WP2B ENERGY RECOVERY

Overview of braking energy recovery technologies in the public transport field

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- GMPTE (Manchester, UK)
- moBiel (Bielefeld, Germany)
- RATP (Paris, France)
- RET (Rotterdam, The Netherlands).

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Executive summary

The objective of this document is to provide an overview of braking energy recovery technologies in the public transport field. To avoid energy losses and reduce the overall energy consumption, solutions are being developed by various suppliers. Three types of applications can be defined: mobile storage applications, stationary storage applications and stationary “back to the grid” applications. Different technologies are developed for these applications: batteries, supercapacitors, flywheels and reversible substations.

The analysis developed in this document shows that braking energy recovery technologies have become a priority for the industry and many pilot projects have blossomed all over the world. However, only a very limited number of transport operators have taken the step to invest in these green technologies. The main reason seems to be that these applications are still young with little experience feedback on the systems lifecycle and return on investment.

The European project *Ticket to Kyoto* aims precisely at countering this lack of experience through the publication of this document and other dissemination activities.

Introduction

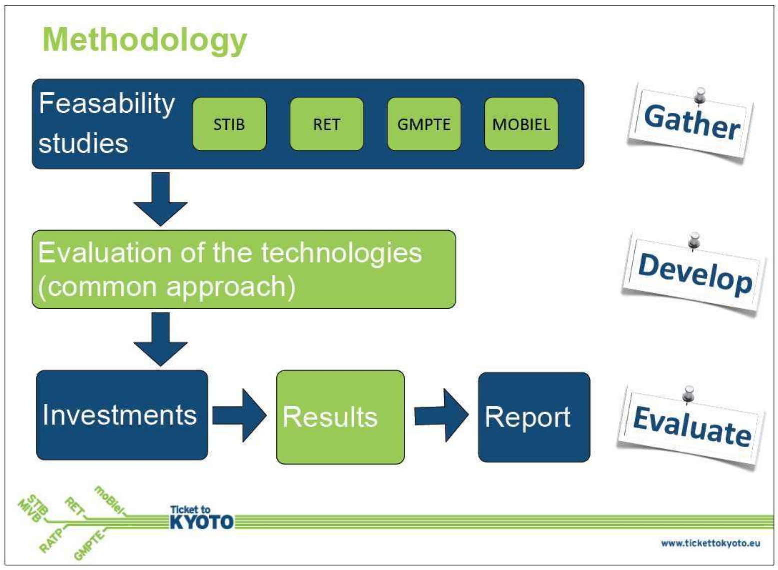
Five European public transport companies have joined forces to reduce CO_2 emissions in public transport. Their actions are centralized through a European project, Ticket to Kyoto (T2K - www.tickettokyoto.eu), that mobilises public transport companies and their stakeholders to take action against climate change.

Among the various investments envisioned in the T2K project, the recovery of metro and tram braking energy is an important target and all partners are following closely the evolution of the market in this field since several years.

This document is the first output of the braking energy recovery workgroup and aims at presenting the main technologies deployed in this field. The technologies presented in Section 2 are batteries, supercapacitors, flywheels and reversible substations. Section 3 presents the concept of energy recovery. Section 4 gives an overview of existing technologies and the current implementations in the public transport field whereas Section 5 aims at comparing these various technologies. Finally, a conclusion is drawn in Section 6, and external references are listed in Section 7.

Methodology

The methodology proposed in this workgroup is depicted below and consists in three steps: gather, develop and evaluate.

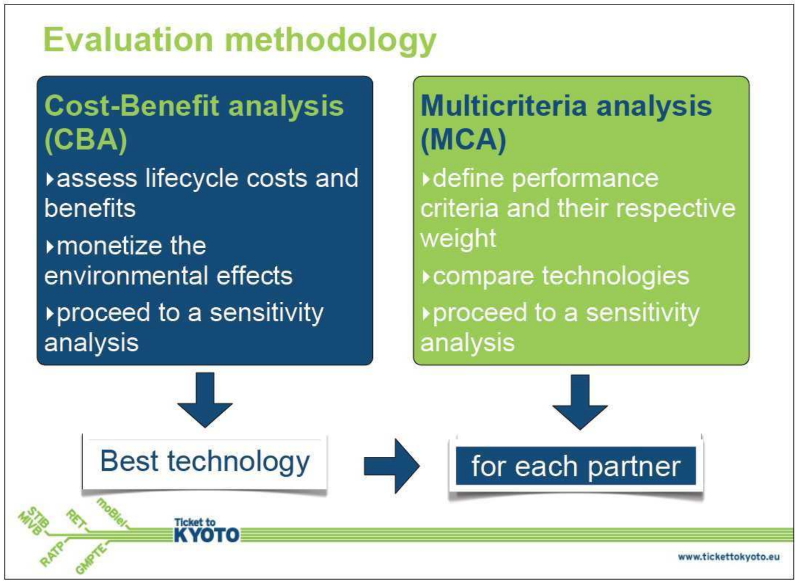


The first step was to **gather** all feasibility studies made by the partners and exchange on the results.

Second step consists in **developing** tools for evaluating the several technologies available on the market. Technologies differ in many aspects: cost, efficiency, maintenance, environmental aspects, … In order for each partner to make the best informed choice, a common approach will be developed consisting in two analyses:

- **Multicriteria Analysis:** this analysis enables to integrate in the same framework quantitative and qualitative criteria and to assign them a specific weight.
- **Cost-Benefit Analysis:** this analysis consists in evaluating the technology costs and benefits during the system lifetime including externalities.

The output of both analyses will help each partner to select the best technology for its context.

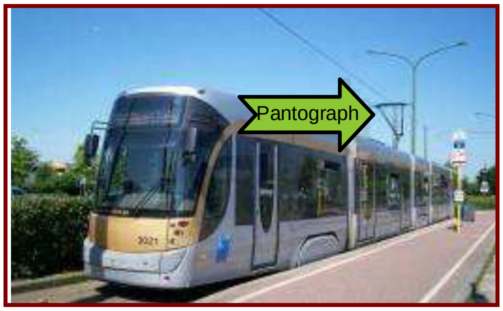


The final step will be to proceed with the investments for energy recovery solutions and to **evaluate** the results of each investment.

The concept of energy recovery for public transport

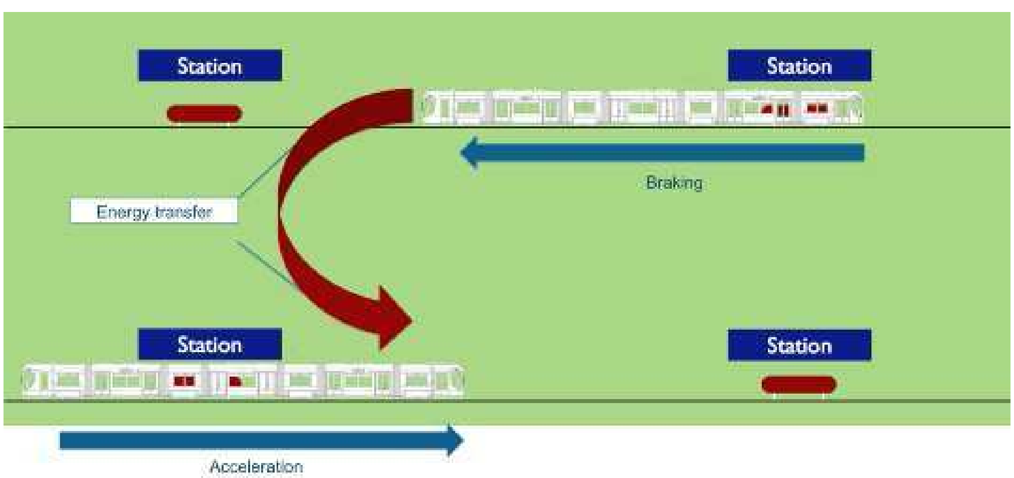
Electricity supply

Urban rail vehicles are propelled by electric motors. In the case of a tram, electricity is generally supplied by an overhead line (also called "catenary") through the pantograph. In the case of a metro train, the electricity is supplied by a third rail running all along the track. Both overhead lines and third rails are fed in electricity by substations placed along the tracks.



Dynamic braking

Most recent rail vehicles have the ability to regenerate the braking energy into electrical energy. In that case, the electric motor can be configured to recover the mechanical energy produced by the vehicle inertia (kinetic energy) and works then as a generator producing electricity. In these vehicles, while a small portion of this kinetic energy can be reused to power vehicles auxiliaries, the remaining energy can be sent back to the network and hence recovered only if a vehicle is accelerating nearby. In this case, the accelerating vehicle takes advantage of this energy transfer. If it is not the case, the network voltage increases due to the energy excess and this extra energy has to be burnt in braking resistors. This principle is shown on the figure below. In a metro network, these energy transfers between vehicles usually amount to 20-30% of the total consumption.



