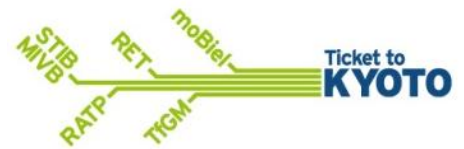


WP2B ENERGY RECOVERY

Guidelines for braking energy recovery systems
in urban rail networks

Deliverable 2 - September 2014





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The partners of this project are:

- STIB (Brussels, Belgium) as lead partner
- TfGM (Manchester, UK)
- moBiel (Bielefeld, Germany)
- RATP (Paris, France)
- RET (Rotterdam, The Netherlands).

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Executive summary

Braking energy recovery technologies have recently become a new opportunity for the public transport sector and the industry has been investing in research and development in this field. Different technologies are competing for the same sector, with no clear leader. Each technology has advantages and drawbacks, depending on its context.

The partners of the Ticket to Kyoto (T2K) project have thoroughly investigated braking energy recovery technologies. Three of these partners have simultaneously implemented systems on their network. This joint approach is unmatched anywhere in the world and has enabled them to gain significant expertise in this field. The main conclusion is that investing human and financial resources in this concept is worth the effort, as it can substantially improve the energy efficiency of urban rail networks. Technology is mature and experiences around the world validate the profitability of the investments. However, the research and investments achieved during the T2K project show that the payback time and return on investment can vary significantly from one operator to another, depending on various technical parameters (electrical network, vehicles, headways, etc.). Simulations are necessary to remove this uncertainty and build a robust business case.

This document will guide operators through the different steps for investing in braking energy technologies. First, the various technologies available are analysed and decision-making tools are presented. Then, procurement and implementation aspects are presented. Finally, the case studies of four operators are described.

moBiel (Bielefeld) invested in a braking energy recovery system to decrease the energy consumption of its light-rail network. The first step was a network study done by an external consultancy, to gain an overview of the potential savings and identify potential locations for implementing the recovery systems. In a second step, moBiel launched a European tender and opted for a flywheel and two inverters.

Since **STIB** (Brussels) owns its high-voltage electrical network, inverters appeared to be the most cost-effective solution in this context. A European tender was launched and three suppliers were invited to test their system on the network for several weeks in order to compare their efficiency and the delivered savings. This empirical approach

produced useful insights on the way braking energy can be recovered by the use of inverters. The best system is now progressively installed on the entire metro network.

RET (Rotterdam) identified braking energy recovery as a great opportunity to reduce the energy used by its metro system and assessed several energy recovery systems that had been tested previously on the network (supercapacitors, on-board flywheel). A reversible substation was seen as the best option for the metro network in the Rotterdam area and RET decided to invest in two inverters, where no storage is needed and energy can be used directly on the 10kV network. A European tender was launched and one company was selected. The success of these two substations will determine whether RET will place new orders.

TfGM (Manchester) has carried out an opportunity analysis for investing in stationary braking energy recovery systems based on supercapacitors for its light rail network. These studies have concluded that the payback time was too long. TfGM did not implement any solution within the T2K project but actively participated to the discussions.

Introduction

1.1 Ticket to Kyoto project

Five European public transport companies have joined forces to reduce CO₂ emissions in public transport. Their actions are centralized through a European project, Ticket to Kyoto (T2K - www.tickettokyoto.eu), which 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 was an important target. Modern railway vehicles have the ability to regenerate the braking energy into electrical energy. In conventional vehicles, a small portion of this kinetic energy can be reused to power the vehicles auxiliary systems, the remaining energy being sent back onto the network in order to feed another vehicle accelerating nearby. If no vehicle consuming energy is located nearby, the network voltage increases due to the energy surplus and this extra energy has to be dissipated in braking resistors. To avoid such energy losses, manufacturers are putting energy recovery solutions on the market, both on-board and stationary.

1.2 Goal of this report

During the first phase of the Ticket to Kyoto project, the T2K partners have gathered all available information on existing technologies and on-going projects all around the world to acquire an exhaustive knowledge on the topic. Meetings with most suppliers were organized during the Innotrans 2010 trade fair in Berlin. A first deliverable gives a state of the art of current technologies and projects and is available on the Ticket to Kyoto Website:

http://www.tickettokyoto.eu/sites/default/files/downloads/T2K_ER_overview_technologies_web.pdf

A European workshop on braking energy recovery technologies was also organized by the T2K partners in May 2011 in Bielefeld (Germany). Exchanges took place in a very transparent way allowing participants to increase their knowledge in this field.

In a second phase of the project, T2K partners have exchanged regularly about various topics related to the implementation of a braking energy recovery system on their

network. These discussions allowed the different teams to better apprehend the complexity of this innovative concept in the public transport field and to succeed in implementing reliable systems on their network.

The aim of this **second report** is to:

- Highlight specific benefits and issues related to investing in braking energy recovery technologies;
- Help public transport managers choosing the appropriate technology for their network;
- Give advices regarding the tendering procedure;
- Assess the implementation process of the systems ;
- Publish the results achieved within the T2K project.

2 Braking energy recovery technologies for public transport

This section presents the various braking energy recovery technologies and applications available for public transport operators.

2.1 Braking energy recovery concept

Public transport rail vehicles are propelled by electric motors supplied by substations placed along the tracks. The electricity is transferred via an overhead line through the pantograph in the case of a tram, and by a third rail running all along the track in the case of a metro.



Figure 1 : View of a pantograph (tram network) and a third rail (metro network)

Most recent rail vehicles have the ability to brake electrically using regenerative braking techniques. In that case, the electric motor can work as a generator recovering the vehicle's kinetic energy and converting it into 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 that is not the case, the network voltage increases due to the energy surplus and this extra energy has to be dissipated in braking resistors. This principle is shown in the figure above.

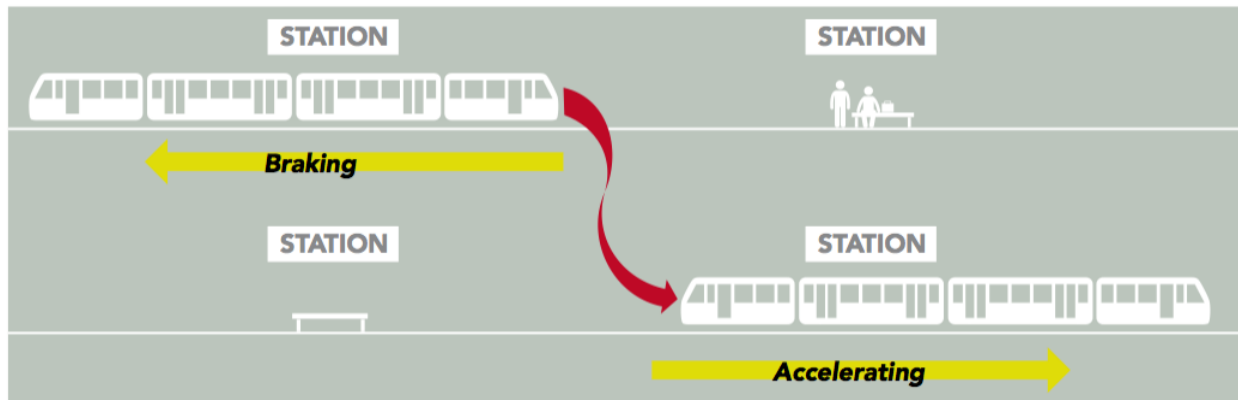


Figure 2 : Braking energy transfer between rail vehicles

These energy transfers between vehicles depend on parameters such as the traffic density, distances between the stations and slopes. In a metro network, these transfers usually amount to 20-30% of the total consumption. However, in many situations, the energy cannot be recovered on the network because no vehicle is accelerating exactly when another is braking. This represents an interesting opportunity to integrate braking energy recovery technologies described in the following section.

2.2 Types of applications

To avoid the energy losses described in section 2.1 and to reduce the overall energy consumption, several applications have been developed. By reducing the energy consumption, these systems can strongly impact the operational costs linked to the energy prices and substantially lower CO₂ emissions as well as other harmful pollutants emissions induced by the production of electricity in power plants.

Braking energy recovery technologies can be classified in three families:

- **Mobile storage applications**
- **Stationary storage applications**
- **Stationary 'back to the grid' applications.**

2.2.1 Mobile storage applications

Mobile storage applications consist of onboard energy storage systems, usually located on the vehicle roof, every system working only for one vehicle. When the recovered energy cannot be used by another vehicle nearby, the energy is directly sent to the storage system placed on the vehicle. The stored energy is then used to power the vehicle when it accelerates or supply its auxiliaries (heating, cooling, lighting, etc).

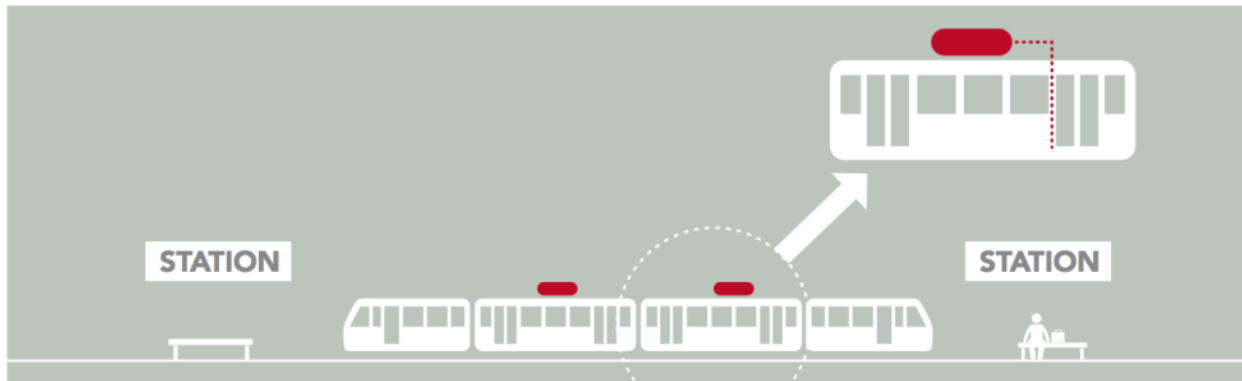


Figure 3 : Mobile storage application for rail vehicles

2.2.2 Stationary storage applications

Stationary (wayside) storage applications consist of one or several energy storage systems placed along the tracks. They can recover the energy from any braking vehicle and power any accelerating vehicle within the area of influence of the system.



Figure 4 : Stationary storage application for rail vehicles

2.2.3 Stationary “back to the grid” applications (reversible substations)

The main difference with the previous applications is that ‘back to the grid’ applications do not store the recovered energy. Instead, they send it to the main electrical grid to be used by other consumers or potentially sold back to the energy distributors.

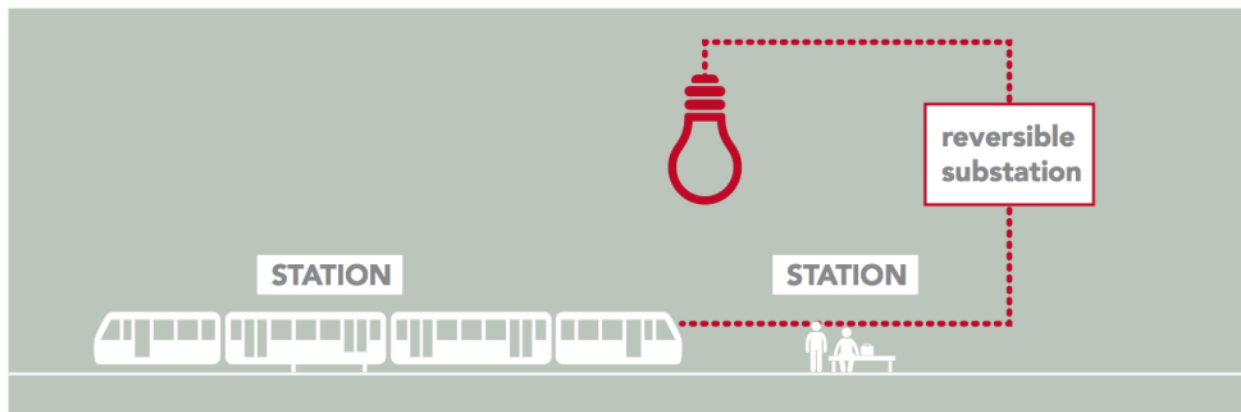


Figure 5 : Back to the grid application for rail vehicles – reversible substation

2.2.4 Applications comparison

Table 1 gives a comparison of braking energy recovery applications for urban rail vehicles.

	MOBILE STORAGE SYSTEMS	STATIONARY STORAGE SYSTEMS	REVERSIBLE SUBSTATIONS
Overhead line or third rail losses are reduced.	×		
High efficiency due to lower transformation and storage losses.			×
Recovered braking energy can supply any equipment (lighting, escalators, etc.).			×
Vehicles can be operated without overhead lines/ third rail on short sections.	×		
The systems can be installed without having to modify the vehicles.		×	×
Lower safety constraints as not on-board of the vehicle.		×	×
Tunnels and stations warming can be avoided by reducing the heat produced by the braking resistors.	×	×	×
Voltage stabilisation and peak-shaving opportunities.	×	×	

Table 1 : Comparison of the advantages of each type of application, Ticket to Kyoto

Both mobile and stationary systems aim to reduce the overall consumption of metro and light rail networks but mobile systems can also allow catenary-free operations. A limited number of systems have yet been implemented in the public transport field worldwide, which makes it difficult for transport operators to take investment decisions due to the lack of experience feed-back and uncertainties about the return on investment and life cycle of these technologies. Costs could decrease when this market expands, as a result of technological improvements and a reduction in material costs (especially in the case of batteries or supercapacitors).

