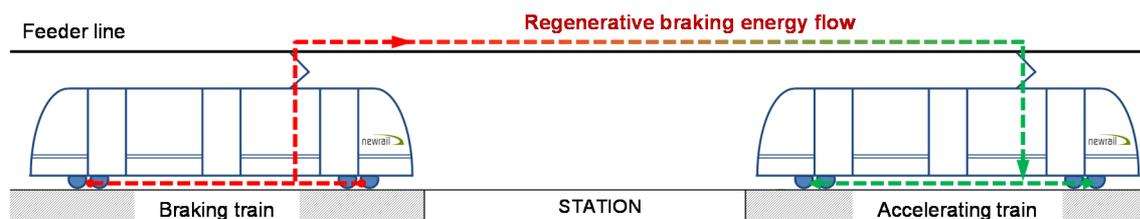


Figure 1 Schematic representation of regenerative energy exchange between trains

In the literature it is possible to find several studies dealing with the optimisation of timetables for energy saving purposes. For instance, in [24] an optimisation method based in Genetic Algorithm is proposed to maximise the energy exchange between trains in a metro system. The authors of that paper claim that energy savings of up to 14% can be achieved applying that method, which essentially determines the optimum values of the reserve time (stop time) that maximise the usage of regenerative braking. They have considered the influence of the headway time as well, but even though this parameter has a considerable effect on the energy recovery, it is a less flexible factor normally limited by traffic demand and operational restrictions.

A different approach to improve energy transfer between trains can be found in [25]. In this paper, a timetable model stated as a mixed-integer optimisation problem was proposed to synchronise acceleration and braking processes of vehicles in the same electrical section. This study was mainly focused on increasing the exchange of recovered braking energy in off-peak hours, when the likelihood of having simultaneous acceleration and braking processes is much lower. The proposed timetable was implemented in line 3 of the Madrid metro system and, after one week of real application, a mean energy saving of 3% was measured. However, the authors underlined that these results were obtained with a timetable modification of less than a minute with respect to the original one. They claimed that energy savings could grow up to 7% by slightly relaxing the timetable constraints.

As another interesting example of timetable optimisation to reduce the total energy consumption, it is worth mentioning the case of the Rennes metro in France, where annual savings of 12% were achieved, [26]. Like other studies, both the frequency of service and the stop durations were considered as the main parameters to be optimised. It was concluded that the energy savings which can be achieved with high frequencies or low number of running trains are not significant.

On the other hand, design of driving strategies may play an important role when trying to synchronise departures and arrivals of trains in urban transit systems. In general, passengers' perception of service quality is more negatively affected by an increase in the stop time than in the journey time. Therefore, energy-efficient driving strategies can be applied to increase the energy recovery without reducing the quality of service, [56], [57].

Needless to say a successful application of optimised timetables requires the implementation of a real time control system that, apart from advising drivers on the departure times and driving strategies, enables an automatic recalculation of the schedule in case of unforeseen events such as delays and accidents. The development and implementation of such a software technology represents relatively low investment costs, especially if compared with installation of ESSs or reversible substations. For that reason, optimising timetables should be regarded as the first option to take into consideration when aiming at increasing the benefits of regenerative braking in urban transit systems. Installation of ESSs and reversible substations should be considered as an option to recover the amount of energy that other vehicles in the system are not able to absorb.

3. Energy storage systems for urban rail

The fast and outstanding development of both energy storage technologies and power electronics converters has enabled ESSs to become an excellent alternative for reusing the regenerated braking energy within its own urban rail system, [58]. ESSs can be installed either on board vehicles or at the track side. On-board ESSs permit trains to temporarily store their own braking energy and reutilise it in the next acceleration stages. On the other hand, stationary ESSs absorb the braking energy of any train in the system and deliver it when required for other vehicles' acceleration. Below, ESSs systems will be generally described and both on-board and stationary applications will be discussed. An overview of the

technologies currently available for ESS and a list of the most relevant examples of application in urban rail systems will be given.

3.1 Components of Energy Storage Systems

Regardless of whether they are used for mobile or stationary applications, it can be said that ESSs typically consist of three main functions: the energy storage device itself, a power converter to condition the input and output electrical flows, and a controller managing the charge and discharge processes. Figure 2 illustrates the structure of ESSs.

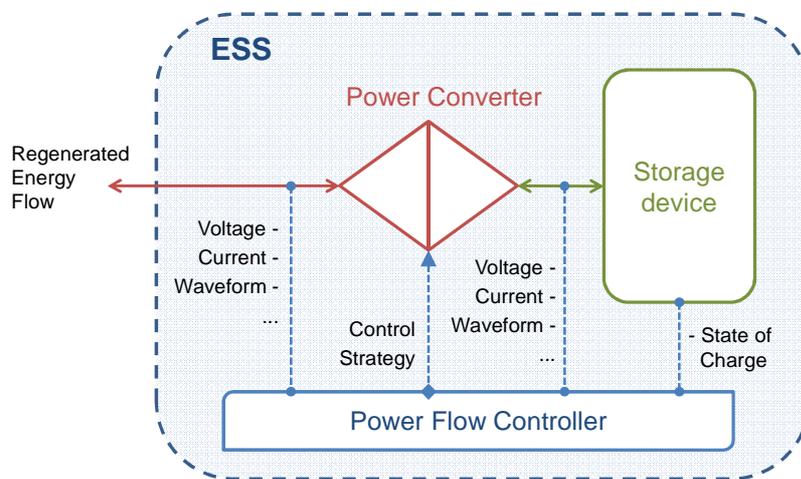


Figure 2 Components of an ESS for railway applications

Selection of the energy storage technology depends on the specific characteristics of each application. But, in general, it can be claimed that the most sought after features for urban rail applications are the following: large number of load cycles, typically between 100,000 and 300,000 per year depending on the characteristics of the transport system, [14]; high power peaks of charge and discharge, typically between 0.1 and 10 MW depending on transport system and whether stationary or mobile applications are considered, [59], [60]; intermediate energy capacities, although in the case of on-board systems the required storage capacity may be high; reduced weight and volume, which is of great importance for mobile systems. As

will be discussed in section 3.2, there are a few technologies meeting these requirements to a different degree.

ESSs normally work with different input and output conditions than those required in railway networks. Therefore, they need power conversion systems in order to guarantee a proper operation of the energy storage. Although their topology depends on the storage technology and the specific application, power converters basically consist of electronic devices that adapt the characteristics of the electricity regenerated in the braking process to the working conditions of the energy storage device (voltage, current and/or waveform). Power converters are required to efficiently manage the energy flow in a bidirectional way and must present a small size and weight, especially in mobile applications. An overview of the most commonly used topologies for power converters can be found in [59].

Irrespective of the technology selected for the energy storage device, power flow controllers are needed to optimise the ESS performance. These controllers must manage the charging and discharging cycles according to several parameters such as the state of charge (SoC) or the network voltage. In general terms, ESSs are charged only when voltage at the contact line is above the threshold value, which means that no more regenerated energy can be absorbed by the feeder network.

3.2 Energy storage technologies for urban rail applications

A brief description and comparison of the most important storage technologies available for urban rail applications will be given in this subsection. Table 1 summarises the main features of each technology.

3.2.1 Electrochemical double layer capacitors

Electrochemical double layer capacitors (EDLC), also known as ultracapacitors or supercapacitors, consist in storage devices that essentially work under the same principle as

conventional electrolytic capacitors. That is, energy is stored in an electrostatic field by simple charge separation and no chemical reactions take place. EDLCs are characterised by a very large electrode surface area, a high permittivity dielectric and an extremely small charge separation, which gives them an outstanding energy density compared with conventional capacitors.