Types of applications

To avoid these energy losses and reduce the overall energy consumption, solutions are developed and tested in different conditions and contexts. By reducing the energy consumption, these systems can strongly impact the operational costs linked to the energy prices and substantially lower CO_2 emissions as well as other harmful pollutants emissions induced by the production of electricity in power plants.

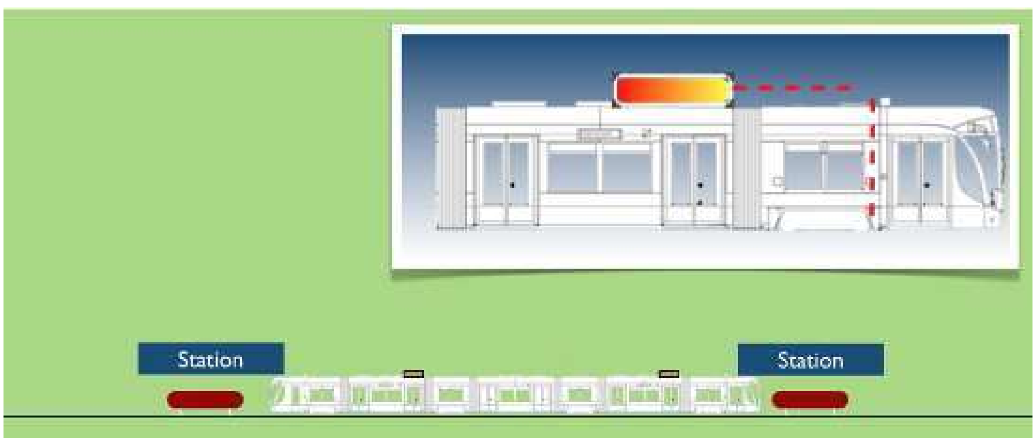
Three types of applications can be defined:

- **Mobile storage applications**
- **Stationary storage applications**
- **Stationary "back to the grid" applications**

In the remainder of this section, we describe each application and present its main benefits and drawbacks.

Mobile storage applications

Mobile storage applications consist of onboard energy storage systems (ESS) usually located on the vehicle roof. Every system works independently and the recovered energy is directly sent to the storage system placed on the vehicle When the vehicle accelerates, energy is used in priority from the ESS to propel the vehicle. This principle is illustrated in the figure below.



Benefits

- High efficiency due to reduced overhead line losses, the storage being located on the vehicle
- Possibility to operate the vehicle without overhead lines on certain sections of the route (urbanistic integration)
- Voltage stabilization by mitigating voltage sags[1]
- Reduction of the peak power demand by averaging loads over a period of time
- Potential down-sizing of the onboard braking resistors

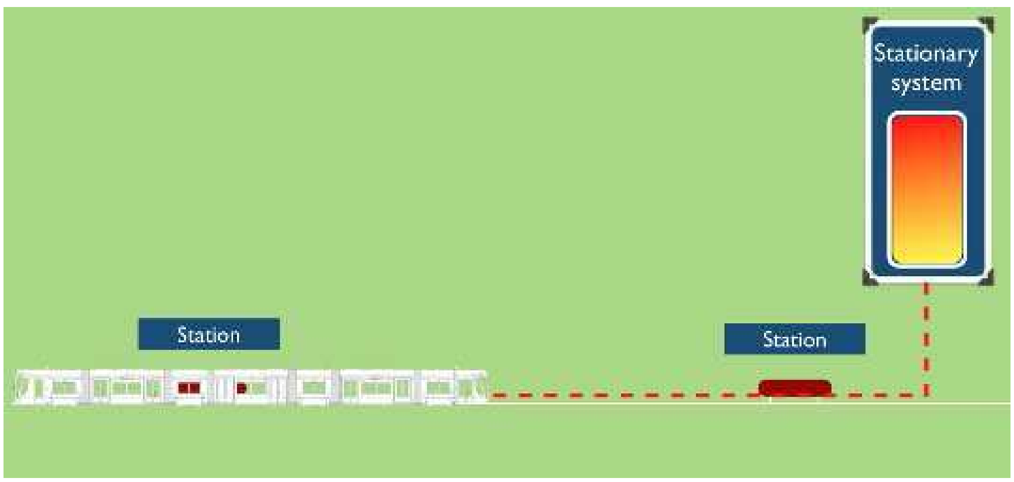
- [1] A voltage sag is a temporary drop below a certain threshold of the nominal voltage level

Drawbacks

- Retrofitting of old vehicles (space availability and weight constraints)
- Placement of one ESS per vehicle (increase in the costs)
- Standstill of the vehicle for implementation, maintenance and repair
- High safety constraints due to passengers onboard

Stationary storage applications

Stationary storage applications consist of one or several energy storage systems (ESS) placed along the tracks. These devices recover the exceeding energy when no other vehicle is receptive meanwhile. The principle is shown on the figure below.



Benefits

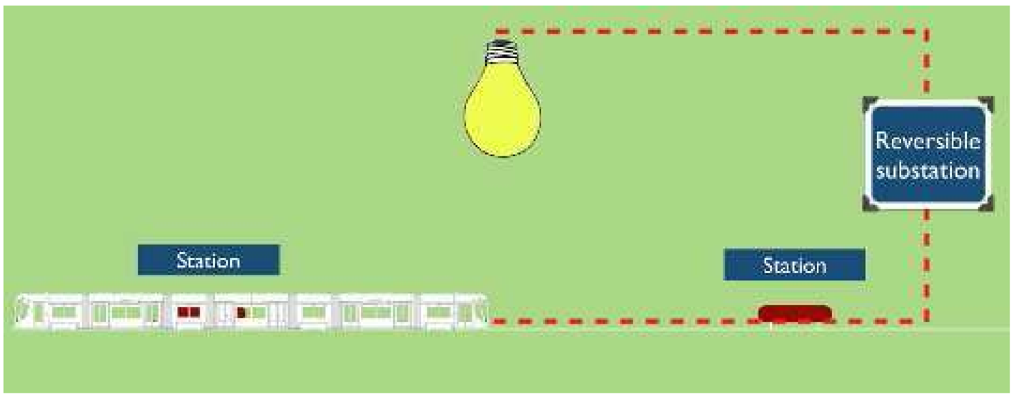
- Can be used by all vehicles running on the line
- Voltage stabilization by mitigating voltage sags
- Reduction of the peak power demand by averaging loads over a period of time
- Reduction of the number of traction substations or possibility to add vehicles without upgrading the electrical network
- Reduction of the waste heat, which avoids warming tunnels and stations
- Potential down-sizing of the line-side braking resistors
- Lower safety constraints in comparison with onboard systems
- Implementation, maintenance and repair do not affect operations (switch off mode)

Drawbacks

- Fine-tuned analysis for sizing the systems and for choosing the right locations
- Less efficient system due to overhead line losses increasing with the distance of the vehicle
- If undersized, some energy may still be lost in the braking resistors
- Place availability in the substations or along the line
- No opportunity for catenary-free operations

Stationary “back to the grid” applications

The main difference with the previous applications is that “back to the grid” applications do not store the recovered energy but send it to the main electrical grid for other consumers such as lighting, escalators, administrative and technical buildings or potentially sold back to the energy provider. The principle is shown on the figure below.



Benefits

- Can be used by all vehicles running on the line
- Very energy efficient due to fewer transformation losses than in storage applications
- Compared to storage applications, reduction of the waste heat, which avoids warming tunnels and stations
- Potential down-sizing of the line-side braking resistors
- Lower safety constraints in comparison with onboard systems
- Implementation, maintenance and repair do not affect operations (switch off mode)

Drawbacks

- Fine-tuned analysis for choosing the right locations
- Place availability in the substations or along the line
- No opportunity for catenary-free operations
- No voltage stabilization and reduction of the peak power demand due to the lack of energy buffer (no storage)
- No reduction in the number of traction substations

Technology overview

In this section, we present the main technologies envisioned for braking energy recovery applications. These technologies are:

- **Batteries**
- **Supercapacitors**
- **Flywheels**
- **Reversible substations**

For each technology, we present a short technical description and examples of prototypes in the public transport sector.

Batteries

Technical description

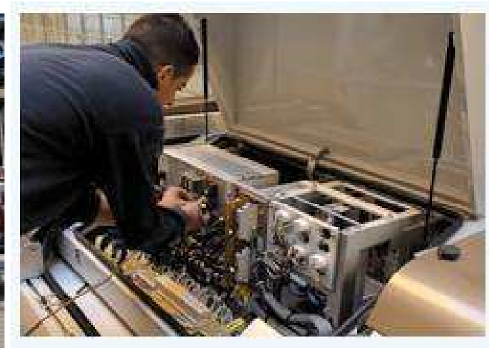
In the context of energy recovery, batteries act as an energy storage system (ESS) by storing energy through an electrochemical reaction. Batteries are found in a large range of sizes and power ratings and most of them work on the same principle: between two different materials (electrodes) immersed in an electrolyte solution, a potential difference occurs.