2.3 Types of technologies

The energy storage applications described in section 2.2 can be based on different technologies:

- A **battery** stores energy through an electrochemical reaction. Batteries are found in a large range of chemistries, sizes and power ratings.

- A **supercapacitor** is an electrochemical storage device where the energy is stored in an electrostatic field by means of charge separation (a concentration of electrons on the surface of a high specific surface area material). No chemical reaction occurs. They bridge the gap between conventional capacitors and batteries and can deliver at least 10 times higher power than most batteries of equivalent size.
- A **flywheel** is a rotating wheel 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. Flywheels can be used to produce high power peaks.
- Most conventional substations allow only for unidirectional energy flow. A **reversible substation** uses an inverter allowing the energy to flow in both directions. Unlike the storage technologies described previously, the recovered braking energy is not stored but sent back to the electrical network.

In terms of power and energy density, the different storage technologies perform differently. Supercapacitors have a relatively low energy density but a high power density (fast electrical response) whereas batteries have a high energy density but a low power density (slow electrical response). Flywheels have similar power density to EDLCs and are reported to benefit from higher energy densities.

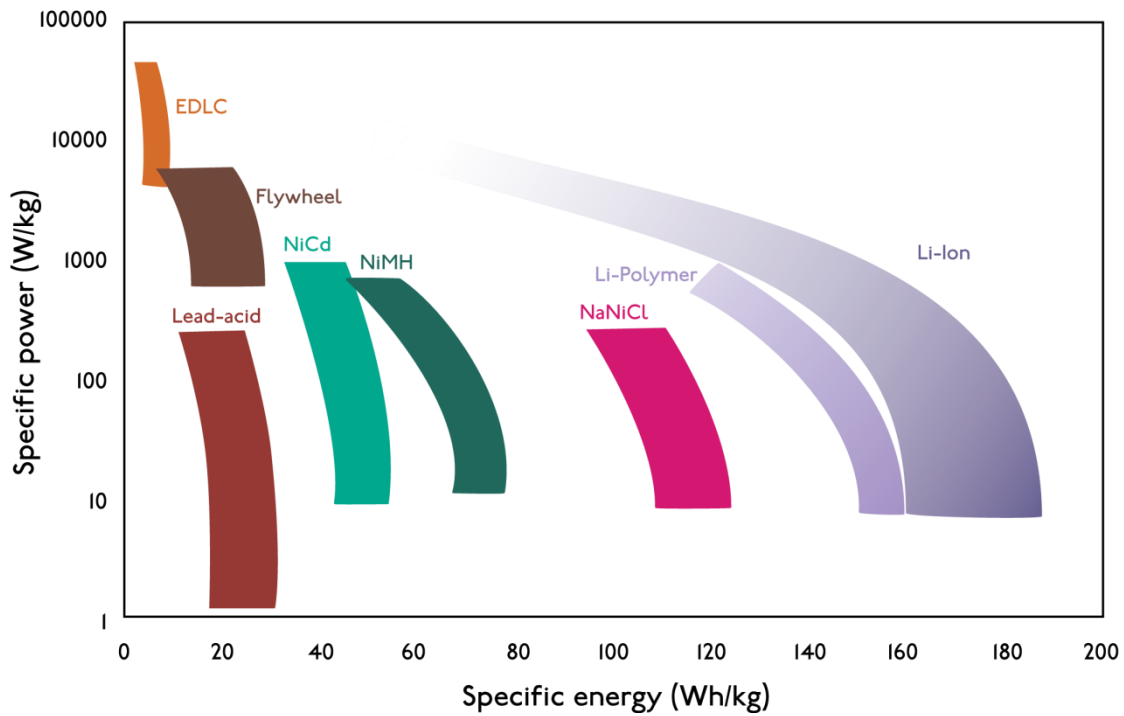


Figure 6: Ragone diagram (cell level)¹

However, other RESS important characteristics are the following: efficiency, lifetime (or cycle life) and self-discharge.

¹ Peter Van Den Bossche et al., "The Cell versus the System: Standardization challenges for electricity storage devices," World Electric Vehicle Journal, vol. 3, pp. 1-6, 2009.

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)	Self Discharge
Pb-Acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	< 3000	High
Li-Ion	70–85	100–200	360	500–2000	Med
Li-polymer	70	200	250–1000	> 1200	Med
NaS	70	120	120	2000	–
VRB	80	25	80–150	> 16000	Negligible
EDLC	95	< 50	4000	> 50000	Very high
Pumped hydro	65–80	0.3	–	> 20 years	Negligible
CAES	40–50	10–30	–	> 20 years	–
Flywheel (steel)	95	5–30	1000	> 20000	Very high
Flywheel (composite)	95	> 50	5000	> 20000	Very high

Table 2 : Comparison of different ESS technologies²

Table 2 shows that EDLCs and flywheels have the highest power density, efficiency and lifetime (ignoring pumped hydro and CAES). These characteristics will be very important for urban transport applications, where the RESS will subject to frequent and large peak powers due to the acceleration and braking patterns of the urban vehicles (city buses, trams and metro trains).

The difference among flywheels and EDLCs is that flywheels have higher energy density while EDLCs have slightly better efficiency and suffer from lower self-discharge. Other aspects that have to be considered when dealing with flywheels, especially for on-board applications, are the gyroscopic forces and safety enclosures.

² S. Vazquez, S.M. Lukic, E. Galvan, L.G. Franquelo, and J.M. Carrasco, "Energy Storage Systems for Transport and Grid Applications," IEEE Transactions on Industrial Electronics, vol. 57, no. 12, pp. 3881 - 3895, December 2010.

3 Choosing the right technology

The goal of this section is to help public transport operators understand and choose the right technology for their network. First, the main parameters influencing the energy recovery potential are presented. Then, the several decision making tools used by partners for their investments are described.

3.1 Influencing parameters

Throughout the Ticket to Kyoto project, the partners have demonstrated that it is not easy to compare technologies, assess likely performance and determine the optimum technological solution. Finding the best-adapted technology and opting for the right implementation require a holistic approach that takes many parameters into consideration:

- Catenary free-operations
- Electrical network
- Vehicles
- Headways

3.1.1 Catenary-free operations

Catenary-free operations offer a new opportunity for public transport, particularly for trams operating in historic city centres where authorities wish to avoid the visual impact from overhead lines. Ground-level power supplies have been implemented in several cities and inductive systems are currently developed to improve the system reliability while targeting high energy efficiency. Energy storage systems placed on-board the vehicles can be part of the solution to allow a tram to cover a certain distance (1-2 km) without the need to be powered by an overhead line. The system is charged through regenerative braking and/or fast-charging infrastructure in the stations when passengers are boarding.

In the case of a tram network, this requirement has to be assessed from the very beginning as it will determine whether the operator should consider the use of on-board storage systems. The analysis carried out by the T2K partners came to the conclusion that on-board systems seem to be too expensive for the sole objective of energy

recovery. However, they may offer a reliable solution for catenary-free operations on a short distance.

Nice (Lignes d'Azur)

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.



3.1.2 Electrical network ownership

Urban rail systems are powered by electricity either by the use of catenaries (overhead lines) or a third rail placed along the track. The network is fed with electricity thanks to several substations delivering the required energy. Substations are linked to the high voltage network, which is sometimes owned by the local energy provider.

This ownership is the second critical issue when investigating the opportunity to install a braking energy recovery system.

When owned by the local energy provider, transport companies have limited latitude on this electrical network. In this case, feeding the energy back to the high voltage grid is only possible when an agreement with the energy provider has been signed or if there is a legislation regulating the discount of energy fed back on the public transport operator's energy bill, as it is the case in Spain (see below). If this is not the case and if energy cannot be sent back to the grid, **stationary storage solutions** should be preferred.

When the operator owns its electrical network, this situation is often from the past, when tram networks were built by electric companies, this offers more flexibility for sending the energy back to the high voltage grid through **reversible substations**.

Sending energy back to the main grid in Spain

In Spain, law RD-1011-2009 stipulates that electricity consumers connected to a high voltage grid can be exceptionally authorized to feed back that energy to the network. These consumers must have electricity surplus that they cannot consume in their own installation at certain times due to the implementation of energy efficient systems. These systems must meet requirements such as a certification proving the right of access to the network and a document stating the measures adopted to guarantee this will not affect the network. The supplied energy will be deducted on the bill of the owner of the facility.

3.1.3 Electrical network characteristics

The configuration of the electrical network is an important element to consider when evaluating the potential savings of a braking energy recovery system as it will determine the perimeter in which energy exchanges between vehicles might occur. In some interlinked tram or metro networks, one substation can provide energy to different lines. When interconnected, the energy of a vehicle braking on a given line could be sent to a vehicle accelerating on another line. It must be also borne in mind that the energy exchange between modern tram and metro trains already account for significant energy savings.

Braking energy recovery systems must be fine-tuned to recover as much energy as possible from the vehicles without taking energy from the grid (adjacent substations). The issue with recirculation (energy coming from the high voltage grid through a substation which is directly sent back to the high voltage grid through the inverter) is that it does not entail any energy savings; on the contrary, it implies losses caused by the current passing through the different electrical components.

Some networks must also cope with voltage drops occurring when several vehicles accelerate simultaneously. This results in the network voltage going under a certain threshold. In such cases, only storage systems can relieve the network by supplying the required power when needed, thus avoiding to oversize the substations or to add new ones.

3.1.4 Line topology and headways

The number of stations on the line combined with the distance between those stations will greatly influence the braking energy to be recovered. Urban networks such as metro or light rail are more suitable than regional trains for energy recovery due to the fact that the distance between stops is reduced. However, even if the proportion of recovered energy is lower, the absolute amount of energy can still be quite high and justify the investment in recovery solutions.

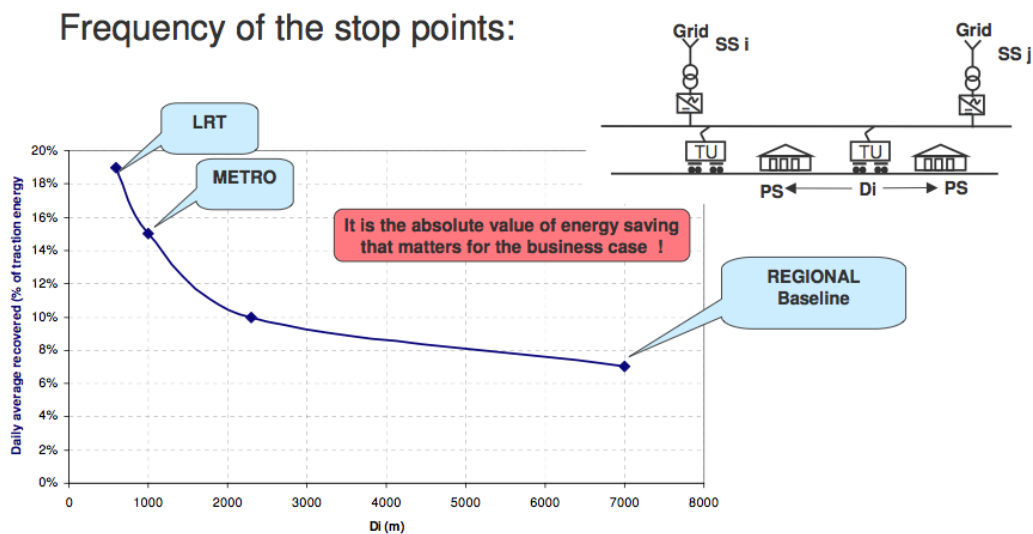


Figure 7: Influence of the distance between stops on the braking energy recovery potential (source : Alstom)

According to simulations made by Alstom, a reversible substation along a regional train line (1.5kV) of 87 km with 15 stations and 15 minutes headway would offer **7% energy savings** compared with the same substation along a LRT line of 14km with 27 stations and 5 to 15 minutes headway offering **19% energy savings**. Dense urban networks are more suitable for the use of braking energy recovery systems, as energy savings will allow recouping the investment on a shorter period.

Slopes can also influence the available braking energy recovery potential by increasing the vehicle inertia. In some situations, braking energy recovery systems will have to be oversized to cope with the total energy generated by vehicles driving downhill.

The headways between the vehicles will strongly determine the line receptivity (energy demand on the line due to energy exchanges between vehicles). The more vehicles are running simultaneously on the line, the more opportunities occur for energy being transferred from a braking vehicle to an accelerating one. In big networks with high frequencies (short headways), energy exchanges between vehicles can be so high that energy savings might be low when implementing an energy recovery system. However, substantial gains may be obtained during off-peak, at night or during the weekend when fewer vehicles are operated, thus decreasing the line receptivity.