Table 1

	Energy and power density			Discharge time	Efficiency (%)	Self-discharge (daily % of rated capacity)	Durability (number of cycles)	Capital cost (\$/kWh)	Capital cost (\$/kW)	References
	Wh/kg	W/kg	kWh/m ³							
Lead-acid batteries	20-50	25-300	50-80	Seconds-hours	70-90	0.05-0.3	200-2,000	50-400	300-600	[59], [66], [92], [107], [108].
Ni-Cd batteries	30-75	50-300	60-150	Seconds-hours	60-80	0.2-0.6	1,500-3,000	400-2,400	500-1,500	[59], [66], [92], [107], [108].
NiMH batteries	60-80	200-250	100-150	Seconds-hours	65-70	1-2	1,500-3,000	400-2,400	-	[66], [88], [108].
Li-ion batteries	75-200	100-350	150-500	Seconds-hours	90-100	0.1-0.3	1,000-10,000	500-2,500	1,200-4,000	[59], [66], [92], [108].
Li-poly batteries	100-200	150-350	150-200	Seconds-hours	90-100	0.15	600-1,500	900-1,300	-	[66], [108].
NaS batteries	120-240	120-230	110-250	Seconds-hours	75-90	20	2,000-3,000	300-500	1,000-3,000	[66], [108].
ZEBRA batteries	100-120	150-200	120-180	Seconds-hours	85-90	15	>2,500	100-200	150-300	[92], [108], [109].
Flywheel	5-100	1,000-5,000	20-80	Milliseconds-minutes	90-95	100	<10 ⁷	1,000-5,000	250-350	[59], [66], [92], [108].
EDLC	2.5-15	500-5,000	10-30	Milliseconds-minutes	90-100	20-40	<10 ⁶	300-2,000	100-300	[59], [62], [63], [92], [108], [110].
SMES	0.5-5	500-2,000	0.2-2.5	Milliseconds-seconds	95-100	10-15	>100,000	1,000-10,000	200-300	[92], [110].

Owing to the lack of chemical reactions on the electrodes (ideally), supercapacitors present very low internal resistance and consequently have very high efficiencies, typically around 95%. Besides, supercapacitors allow very fast charge-discharge processes with high currents, see Table 1. They can be completely discharged and can work in a wide range of environmental conditions, [61]. Interestingly, their lifetime may be as long as 10^6 charge–discharge cycles because of the electrostatic storage process, [62]. Supercapacitors have a considerably high power density but, conversely, they present a relatively low energy density, [63]. Another advantage is that their state of charge can be easily determined by measuring the terminal voltage. By contrast, EDLC are characterised by high self-discharge rates. Recent research on supercapacitors focuses on increasing their energy capacity by developing composite and nanostructured materials, [64], [65]. Thus, it has been reported that the use of carbon nanotubes instead of the usual porous carbon-based materials might lead to energy densities of 60 Wh/kg and power densities of 100 kW/kg, [66]. Alternatively, recent development of lithium-ion ultracapacitors may lead to increased operating voltages as well as higher energy and power densities, [67] – [69].

Characteristics of supercapacitors make them a very suitable option for energy storage in both railway and power applications. Due to their rapid response they may be effectively used for supplying power peak demands and for voltage stabilisation purposes. A proper conversion and management of the power flows is required to achieve an optimum performance in those functions though, [70]. Interesting to note is that the configuration of the converter strongly influences the efficiency and final size of the system. In fact, according to [71], the number of supercapacitors in an ESS may be minimised by operating them at their highest current rate, although this will lead to greater size and weight of the associated power electronics. On the other hand, one should note that the lower the current through the cells, the higher is the storage efficiency, [2].

3.2.2 Flywheels

Flywheels are electro-mechanical storage devices that store kinetic energy in a rotating mass so-called rotor. The stored energy is proportional to the inertia of the rotor and to the square of its rotational speed. Whereas early systems used large steel masses rotating on mechanical bearings, the new generation of flywheels are made of carbon-fibre composite rotors suspended by magnetic bearings, [72]. The use of light composite materials reduces the inertia of flywheels but allows much higher rotational speeds because of their significantly higher tensile strength, [73]. Magnetic bearings, in turn, offer very low friction enabling a considerable reduction of internal losses during long-term storage, [74]. All the components of a flywheel are typically mounted in vacuum enclosures so that friction losses are minimised. Notwithstanding, due to the complexity associated with vacuum systems, other alternatives such as using a helium–air mixture gas have been proposed in the literature to reduce the windage loss, [75].

The flywheel's rotor is connected to an electrical machine than can operate either as a motor or as a generator. It acts as a motor in the charging process, when the electrical supply is used to increase the kinetic energy of the flywheel by speeding up its rotational speed. Conversely, the electrical device performs as a generator when the flywheel releases the stored energy. In this case, the applied torque will decrease its rotational speed. The need of an effective system to transform and control both the input and output power flows has strongly limited the application of flywheels in high power applications for many years, [76]. However, recent progress in power electronics has enabled a reliable and efficient operation of flywheels at high power rates.

One of the main advantages of flywheels is that they allow a fast charge-discharge process for a potentially infinite number of cycles. Additionally, they present relatively high overall efficiencies and elevated energy and power densities, see Table 1. Other important

characteristics of flywheels are the following: their state of charge can be easily measured as a function of angular velocity; their temperature range of operation is very wide and they use low-environmental-impact materials. All these advantageous features make ESS based on flywheels a very suitable option for different applications such as transportation or quality power applications, [39], [77] – [81].

However, flywheels present a number of drawbacks that hinder their extensive use in railway applications. First, they have a potential risk of explosive shattering in case of catastrophic failure, for example due to overload. Although modern fibre reinforced composite rotors fail in a less destructive manner than metallic ones, [82], and despite the fact that they are typically protected by a multiple-barrier containment system (in which the vacuum chamber acts as the first safety enclosure) this potential danger is regarded as a major safety issue in public transport applications. Another serious disadvantage for the use of flywheels in vehicles is their relatively high weight. Last but not least, flywheel technology is characterised by high self-discharge rates, which is caused by different factors like internal friction or orientation changes produced by vehicle movements.

3.2.3 Batteries

Batteries store and deliver energy by means of reversible electrochemical reactions taking place between two different materials (electrodes) immersed in an electrolyte solution. These reactions occur inside cells, which are the basic units forming a battery. Depending on the core chemistry utilised, batteries may offer a wide range of operational characteristics. A brief description of the most common and promising battery configurations available for energy storage in urban rail systems is given below.

3.2.3.1 Lead-acid batteries

Among rechargeable electrochemical devices, lead-acid batteries are the oldest and most extensively used. In charged lead-acid batteries the electrodes are made of lead metal and lead oxide, while a diluted sulphuric acid solution acts as electrolyte. In the discharged state both electrodes turn into lead sulphate and the electrolyte becomes primarily water. These kinds of batteries are characterised by relatively low costs, high reliability and efficiency, a very limited lifespan, low energy density and relatively high power density when compared with other batteries, see Table 1. Additionally, the self-discharge rates for these types of batteries are very low. They present a poor low temperature performance, requiring therefore a thermal management system. Other clear disadvantages of these batteries are the fact that they cannot be completely discharged and their negative influence on the environment because of the lead processing.

Lead-acid batteries are mainly used in cost sensitive applications where limitations like low energy density or short cycle life do not represent an issue. Regarding railway systems, they can be found mainly in back up applications, [83]. Recent research studies focus on increasing the energy and power density by replacing lead with lighter materials such as carbon, which might allow for a wider use of lead-acid batteries in traction [84], [85].

3.2.3.2 Nickel-based batteries

Nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) are the most common nickel-based batteries on the market. Both types use nickel hydroxide as a positive electrode and an alkaline solution as electrolyte. As for the negative electrode, the NiCd type uses cadmium hydroxide whereas the NiMH technology has a metal alloy capable of absorbing and desorbing hydrogen. These batteries have a robust reliability and require low maintenance.