Prototypes in the public transport sector

In this section, we present five examples of recovery solutions based on batteries from ALSTOM, SAFT, KAWASAKI and KINKI SHARYO.

ALSTOM/SAFT – Ni-MH batteries

An ALSTOM Citadis tramway operates in Nice (France) using an autonomous Ni-Mh (nickel-metal hydride) battery on-board system. This system avoids the use of overhead contact lines over part of the route (11% of the line’s 8.8km) as the vehicle is able to switch its source of traction power between overhead catenaries and the on-board batteries for catenary-free operation. The system helps to preserve the historical character of the city centre when crossing the Massena and Garibaldi town squares. The battery system was supplied by SAFT.



Source: http://tramway.nice.fr

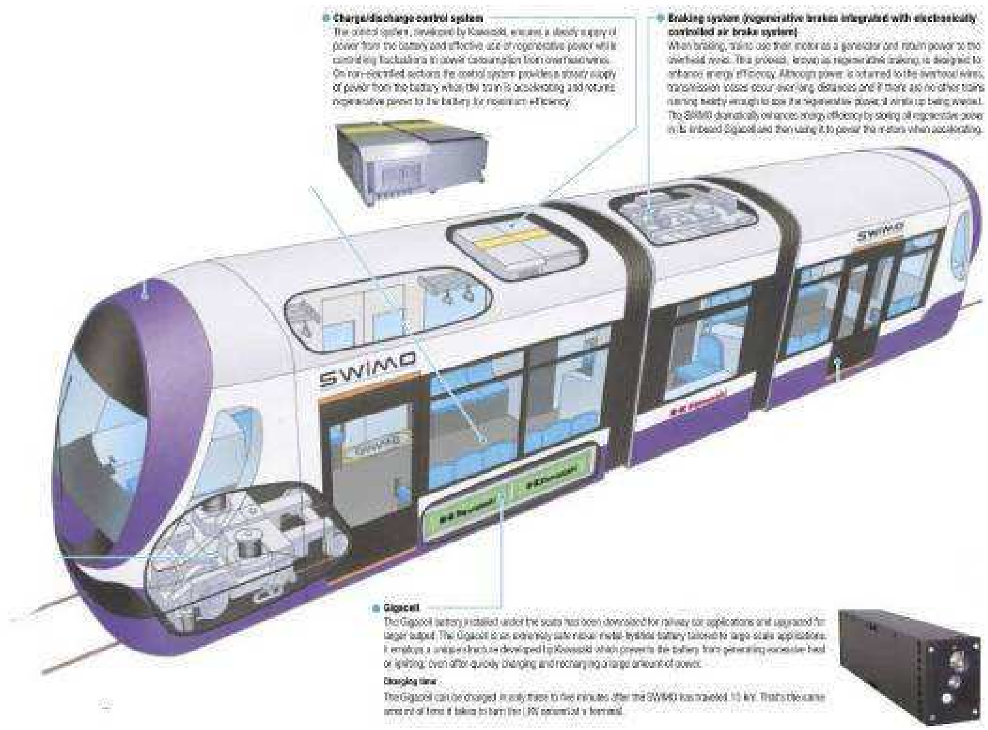
SAFT – High power/high voltage battery

SAFT is developing a braking energy recovery system for railway applications consisting in sending the energy back to the electrical grid through reversible substations but adding a battery buffer for residual excess energy. The system is composed of Lithium-Ion battery pack of 7kWh (230V) that can be connected in parallel or in series. This system is still at the prototype stage as no system has so far been implemented in real operations.

Source: SAFT

KAWASAKI - Swimo catenary-free system

KAWASAKI has been testing its Swimo catenary-free light rail vehicle in the Japanese city of Sapporo. Swimo uses Kawasaki Gigacell NiMH batteries, which can be fully charged in five minutes through the 600V dc overhead catenary. This allows the vehicle to operate for up to 10 km on non-electrified lines under standard operating conditions. The system can also store energy from regenerative braking and use it for traction.



Source: KAWASAKI (http://www.kawasakirailcar.com/overview-of-swimo.html)

KAWASAKI –Gigacell Battery Power System (BPS)

Kawasaki is manufacturing stationary battery systems for braking energy recovery and network voltage stabilization. The system is made of 20 modules offering different voltage configurations and may be placed in parallel. In certain conditions, this system could replace a substation and it offers a good reliance in case of emergency as the high amount of energy stored in the modules would allow trains to move to the nearest stations when main power has failed.

Typical 20 module Single Unit Dimensions

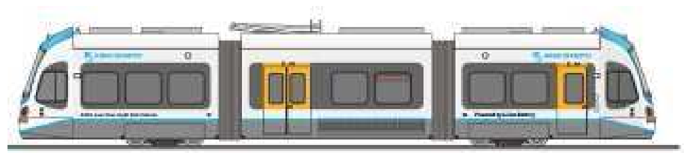
Size: 2.4 x 1.4 x 1.5 (m)
5.0m (176.4ft)/ Unit
Weight / Unit: 5 Tons

Voltage	No. of Modules per Unit	Capacity	Application
600	16	148kWh/unit	Light Rail
650	17	160kWh/unit	US Authorities (NYCTA)
750	19	185kWh/unit	US Authorities (WMATA)
1500	38	370kWh/unit	JR (Japanese Railways)

Source: KAWASAKI (http://www.kawasakirailcar.com/battery-power-system.html)

KINKI SHARYO - LFX-300 hybrid streetcar

A prototype of the LFX-300 100% low-floor hybrid streetcar has been developed by Kinki Sharyo for the US market and marketed as « ameriTRAM ». The vehicle is 20 m long and 2 650 mm wide and is powered by four 120 kW motors. Using technology branded as 'e-Brid', the vehicle can operate by drawing power from overhead catenary or on-board lithium-ion batteries which store regenerated braking energy. According to Kinki Sharyo International, the tram will be able to run for up to 8 km on battery power. This prototype was tested in December 2010 in the city of Charlotte in partnership with Charlotte Area Transit System.



Propulsion control		VVVF inverter control (IGBT) with regenerative and rheostatic brake
Auxiliary power supply		AC440V-60Hz,DC24V
Battery equipment		Li-ion rechargeable battery 40kWh
Trucks	Wheel	Resilient wheel
	Wheel base	1800 mm (5.9ft 70.8in)
	Gear ratio	44/7 = 6.29
	Brake system	Spring applied hydraulic brake Electrical regenerative brake Track brake
	Motor	120kw x4, 550V, 2370rpm (self-cooling type)

Source: KINKI SHARYO (http://www.kinkisharyo.co.jp/eng/e_news/e_news100819.htm)

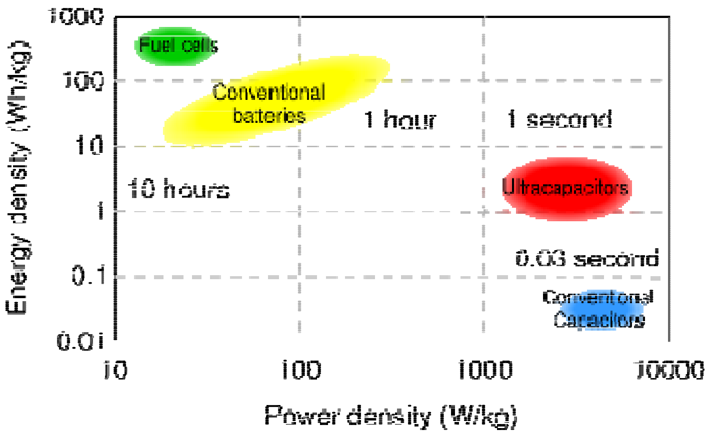
Supercapacitors

Technical description

Supercapacitors are electrochemical storage devices that operate like large versions of common electrical capacitors where energy is stored in an electrostatic field by means of charge separation. In contrast to batteries that are charged and discharged through an internal chemical reaction, in a supercapacitor, the energy is stored as a charge or concentration of electrons on the surface of a material [i] and no chemical reaction occurs.

Supercapacitors, which are also called *"ultracapacitors" or "electrochemical double layer capacitors (ELDC)",* are not a new concept since scientists have studied the electrical charge in the interface between a metal and an electrolyte since the 19th century. NEC produced the first commercially successful double-layer capacitor under the name of *"supercapacitor"* in 1971. These devices were designed for memory back-up in low power applications due to the high internal resistance of the first models. Nowadays several companies produce supercapacitors at commercial level in several countries [ii].