The particular context of automated metro systems must also be pointed. Metros have to constantly improve their performance in order to meet growing demand without compromising safety. The major development of the last years is the development of driverless train operation (also known as automated metro systems). Already 30 driverless lines are in operation worldwide. A study among UITP manufacturing members forecasts that by 2020, 75% of all new metro lines will be designed and implemented for automated systems. Existing lines will also be massively retrofitted to driverless operation on the occasion of periodic modernisation of rolling stock or signalling equipment.

Operating an automated metro system has a straight and evident impact on potential energy savings as they are usually characterized by very high frequencies. As a result, line receptivity is strongly improved and the need for braking energy recovery systems must be thoroughly assessed.

Compared to a manual driving system, an automatic system also offers significant opportunities to improve the line receptivity by synchronising the acceleration and deceleration phases of the vehicles. The timetables can be set up accordingly and very small time intervals can be added to the departure of a vehicle to ensure a higher energy exchange with a braking vehicle.

Optimising energy exchanges on the automated metro system in Rennes (France)

Opened in 2002, the STAR metro in Rennes (France) is based on the Siemens Transportation Systems VAL (véhicule automatique léger) technology. The 9.4km line runs north-west to south-east via Gare de Rennes, with fifteen stations. Services run between 05:20 and 00:40 each day, with a two-minute headway at peak time and a 4 min headway off-peak time. The system has 24 trains, each weighing 28 tonnes and 26 metres long, with a capacity of 158 passengers (50 sitting and 108 standing).

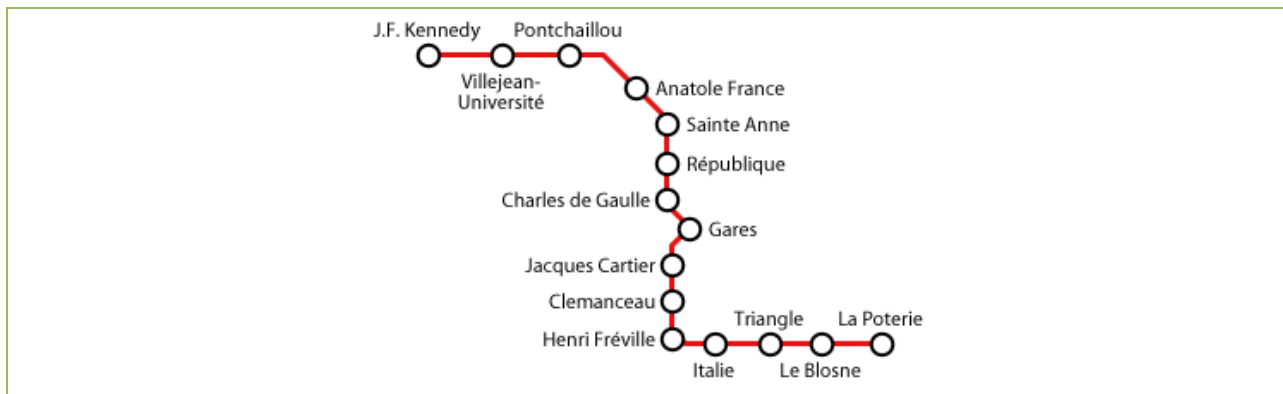


Figure 8 : Plan of the automatic metro (VAL) in Rennes (source: Wikipedia)

The metro network has annual energy consumption of some 6.5 GWh. Thanks to the simulation of the resistors banks located along the line (not on the vehicles), staff could evaluate the energy lost due to the lack of energy exchanges between vehicles. They then decided to improve the energy efficiency by developing a timing model aiming at shifting train departures and arrivals by a few seconds, thus increasing the simultaneity. This system allows an annual reduction of some 600.000 kWh without any impact on operations, safety and customer satisfaction.

Besides this optimization, Rennes transport authority and Keolis also investigated energy braking recovery technologies. Sending energy back to the grid was not an option for Rennes as the transport company does not own the electrical grid. Supercapacitors and flywheels were compared and several offers were received after the company launched a tender. They opted for a PILLER 1MW flywheel system located in the middle of the metro line. The estimated annual savings amount to 230.000 kWh with a maximum of 150kWh/h. Best savings are achieved at the timetable change when switching from peak to off-peak and inversely. During that period, energy exchanges between vehicles can hardly be optimized through modelling and excess energy is then recovered in the flywheel.

3.1.5 Vehicles

The type of vehicles used on the line will impact the achievable results. Most recent vehicles have the ability to recover braking energy and to send it back to the catenary or the third rail. In some cities and networks, old and recent vehicles are operated simultaneously so that energy exchanges between vehicles may be less efficient. Some

old vehicles also do not have the ability to regenerate braking energy. In this latter case, investments in braking energy recovery are of course useless.

The heavier the vehicles, the more braking energy is available. Ridership plays thus an important role when estimating the potential savings. Average occupancy rates of the lines must be known to integrate them in the simulation tools and analysis.

3.1.6 Electric consumption of the recovery system

The system itself may require energy for functioning or being correctly ventilated. This consumption must be accounted for as it will reduce the expected savings. An analysis carried out during the T2K project and aiming at comparing different technologies showed that flywheels seem to be the most consuming devices due to their need to make the wheel spin around its axis at a very high speed.

	Supercapacitors		Flywheels		Reversible substations		
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
A. Performance							
System efficiency	96%	80%	85%	95%	95%	97%	97%
Peak power	0,33 MW	0,70 MW	1,00 MW	0,20 MW	1,50 MW	1,50 MW	2,70 MW
Available energy	1 kWh	2,5 kWh	5 kWh	1,5 kWh			
Maximum energy recovery per hour	50 kWh/h	80 kWh/h	127 kWh/h	67,5 kWh/h	900 kWh/h	300 kWh/h	800 kWh/h
Auxiliaries consumption	4000 kWh/year	18000 kWh/year	79000 kWh/year	13000 kWh/year	1700 kWh/year	19000 kWh/year	1500 kWh/year

Table 3 : Comparison of the electric consumption of energy recovery systems, Ticket to Kyoto based on suppliers information

3.1.7 Shared storage system

In the case of storage options, an infrastructure shared between the transport operator and the electrical grid operator can be a clever solution, as investment costs will be shared and benefits can be more significant. The transport operator will be using the storage capacity during the day for supplying its rail network thus reducing its primary energy demand. The electrical grid operator will take advantage of this stored energy as a "distributed energy resource" and use it on the market:

- **Demand Response:** As a distributed energy resource, the storage device will enable load-shedding when marginal electricity prices are high - such as hot summer days. The device will also serve as a resource during emergency conditions.
- **Frequency Regulation:** To ensure a functional and reliable electrical grid, frequency must remain very close to 50 hertz (cycles per second). To achieve this stable frequency, the supply of electricity must exactly match demand. The

storage device can be "on call" to maintain the proper frequency by increasing or decreasing small amounts of power output in response to minute-by-minute frequency deviations.

Large-scale battery storage shared in Philadelphia (USA)

The Southeastern Pennsylvania Transportation Authority (SEPTA) captures the braking energy of its trains on the Market-Frankford Line through a large-scale battery storage system to integrate that power into the regional electric grid. Energy storage has proven to be a solution for capturing regenerative braking to provide supply savings but has also been proven that energy storage can provide support to the electric grid. SEPTA launched a pilot project in partnership with Viridity Energy, a smart grid technology firm specialized in electric market integration. A six-car train can on the Market-Frankford Line produces up to 3 MW in 15 seconds of braking. The device captures most of the regenerated energy, stores it, and pumps it back into the system as needed. The project team selected Saft Batteries to manufacture the storage device and Envitech to supply the electronic controls for system integration. SEPTA anticipates that the device will supply approximately 10 percent of the power demand, reducing electricity bills by more than \$100,000. While the energy storage device will save SEPTA money by reducing grid-based electricity demand, Viridity will work with the system to extend the project's benefits beyond just energy savings. By partnering with a smart grid service provider, SEPTA will be able to use its stored energy in markets as a "distributed energy resource." In so doing, Viridity will help SEPTA to maximize economic value. Viridity projects that the project will return more than \$250,000 in total economic benefits: energy savings plus new market-based revenue (demand response and frequency regulation) offering compensations from the energy provider. Following the success of the first installation, SEPTA announced in January 2014 the installation of a second energy storage and recovery system.

3.2 Decision making

3.2.1 Quick scan

Based on their gained experience in the braking energy recovery field, T2K partners have developed a quick scan tool for helping transport operators identifying rapidly what applications would best suit their context.



Figure 9 : Quick scan for identifying suitable braking energy recovery applications, Ticket to Kyoto

3.2.2 Multi-criteria analysis (MCA)

The choice of an optimal braking energy recovery solution is difficult and must respond best to different criteria as we have demonstrated above that several parameters could influence the efficiency of the system. Fortunately, decision-aid methodologies can support this difficult task and are strongly advised.

The multi-criteria analysis (MCA) is a methodology used for decision-making in economical and environmental policy evaluation due to the complexity of issues and the inadequacies of other conventional tools for capturing the full range of impacts. MCA tools are increasingly being used by decision-makers in order to:

- evaluate priorities, preferences, values and objectives;
- improve the quality of decisions by making choices more explicit, rational and efficient;
- capture less tangible impacts through qualitative assessment.

MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities. The main role of these techniques is to deal with the difficulties that human decision-makers have in handling large amounts of complex information in a consistent way. Typically, most decision problems have a multi criteria nature and refer to several concerns at the same time: technological, economical, environmental, social etc. As there is no alternative optimizing all the criteria at the same time, a compromise solution must be selected.

A typical multi-criteria analysis consists of 5 steps:

1. Identification of the problem and selection of the alternatives
2. Translation of the objectives into several criteria
3. Quantification of the relative importance of each criterion (weights)
4. Assessment of the performance of each alternative to the identified criteria
5. Sensitivity analysis

The outcoming categorisation is noticeably influenced by the established weights attributed to each criterion. Thanks to the flexibility of the MCA, it is possible to measure the stability of this ranking through a sensitivity analysis for each field to see if the result

significantly changes when the weights are changed. MCA softwares are available on the market but it is recommended to be supported by decision-aid analysts when performing the data collection and running the simulations.

During the Ticket to Kyoto project, a MCA approach has been developed and consists in the following criteria. A value and weight must be attributed to every criterion in order to compare them and rank the best options. A detailed analysis is provided in the STIB case study (see below).

	Value	Technology 1		Technology 2		Technology 3	
		Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
A. Performance							
System efficiency	%						
Peak power	MW						
Available energy	kWh						
Maximum energy recovery per hour	kWh/h						
Auxiliaries consumption	kWh/year						
B. Implementation							
Volume	m ³						
Mass	kg						
C. Maintenance and reliability							
Mean time between maintenance (MTBM)	number/year						
Mean time to maintain (MTTM)	hours						
Mean time between failure (MTBF)	years						
Mean time to repair (MTTR)	hours						
Lifecycle	years						
D. Environment							
Harmful materials	Low - Middle - High						
Noise	dB						
Recycling	%						

Table 4 : Example of a MCA for ranking different braking energy recovery technologies and products, Ticket to Kyoto

3.2.3 Simulation tool

One key element when investigating braking energy recovery technologies is simulation. Simulations enable you to quantify precisely the various influencing parameters described in Section 3.1 (vehicles, electrical network characteristics, topology, etc.), and the interactions between these parameters.

A comprehensive analysis of the network and a clear evaluation of possible gains are recommended. Most suppliers will offer their services and experience in this field. However, results might be affected by their obvious interest in selling their own devices, which might not always be the most appropriate. Other consultancies are also developing simulation tools for this purpose and may offer more neutral assessments.

The development of a simulation tool adapted to the situation of one network is a hard job requiring a good understanding of all the factors influencing the modelling but will pay off in the long term as it will serve in other circumstances such as vehicle retrofit or procurement, line extension or automation, etc.

3.2.3.1 Electric consumption monitoring

The monitoring of the real consumption of the vehicles and substations is a very important issue regarding braking energy recovery systems. Accurate knowledge of the energy flows both at vehicle and substation level will be required to validate the simulations in order to evaluate the opportunity of an investment. The information should be very precise and on a sufficiently long period to take into account the differences in ridership (peak, off-peak, night and week-end) and the seasonal variations.

Experience during the Ticket to Kyoto project has shown how important and how difficult accurate energy measurements are. Detailed information is available of the consumption at each sub-station but the assessment of the impacts of an energy storage system is difficult as that change cannot be readily isolated from the effects of system expansion and the changing mixture of the types of vehicles operated.

In addition, a high variability in the substations energy consumption has been noticed from one day to another during measurement campaigns. This variability could mask the influence of an energy storage system installed on the network. Owing to this consumption variability, it is necessary to approach the energy measurements over longer periods of time that could compensate for the variability.

3.2.3.2 Building the model

Building a network model and a vehicle model in order to evaluate potential gains following the implementation of braking energy recovery systems is a tough job that requires time and expertise. The purpose of this report is not to describe in-depth how to build such models, as many scientific articles will be found in the literature on this topic.

For any person interested in this field, please refer to the available literature and in particular to the PhD thesis of Ricardo Barrero at the Vrije Universiteit Brussel, which was carried out in parallel to the Ticket to Kyoto project and could benefit from extensive network and vehicle data from STIB.