Compared to lead-acid, NiCd batteries have higher energy and power densities, as well as larger lifespan, see Table 1. In contrast, their cost is considerably higher and they present lower efficiency. In addition, self-discharge rates are much higher for NiCd than for lead-acid batteries. In railway applications, NiCd batteries have been mainly used as backup for auxiliary systems, [86], [87]. In traction functions, they have been superseded by NiMH batteries, which offer higher energy and power densities, longer lifespan, reduced memory effect and, what is more, avoid the use of a toxic heavy metal like cadmium. The efficiency of NiMH batteries is not particularly high, but their main disadvantage is the high self-discharge rate. However, the introduction of novel separators might mitigate this issue, [88].

3.2.3.3 Lithium-based batteries

The principle behind lithium rechargeable batteries is based on the migration of lithium ions between the electrodes through the electrolyte. Although a wide variety of materials are available for use in these kinds of batteries, lithium-ion (Li-ion) and lithium-polymer (Li-poly) represent the major families of cells, [89]. The primary difference between them is that in Li-poly batteries the electrolyte (made of lithium salts) is held in a solid polymer composite instead of an organic solvent.

The main advantages of this battery technology are the following: relatively high energy and power densities, high efficiency, low self-discharge rate, elevated number of cycles, no memory effect and extremely low maintenance, see Table 1. In contrast, they require a battery management system to keep working temperatures, voltages and SoC within a safe and efficient range of operation, [90], [91]. However, the main hurdle of lithium-based batteries is their high cost, primarily motivated by the required special packing and protection circuits, [92]. In this sense, Li-poly technology offers potentially lower manufacture costs and wider adaptability to packing shapes. Furthermore, they are lighter and present lower

flammability risk than Li-ion batteries. However, Li-poly batteries present a lower temperature range of operation and a considerable shorter lifetime.

Lithium batteries are widely used in portable equipment such as laptops or mobile phones, but due to the outstanding progress achieved in terms of energy and power densities, they represent a very promising option for hybrid and electric vehicle applications, power quality support or even aerospace applications, [59], [66], [93]. Interestingly, the OSIRIS European Project (FP7 – 28468) has as one of its objectives the evaluation of Li-ion batteries as on-board ESS for urban rail systems. Current research on lithium-based batteries is focused on finding new electrochemical combinations and nanostructures that improve their energy and power densities, durability, cost and safety, [94] – [96].

3.2.3.4 Sodium-based batteries

This kind of rechargeable battery is based on the movement of sodium ions between both electrodes. Sodium sulphur (NaS) and sodium nickel chloride (better known as ZEBRA) are the most widely used cells. Both of them present a molten sodium negative electrode, but they have different positive electrodes and electrolytes: whereas the former technology uses molten sulphur as positive electrode and a solid beta alumina ceramic as electrolyte, the latter uses nickel chloride and liquid sodium chloroaluminate, respectively. Sodium-based batteries present high self-discharge ratios because part of their stored energy is used to maintain the high working temperatures (about 300°C).

NaS batteries are highly energy efficient, have a typical cycle life of about 2500 cycles and their energy and power densities are relatively high, see Table 1. ZEBRA batteries improve the safety characteristics and the cell voltage of NaS batteries; however, they present lower energy density and lower power density. The high operation temperature is an intrinsic

disadvantage of the sodium-based batteries that may limit their use to large-scale stationary systems like power quality and peak shaving applications, [97].

3.2.3.5 Other emerging battery technologies

As examples of other battery technologies currently under investigation and development it is interesting to mention Metal-Air batteries and Redox Flow Storage systems. Metal–Air technology offers high energy densities (up to 3,000 Wh/kg) at reasonable costs. Therefore they represent a favourable option for a wide range of applications, from portable electronics to electric vehicles. However, intensive research is still needed in terms of cathode materials and electrolyte systems to improve their low efficiency, [98], [99]. In turn, Redox technologies, for instance Vanadium Redox batteries (VRB), have important advantages such as no self-discharge, no degradation for deep discharge and long lifecycle. Nevertheless, they still require high investment costs and need further technical development, especially to increase their energy capacity, [100].

3.2.4 Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) enables electric energy to be stored in the magnetic field generated by a direct current flowing through a coil cryogenically cooled below its superconducting critical temperature. The current circulates indefinitely in the coil due to the nearly zero resistance of the superconducting cables, which are typically made of niobium-titanium (NbTi), [101]. The stored energy is released when the DC potential is removed. In order to maintain the superconducting state of the coil, it is immersed in liquid helium contained in a vacuum-insulated cryostat. Like other energy storage technologies, SMES need a dedicated power conversion system conditioning the input and output electric flows, [102].

The main advantages of SMES systems are their great energy storage efficiency and very fast responses, see Table 1. Additionally, they can be almost completely discharged and present a very high cycle life. Their major drawbacks are, by contrast, the high investment and operational costs due mainly to the refrigeration system. Another serious issue is the strong magnetic fields generated by these kinds of systems, especially when very large capacities are involved. SMES systems have been mostly used for network stability applications, [103], [104]. However, their features make them potentially suitable for railway applications as well, especially for the case of stationary ESSs, [105], [106].

3.2.5 Techno-economic comparison of different storage technologies for urban rail

In order to compare and assess the suitability of the above discussed technologies for energy storage in urban rail applications, one of the first criteria to be considered is technical maturity. In this regard, it can be said that lead-acid batteries are the most mature option since they have been used for over 100 years. NiCd batteries can be regarded also as a completely established storage technology. In turn, NiMH, lithium-based and sodium-based batteries can all be considered proven technologies already available on the market. Despite the significant improvements experienced in recent years, flywheels and supercapacitors are based on very well-known technologies; therefore they can be considered mature technologies. As for SMES systems, they have been demonstrated to be technically available but not largely commercialised yet. Lastly, the Metal-Air batteries and the Redox Flow Storage system are still under development and they cannot be considered commercially mature technologies.

Energy and power density are decisive parameters to take into account when selecting storage technologies for railway applications, especially for the case of mobile ESSs where both weight and space are critical. Table 1 shows that batteries present considerably higher energy capacity per unit of weight and volume than flywheels, supercapacitors or even SMES

systems. Among batteries, lithium-based technologies offer the greatest energy density range, followed by sodium-based ones. However, lithium batteries present higher compactness (energy per unit of volume), which makes them more suitable for on-board ESSs. On the other hand, the power density offered by batteries is significantly lower than flywheels, supercapacitors or SMES systems. Flywheels and EDLCs present the highest power densities, but the former have slightly higher energy density and compactness.

Regarding the time of discharge, a crucial aspect for peak shaving and voltage stabilisation functions, batteries are clearly disadvantaged in comparison with flywheels, supercapacitors and SMES, which allow for very fast responses. SMES systems offer the shortest discharge times as they are the only technology to store energy directly into electric current.

The efficiency of charge-discharge cycles and the self-discharge rate of ESSs are two important parameters to consider when evaluating storage technologies as they have a strong influence on the overall system costs. Thus, low efficiencies and high self-discharge rates reduce the fraction of the total stored energy that can be effectively used, consequently increasing the costs of the system. Lithium-based batteries, flywheels, supercapacitors and SMES systems offer the highest efficiencies, with values around 95% or above. As for the self-discharge rates, batteries present much lower values than other technologies (except for sodium-based batteries). Actually, it is observed that flywheels might completely dissipate their stored energy in one day. However, since urban rail applications involve short storage periods (minutes), elevated self-discharge ratios do not imply serious issues.