Supercapacitors bridge the gap between conventional capacitors and batteries. They can store 10 to 100 times more energy than conventional capacitors and can deliver around 10 times higher power than most batteries of equivalent size [[iii]]. The position of supercapacitors against other energy storage devices is shown on the graph below.



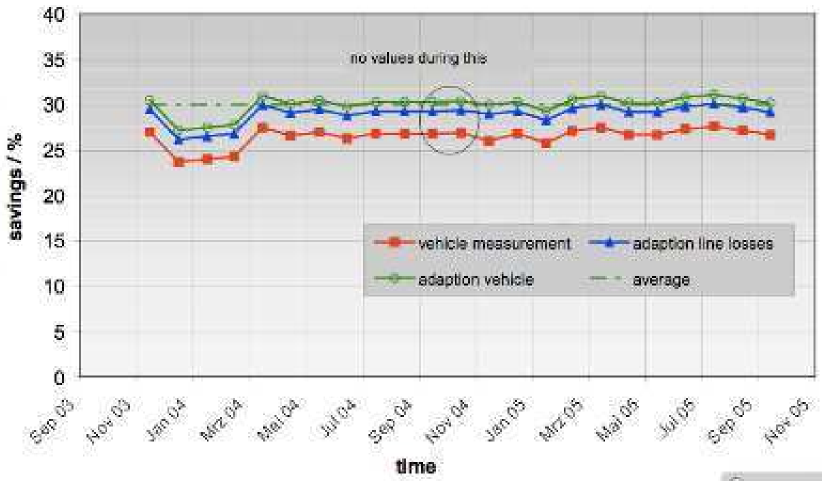
Source: Wikipedia

Implementation in the public transport sector

In the following, we present seven solutions deployed by BOMBARDIER, SIEMENS, ALSTOM, CAF, ADETEL and WOOJIN.

BOMBARDIER - MITRAC energy saver

Bombardier Transportation has developed the MITRAC energy saver designed for a use aboard light rail vehicles (LRV) with the main objective of energy recovery. A vehicle prototype of the Mannheim public transport operator MVV (Germany) has completed four years of trial in passenger operation between 2003 and 2007. Long-term results showed that the tram's traction power consumption was reduced by 30% and the overall power needs including doors, air-conditioning and lighting were cut by a total of 20%. The 1 kWh unit enabled the vehicle to run with its pantograph lowered over 500 meters. The savings come from the braking energy recovery, which is converted into electrical energy by the motor/generator, sent to the DC link via the traction inverter and stored in the on-board supercapacitor banks. MVV has decided to include MITRAC energy saver on 19 trams ordered in October 2007. This will allow the city of Heidelberg to avoid erecting catenaries through the planned extension of the university campus. The company expects that the additional cost per vehicle will be recovered over the first 15 years of the vehicle life [iv].



<u>Source</u>: BOMBARDIER

The MITRAC energy saver can develop other functions such as network voltage stabilization or catenary-free operation but in this prototype, it was optimized for energy recuperation. The MITRAC energy saver is made up of some 300 Maxwell supercapacitor cells and includes a voltage balancing system, a temperature controller and a power converter [v].

Technical data of the Mitrac Energy Saver:

- Maximum power: 300 kW
- Installed energy: 850 Wh
- Weight: 477 kg
- Dimensions: 1900 x 950 x 455 mm
- Cooling: forced air

<u>Source</u>: BOMBARDIER

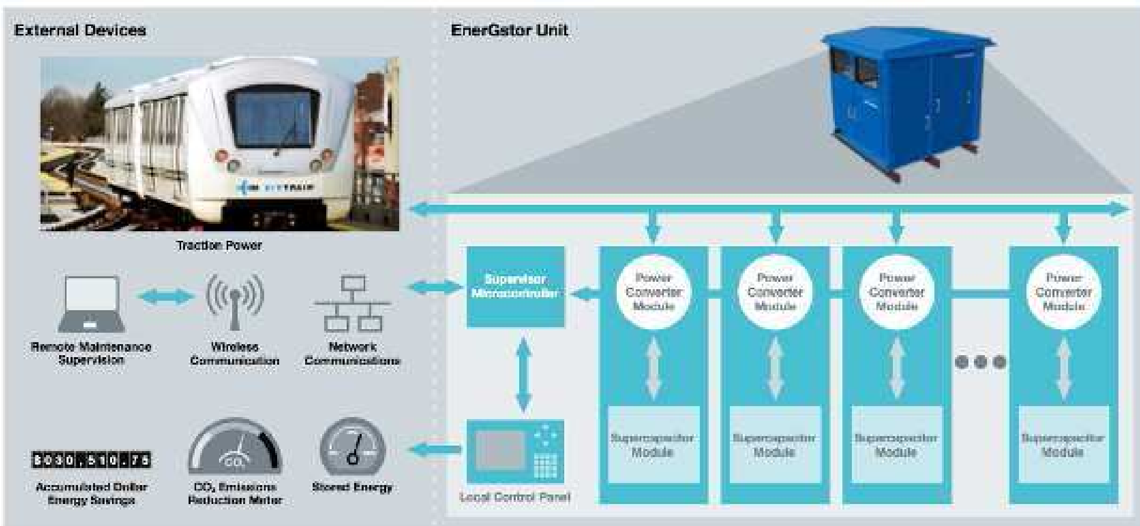
BOMBARDIER – EnerGstor – Wayside energy storage system

BOMBARDIER developed a wayside energy storage system based on supercapacitors called EnerGstor. Besides recovering braking energy, the system can also reduce the peak demand and mitigate the voltage sags. The EnerGstor is composed of different modules as depicted below. These modules can be placed in parallel and can be monitored by a remote system. The system is still at a prototype stage.

Technical data

EnerGstor Wayside Energy Storage (for 1kWh unit)

Voltage	600Vdc or 750 Vdc, 1500 Vdc (optional)
Max Energy (kWh)	1.0
Max output power (kW)	650
Cooling	Cooling/Ventilation unit
Dimension (mm)	1800H x 1800W x 2000L
Operating Ambient Temperature	-30C to +40C



Source: BOMBARDIER

SIEMENS – SITRAS MES & HES

Siemens has developed the SITRAS MES mobile energy storage system for on-board applications and the SITRAS HES, hybrid system, combining the supercapacitors modules with a Ni-MH traction battery. The MES system is used mainly for energy recovery to reduce the vehicle consumption whereas the HES system allows the vehicle to store both braking energy and power drawn from the catenary and enables longer operations without overhead contact lines as both the supercapacitors and batteries can be used in parallel to further enhance the energy saving capabilities. The roof-mounted modules have been installed in spare roof space on an MTS Siemens Combino Plus LRV, and are electrically connected to the vehicle's power by means of a step-up/step-down chopper. SITRAS HES can complete its charging cycle in just 20 seconds, taking power from the catenary or a charging point while the LRV is standing in a station. This provides sufficient power for the vehicle to run independently for up to 2.5 km, depending on the operating conditions.

Technical data*		
Energy storage: Double-layer capacitors		
Usable energy content	[kWh]	0.85
Maximum power	[kW]	2 x 144
Range of operating voltage	[V]	190 - 480
Cooling		forced air cooling
Dimensions (width x depth x height)	[mm³]	2,000 x 1,520 x 630
Weight	[kg]	820
Energy storage: Traction battery		
Usable energy content	[kWh]	18
Maximum power	[kW]	105
Nominal voltage	[V]	528
Cooling		water cooling
Dimensions (width x depth x height)	[mm³]	1,670 x 1,025 x 517
Weight	[kg]	826

* other values on request

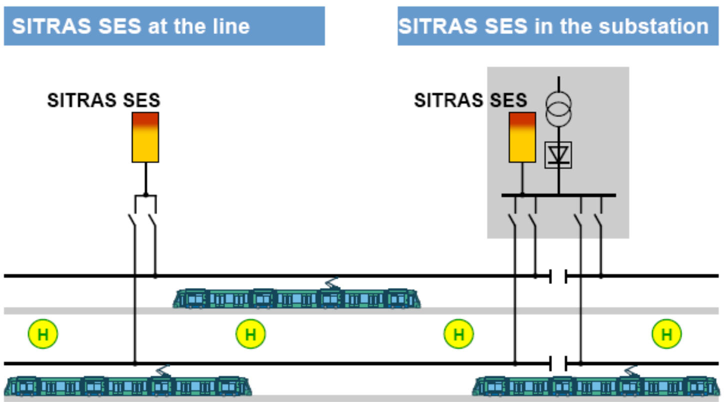
Source: SIEMENS

The SITRAS HES energy storage system has completed a successful six-month trial, which has been used in passenger service on Lisbon's Metro South (MTS) light rail network. The test vehicle operated without overhead power supply on a 2.6% gradient with auxiliary power of 5kW and a maximum speed of 30 km/h. This vehicle has operated 20.000 km in revenue service since November 2008 with almost 100% reliability, achieving an energy saving of 10.8% compared with the standard Combino Plus vehicles in the MTS fleet. Siemens says the system can reduce CO_2 emissions by up to 80 tonnes per year [vi]. On new vehicles supplied by Siemens, the chopper is integrated into the traction converter. The system can also be mounted on older vehicles, including those of other manufacturers. TUV Süd has approved both integrated and independent systems in accordance with the German construction and operating code for tramways [vii].