Energy Recovery Technologies in Public Transport, Ricardo Barrero, under the supervision of Prof. Joeri Van Mierlo, Vrije Universiteit Brussel, Faculty of engineering, Department of electrical engineering and energy technology, November 2012.

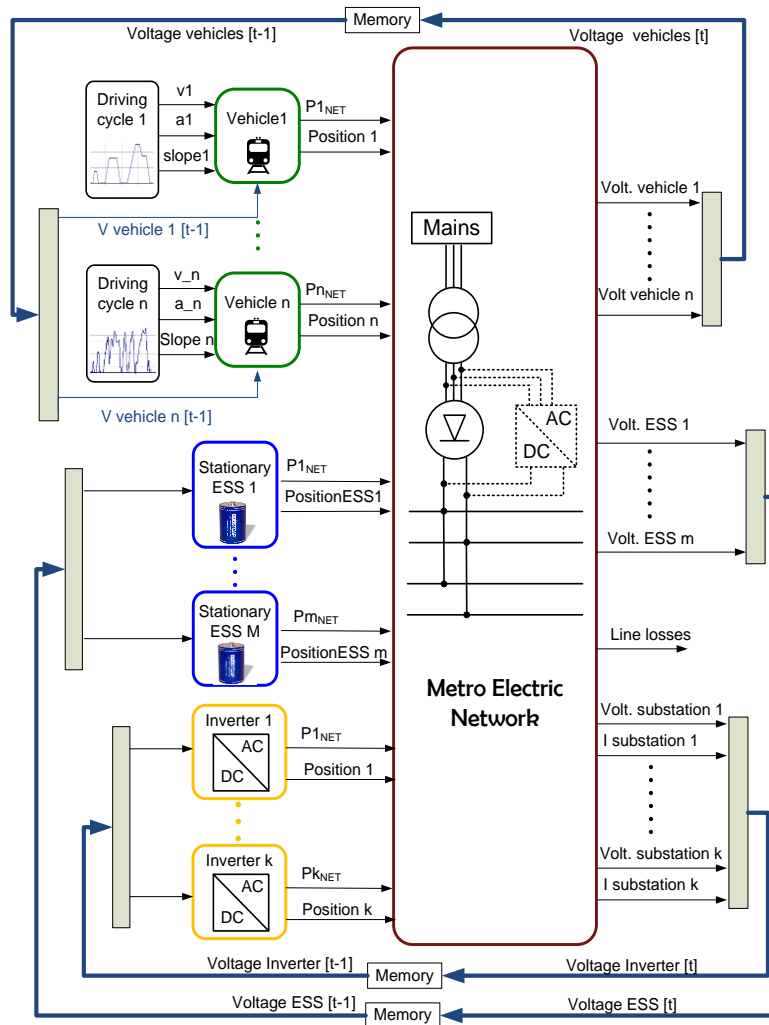


Figure 10: View a network model aiming at assessing braking energy recovery technologies, R. Barrero, VUB

3.2.3.3 Calibrating the model

The simulation tool should be calibrated with the conventional network (without braking energy recovery systems) before developing a feasibility study based on energy recovery technologies.

The validation of a multi-train simulation tool is extremely complicated when studying a whole metro line with many vehicles and substations working simultaneously. For a complete validation, an enormous amount of synchronized data would be needed i.e. at least current and voltage at every substation and current and voltage in every vehicle at the contact shoe level as well as the vehicles speed cycle.

A more reasonable approach is to validate the tool at vehicle level and at substation level. At vehicle level, a power and energy validation can be done, while at substation level, it is better to perform an energy validation due to the uncertainty of the exact instantaneous traffic in order to compare the current and voltage profiles.

Based on the results, the parameters can be adjusted in order to have a simulation tool representative of reality.

The use of random delays between trains helps avoiding unwanted synchronization between vehicles that could eventually jeopardize the validity of the energy consumption results. Adjusting the Open Circuit Voltage (OCV) and the internal resistance of each substation individually and modifying the regenerative braking control of the vehicles by adjusting their maximum braking voltage is recommended. This latter feature, ignored in many simulations, is crucial to determine the energy exchange among vehicles and the potential savings when using energy recovery technologies.

4 Procurement

This chapter deals with important aspects, which should be taken into account during the procurement process of braking energy recovery solutions. Defining the suggested implementation and environmental aspects in the tendering phase is key to improve the quality of the investment.

4.1 Implementation aspects

4.1.1 Location and number of systems

The place to implement a braking energy recovery system along the network must be thoroughly assessed. As described previously in Section 3.2.3 (Simulation tool), systems will mostly be placed in existing substations and directly linked to the electrical network. The place on the network can also influence the results. In the case where the operator is experiencing voltage drops, storage systems will be placed close to the weakest points of the network, often at the end of the lines or where substations are undersized.

The number of systems required has to be carefully evaluated in order to properly size the whole system. If the number of systems is too low, a significant part of the energy savings might be lost. If the number of systems is too high, the investment costs might be difficult to recoup in a short period of time as each individual system will recover less energy. A costs-benefits analysis on the duration of the systems (typically: 20 years for a reversible substation) is required to calculate the optimal number of systems, based on the amount of energy recovered calculated in the simulation phase.

4.1.2 System size and weight

The size and the weight of the chosen system have an impact on the locations and/or the construction works needed for accommodating the system. In some case, existing substations will be undersized and second best options will have to be taken to avoid unbearable costs. The delivery of the system must also be borne in mind when evaluating the different options. Some systems may require very specific delivery techniques (cranes, delivery train) or adaptations of the access.

An analysis of the size and weight of different systems was carried out during the Ticket to Kyoto project. Flywheels appeared to be the heaviest systems.

	Supercapacitors		Flywheels		Reversible substations		
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
A. Performance							
System efficiency	96%	80%	85%	95%	95%	97%	97%
Peak power	0,33 MW	0,70 MW	1,00 MW	0,20 MW	1,50 MW	1,50 MW	2,70 MW
Available energy	1 kWh	2,5 kWh	5 kWh	1,5 kWh			
B. Implementation							
Volume	3,00 m ³	12,00 m ³	11,50 m ³	3,00 m ³	14,00 m ³	7,50 m ³	5,50 m ³
Mass	1.000 kg	4.300 kg	10.000 kg	1.500 kg	2.500 kg	2.700 kg	2.600 kg

Table 5 : Comparative table of the weight and size of different technologies and systems, Ticket to Kyoto

4.1.3 Security

Power electronics devices are potentially hazardous and must be placed in properly secured areas. Security measures might be necessary to prevent the system from vandalism and misuse. However, energy recovery units will be usually placed inside a substation that is only accessible for designated maintenance staff.

4.1.4 Safety

The safety of the workers and the citizens must be ensured at all times. Some technologies may require more attention for ensuring a certain safety level. The use of flywheels, for example, require specific security measures regarding the risk of having the wheel going loose from its axis.

4.1.5 Cooling and ventilation

Electrical devices must cope with heating issues that need to be controlled through the use of natural or forced air-cooling systems. Adapting rooms to these constraints may prove to be unfeasible or very expensive. A HVAC calculation of the energy recovery unit in the substation has to be made to determine the necessary adaptations. On the other hand, heat can be potentially recovered for heating other rooms located nearby and improve the global energy efficiency.

4.2 Environmental aspects

4.2.1 Noise and vibrations

The noise produced by the equipment can affect the location choice if the installation of the system is planned in a populated environment. The safety and comfort of the staff must also be taken into account. Noisy systems may impose workers to wear acoustic protection.

4.2.2 Electromagnetic interference



The railway electromagnetic environment is much more severe than the one found in domestic or commercial premises. City light rail or metro lines may run close to public premises such as hospitals, university or IT companies, which may want to prevent any electromagnetic interference with their equipment. The use of braking energy recovery systems must be analysed from this point of view.

4.2.3 Harmful materials

Every technology is different regarding the use of potentially harmful materials. The environmental aspects certainly add further risk to the project, which would have an adverse effect on the cost.

Mechanical devices such as flywheels or inverters do not contain chemical substances whereas supercapacitors contain acetonitrile, which is a volatile, flammable and carcinogenic substance. There is still a lot of uncertainty about the lifecycle of supercapacitors and the costs of disposal. Batteries also use different types of chemical substances.

5 Case studies

5.1 STIB – Brussels

5.1.1 Context

STIB is the largest Belgian urban public transport company and serves the 19 municipalities of the Brussels-Capital Region as well as 11 other outlying communes. It provides transport for a population of over 1,100,000 inhabitants and thousands of commuters. STIB network has 4 metro lines, 19 tram lines, 50 bus lines and 11 night bus lines. In 2013, over 355 million people chose public transport to get around the capital. Facing a rapid growth in ridership over the past 10 years, the Brussels Government decided to invest massively in the public transport network by optimizing the metro network (new trains, higher frequencies) and by boosting the bus and tram networks (new vehicles, better frequencies, new lines). This resulted in a 50% increase of the offered capacity.

5.1.1.1 Past experience

Braking energy recovery technologies have been studied at STIB since 2004. After various contacts with industrials presenting their products on the market, STIB rapidly realized that a global approach was necessary to apprehend the different aspects.

In the context of the program « Prospective Research for Brussels », organized by the Brussels Capital Region (IRSIB), a four year research project has been carried out between 2007 and 2010 and focused on the implementation of supercapacitors-based technologies, both for metro and tram networks. This project, which joined expertise from the ULB (Université Libre de Bruxelles) and the VUB (Vrije Universiteit Brussel), was achieved in close collaboration with STIB and gave interesting results on the implementation of such technology, in particular for the metro network. VUB also developed a first version of a simulation tool aiming at calculating the energy flows between the vehicles and the potential energy savings obtained with on-board (for trams) or wayside energy storage system.

5.1.1.2 Line topology and headways

Brussels has a metro network composed of 4 lines but only metro lines 2 and 6 have been so far investigated for braking energy recovery purpose. Metro line 2 consists in

STIB metro lines 2 and 6 have a common section where frequencies are doubled. Trains headways are given in the table below for each period.

	Trains Headway	
	2 6	6
Peak	3'	6'
Off-Peak	3' 45"	7' 30"
W.E. & Night	5'	10'

Table 7 : Trains headway on line 2 and 6, STIB

It is worth noting that STIB intends to convert its metro lines 1 and 5 to driverless operations by 2018. Those lines currently face a lack of capacity at peak time and must be upgraded to cope with the foreseen demand in the Brussels-Capital region by achieving headways below 2 minutes. Automated operations on lines 2 and 6 are not foreseen before 2025 so that this issue was not thoroughly considered during the T2K project.

5.1.1.3 Vehicles

In the case of STIB, all metro trains have the ability to recover braking energy. However, the latest generation of CAF boa trains regenerate a higher amount of braking energy as power electronics devices were optimized.

As far as tram vehicles are concerned, the situation is less ideal as the first generation PCC trams do not recover braking energy and still account for a significant part of the fleet.



	M6	U 1,2,3,4
		
Weight	160 t	31,4t
Length	94 m	18 m
Motor power	16 x 135kW	2 x 264 kW per car
Acceleration	max 1.3 m/s ²	max 1,33 m/sec ² (0 to 26 km/h)
Deceleration	max -1.2 m/s ²	-
Trains on lines 2 and 5	None	3 to 5 cars coupled

Table 8 : Vehicle characteristics of the metro trains, STIB

5.1.1.4 Electrical network

The electrical network is composed of different electrical segments fed by two irreversible diode substations as represented on the figure below. The average distance between consecutive substations is around 1 km. Although those segments are not connected to each other directly, they are electrically connected through the substations. Thus, the vehicles are able to send energy from one segment to another thanks to the substation connection. The same applies to the 2 different directions; although not connected directly, there is a connection point at every substation.

The Brussels-Capital region is fed by a high-voltage network (150 kV and 36 kV) operated by ELIA and by a medium- and low-voltage network operated by SIBELGA. STIB is 100% supplied by ELECTRABEL-SUEZ and the electricity provided to STIB is a 36kV Volts AC. Transformers step down this energy to 11kV and traction substations transform this energy in “usable” electricity either as 900 Volts DC for the metro traction or as 700 Volts DC for the tram traction and in 230-400 Volts AC for the administrative buildings, depots, stations or maintenance halls. STIB has the particular advantage of owning and ensuring the maintenance of its electrical network and can therefore send energy back to the grid more easily.