Durability of the ESSs is also a basic parameter to take into consideration for the selection of storage technologies as it is directly related to the final costs of the system. This is especially relevant for urban rail applications, where the number of charge-discharge cycles is substantially higher than for other cases. In this regard, from Table 1 one can conclude that batteries present considerably shorter cycle lives than EDLCs, flywheels and SMES systems,

which can last for several hundred thousand cycles. Notwithstanding, it is worth mentioning that modern Li-ion batteries may offer up to 10,000 cycles.

Lastly, the capital costs cannot be avoided when comparing different energy storage technologies. Table 1 shows the typical costs per unit of stored energy and per unit of rated power (taking into account the efficiency). Note that in this comparison, the costs of operation, maintenance and replacement have not been considered. Batteries, especially lead-acid ones, offer the best capital costs per kWh of stored energy. However, when costs per rated power are considered, batteries are considerably more expensive than flywheels, supercapacitors and SMES systems. Moreover, for a more accurate evaluation of ESSs costs in frequent charge-discharge applications such as urban rail, it is interesting to consider the cycle life as well. In this regard, Figure 3 compares the capital costs per cycle for the considered storage technologies. It is seen that, in general, batteries are the most costly options with respect to their cycle life.

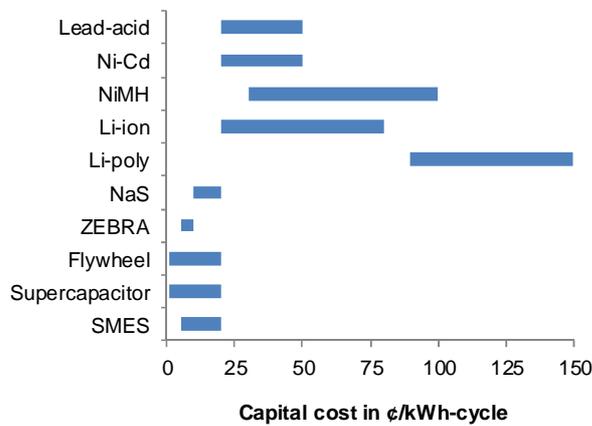


Figure 3 Comparison of energy storage capital costs

3.3 On-board energy storage systems

3.3.1 Main characteristics of on-board applications

On-board ESSs can considerably contribute to energy savings in urban transit systems since the energy recovered and stored during the braking process can be used to power the vehicle itself during the next acceleration, see Figure 4. Moreover, from the installation of on-board ESSs the following advantages can be expected:

- Shaving of power peaks demanded during acceleration of vehicles, which leads to reduced energy costs and minimum resistive losses in the supply line.
- Limitation of voltage drops in the system network, which might eventually allow for a higher traffic density without further modification in the existing infrastructure.
- Certain power autonomy, for instance in emergency situations, in depot operations or in free-catenary applications such as lines going through historical city centres with visual impact restrictions.

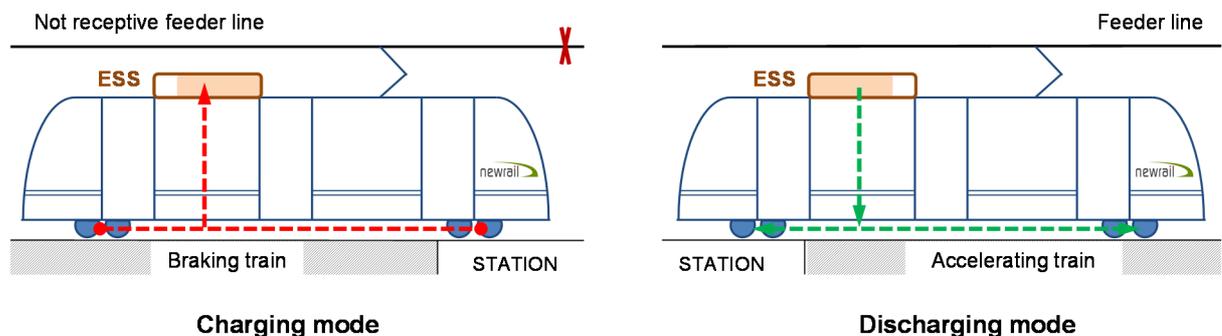


Figure 4 Schematic of on-board ESSs operation in urban rail

In comparison with wayside storage solutions, on-board ESSs have the advantage of operating with higher efficiency due to the absence of line losses. Besides, the management of the recovered energy is simpler since the control is independent of traffic conditions. In contrast, on-board ESSs typically require a large space on the vehicle and introduce a significant increase of weight. Some studies have assessed that the additional mass due to on-

board ESSs increases the traction energy consumption by 1% to 2%, [4], [21]. Owing to these hurdles, the installation of on-board ESSs is not commonly considered when retrofitting existing rolling stock, but when designing new vehicles.

A fine-tuned analysis is required to achieve an optimal design of on-board ESSs. Oversizing might unnecessarily increase mass and volume of the system, whereas undersizing might lead to considerable energy waste. The sizing method for mobile ESSs depends upon their main function; that is, the design requirements will be different when aiming at maximising the energy savings, reducing the voltage drops at the line or running the vehicles in free-catenary mode. A general criterion for energy saving purposes is that the ESS must absorb the maximum amount of braking energy that can be recovered in a sudden braking, assuming that no energy can be returned to the network, [7]. However, due to the fact that vehicle speeds and occupancy rates are variable, a careful analysis considering weights and costs must be carried out to determine the optimum capacity, [3]. Designing mobile ESS for voltage stabilisation applications requires considering the operational characteristics of the whole line, e.g. distance between substations and trains timetables, [14], [21]. Lastly, if the main purpose of the ESS is to enable free-catenary operation, the system has to be sized to fully drive both traction and vehicle auxiliary systems in the sections without overhead contact line (OCL). In that case, it is also common practice to optimise the driving style so as to minimise the size of the mobile ESS, [19], [21]. Whichever is the main function of an on-board ESS, they are normally installed together with braking resistors that protect the system when the recovery energy exceeds the storage capacity.

As for the control of on-board ESSs, different parameters such as vehicle speed, SoC, requested traction power and network voltage must be considered. Generally speaking, control systems have to ensure that ESSs are charged enough to power the vehicle during

accelerations and that they remain completely discharged at high vehicle speeds so as to accept the highest amount of energy when braking or at stand-still (charging from the net).

3.3.2 Technologies for mobile storage systems

Given their fast response, high power density and relatively low costs, it can be said that supercapacitors currently represent the best option for regenerative energy storage on board vehicles. However, their low energy capacity hinders their use in applications where the main purpose is providing autonomous operation to trains. In this case, Li-ion batteries, or to a lesser extent NiMH batteries, might offer a better performance, especially if higher power densities and reduced costs are achieved in the near future, as expected. Note that flywheels and SMES systems may not be regarded as suitable options for mobile systems due to safety and operability issues (see section 3.2).

Interestingly, the combination of batteries and EDLCs appears to be a very promising option for on-board ESS, especially if operation without OCL is sought. In this kind of system, supercapacitors would absorb the peaks of braking energy and would provide the needed power for vehicle accelerations. In turn, batteries would absorb the remaining regenerated energy and would be discharged during the coasting/rolling phases of the catenary-free operation. In this manner, batteries would be protected against peaks and would suffer much less charge-discharge cycles, which could significantly increase their life and performance, [111], [112].

3.3.3 Overview of case studies and commercial systems for on-board applications

A summary of the most relevant studies published so far on regenerative energy storage on board vehicles is presented in Table 2. At first glance, it can be seen that the great majority of works focus on the application of EDLC technology. This may be seen as evidence that supercapacitors have been considered as the most suitable option for mobile applications.