SIEMENS – SITRAS SES

The SITRAS SES (Static Energy Storage) consists in a bank of supercapacitors (3000 Farads and 2.7V) installed at some points of the network to recover the energy of the vehicles operating on the line [viii] and to stabilize the voltage at weak points [ix]. The system is composed of supercapacitors interconnected and mounted in a massive shelf located either at the substation level, in parallel with the power supply, or at critical points such as end of lines where voltage drops are prone to occur. Voltage balancing and temperature control devices are provided and a power converter is included. The system offers a usable energy content of 1.7kWh to 2.5kWh depending on the chosen configuration. The system is in full time service in many cities including Bochum, Cologne and Dresden (Germany), Madrid (Spain), Peking

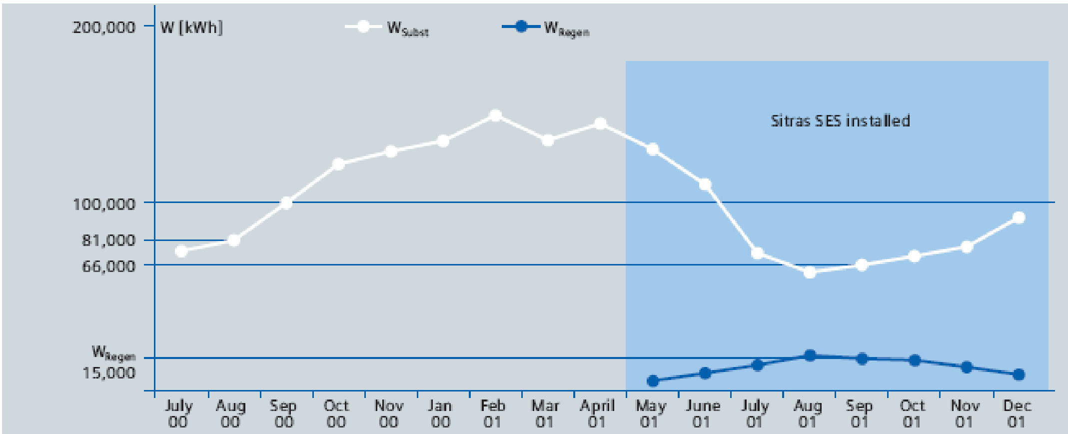
(China). This static system is designed for energy recovery at the substation level and can be used for several vehicles operating on the same line.



Technical data			
Input voltage (tolerance range according to EN 50163)	[V DC]	600	750
Total number of double-layer capacitors		1,050	1,344
Total capacity	[F]	103	80
Usable energy content	[kWh]	1.7	2.5
Maximum energy saving possible per hour	[kWh/h]	50	80
Peak power	[MW]	1	1
Auxiliaries supply	[V]	3 AC 400	3 AC 400
Permissible ambient temperature	[°C]	-20...+40	-20...+40
Maximum operating height above sea level*	[m]	2,000	2,000
Dimensions of the four double cubicles (Width x Depth x Height)			
– Cubicle +S1/+S2 and +S3/+S4	[m]	1.4 x 0.7 x 2.7	1.4 x 0.7 x 2.7
– Cubicle +S5/+S6 and +S7/+S8	[m]	1.2 x 0.9 x 2.7	1.2 x 0.9 x 2.7
Weight	[t]	approx. 4.0	approx. 4.3
* other values on request			

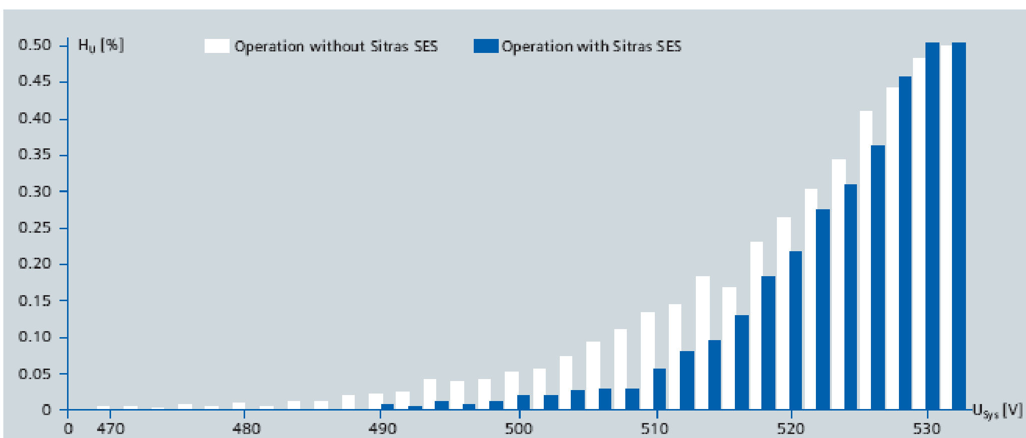
Source: SIEMENS

In Cologne, the system is used in energy-saving mode. A reduction of 40kWh/h in primary power consumption has been observed, resulting in 320.000 kWh saved annually. Depending on the circumstances, a maximum of 500.000 kWh could be saved annually by using a single system and potential reductions of 300 tons CO_2 emissions are expected on a yearly basis.



Source: SIEMENS

In the metro of Madrid, the main goal of the system is to stabilize the network voltage. The principle of the SITRAS system is, in this case, to provide energy to the vehicles accelerating when the network voltage falls below a predefined level. After the acceleration, the system is recharged either slowly from the network or fast during a vehicle deceleration. Voltage stability was significantly improved since voltages below 490 V do not occur anymore and the frequency of voltages under 530 V is considerably reduced [x].



Source: SIEMENS

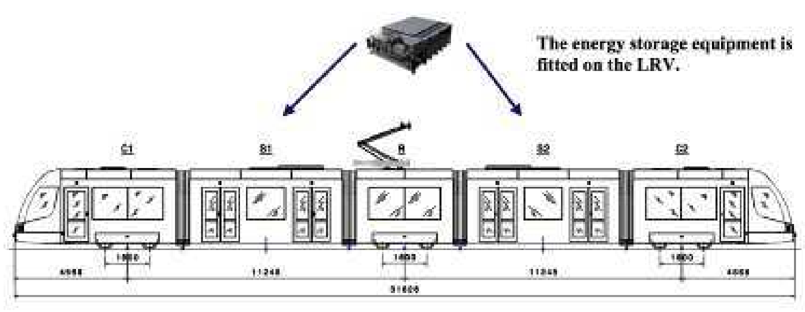
ALSTOM – STEEM project

ALSTOM and Paris transport operator RATP launched in July 2009 a trial phase for a supercapacitors-based on-board energy storage system. Developed under the STEEM (Système de Tramway à Efficacité Energétique Maximisée) research and development project, this system has been mounted on the roof of one low-floor Citadis tram operating on tram route T3 ("Boulevard des Maréchaux"). A bank of 48 supercapacitor modules stores the energy regenerated during the braking phases. One of the braking resistors had to be removed, one converter moved and the pantograph raised to allow the placement of this system. The system can also be topped up from the overhead wire and recharged through the catenary in 20 seconds during dwell times at a stop. The autonomy when driving without catenaries is around 400m at 30km/h. The usable energy amounts to 1.6kWh and will be upgraded to 2kWh. It is estimated that the potential reduction in energy consumption could range up to 30%. The supercapacitors modules are manufactured by the French company Batscap, a Bollore group subsidiary [xi].


Source: ALSTOM

CAF – ACR System

The ACR system developed by CAF is an on-board energy storage system based on the use of supercapacitors which enables trams to run between stops without catenaries, as well as to save energy through the full regeneration of braking energy. The supercapacitors are charged in 20 seconds while the train is stopped at a station. The system can store both the braking energy and the energy received from the network during the journey. The ACR system has been tested on a CAF Urbos-2 LRV for Seville, and will be available pre-installed on its next-generation LRV, the Urbos-3. The system has a working autonomy without catenaries of around 1.200 metres, depending on the capacity installed and the characteristics of each tramline. This system is compatible with other technologies and suitable for use on rolling stock of any type and manufacturer, and on new or existing facilities and infrastructure.