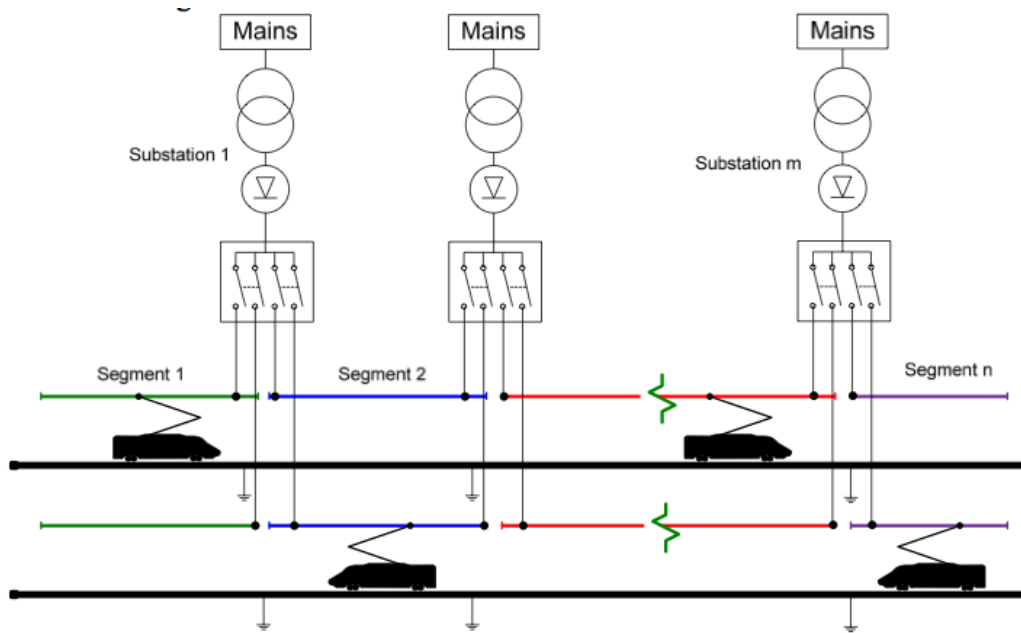


Figure 13: Schematic of metro line fed by unidirectional substations (Source: VUB – R. Barrero)

The Brussels metro network has a nominal voltage of 900V and is not prone to voltage drops due to the presence of many substations feeding the line. According to simulations, voltage drops should remain exceptional even if more vehicles were operated on the line. As a result, storage applications did not appear as necessary for preventing voltage drops.

Medium Voltage network	900V
Nominal Traction voltage	824 Vdc
No Load Traction voltage	880 Vdc
Nominal power of substations	2x1.65 MW
Average distance between substations	1,14 km
Feeding system	3rd rail

Table 9 : metro electrical network characteristics, STIB

5.1.2 Decision making

5.1.2.1 Multi-criteria analysis

STIB worked together with VUB (Vrije Universiteit Brussel) and D-sight to develop a multi-criteria analysis (MCA) for choosing the most appropriate technology for the metro network, especially lines 2 and 6.

This MCA compared reversible substations, flywheels and supercapacitors solutions for the specific context of the Brussels metro. It must be pointed out that the results of the analysis cannot be replicated as such in other contexts but can be useful for other operators wishing to learn more about the methodology followed.

A selection of criteria has been chosen for this evaluation based on their relevancy and data availability. The criteria, their specific weight and evaluation scale are presented in the table below.

Code	Criteria	Weight	Min/Max	Unit	Scale Numerical/qualitative
A.1	Investment cost/Peak Power	33%	Minimize	€/MW	Numerical
A.2	Investment cost/Maximum energy recovery	40%	Minimize	€/kWh/h	Numerical
A.3	Voltage balancing function	13,3%	Maximize	Yes/No	Voltage balancing function
A.4	Auxiliaries consumption/Maximum energy recovery per hour	13,3%	Minimize	h/year	Numerical
		Tot. 100%			
B.1	Volume	30%	Minimize	m3	Numerical
B.2	Mass	20%	Minimize	kg/kWh/h	Numerical
B.3	Stage of development	30%	Maximize	Product/Prototype	Stage of development
B.4	Systems in service worldwide	20%	Maximize	Number	Numerical
		Tot. 100%			
C.1	Mean time between maintenance (MTBM)	20%	Minimize	Times/year	Numerical
C.2	Mean time to maintain (MTTM)	10%	Minimize	Hours	Numerical
C.3	Mean time between failure (MTBF)	40%	Maximize	Years	Numerical
C.4	Mean time to repair (MTTR)	10%	Minimize	Hours	Numerical
C.5	Lifecycle	20%	Maximize	Years	Numerical
		Tot. 100%			
D.1	Toxicity	50%	Minimize	Low/Middle/High	Toxicity
D.2	Noise	25%	Minimize	dB	Numerical
D.3	Recycling	25%	Maximize	%	Numerical
		Tot. 100%			
A	Performance	40%			
B	Implementation	20%			
C	Maintenance and reliability	30%			
D	Environment	10%			
		Tot. 100%			

Table 10 : Criteria selected in the MCA analysis, STIB

The criteria are represented by the axes. An axis indicates the direction of the most preferred alternatives for the related criterion. One can observe that the Environment and the Performance axes are close to each other. This means that, on average, the systems having good Performance scores also have good Environment score (correlation).

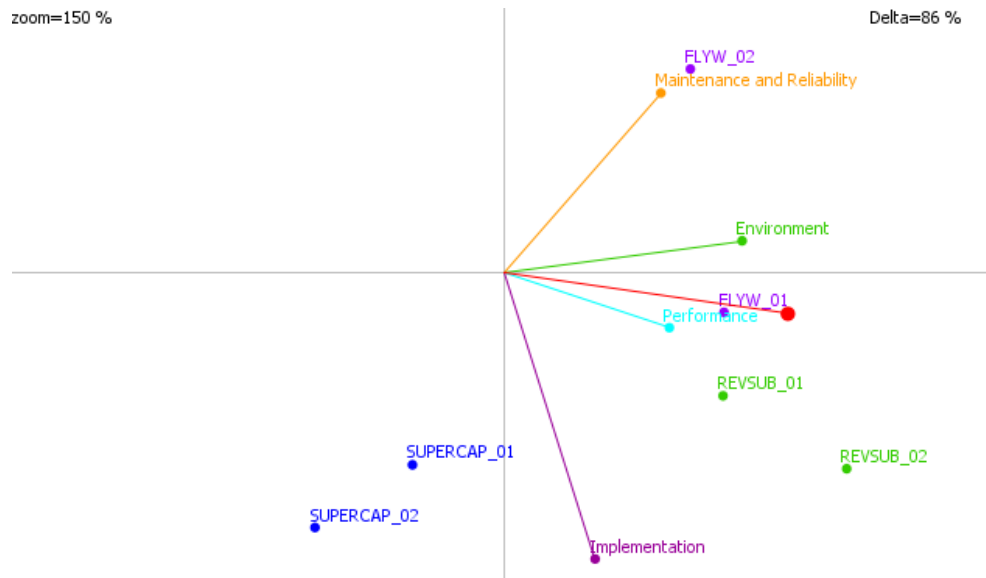


Figure 14: Global Visual Analysis of the assessed braking technologies, VUB/D-Sight

If the projection of an alternative goes far on the axis, it means that it is well scored for the criterion.

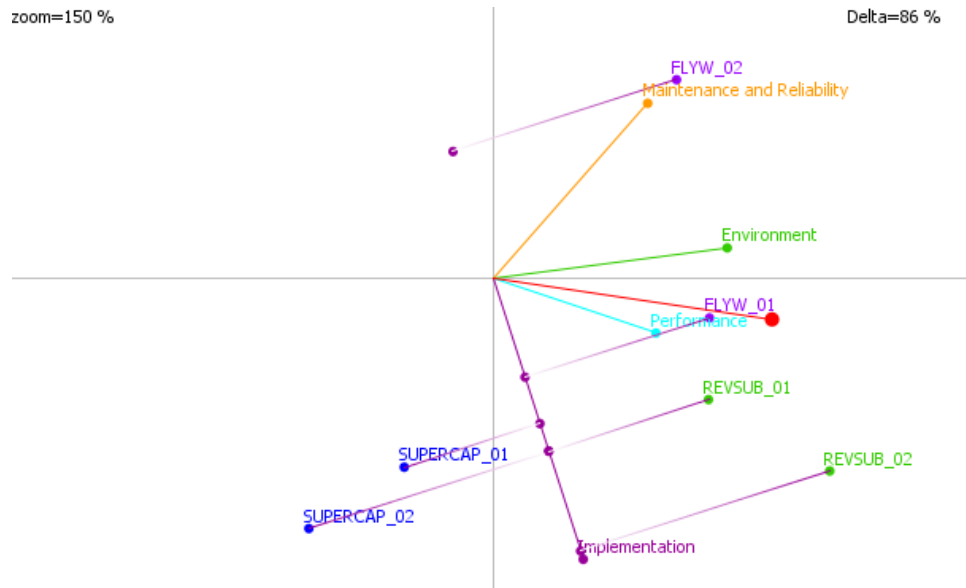


Figure 15: Visual Analysis of the implementation criteria, VUB/D-sight

Based on the MCA, it can be concluded that there are three interesting alternatives: 2 reversible substations and one flywheel solution. Indeed, none of them has negative aspects (e.g. have negative projections on the axes). The results of the MCA showed a clear advantage regarding reversible substations compared to flywheels and supercapacitors especially in terms of performance and environment. As a result, STIB decided to launch a tender exclusively for the procurement of reversible substations (inverters).

5.1.2.2 Simulation

Based on a previous cooperation, STIB asked the Vrije Universiteit Brussel (VUB) to enhance their metro network simulation tool in order to best evaluate the different technologies. The first step was to calibrate the simulation model with real measurements of the network energy consumption without any energy recovery system installed. In order to evaluate the performance of the model, experimental measurements were taken on one car on a metro in regular service on metro line 6. STIB recorded the energy consumption of the substations during one whole month (May 2011) and the total distance covered by the vehicles in service during that period.

The figure below presents a comparative study between the experimental measurements and the simulation results. The output of the model matched pretty well

the real measurements both at vehicle and substation level. This was made possible thanks to the precise measures of the open-circuit voltage (OCV) and internal resistors available for each substation.

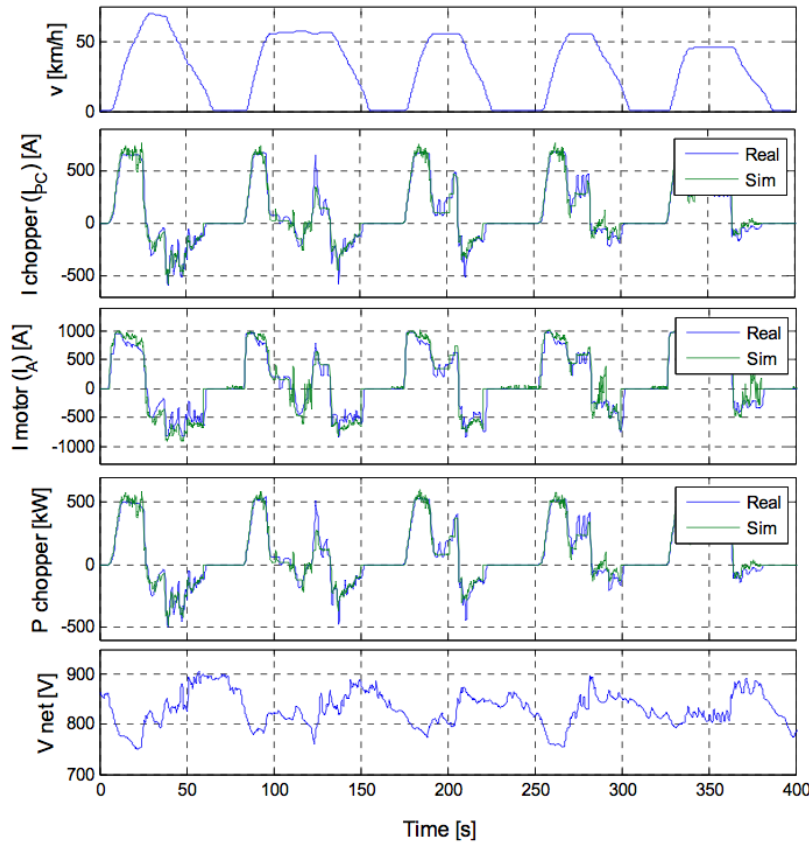


Figure 16 : View of the simulation tool, VUB – R. Barrero

Another interesting thing to remark is the variation in the amount of energy supplied by consecutive substations and the influence of the substation OCV in this matter. It is observed that, in general, the substations with a higher OCV supply more energy to the network. These data were very useful for calibrating the simulation model and make sure its results were matching the real operations.

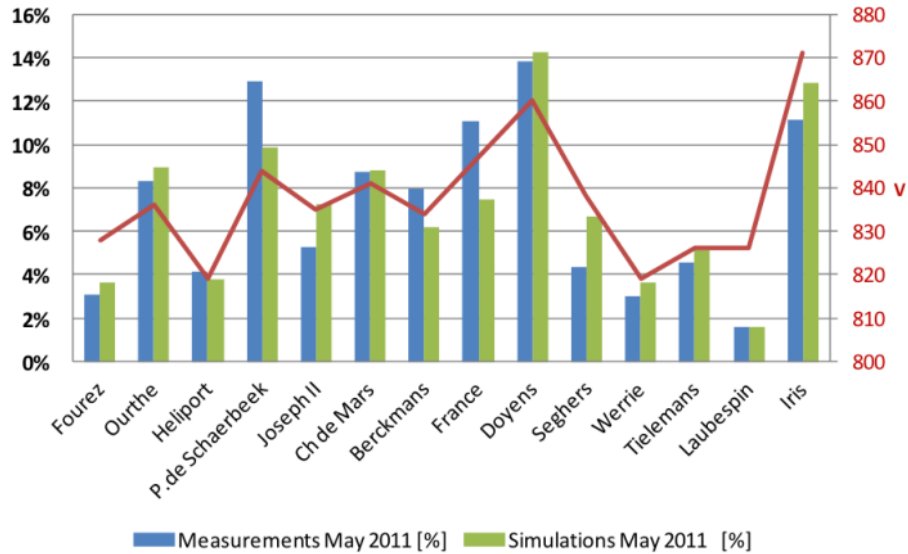


Figure 17 : Comparison between the real measurements and the simulation results, VUB – R. Barrero

A comprehensive explanation of the simulation tool and results is available in the Ph.D. thesis of Ricardo Barrero – **Energy recovery technologies in the public transport** – published in November 2012 at the Vrije Universiteit Brussel.