Regarding the use of on-board flywheels in urban rail, only one publication has been found in the technical literature, [18]. It reports on the construction of a prototype for hybrid light rail vehicles within the “Ultra Low Emission Vehicle – Transport Advanced Propulsion 2 (ULEV – TAP2)” project. Developed by the Centre for Concepts in Mechatronics (CCM), this ESS consisted of a 250-kW high speed carbon-fibre flywheel with 4 kWh of effective energy storage capacity. The prototype was intended to be roof-mounted in the Siemens Avanto vehicle, but no results of real application have been reported. On the other hand, CCM has collaborated with Alstom to integrate a flywheel-based ESS in their Citadis tram, but no application results have been published either, [19], [113].

Regarding batteries, their use as on-board ESSs has not been extensively discussed in the scientific literature so far. Their low power density and short lifecycle seems to be the main reason for that. Nevertheless, two recent studies have revealed promising results for the application of lithium-based batteries on board. On the one hand, the Railway Technical Research Institute (RTRI) in Japan has developed and successfully tested a hybrid electric light rail prototype incorporating a Li-ion battery to recover braking energy, [19]. On the other hand, the Korea Railroad Research Institute (KRRI) has designed a new low-floor LRV with Li-poly batteries on board to recover braking energy and allow for a catenary-free operation, [20]. Several simulations have assessed the performance of this system, but no results of real operation have been published.

Table 2

Ref.	EES	Study*	Main purpose	Main results
[2]	EDLC	T	Design for energy consumption reduction.	-Energy savings of 18 to 33% in one Brussels tram line.
[3]	EDLC	T	Sizing for energy consumption reduction.	-Energy savings of 26.3 to 35.8% in one Brussels metro line.
[4]	EDLC	T	Assessment of energy consumption reduction.	-Energy savings of 24% in one Madrid metro line.
[5]	EDLC	T	Assessment of energy	-Energy savings of 30% in

			consumption reduction.	Blackpool tramway.
[6]	EDLC	T	Control for energy consumption reduction.	-Method validation by means of simulations.
[7]	EDLC	T/ E	Control for energy savings and voltage stabilisation	-Method validation at laboratory; -Energy savings of 12%.
[8]	EDLC	T/ E	Assessment of energy consumption reduction.	-Energy savings of 19.4 to 25.6% in Mannheim tramway.
[9]	EDLC	T/ E	Control for energy consumption reduction.	-Method validation at laboratory; -Energy savings of 38%.
[10]	EDLC	T/ E	Sizing and control for power peak reduction.	-Method validation at laboratory; -50% of power peak reduction; -30% energy recovery.
[11]	EDLC	T/ E	Control for power peak reduction	-Method validation by means of simulation and laboratory tests.
[12]	EDLC	T/ E	Development for catenary-free operation.	-Validation in real tramway system.
[13]	EDLC	T/ E	Development for catenary-free operation.	-Preliminary test results at laboratory level.
[14], [15]	EDLC	T/ E	Testing MITRAC™ Energy Saver.	-30% of energy savings in Mannheim LRV system; -50% of power peak reduction;
[16]	EDLC	T/ E	Development for energy consumption reduction.	-Method validation at laboratory level.
[17]	EDLC	E	Development for energy consumption reduction and catenary-free operation.	-Energy savings of 16% in one tram line in Paris; -300 m of autonomy.
[18]	Flywheel	E	Development for energy savings.	-Construction of a prototype by CCM.
[19]	Li-ion	T/ E	Development for energy savings.	-30% of energy savings in one light rail line in Sapporo.
[20]	Li-poly	T	Development for catenary-free operation.	-Validation of the system with simulations.
[21]	EDLC + NiMH	E	Testing Sitras® HES.	-10.8% of energy savings in LRV in south Lisbon; -2.5 km of autonomy.

*T: Theoretical; E: Experimental

As for hybrid ESSs, it can be said that they have been hardly studied for urban rail applications. In fact, [21] is the only available publication in the literature dealing with this solution. As will be further discussed below, this publication presents an EDLC-battery hybrid ESSs developed by Siemens and shows some results of in-service operation at a light rail network in the south of Lisbon, Portugal.

In the light of the great potential offered by on-board ESSs in urban rail applications, the major companies dedicated to the railway business have developed their own solutions. As seen in Table 3, most of the manufacturers have opted for the EDLC technology in their proposals. Thus, Bombardier Transportation developed a supercapacitor-based system for recovering braking energy in light rail vehicles (LRV), metro trains and diesel multiple units, the so-called MITRAC™ Energy Saver. After being successfully tested in revenue service, the system is currently available as a standard solution in the new light rail vehicle of Bombardier: FLEXITY 2. Similarly, Siemens has developed the Sitras® MES (Mobile Energy Storage) system for braking energy storage in rail vehicles, electric or diesel trains. According to the manufacturer, the system has been used to retrofit Innsbruck tramway (Austria) in 2011, but no operation results have been published so far. Another EDLC-based ESS available on the market is the ACR system (Rapid Charge Accumulator) developed by CAF. This system has been successfully tested on a CAF Urbos-2 vehicle in Seville, and is currently available as a standard option in the new Urbos-3 trams. Lastly, Alstom has developed the STEEM (Maximised Energy Efficiency Tramway) system aiming at increasing the energy efficiency in tramway systems while allowing catenary-free operation. This solution was tested on a RTPA tramway (Paris) in regular operation from May 2009 to September 2010. However, no results of commercial application have been reported so far to the best knowledge of the authors.

Table 3

Brand name	Manufacturer	ESS	Application in urban rail	Ref.
MITRAC™ Energy Saver	Bombardier	EDLC	-LRV in Mannheim, in service from 2003 to 2007; -Rhein-Neckar-Verkehr GmbH tramway, to be run in 2013.	[14], [15], [114], [115], [116].
Sitras® MES	Siemens	EDLC	-Innsbruck tramway.	[117], [118].
ACR	CAF	EDLC	-Seville, Saragossa and Granada tramway systems, in service.	[119].

STEEM	Alstom	EDLC	-Paris tramway, in service from 2009 to 2010.	[17], [120].
-	Alstom – Saft	NiMH	-Nice tramway, in service since 2007.	[17], [19], [121].
LRV Swimo	Kawasaki	NiMH	-Prototype tests in Sapporo Municipal Transport network, 2007 – 2008.	[19], [122].
LFX-300 streetcar	Kinki Shayro	Li-ion	-Prototype tests in Charlotte, 2010.	[123].
Sitras [®] HES	Siemens	EDLC + NiMH	-MTS light rail system in south Lisbon, in service since 2008.	[21], [124].

For applications where relatively long distances of catenary-free operation are required, battery-based solutions have been preferred by manufacturers. In this regard, Alstom has equipped twenty Citadis trams in the city of Nice (France) with on-board NiMH batteries developed by Saft. This ESS enables a catenary-free operation in two non-electrified sections of about 450 m in the historical city centre. In turn, the Japanese manufacturers Kawasaki and Kinki Shayro have developed new hybrid electric vehicles for operation without OCL: Swimo (NiMH batteries) and LFX-300 (Li-ion batteries), respectively. In both cases, the batteries are able to absorb the regenerative braking energy, but they are mainly recharged through the feeder line during stops.

A different approach for catenary-free operation of LRV has been proposed by Siemens, which has developed a hybrid ESS known as Sitras[®] HES. The system consists of a Sitras[®] MES mobile energy storage unit and a traction battery made of NiMH cells provided by Saft. This solution has been tested in passenger operation at MTS network (Metro Ligeiro da Margem Sul do Tejo) since 2008 with very promising results. Currently, both Sitras[®] MES and Sitras[®] HES energy storage systems are optional components of Siemens' new Avenio tram platform.