The energy storage modules are fitted on the train connected in parallel with the pantograph.

ACR BOX -number of ACR boxes are defined for each application-	
Nominal Power	226 kW
Maximum Power	400 kW
Energy	Configurable up to 18,1 kwh Up to 5 independent branches of supercaps or batteries
Each branch of supercaps	0,775 kWh (nominal) / 1 kWh (total)
Each branch of batteries	15 kWh
Voltage (nominal / operation)	750V / 500V – 900V
Dimensions ACR box	Max. 2455 mm x 1600mm x 750mm
Weight ACR box	
1 branch	800kg
2 branches	1150kg
3 branches	1500kg
4 branches	1850kg
5 branches	2200kg
Low voltage (nominal / operation)	24V / 16,8V – 32V
Communication interfaces	
Vehicle network	TCN-MVB
Maintenance network	Ethernet
Temperature	-25°C / +50°C
Cooling	Air forced ventilation

Source: CAF

Basque regional operator Euskotren and CAF have agreed to research jointly an on-board energy storage system based on supercapacitors, with the aim of installing a prototype on one of the operator's trains. As part of its Euskotren 21 programme, the railway ordered 27 three-car EMUs from CAF in December 2009 that will be fitted with CAF's Cosmos train control system and regenerative braking to minimise energy consumption.

The CAF-Santana joint venture has also been selected to supply 13 low-floor trams with energy storage for Granada's initial 15.9 km light rail route. The bidirectional trams will be 30 m long and 2 600 mm wide with a total capacity of 200 passengers. The trams will operate using a 750 V DC overhead power supply but will switch to an on-board ACR energy-storage system for catenary-free operation on four separate sections of the route totalling 4.7 km. The maximum speed will be 70 km/h [xii].

ADETEL – NeoGreen Power

The Adetel group has developed the NeoGreen Power system based on supercapacitors and for use in railway applications in energy saving or voltage stabilizing mode. The system offers a storage modularity by autonomous storage branches: every branch includes its own storage, conversion, monitoring and control. The basic system is built in 3 bays but can be extended by optional bays of 0,3 MW peak and 1 kWh energy. The autonomy of every branch allows the system to remain operational in case of one branch faulty [xiii].

Electrical Characteristics

- Input voltage : 750VDC according to EN 50163
- Capacity : 160 F
- Available energy : 3 kWh
- Maximum energy saving per hour : 100 kWh/h
- Peak power : 1MW
- Ambient temperature : -20 to +40 °C
- Humidity : Lower than 92%

- Internal safety : Isolating switch and High Speed Circuit Breaker
- External communication :
  - ➔ Serial link RS232 opto-isolated 115200 Bds
  - ➔ Ethernet 100 Mbps
  - ➔ CAN 2.0B or CANOpen

- Auxiliary power : 400VAC 3ph
- Dimensions : 3 bays of 700 x 1600 x 2100mm
- Weight : < 3000 kg

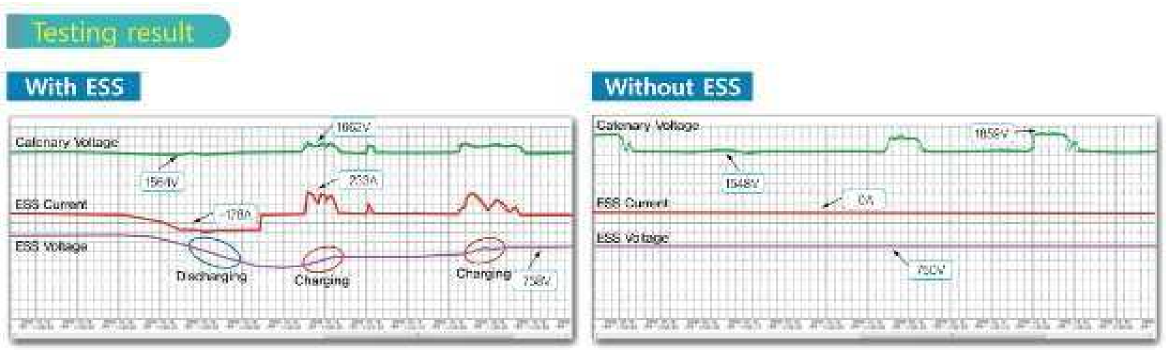
Source: ADETEL

WOOJIN industrial - Seoul metro stationary system

National Korean railway research agency (KRRI) has been trialling the use of lineside supercapacitor modules to store braking energy on the Seoul and New York metro networks. KRRI has contracted Woojin Industrial Systems to manage the pilot project in Korea in 2008. The equipment has been tested at 750 V and 1.5 kV DC at a facility in Gyeongsan. Initial tests suggest that the use of this stationary system could reduce overall energy consumption by 23,4% and would help stabilizing the voltage as shown on the graphs below. If this reduction can be achieved in service operation, KRRI claims that the cost of installing the equipment could be recouped within four years.

Specification (DC 750V)

Super capacitor	Configuration	Size		2.37m(H)x1.84m(W) x1.75m(D)
	Electrical Characteristic	Max. Volt		583.2 [V]
		Max. Amp		1,200 [A]
		Capacitor		82.5 [F]
		Max. Capacity		10.5 [MJ]
Chopper	Configuration	Size	main	1.89m(H)x1.2m(W) x1.54(D)
			sub	1.89m(H)x1.2m(W) x1.54(D)
	Feeder Volt	Charging Volt		800 [V]
		Discharging Volt		700 [V]

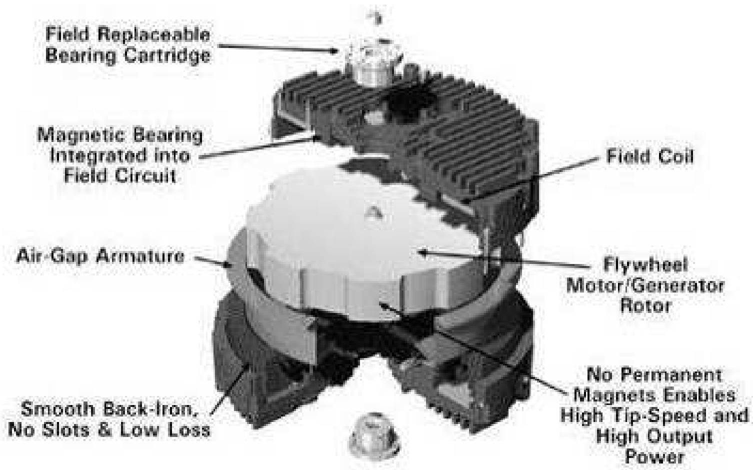


Source: WOOJIN

Flywheels

Technical description

A flywheel is a rotating disc spinning around an axis used for storing energy mechanically in the form of kinetic energy. The flywheel works by accelerating a rotor to a very high speed and maintaining the energy in the system as rotational energy [xiv]. Flywheels can be used to produce high power peaks.



Source: www.activepower.com

Implementation in the public transport sector

In the following, we present solutions developed by ALSTOM, KINETIC TRACTION and PILLER.

ALSTOM – On-board flywheel experience in Rotterdam

ALSTOM developed and tested in real operating conditions a flywheel system for its Citadis tram in Rotterdam. This system was composed of a carbon fibred rotating permanent magnet motor-generator located on the roof of the tram, which works on the same principle as a spinning top. ALSTOM abandoned the project due to technical reasons.

KINETIC TRACTION – GTR SYSTEM

KINETIC TRACTION (formerly PENTADYNE) has developed carbon fibre flywheels (GTR system) to store energy regenerated during braking. The GTR system is a 200kW high cycling flywheel energy storage system featuring a high speed composite rotor running on frictionless bearings requiring no maintenance. It has an available energy of 1.5kWh.

Source: KINETIC TRACTION

New York MTA selected KINETIC TRACTION to provide an improved version of a demonstration flywheel system, which was successfully tested on the Far Rockaway line in 2002. Unfortunately the project was stopped for budget constraints. KINETIC TRACTION is now seeking new opportunities for its technology deployment in the public transport field.

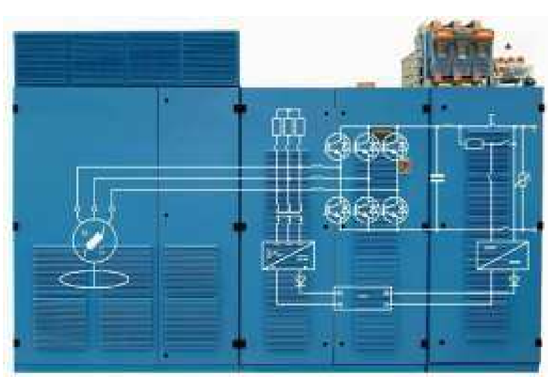
PILLER - Powerbridge

The German company Piller has developed a flywheel energy storage system for the rail transport sector. The Powerbridge storage system consists of the kinetic energy storage unit and the interface between the unit and the contact wire.