The simulations on metro lines 2 and 6 have also shown that line receptivity (energy exchanges between accelerating and braking vehicles) was higher at peak time as more vehicles were running simultaneously. The ratio between restored energy and available braking energy amount to around 69% in the case of low traffic volume, around 71% in the case of medium traffic volume and around 75% in the case of high traffic volume.

	Test 1	Test 2	Test 3	Test 4	AVERAGE	Test 1	Test 2	Test 3	Test 4	AVERAGE
Number of cars/train	4	4	4	4	4	4	4	4	4	4
Occupancy	seats	seats	seats	seats	seats	seats	seats	seats	seats	seats
Maximum vehicles voltage	925	925	925	925	925	905	905	905	905	905
Energy delivered by Substations [kWh]	2582.27	2615.36	2558.02	2622.94	2594.65	2707.62	2662.71	2723.65	2662.03	2689.00
Energy taken back by substations [kWh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Substation Losses [kWh]	52.85	54.21	50.63	53.76	52.86	53.77	51.51	54.52	51.24	52.76
Line Losses [kWh]	130.11	130.14	131.43	131.44	130.78	120.64	122.79	122.43	122.23	122.02
Consumed energy by vehicles [kWh]	3210.00	3226.83	3231.31	3251.92	3230.01	3226.53	3232.61	3241.69	3237.86	3234.67
Restored energy by vehicles [kWh]	-815.03	-800.90	-859.24	-818.93	-823.52	-699.14	-749.19	-700.79	-754.56	-725.92
Braking energy available [kWh]	-1188.74	-1183.26	-1190.89	-1196.57	-1189.87	-1182.71	-1184.94	-1192.74	-1204.10	-1191.12
Restored/Consumed [%]	-25.39%	-24.82%	-26.59%	-25.18%	-25.50%	-21.67%	-23.18%	-21.62%	-23.30%	-22.44%
Restored/Available braking [%]	68.56%	67.69%	72.15%	68.44%	69.21%	59.11%	63.23%	58.75%	62.67%	60.94%
Total distance by all vehicles [km]	181.90	179.25	179.68	180.18	180.25	179.39	179.33	180.04	180.92	179.92
kWh/km	14.20	14.58	14.23	14.55	14.39	15.08	14.83	15.11	14.70	14.93
kWh/km*Car	3.55	3.65	3.56	3.64	3.60	3.77	3.71	3.78	3.67	3.73

Table 11 : Simulation results at low traffic volume – weekend, VUB – R. Barrero

	Test 1	Test 2	Test 3	Test 4	Test 5	AVERAGE	Test 1	Test 2	Test 3	Test 4	AVERAGE
Number of cars/train	5	5	5	5	5	5	5	5	5	5	5
Occupancy	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²	seats + 2p/m ²
Maximum vehicles voltage	925	925	925	925	925	925	905	905	905	905	905
Energy delivered by Substations [kWh]	5042.57	5117.07	4990.67	5130.83	4988.98	5054.02	5317.54	5238.75	5334.85	5241.05	5283.05
Energy taken back by substations [kWh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Substation Losses [kWh]	175.36	181.03	161.45	182.08	168.46	173.68	184.88	173.98	181.94	176.54	179.33
Line Losses [kWh]	381.49	381.16	385.22	376.36	380.61	380.97	363.26	366.05	365.06	361.93	364.07
Consumed energy by vehicles [kWh]	6177.19	6171.47	6227.28	6165.95	6156.69	6179.72	6192.37	6244.76	6205.97	6189.95	6208.26
Restored energy by vehicles [kWh]	-1694.39	-1620.74	-1785.69	-1597.42	-1719.82	-1683.61	-1427.39	-1549.47	-1422.66	-1491.54	-1472.77
Braking energy available [kWh]	-2352.71	-2356.35	-2366.24	-2344.50	-2331.42	-2350.24	-2369.70	-2360.35	-2358.57	-2367.13	-2363.94
Restored/Consumed [%]	-27.43%	-26.26%	-28.68%	-25.91%	-27.93%	-27.24%	-23.05%	-24.81%	-22.92%	-24.10%	-23.72%
Restored/Available braking [%]	72.02%	68.78%	75.47%	68.13%	73.77%	71.63%	60.24%	65.65%	60.32%	63.01%	62.30%
Total distance by all vehicles [km]	238.16	238.02	240.24	238.72	237.58	238.54	240.27	239.85	239.12	239.53	239.69
kWh/km	21.16	21.49	20.76	21.48	20.99	21.18	22.12	21.83	22.30	21.87	22.03
kWh/km*Car	4.23	4.30	4.15	4.30	4.20	4.24	4.42	4.37	4.46	4.37	4.41

Table 12 : Simulation results at medium traffic volume – off-peak time, VUB – R. Barrero

	Test 1	Test 2	Test 3	Test 4	AVERAGE	Test 1	Test 2	Test 3	Test 4	AVERAGE
Number of cars/train	5	5	5	5	5	5	5	5	5	5
Occupancy	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²	4p/m ²
Maximum vehicles voltage	925.00	925.00	925.00	925.00	925.00	905.00	905.00	905.00	905.00	925.00
Energy delivered by Substations [kWh]	7059.50	7120.71	7178.65	7176.27	7133.79	7484.01	7437.81	7489.44	7574.83	7496.52
Energy taken back by substations [kWh]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Substation Losses [kWh]	311.62	314.12	330.07	322.58	319.60	343.99	348.12	348.87	372.06	353.26
Line Losses [kWh]	645.11	641.86	655.20	647.32	647.37	636.81	622.47	626.71	629.93	628.98
Consumed energy by vehicles [kWh]	8695.44	8703.27	8711.71	8773.39	8720.95	8717.15	8680.12	8707.15	8658.23	8690.66
Restored energy by vehicles [kWh]	-2594.83	-2541.03	-2520.92	-2569.09	-2556.47	-2217.26	-2216.10	-2196.92	-2089.06	-2179.84
Braking energy available [kWh]	-3392.07	-3389.70	-3391.50	-3408.65	-3395.48	-3415.44	-3424.83	-3379.17	-3378.52	-3399.49
Restored/Consumed [%]	-29.84%	-29.20%	-28.94%	-29.28%	-29.31%	-25.44%	-25.53%	-25.23%	-24.13%	-25.08%
Restored/Available braking [%]	76.50%	74.96%	74.33%	75.37%	75.29%	64.92%	64.71%	65.01%	61.83%	64.12%
Total distance by all vehicles [km]	297.79	297.53	298.66	299.60	298.39	298.29	298.15	297.01	296.26	297.43
kWh/km	23.70	23.93	24.03	23.94	23.90	25.08	24.94	25.21	25.56	25.20
kWh/km*Car	4.74	4.79	4.81	4.79	4.78	5.02	4.99	5.04	5.11	5.04

Table 13 : Simulation results at high traffic volume – peak time, VUB – R. Barrero

STIB then investigated the best locations for implementing an energy recovery system by the use of its simulation tool. The challenge consisted in finding the solution that provides the most energy savings with the minimum amount of inverters. If all substations of metro lines 2 and 6 were able to send energy back to the network, around 10% of energy savings could be achieved. However it was necessary to find the best trade-off solution providing high energy savings with a low investment, i.e. with as few inverters as possible with the lowest possible power rating. In the case of STIB, a good trade off solution seems to be in the range of 6 to 8 inverters installed of 1 to 1.5 MW rated power as it can be observed from Figure 18. Savings increase with the number of inverters very clearly until 6 or 8 inverters installed. From that point on, increasing the number of inverters, increases the savings but not in the same proportion.

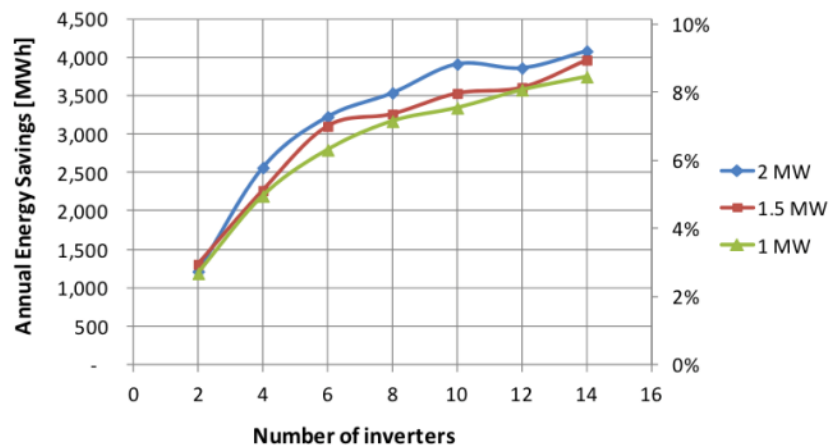


Figure 18 : Evolution of the annual energy savings when increasing the number of inverters, VUB – R. Barrero

To find the optimal locations, it was necessary to make several simulations with inverters installed in different places and at different traffic conditions. The methodology consisted in running a simulation with an inverter installed at every substation. The two inverters that recovered the less energy were then removed and a new simulation was performed. The process was repeated incrementally following the same logic to identify the best locations.



Figure 19 : Incremental approach for selecting the highest-potential substations, VUB – R. Barrero

5.1.2.3 Mobile systems and catenary-free operations for tram

Within the T2K project, STIB has been focusing on its metro network where catenary-free operations are not an option. In previous studies, STIB investigated the use of on-board supercapacitors-based technologies for its tram network, especially on line 7 (former line 23). This 20,8 kilometres line, operated with new Bombardier Flexity T3000, benefits of high occupancy rates and consists of various section types: tunnels, dedicated lanes and mixed lanes.

Four alternative supercapacitors systems configurations were compared with an energy content ranging from 0.91 kWh to 1.56 kWh and energy savings were simulated in a Matlab/Simulink environment. The expected energy savings at substation level are given in and range from 21% to almost 26%.

Module option	Energy content (kWh)	Energy savings at substation level (%)
Module A	1,2	25,60%
Module B	1,23	24,83%
Module C	1,56	25,88%
Module D	0,91	24,65%

Table 14 : Energy savings for a T3000 on line 23

Module configurations A and D were further assessed, as they seemed to be the best trade off solution considering the energy savings achieved and their energy content. Annual and lifetime energy savings are given in Table 14 with a lifetime of the ESS set to 15 years and considering the efficiency of the supercapacitors cells decreasing over time. Potential energy exchanges between vehicles were not considered in these simulations.

Module configuration	Annual mileage (km)	Marginal consumption (kWh/km)	Annual consumption (kWh)	Annual energy savings (kWh) [Full efficiency]	Annual energy savings (kWh) [End of life]	Lifetime energy savings (kWh) [15 years]
Module A	50 000	5,203	260 156	66 612	61 189	958 505
Module D	50 000	5,203	260 156	64 116	54 373	888 665

Table 15: Annual energy savings due to the inclusion of an ESS aboard a tram

To evaluate the economic benefits of reducing the energy consumption of the trams, a baseline price was set at 75€/MWh and various price increases were considered. The expected benefits on a lifetime basis (15 years) are shown on Figure 20

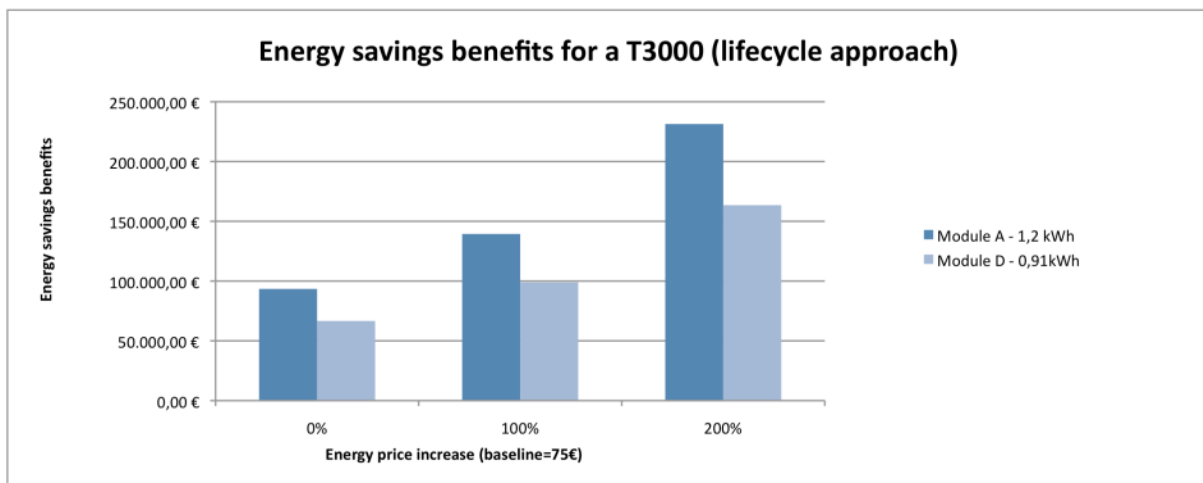


Figure 20 : Energy savings benefits for an ESS aboard a tram on line 23

Despite the significant energy savings, the study concluded that the costs of implementing an ESS on-board of a tram exceed by far the expected benefits even in the case of a strong increase of the energy prices. The reason is that the technology was still too expensive due mostly to high development costs and vehicles retrofit. These costs could be reduced if several transport operators would invest massively in the technology and if a standard system could be designed to meet the customers' expectations. In the case of STIB and given the benefits measured in this analysis, the investment cost of an ESS on board of a tram should not exceed more or less 100.000€ per vehicle to become a beneficial solution for energy savings, assuming the system would last for 15 years. Another element that could make such a system more attractive is the possibility to operate the tram without overhead lines on certain sections of the route. This requirement is not on the agenda of the Brussels region where several tram lines are already in service.