3.4 Wayside energy storage systems

3.4.1 Main characteristics of wayside applications

Stationary ESSs essentially work absorbing the regenerated braking energy that cannot be used simultaneously in the system. The ESS delivers the stored energy when it is required for the acceleration of any vehicle in its same electric section, Figure 5. The charge and discharge processes require an electronic controller that generally operates as a function of the voltage on the line, [41]: when an overvoltage takes place as a result of any braking process, ESSs operate in “charging” mode absorbing the excess of regenerated energy on the line; in turn, when a voltage drop is detected, ESSs deliver the stored energy in order to keep the threshold value on the network. 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.

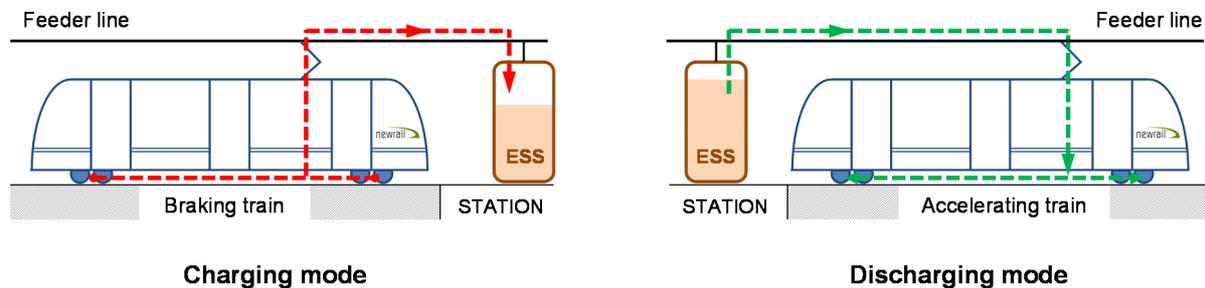


Figure 5 Schematic of wayside ESSs operation in urban rail

Stationary ESSs can be used to reduce the energy demand of the whole system, but also to stabilise the network voltage at weak points of the network, which is a major advantage over reversible substations. In fact, wayside ESSs might eliminate the need of additional feeding substations to compensate the voltage drops typically associated with end of lines, [37].

Similarly to on-board ESSs, stationary devices can greatly contribute to shave peaks of energy consumption during acceleration of vehicles, which in many cases imply considerable cost savings for operators. Besides, they might enable trains to reach the nearest station in

case of failure of the power supply, increasing the system security. When compared with on-board devices, wayside systems present the advantage of having fewer restrictions in terms of weight and required space. Moreover, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. On the contrary, stationary systems are generally less efficient due to transmission losses taking place in the network. This fact, which is directly related to the distance between the braking vehicles and the ESS, makes it indispensable to carry out a careful study to determine the optimal position of the storage devices along the line, [27].

When designing stationary ESSs, it is also very important to take into account the variability of the traffic conditions, [3]. Provided the receptivity of the line heavily depends on the frequency of trains, the optimal size of the ESS will be different for every scenario. A fine-tuned analysis is required to reach a compromise solution that optimises the capacity of stationary ESSs. In this regard, an optimisation procedure based on a nonlinear programming technique has been developed. Alternatively, a probabilistic method to size wayside ESSs in metro lines has been presented in [28]. The stochastic nature of the design variables has been considered in the sizing methods developed in [31] and [33]. In turn, a simpler and probably less accurate algorithm based on predicting the maximum instantaneous regenerative energy has been proposed by [32].

On the other hand, sizing wayside energy storage devices is strongly dependent on the main function of the system. A recent project on stationary systems for railway applications concluded that the most practical design strategy is to consider the ESS as a solution for simultaneous problems rather than focusing on a single objective, [60]. As a first approach to size and optimise the ESS, the authors of that report suggest using voltage sag design. Then, maximisation of other simultaneous benefits such as peak power shaving or energy consumption reduction could be considered by varying some design parameters.

Alternatively, one could focus primarily on energy savings and peak reductions, but careful economic analyses would be then required. Anyhow, that design guide recommends performing detailed simulations and full-scale tests to obtain the best performance results of stationary ESSs, as each transit system has unique characteristics.

3.4.2 Technologies for wayside storage systems

Since stationary ESSs have less weight and volume restrictions than mobile systems, the range of suitable storage technologies is wider in this case. EDLCs present excellent characteristics to be used in power shaving and voltage stabilisation functions, but as for mobile applications, the reduced energy capacity could limit their use depending on the specific requirements of each system. In this sense, flywheels can provide similar power capacities but with slightly higher energy densities. The safety concerns related to flywheels are less limiting in wayside applications as they may be installed within heavy containers or even underground. SMES systems appear to be a very suitable alternative for stationary ESSs due to their fast response, but their elevated costs, their high complexity and the associated electromagnetic fields may hinder an extensive application. Among batteries, sodium-based technology might represent a good solution due to the relatively high power capacities and the reduced capital costs per unit of energy and cycle. Expected advances in Li-ion and NiMH might make them interesting alternatives as well.

3.4.3 Overview of case studies and commercial systems for wayside applications

In the scientific literature it is possible to find several works developing stationary ESSs for urban transport applications, as shown in Table 4. As in the case of on-board ESSs, it is interesting to note that EDLC has been the preferred technology for stationary systems so far. Most of the studies dealing with the application of this technology focus on the development of methodologies to obtain optimised ESS designs for urban rail (see section 3.4.1).

Regarding the development of stationary energy storage prototypes based on EDLCs, it is worth mentioning the work of Konishi, [35]. After a few preliminary tests carried out at DC 75V to compare charge-discharge characteristics of EDLCs and lithium batteries, the authors of that paper opted for the former technology to develop an ESS for voltage stabilisation purposes. The tests performed at 400 V (laboratory level) revealed very promising results for railway applications. Another interesting work developing EDLC-based wayside systems is [36], where two prototypes built by RTRI are experimentally validated. Interestingly, in [37] the design of a EDLC-based storage system is proposed for use as a voltage compensation substation in a trolley bus system in the city of Lausanne (Switzerland).

As for the use of flywheels in wayside ESSs, [38] reports on the development of a new system within a project promoted by the Spanish Administrator for Railway Infrastructures (ADIF) in collaboration with CIEMAT (Public Research Centre for Energy, Environment and Technology). The authors of that work claimed that, owing to Joule effect losses in the electric machine and aerodynamic losses in the flywheel, the original design capacities of 350 kW and 200 MJ had to be limited to 150 kW and 50 MJ, respectively. The system feasibility was proved in a 3,000 V DC network with no train interactions, though trials under real traffic conditions are expected to be performed in Madrid commuter lines. Another paper dealing with the use of flywheels in stationary systems is [39], which reports on the performance results of a flywheel ESS developed by the defunct company Urenco.

On the other hand, [40] is the only paper on battery-based ESS for stationary applications available in the scientific literature. It describes the Gigacell[®] Battery Power System developed by Kawasaki and presents the experimental results obtained from a pilot project carried out in 2010 to test its performance in real traffic conditions. As shown in Table 5, this commercially available system is based on NiMH technology. Tests conducted at the New

York City Transit network demonstrated the capability of the system to capture and manage regenerated braking energy.