Technical Data
POWERBRIDGE for 600V and 750V DC systems

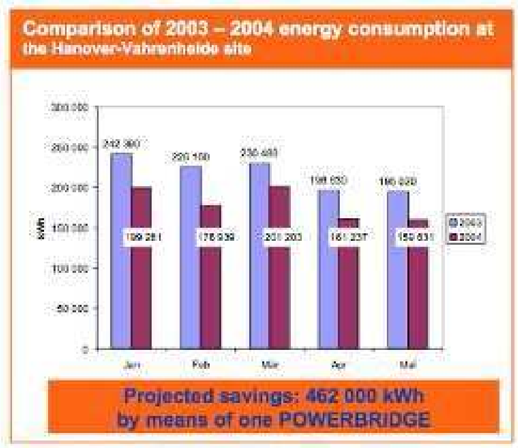
Type		PB 1000-600/750 DC
Electrical data		
Rated Voltage	V	600/750
Minimum permanent voltage	V	400
Maximum permanent voltage	V	900
Maximum non permanent voltage	V	1000
Voltage range according to EN 50 163		
Rated current	A	1500
Maximum power	kW	1 MW
Total energy content	kWh	7.3
Useable energy content	kWh	5

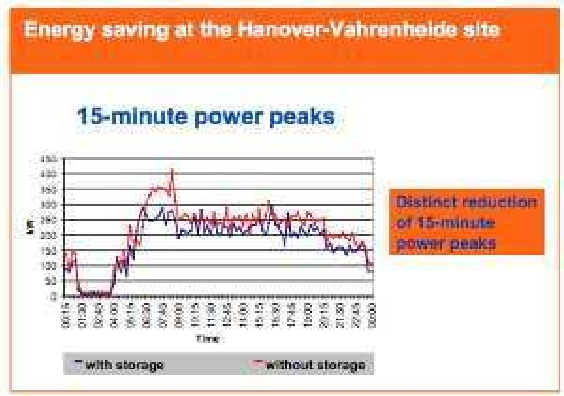
General data		
Operating speed range	rpm	3450 – 1800
Operating temperature	C [F]	0° – 40° (< 35° in average) [32° – 104° (< 95° in average)]
Rel. Humidity		< 85% (non condensing)
Max. altitude (without derating)	m	1000
Air flow	m^3/h	5000
Max. back pressure	Pa	50
Dimensions (depth x width x height)	mm [inch]	1325 x 3300 x 2600 [52.2 x 130 x 102.4]
Weight	kg	10 000
Paint finish		RAL 5012



Source: PILLER

The system has been installed in Hanover in 2004 and the results achieved in this pilot project amounted to 462.000 kWh saved annually and energy costs reduced by 40.000€ per year (80€/Mwh).





Source: PILLER

The French city of Rennes (Britain) installed a 1 MW flywheel system in September 2010 on their VAL automatic metro network. The objective for Rennes was to recover the residual braking energy that could not be recovered despite the efficient scheduling of their metro trains set up for optimizing the line receptivity. The 5kWh available energy system is located in the middle of the metro line and the average efficiency is around 80% except when there are fewer trains where efficiency goes up to 90%. The public transport operator (STAR network) expects 5000kWh savings per week.

Source: PILLER

Reversible substations

Technical description

A substation consists in an electricity distribution system where voltage is transformed from high to low voltage (and vice-versa) using transformers. As it is more efficient to transmit electricity over long distances at very high voltages, the function of a substation is to reduce the voltage from transmission level to values suitable for local distribution. Substations provide current only in one direction and are not able to absorb energy generated by other sources. A reversible substation consists in allowing the system to act in both ways.

The quantity of energy a public transport network is able to absorb is mainly conditioned by the probability of trains braking and accelerating simultaneously [xv]. This absorption phenomenon is called the receptivity of the line. The target of a DC reversible substation is to improve the power line receptivity, in order to regenerate almost completely the trains braking energy. The goals are:

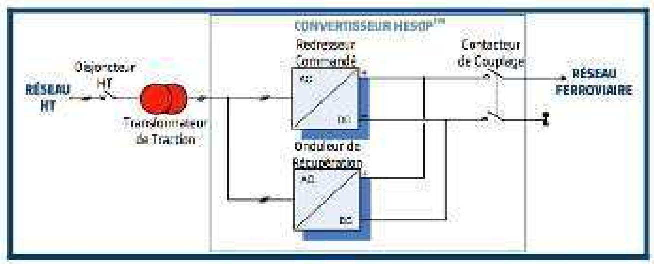
- to maximize the braking energy feedback to the upstream network,
- to leave priority to natural exchange of energy between trains
- to regulate its output voltage in traction and regeneration modes to reduce losses
- to ensure a good quality of power supply, for the DC and AC part of power supply systems, by reducing the level of harmonics.

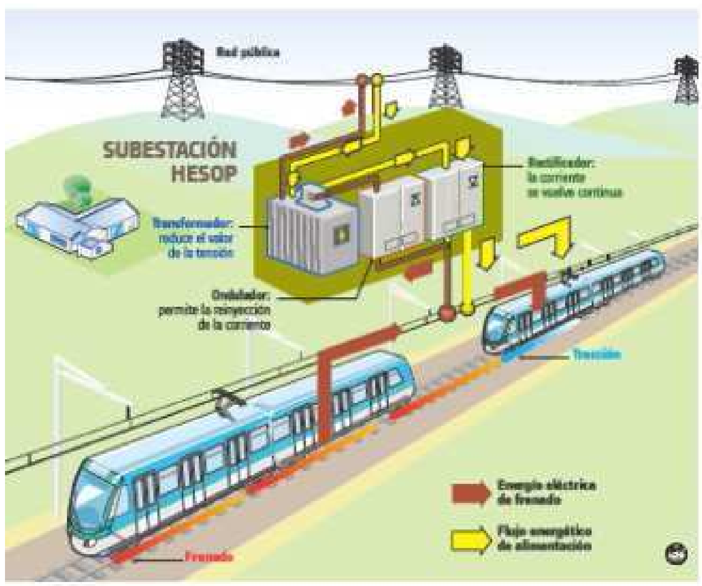
Implementation in the public transport sector

We present below reversible stations solutions implemented by ALSTOM, SIEMENS and INGETEAM.

ALSTOM – HESOP system

The HESOP system consists in a reversible electrical substation for tramways. These substations should eventually make it possible to return the quasi-totality of the braking energy generated by trams to the electric grid, even when no other trams are operating on the network. The main development objective of HESOP is therefore electric energy conservation. Its design will result in better yields and absolute control over the amount of current and quality of energy consumed and then reinjected into the electrical grid [xvi].

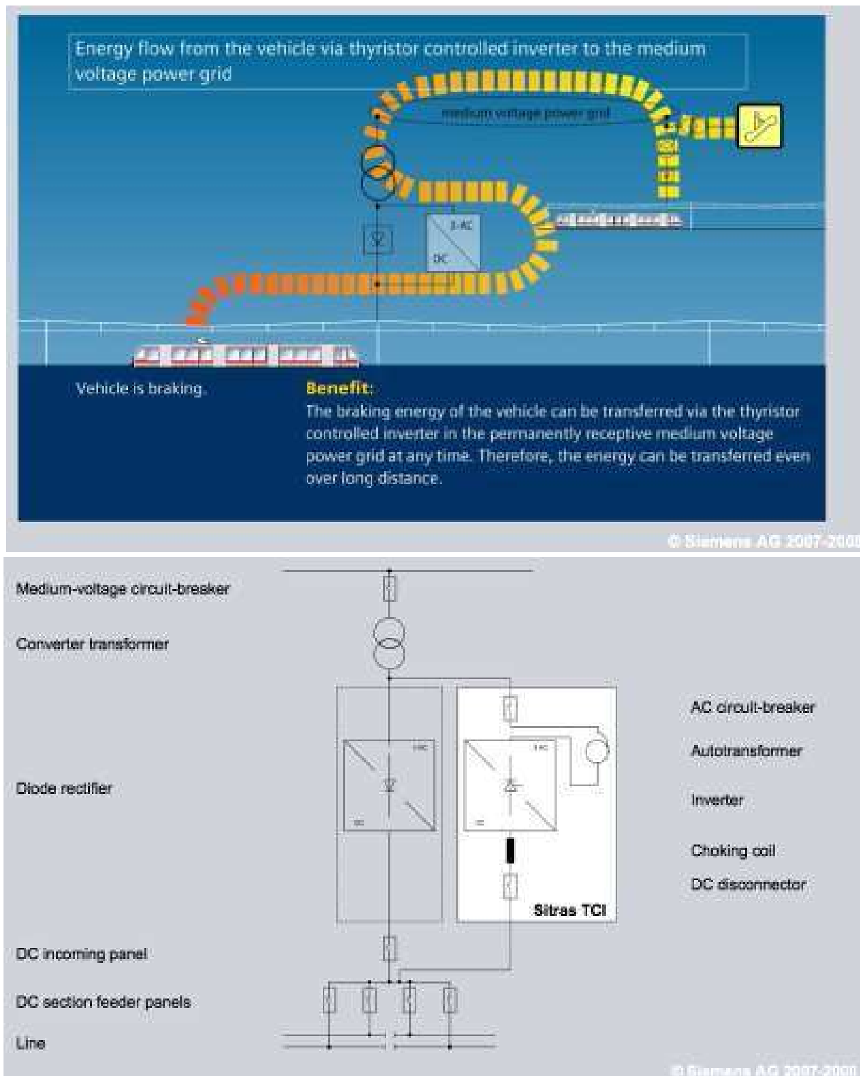




Source: ALSTOM

SIEMENS – SITRAS Thyristor Controlled Inverter (TCI)