5.1.3 Tender

Since STIB owns its medium-voltage electrical network and for the other reasons presented above, inverters appeared to be the most cost-effective solution in this context. A European tender was launched and three suppliers were invited to test their system on the network for several weeks in order to compare their efficiency and the delivered savings. This empirical approach produced useful insights on the way braking energy can be recovered by the use of inverters. The analysis came to the conclusion that the best system in the specific context of the Brussels metro network was the inverter manufactured by INGETEAM. 5 new inverters will now be procured and installed along the network.

Technical data of the INGETEAM inverter

- Technology: IGBT
- Voltage range: 400-1000 V DC
- Maximum power: 1.5 MW
- Feedback current : 680A AC
- Efficiency rate: 92% to 96% ³

³ The inverter efficiency at peak power is 98.5%. The whole system efficiency, including the inductive elements (DC inductance and transformer) varies between 92 % to 96% depending on the working point and the system design.

- Weight: 4.8 tons
- Noise : <65dB(A)

5.1.4 Implementation

In order to have an empirical approach and since it was difficult to select the best suppliers only from the simulation results, STIB decided to buy one system from each supplier and to test them in the same conditions for comparison purpose. All three systems have been installed in the same substation (Laubespain) on line 6, which was big enough for allowing the implementation of three systems. After delivery and once the installation was complete, a test run was organized for each supplier during the night with only one metro running on the network. This was more secure in case of a major failure as this would not impact the daytime service. It was also easier for the supplier to test thoroughly their system and make sure it was recovering energy from the braking phase of the vehicle and not from a nearby substation. Some minor issues happened during the implementation but could easily be fixed.

Then, the three systems have been tested in real conditions during 3 months. Every system was tested during one day before testing the system of another supplier on the next day and so on. In order to have good measurements, each system was switched on during 15 minutes, then switched off during 15 minutes. In this way STIB could gather information on the consumption of the electrical network with and without braking energy recovered from the inverters. This technique allowed to observe that the neighboring stations were consuming a little more when the inverter was on. This is due to the fact that the threshold voltage level from which the inverter recovers energy has to be set as low as possible to recover the maximum braking energy. Since the open-circuit voltage (OCV) of the substations were slightly different, the optimum in terms of energy savings could result in tolerating a certain level of energy taken from the neighboring substations (phenomenon referred as “recirculating energy”).

STIB also experienced that connecting three inverters in the same substation was a difficult task due to the fact that medium voltage cables had to be connected for the three systems. This led to higher costs than expected.



Figure 21: Adaptation of the connections of the high voltage cables to the transformer, STIB

5.1.5 Results

The results of all the suppliers were satisfactory.

A fine-tuning of the system was required as STIB noticed that a difference of 5V when defining the energy recovery threshold can result in a reduction of 20% of the energy savings. As a result, it is recommended to actively collaborate with the supplier to make sure that the system is properly set and that no correction can be made regarding the parameters.

Following this successful pilot project, STIB intends to deploy this innovative technology on the entire metro network. When the six systems will have been installed along the metro lines 2 and 6, STIB expects to recover around 3,400,000 kWh per year. This corresponds to a 9% reduction of the metro traction energy. The payback time is 5 years (without funding).

Technical Data (extrapolation for deployment on whole lines 2 and 6)	
Investment costs (€)	€1,800,000
Energy savings (%)	9%
Annual energy savings (kWh)	3,400,000 kWh
Annual CO ₂ savings (TCO ₂)	568 TCO ₂
Payback time (years)	5 years

Table 16 : Extrapolation of the results for the deployment of braking energy recovery systems on lines 2 and 6, STIB

5.2 moBiel – Bielefeld

5.2.1 Context

Providing mobility services for 325,000 inhabitants of Bielefeld and a further 125,000 in the surrounding region, moBiel is the biggest public transport provider in the German region of Eastern Westphalia. moBiel is a city-owned operator and partially the owner of the public transport infrastructure. Four light rail lines form the backbone of the network and pass under the city centre through a tunnel section with seven underground stations. The bus network is formed by 79 lines. moBiel aims to increase passenger numbers with line extensions of the existing network.

5.2.1.1 Past experience

moBiel had no previous experience in the braking energy recovery field before starting the Ticket to Kyoto project.

5.2.1.2 Line topology and headways

moBiel operates a light rail network of four lines with a total length of 71,6 km. All lines are crossing the city centre in a tunnel section and are composed of 62 stations. The average distance between two stations is 450m. The tram lines are relatively flat except the slopes to enter the tunnel sections.

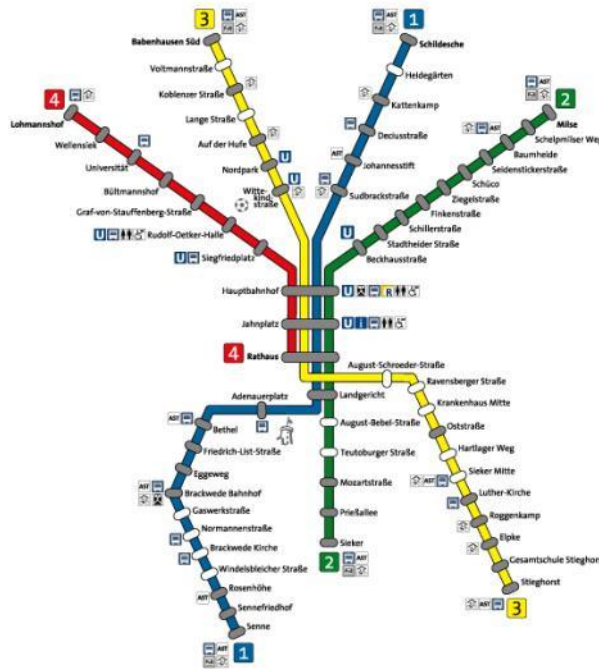


Figure 22: Plan of the moBiel tram network composed of 4 lines

The headway on each line is around 5 minutes during peak time and 10 minutes during off peak time.

5.2.1.3 Electrical network

The electrical network is composed of 7 substations. The catenaries are interconnected.

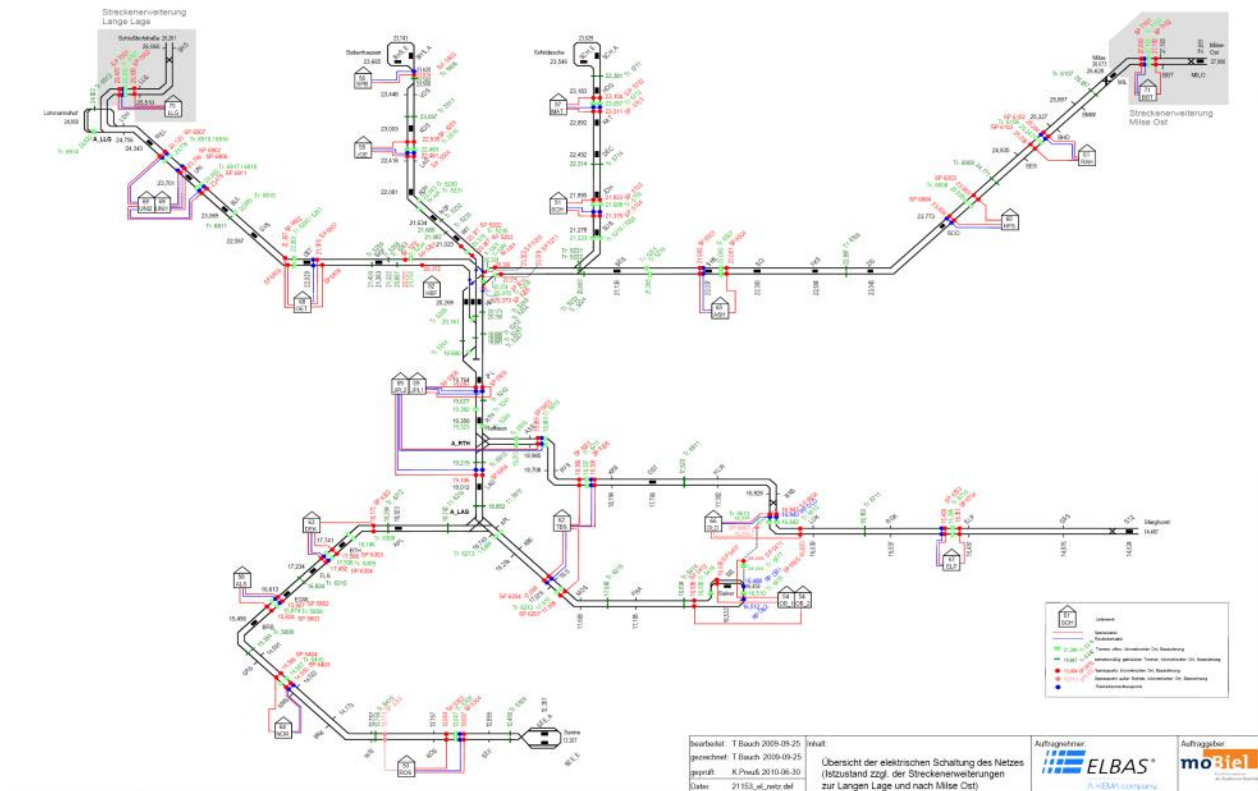


Figure 23 : View of the electrical network configuration of the moBiel tram network, moBiel

Medium Voltage network	10 kV
Nominal Traction voltage	750 VDC
Zero Load Traction voltage	825 VDC
Maximum Traction voltage when braking	925 VDC
Number of substations	19
Rated power of substations	1500 to 6000 A
Average distance between substations	between 600 m and 1,200m
Traction supply system	bidirectional feeding
Feeding system	Catenaries
Revenue-earning kilometres in 2013	4,928,944 km

Traction energy consumption in 2013	16,165,043 kWh
Number of passengers in 2013	33,149,297 passengers
Degree of capacity utilisation	24%

Table 17 : Overview of the moBiel network data, moBiel

5.2.1.4 Vehicles

In the case of moBiel, all trams have the ability to recover braking energy.

	M8C	M8D	GTZ8-B (Vamos)
Fahrzeuganzahl / number of vehicles	24	36	16
Leergewicht / tara weight	38 t	34 t	55 t
Gesamtgewicht / total weight	52,7 t	49 t	80,7 t
Länge / length	26,5 m	26,6 m	34,3 m
Sitzp-/Stehplätze / seats/standing places (4/m)	52 / 86	63 / 91	68 / 162
passenger capacity of vehicle	138	154	230
Antriebsleistung	2 x 150 kW	4 x 95 kW	8 x 80 kW
Antriebsleistung gesamt	300 kW	380 kW	640 kW
Beschleunigung / acceleration	max. 1,1 m/s ²	max. 1,1 m/s ²	max. 1,1 m/s ²
Verzögerung / delay	max. -1,26 m/s ²	max. -1,26 m/s ²	max. -1,26 m/s ²
Nennspannung DC / nominal voltage DC	750 V	750 V	750 V
Anfahrstrom maximal / starting current	500 A	600 A	900 A
Rückspeisespannung / voltage of feeding bac	925 V	925 V	925 V
Rückspeisestrom maximal / feeding back cur	720 A	900 A	1.600 A
Rückspeisestrom maximal, wenn gekuppelt	1440 A	900 A	1.100 A
Traktion / traction	1 or 2 cars coupled	2 cars coupled	1 or 2 cars coupled

Figure 24 : Overview of the moBiel tram data, moBiel

5.2.2 Decision making

5.2.2.1 Simulation tool

moBiel has commissioned an external independent consultant (Elba), who carried out an analysis of the potential savings and the optimal locations based on the network data. This method was necessary because the savings results provided by the manufacturers varied substantially.

In addition, an evaluation of the vehicle regenerative values and an evaluation of the braking resistor energy was performed by moBiel for each line. These results confirmed the results of the simulation.