Table 4

Ref.	ESS	Study*	Main purpose	Main results
[3]	EDLC	T	Sizing for energy consumption reduction.	-Energy savings of 16.1 to 33.4% in one Brussels metro line.
[27]	EDLC	T	Sizing for voltage stabilisation.	-Procedure validation by simulating a tramway system.
[28]	EDLC	T	Sizing for energy savings and voltage stabilisation.	-Proposal of a stationary ESS for one metro line in Milan.
[29]	EDLC	T	Sizing for voltage stabilisation.	-Procedure validation by means of a case simulation.
[30]	EDLC	T	Sizing for energy consumption reduction.	-Operation costs reduction of 28% in Seoul Metro Line 7.
[31]	EDLC	T	Sizing for voltage stabilisation.	-Method validation by means of a case simulation.
[32]	EDLC	T	Development for energy consumption reduction.	-Energy savings of 25% in Tehran metro; -Amortisation within 10 months.
[33]	EDLC	T/E	Sizing for voltage stabilisation.	-Procedure validation by means of simulations and laboratory tests.
[34]	EDLC	T/E	Sizing for energy savings and voltage stabilisation.	-Procedure validation by means of simulations and laboratory tests.
[35]	EDLC	T/E	Development for voltage stabilisation.	-Construction of a 400-V prototype -Validation at laboratory.
[36]	EDLC	T/E	Development for energy consumption reduction and voltage stabilisation.	-Validation of two prototypes in Osaka (600V and 750V DC); -Laboratory tests for 1,500 and 3,000V DC systems.
[37]	EDLC	T/E	Development for voltage stabilisation.	-Laboratory tests with a scale prototype.
[38]	Flywheel	T/E	Development for power management.	-Validation of a 150-kW prototype for 3,000 V DC lines in Madrid.
[39]	Flywheel	E	Testing a system developed by Urenco.	-Validation in London metro.
[40]	NiMH	E	Testing Gigacell® Battery Power System.	-Validation at the New York City Transit (NYCT) network.

*T: Theoretical; E: Experimental

A list of the stationary ESS currently commercialised is given in Table 5. As seen, only two battery-based systems are available apart from the aforementioned Gigacell® BPS, namely:

Intensium Max system, developed by Saft, and B-CHOP system, developed by Hitachi. Both of them use Li-ion technology and have been tested in urban rail systems for braking energy recuperation purposes. Whereas the Hitachi's system has been in regular operation in Kobe (Japan) since 2007, [140], the Intensium Max system is currently being tested in the Philadelphia public transport network, within an innovative project launched by SEPTA in partnership with Viridity Energy. This project aims at recovering the full regenerated energy capability of the line by means of wayside storage and energy return to the main grid, [143], [144]. The power control and conversion capabilities in that stationary ESS are provided by the Envistore™ system, originally developed by Envitech Energy to work with supercapacitors, [131].

It can be concluded from Table 5 that EDLC is the technology selected by most of the manufacturers to develop their wayside ESSs. The Sitras® SES (Static Energy Storage) system marketed by Siemens appears to be the most used so far, with several prototypes and commercial units installed in different urban rail systems worldwide such as Cologne (Germany), Madrid (Spain), Peking (China) or Toronto (Canada). Bombardier, another major railway manufacturer, has developed its own system based on supercapacitors, the EnerGstor™. In this case, no examples of real application could be found. Adeneo, a member of Adetel Group, has developed a stationary ESS based on supercapacitors that is commercially known as NeoGreen® Power. This system is currently being tested in line T2 of the public transport network of Lyon (TCL), where one 1 kWh bay has been in operation since March 2011 with very promising initial results, [128]. In turn, Woojin Industrial Systems has been contracted by the Korean Railroad Research Institute (KRRI) to install and test an ultracapacitor-based wayside ESS in the Seoul metro system. First results from this project showed that the system could reduce overall energy consumption by 23.4% and would help stabilise the network voltage, [129]. Other EDLC-based systems commercially

available are Capapost, developed by Meiden, and the aforementioned Envistore™ system, marketed by Envitech Energy, a member of the ABB Group. These systems have been reported to be installed in Hong Kong and Warsaw metro systems, respectively.

Table 5

Brand name	Manufacturer	ESS	Application in urban rail	Ref.
Sitras® SES	Siemens	EDLC	-Madrid metro, in service since 2003; -Cologne public transport network, in service since 2003; -Beijing metro, in service since 2007; -Toronto rail transit, in service since 2011.	[118], [125], [126].
EnerGstor™	Bombardier	EDLC	-	[127].
NeoGreen® Power	Adeneo (Adetel Group)	EDLC	-Lyon tramway, pilot project in 2011.	[128].
-	Woojin Industrial Systems	EDLC	-Gyengsan light rail system, pilot project in 2008 and 2009.	[129].
Envistore™	Envitech Energy (ABB group)	EDLC	-Warsaw metro, to be implemented. -Philadelphia transit system, pilot project in 2012 (battery-based).	[130], [131].
Capapost	Meiden	EDLC	-Hong Kong metro, to be delivered.	[132], [133].
Powerbridge	Piller Power Systems	Flywheel	-Hannover metro, pilot project in 2004; -Rennes metro, pilot project in 2010.	[26], [134].
GTR system	Kinetic Traction Systems	Flywheel	-London metro, pilot project in 2000. -New York City transit system, pilot project in 2002. -Lyon metro, pilot project in 2003-2004.	[39], [135], [136].
Regen® system	Vycon	Flywheel	-Los Angeles metro, to be delivered.	[137], [138].
Gigacell® BPS	Kawasaki	NiMH	-New York City Transit network, pilot project in 2010.	[40].
B-CHOP	Hitachi	Li-ion	-Kobe transit system, pilot project in 2005 and regular service since 2007; -Macau metro system, to be delivered.	[41], [139], [140], [141].
Intensium Max	Saft	Li-ion	-Philadelphia transit system, pilot project in 2012.	[142], [143], [144].

As an alternative to EDLC technology, on the market one can find stationary ESSs using flywheels, as for example Powerbridge (by Piller Power Systems), GTR (by Kinetic Traction

Systems) or Regen[®] (by Vycon). The Powerbridge system has been firstly tested within a pilot project carried out in Hanover (Germany) in 2004 with very promising results in terms of power peaks minimisation and energy savings. More recently, a 1 MW unit has been installed in the metro system of Rennes (France) with considerable energy saving results, [26]. As for the GTR system, it is interesting to mention that it has been originally developed by Urenco Power Technologies (UPT), but KTSi holds exclusive license to manufacture and commercialise the technology since 2010, [135]. Some demonstration projects had successfully been carried out prior to the technology acquisition by KTSi, for instance in the London Underground (2000), in the New York City Transit system (2002) or in the metro of Lyon (2003 and 2004), see [39] and [136]. Lastly, the Regen[®] system has been mainly used for braking energy storage in cranes, but the manufacturer offers a version specifically designed for railway applications, [137]. It has been recently announced that Vycon will install a wayside ESS at Los Angeles metro network, [138].

4. Reversible substations

4.1 General characteristics

In DC networks, substations typically provide current only in one direction (power to trains) and are not able to drive the electricity generated in the system back to the distribution grid. This is because conventional substations use diode rectifiers that only permit unidirectional flow of power. In contrast, reversible substations (also known as bidirectional or inverting substations) include an inverter enabling a bidirectional operation, see Figure 6. This means the excess regenerated energy may be used in the operator's network (lighting, escalators, offices, etc.) or eventually sold back to the energy provider, depending on the legislation of

each country or community, [44]. Note that the medium voltage distribution network (AC) is naturally receptive.

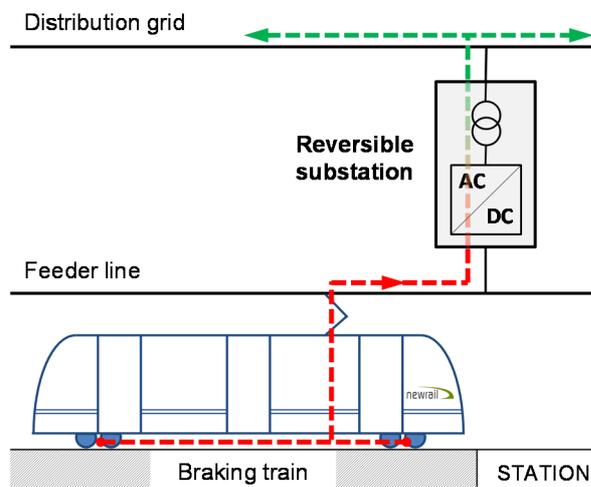


Figure 6 Schematic of reversible substations in urban rail

Although the main objective of reversible substations is to maximise the braking energy feedback to the upstream network, they should leave priority to natural exchange of regenerated energy between vehicles. Additionally, reversible substations are required to minimise the level of harmonics, ensuring a good quality of power supply in both AC and DC sides. Maintaining the output voltage in traction and regeneration modes to reduce losses is another important function that inverting substations have to meet.