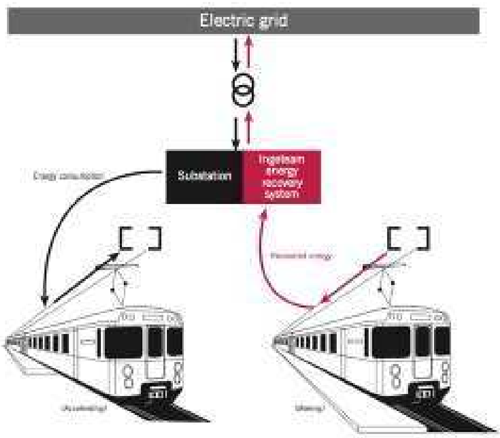
SIEMENS designed a reversible system consisting in a thyristor controlled inverter that allows recovering the braking energy and transferring it in the permanently receptive medium voltage power grid at any time and over long distance. The benefits are that the medium-voltage power system is usually receptive to an unlimited amount of energy. Substations can be upgraded to return surplus energy to the system with an additional inverter. As a result, braking resistors on the vehicles can be kept to a minimum.

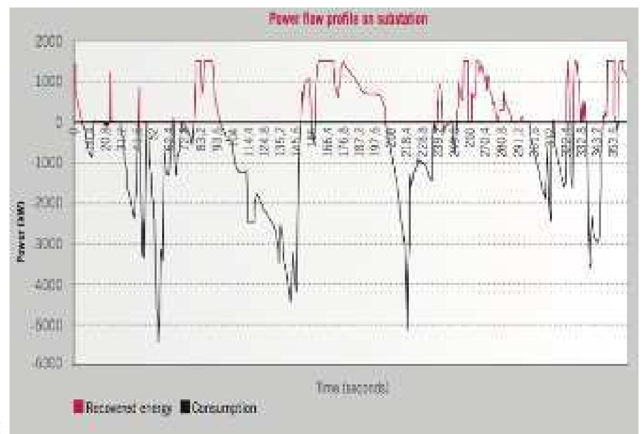


Source: SIEMENS

INGETEAM

INGETEAM Traction has developed a system to recover the kinetic energy in railway systems, which aims at solving existing energy recovery limitations. The system can be integrated into current substations without the need to modify the existing system. The system is made up of a double converter, connected to the catenary in parallel with the substation's rectifier, and to the same already existing transformer. This system monitors the state of the catenary at all times, and if there is energy to be recovered, converts it into high quality alternate current, which is fed back to the general three-phase grid. The system also allows for the control of harmonics present in the three-phase grid, by acting as an active front, that allows for reversible actuation by supplying energy to the catenary even during power consumption peaks, resulting in quality power consumption for the alternate grid.





1 Unit characteristics

Catenary voltage	1,500 Vdc	Direct current, max.	1,000 A
Alternating voltage	1,150 Vac	Total harmonic distortion(THD)	< 3%
Maximum power	1,500 kW	Output frequency	50 Hz
Rated power	800 kW	Cooling system	Air
Alternating current, max.	850 Arms		

Source: INGETEAM

Market analysis

Based on the technologies overview of the previous section and on the several contacts with the suppliers, key elements can be addressed regarding the market for energy recovery systems:

- Braking energy recovery technologies have recently become a priority for the industry and most suppliers are investing in R&D in this field.
- Different technologies are competing on the same segment with no clear leading technology. Each technology has advantages and drawbacks that will depend on each situation and context.
- Mobile and stationary systems aim at reducing the overall consumption of tram/metro networks but mobile systems can also allow catenary-free operations. These different applications will obviously coexist in the future.
- The solutions developed by the manufacturers must be adapted to every transport network. This requires the use of powerful simulation tools for designing the right system. Suppliers have invested significantly in these tools and will continue their efforts.
- Despite the high number of suppliers competing in that market, only very limited systems have yet been implemented in the public transport field. The reason is that most systems are still at the prototype stage, which makes it difficult for transport operators to take investment decisions due to the lack of experience feedback and uncertainties about the return on investment.
- Costs shall decrease when market expands due to technological improvements and elements costs reduction.

Conclusion

This document aimed at presenting the different technologies available on the market for braking energy recovery in the public transport sector.

The overview shows that different technologies are competing in the same segment and that such applications have become a priority for the industry. Many pilot projects blossomed all over the world. However, only a very limited number of transport operators have taken the step to invest in these green technologies. One reason is probably that these applications are still recent with little experience feedback on the systems lifecycle and return on investment.

This analysis has clearly identified that each technology has advantages and drawbacks that will depend from every situation and context. The main objective of stationary energy recovery systems is to reduce the overall consumption of tram and metro networks whereas mobile systems tend to prove useful both for catenary-free operations and energy efficiency purpose.

This being said, Ticket to Kyoto project shall provide added-value in this respect to help the five partners to have a good knowledge of braking energy recovery applications and better assess the costs and benefits of such systems. In the frame of the project, decision-aid tools are being developed (multi-criteria analysis and cost-benefit analysis) for evaluating the different technologies in each partner's context. This common approach will guarantee thoughtful exchanges between partners in order to gain mutual experience and provide a methodology for other operators willing to consider similar investments. This methodology and the results will be presented during the T2K annual conference in Bielefeld in May 2011 then published in a second deliverable.

References

[i] *Supercapacitors*, National Renewable Energy Laboratory, www.nrel.org, last consulted in June 2008.

[ii] Zhu J.G, 'Supercapacitors', Presentation in the subject *Electrical Energy Technology* in the Faculty of Engineering of the University of Technology, Sydney. http://services.eng.uts.edu.au/cempe/subjects_JGZ/eet/SuperCap_1_11_05.pdf

[iii] Douglas H, Pillay P, "Sizing Ultracapacitors For Hybrid Electric Vehicles", ISBN 0-7803-9252-3/05©, IEEE 2005

[iv] SuperCap tests complete, Railway Gazette, 18 March 2008, http://www.railwaygazette.com/news_view/article/2008/03/8235/supercap_tests_complete.html

[v] http://www.bombardier.com/en/transportation/products-services/propulsion---controls/product overview/mitrac-energy-saver?docID=0901260d8000e614

[vi] Barrow, Keith. "*Wireless connections: for well over a century catenary has been familiar street furniture in cities with light rail networks. But an abundance of innovative catenary-free systems is emerging that could enhance the visual impact of light rail, as Keith Barrow discovers*.(Transit special)." International Railway Journal. 2009. E-Library at IBTimes. 17 Apr. 2010. http://elibrary.ibtimes.com.

[vii] www.mobility.siemens.com/mobility/en/pub/urban_mobility/rail_solutions/electrification/ dc_traction_power_supply.htm

[viii] http://www.transportation.siemens.com/ts/en/pub/products/el/products/dc/static_energy/ energy_saving.htm

[ix] http://www.transportation.siemens.com/ts/en/pub/products/el/products/dc/static_energy/ voltage ____.htm

[x] www.mobility.siemens.com/mobility/en/pub/urban_mobility/rail_solutions/electrification/ dc_traction_power_supply.htm

[xi] *Supercapacitors to be tested on Paris STEEM tram*, Railway Gazette, July 2009 http://www.railwaygazette.com/news/single-view/view/supercapacitors-to-be-tested-on-paris-steem-tram.html

[xii] http://www.caf.es/ingles/id/sistema_acr.php

[xiii] http://www.adetelgroup.com

[xiv] *Flywheel energy storage*, Wikipedia.

[xv] UIC Energy efficiency days, 23-24 September 2009, Alstom, Reversible DC Substation

[xvi] RATP and Alstom press kit, July 2009