Inverters typically consist of a reversible thyristor-controlled rectifier (RTCR) that enables the current flow to circulate in both directions. In addition to the bidirectional operation, the use of RTCRs instead of common diode rectifiers may provide additional advantages such as better voltage regulation and fault current limiting, [45].

When compared with ESSs, recuperation of braking energy through reversible substations may be considered a more efficient option as they present fewer transformation losses.

However, the resistive losses could be relatively high if a fine-tuned analysis for selecting the most adequate locations is not carried out. Other important advantages of reversible

substations over ESSs are the following: 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 stabilisation or peak reduction purposes.

One of the main obstacles for the use of reversible substations in urban rail systems may be the high investment costs associated to their installation. As a way to reduce the payback period, the energy sent back to the grid could be maximised by reducing 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. Interestingly, it has been estimated that the payback period might be less than three years depending on the line configuration, [45].

4.2 Overview of case studies and commercial systems

As introduced above, determining the optimal number and location of inverting substations requires a complete study and analysis of the entire transport system. In [42], for instance, a deterministic technique is proposed to ascertain the optimal capacity, location and control of reversible substations in urban rail systems. Applying the proposed methodology to an existing rapid transit system, the study concluded that the optimal solution was to install thyristor inverters in two of the five substations. Energy savings of up to 14% were reported to be potentially achieved with that measure.

A study on the feasibility and the interest of reversible substations as a means to save energy in metropolitan rail systems is presented in [43]. This work of the French National Railway

Company (SNCF) shows that the amount of energy that potentially might be sent back to the main distribution grid in the Regional Express Network of Paris is about 7%.

Regarding reversible substations currently available on the market, one can mainly find the following solutions: the HESOP system developed by Alstom, the Sitras[®] TCI of Siemens and the INGEBER system of Ingeteam.

The HESOP (Harmonic and Energy Saving Optimizer) system consists of a reversible substation for tramways that has been developed by Alstom in partnership with Convertteam within the framework of the RailEnergy project (FP6 – 031458). It is essentially made up of a thyristor rectifier bridge associated with an IGBT converter, [46]. In the traction mode, the rectifier transforms AC into DC, while the inverter acts as an active filter. In the recovering or braking mode, in turn, the converter regenerates the energy back to the AC side while the rectifier remains inoperative. Simulation results showed that the HESOP system would improve the receptivity of the Utrecht-Zwolle regional line (The Netherlands) up to 99%, allowing for energy savings of about 7% in traction consumption. In order to validate the system, two prototype reversible substations were constructed and successfully tested, [46]. Currently, Alstom commercialise units of 750 V-DC reversible substations for tramway systems.

The Sitras[®] TCI developed by Siemens is based on the add-on concept, which means that the inverter is installed in parallel with the diode rectifiers commonly used in substations, [145].

This enables existing substations acquire the capability to work in reversible mode.

According to the manufacturer, there are two versions of Sitras TCI currently available on the market: for 750 and 1500 V DC powered systems. Regarding the 750V system, it has been tested in the Oslo metro, whilst a customised 750 V solution is being developed for the new Singapore downtown line, [146]. As for the 1500 V version, a real application case can be found in the Bayerische Zugspitzbahn Bergbahn railway. This peculiar line presents a great

potential of braking energy recovery when the vehicles travel downhill as the slope is up to 25 %. Unfortunately, and to the best knowledge of the authors, no measurements of the saving energy provided by Sitras[®] TCI system have been reported so far.

Ingeteam Traction has developed its INGEBER system with the aim of enabling existing DC substations to return the exceeding braking energy to the general three-phase grid. The system basically consists of a DC/AC converter installed in parallel to the rectifier of existing substations. In order to demonstrate the viability of INGEBETER, a prototype was installed in the metro system of Bilbao (Spain) in August 2009, [44]. Being fitted on a section with great energy exchange between trains due to the intense transit, the system was able to save up to 11% of the substation annual energy consumption.

Finally it is interesting to highlight a recent project led by the Southeastern Pennsylvania Transportation Authority (SEPTA), where the combination of energy storage and return to the main grid has been proposed for the first time [131]. This innovative solution integrates a wayside ESS based on batteries (Intensium Max of Saft) with a smart grid technology developed by Viridity Energy, see section 3.4.3. The energy flow in the system is managed as a function of the electricity market pricing, the battery state of charge and the availability of braking energy from the trains. With this project, SEPTA aims to capture the full regenerative capability of the Market-Frankford Line (Philadelphia, USA), reducing the overall power consumption by more than 10% (1,200 MWh per year).

5. Conclusions

A comprehensive overview of the currently available technologies for recovery and management of braking energy in urban rail has been presented in this paper. Different methodologies to increase the interchange of regenerated energy between trains have been discussed. Additionally, a state-of-the-art review on the energy storage technologies for urban

rail applications has been presented. Lastly, reversible substations have been analysed as a means to increase the braking energy recovery by improving the receptivity of the line. The main conclusions that can be drawn from the present study are summarised below.

Implementation of timetable optimisation techniques may significantly increase the interchange of regenerated energy between vehicles, therefore reducing the total consumption in the system and the peaks of demand. Energy savings between 3% and 14% have been reported for different urban rail systems analysed in the literature. Since this is a relatively low-cost measure, it could be considered as the first option to increase the amount of energy recovery in urban rail systems. However its application might be limited by service requirements.

The high number of scientific studies, demonstration projects and commercially available systems demonstrates that ESSs can be regarded as a valid solution to improve efficiency and reliability in urban rail systems. From the literature review, it can be concluded that energy savings between 15% and 30% can be achieved by utilising ESSs. In addition to that, it has been identified that ESSs may mitigate other problems typically associated to urban rail such as voltage drops or pronounced peaks of consumption. It has been seen that wayside systems may be more adequate than on-board when no operation without OCL is required.

As for the technologies available for ESSs, it has been concluded that EDLCs, batteries and flywheels are currently the most suitable options for urban rail applications. Notwithstanding, it has been observed that supercapacitor-based systems have been the most utilised ones so far. The main reasons for that are their long lifecycle, high power density and fast response. Interestingly, Li-ion and NiMH batteries may be looked as a valid alternative for on-board ESS when a high degree of autonomy is required. However, more advances in terms of durability and power density seem to be still needed for batteries to be extensively used. Composite flywheels offer great features for railway systems, but safety issues may limit

their application to wayside ESSs. The combination of supercapacitors and batteries has been identified as the most promising solution for on-board systems providing catenary-free operation.

Sending the excess regenerated energy back to the main distribution grid with reversible substations may be regarded as a very interesting alternative to reduce energy consumption in urban rail systems. The greatest advantage of this option is that the upstream AC network is permanently receptive and, as a result, all the regenerated energy may be potentially recovered. However, the economic benefits of reversible substation strongly depend on the possibility to sell the energy to the public network operators and the price set by them.

As a final conclusion, it can be said that, even though regenerative braking is a proven technology, its application in urban rail systems remains relatively unexploited. A transfer of knowledge at international level between operators, manufacturers and other stakeholders is essential to achieve the great potential offered by regenerative braking, both in terms of energy efficiency and emissions reduction.

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