5.2.2.2 Location choice

When choosing an optimal location it is important to make sure that the energy recovery systems will not influence each other in order to get the best of each system. In the case of the moBiel rail network, it was observed that a minimal distance of 6 km was required between two systems.

Other aspects regarding the location choice are the noise pollution for the neighboring environment and the system delivery and installation issues. moBiel initially thought of installing energy storage in a container at the end of line 2 but this idea was not pursued because of the significant additional costs for the container and ground foundation.

When selecting an appropriate site for the inverter, it has to be checked whether the rectifier transformer is correctly dimensioned with regard to the maximum values of the inverter.

5.2.3 Tender

The tendering process has started with an EU-wide invitation to tender for the supply and installation of braking energy recovery systems. During this call, especially economic and technical capacity was queried. Five suppliers were rated as efficient out of the 15 participants in the competition.

The tender was divided into two lots: energy storage systems and inverters.

In the evaluation process, the economic efficiency criterion was given the highest priority with a 60% weighting. Additional criteria included engineering, quality assurance and compliance with deadlines.

Regarding the energy storage system, the flywheel system supplied by Piller ranked first compared to supercapacitors systems manufactured by other suppliers. As far as the inverter is concerned, the system made by INGETEAM turned to be the best offer. moBiel therefore opted for one flywheel from PILLER and two inverters from INGETEAM. A third inverter from INGETEAM was purchased later.

moBiel intentionally opted for two different technologies (energy storage and inverters) for research purposes. In this way, moBiel has the opportunity to gain experience in terms of lifecycle, efficiency, maintenance by comparing both systems.

When selecting the preferred bidder, a crucial factor is that the company has sufficient experience in power traction supply. The deep knowledge in the field of power spikes, surges, sags and electromagnetic issues is of great importance when dimensioning the system and choosing the right elements. The references of the supplier shall be thoroughly checked.

moBiel recommends in any case to perform a factory acceptance. Since these products are not yet ready for series production, some modifications can be taken into account before delivery.

5.2.4 Implementation

When connecting a braking energy recovery system it is essential to make sure that the substation has been correctly disconnected. This is also necessary to account for safety aspects for the workers and to maintain the transport operations even in the case of failure of the substation.

Both the inverter and energy storage were each isolated from the substation building grounding and integrated into the circuit protective device framework of the substation. The driving circuits to and from the adjacent substations have been protected by track switches and 10 kV power switches. In order to precisely monitor the energy recovered and to control the functioning of both the flywheel and the inverter, they have been integrated in the control system of the substation. For remote monitoring purpose, all systems were also connected to the central control providing various error messages and measured values. Connecting the manufacturer troubleshooting system by a DSL remote access can strongly simplify the monitoring. All data are archived on a dedicated computer processing all system errors.

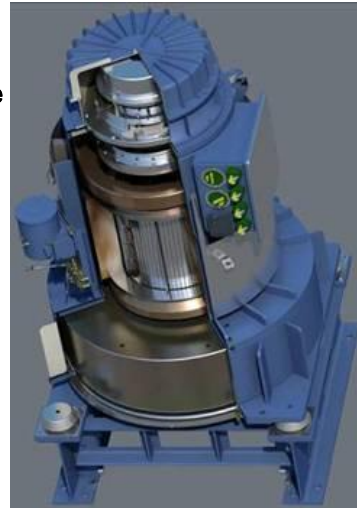
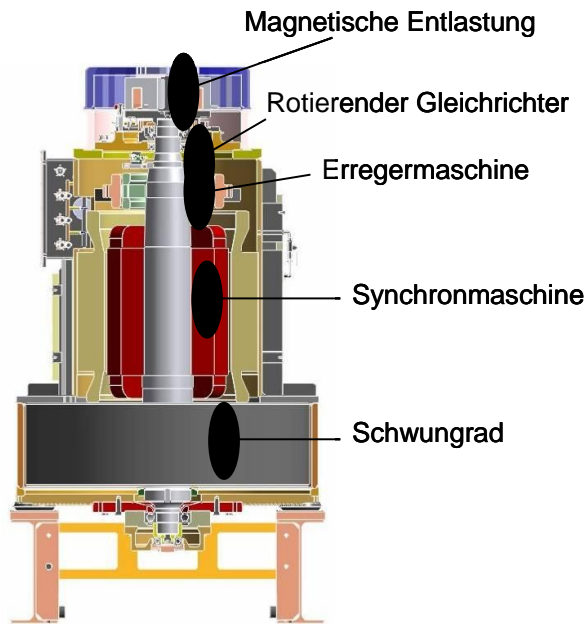


Figure 26: View of the PILLER flywheel system

The flywheel is located at the end of one line but this line will be extended by 1.5 km in a near future. Due to its weight (6 tons), the ground below the substation had to be consolidated with concrete. Additional vibration dampers were incorporated so as to minimize transmission of vibrations to the building. The ground structure had also to be reinforced for very high loads for delivering the system within the substation.

Due to the relatively high power dissipation of the energy storage system, the installation of an air conditioner is required in order to maintain the room temperature at about 26°C. Natural or mechanical ventilation was not sufficient due to the amount of heat at this point. During the winter months, the heat generated by the flywheel system is used for heating the adjacent substation space. The energy consumption of the air conditioning system must be taken into account in the energy balance.

In the case of moBiel, the energy storage device is not used for stabilizing the voltage but is focusing exclusively on energy saving.

The savings are measured from the internal monitoring system of the device. However, the accuracy of the data has been reviewed with an external measurement device and monitoring devices were also installed on vehicles.

In the planning of the energy storage, it should be checked whether the system is equipped with a protection device regarding the di/dt and I_{max} . If during the discharging of the storage system the electrical feeding of the substation is interfered/disrupted and a short circuit takes place on the line at the same time, this protective device must take care of the line protection. To optimize the efficiency of the flywheel, a smart automatic discharge is planned when the system is not on duty. This allows that the flywheel storage is fully discharged with the latest train and charged again with the first train on the next morning. The PILLER flywheel system works with fixed trigger values to start and stop the charging and discharging process. In a new procurement, moBiel would make sure that these values can be adapted to changing operational conditions: winter and summer for example.

The system is quite noisy (96 dB(A)) and obliges staff to wear acoustic protection when close to the equipment.

Shortly after the installation of the flywheel, a driver reported abnormal jerking of his vehicle when braking. These disorders occurred exclusively with the latest tram type Vamos (Vossloh Kiepe). In the older types of vehicles (ABB), this was not apparent.

Through various measurements in the trams and at the flywheel level, it could be shown that a swing occurred during the braking process of the vehicle and the charging process of the energy storage.

The first approach of the company Piller aimed at increasing the clock frequency of the IGBT inverter from the factory-set 400 Hertz to 1600 Hertz. This allowed a slightly noticeable improvement, but the problem was not completely solved.

In a second approach, the inductance of the input circuit has been substantially increased. This measure brought also a slight improvement but the problem could not be completely fixed.

moBiel noticed that the problem was occurring only with vehicles driving nearby the substation where the flywheel was installed. It was proposed internally to test install a vehicle braking resistor in parallel to the input filter of the energy storage system. The measures both at vehicle and flywheel have proven the success of this measure and there no longer jerking problems.

5.2.4.2 Inverter

Technical data of the INGETEAM inverter

- Technology: IGBT
- Voltage range: 400-1000 VDC
- Maximum power: 1MW
- Feedback current : 680AAC
- Efficiency rate: 98%
- Weight: 3.6 tons
- Noise : <65dB(A)



Figure 27: View and technical principle of the INGETEAM inverter in substation Oetkerhalle



Figure 28: Touch panel of the INGETEAM inverter in substation Oetkerhalle

When sizing the inverter, moBiel decided to opt for a 1MW since the price difference was low compared to a 500kW unit. As a result, the higher vehicle peaks foreseen in the future will be recovered. In order to test the maximum power of the 1 MW inverter systems, various braking sessions have been carried out in the vicinity of the inverter.

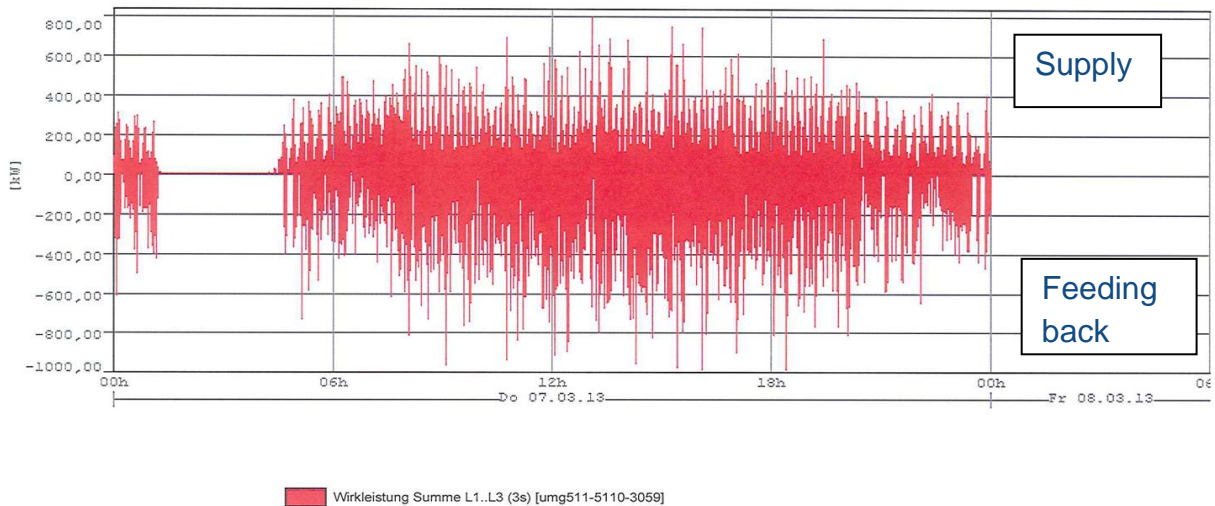


Figure 29: View of power peaks of substation Oetkerhalle, measured on 07.03.2013

When selecting the components of the inverter, moBiel paid attention to a low-loss transformer. A mechanical ventilation system was installed in order to conduct the waste heat of the inverter out of the substation building and avoid overheating of the equipment.

When planning the installation of an inverter system, the requests stated in the technical connection conditions (Technische Anschlussbedingungen, TAB) have to be respected when connecting an energy generating system to the medium voltage grid. According to this, a separate protective relay has to be fixed for the disconnection of over-voltage, and it has to be proved that the inverter system disconnects in case of power failure.

A network analyzer is used to check the value of the recovered energy and whether the system complies with the limits in terms of harmonics.



Figure 30: Meter “Janitza” measuring ripple harmonics in substation Oetkerhalle

For the inverter systems, the existing charging meter of the local energy supplier has to be replaced by a 4quadrant meter. The figures/results from these calibrated meters used for internal analysis are reported and controlled by remote readout from the inverters.

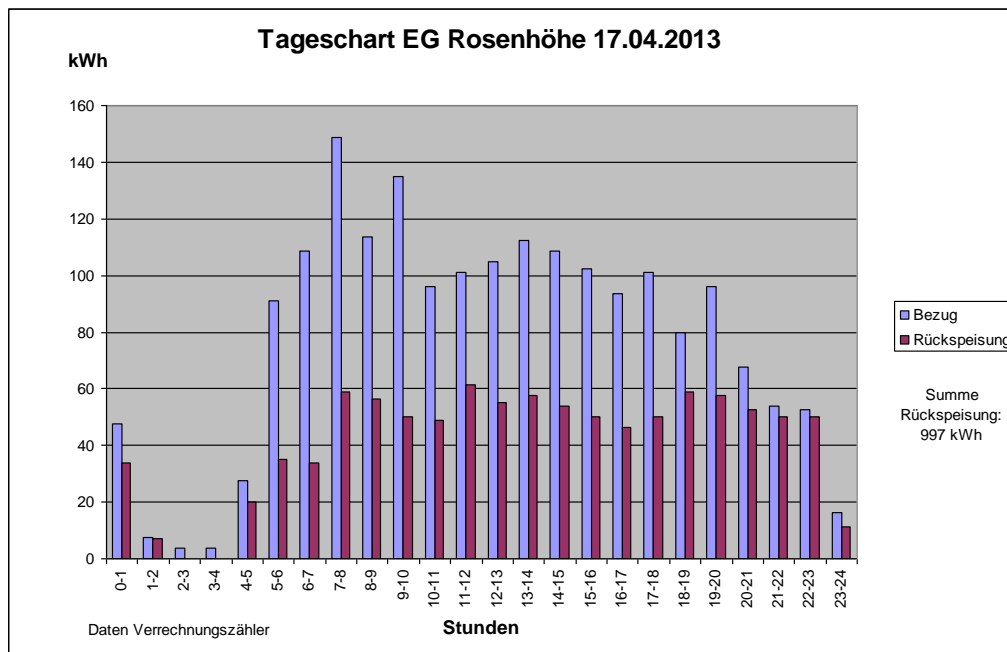


Figure 31: Results of supply and feeding back over a day; measured on 17.04.2013

in substation Rosenhöhe

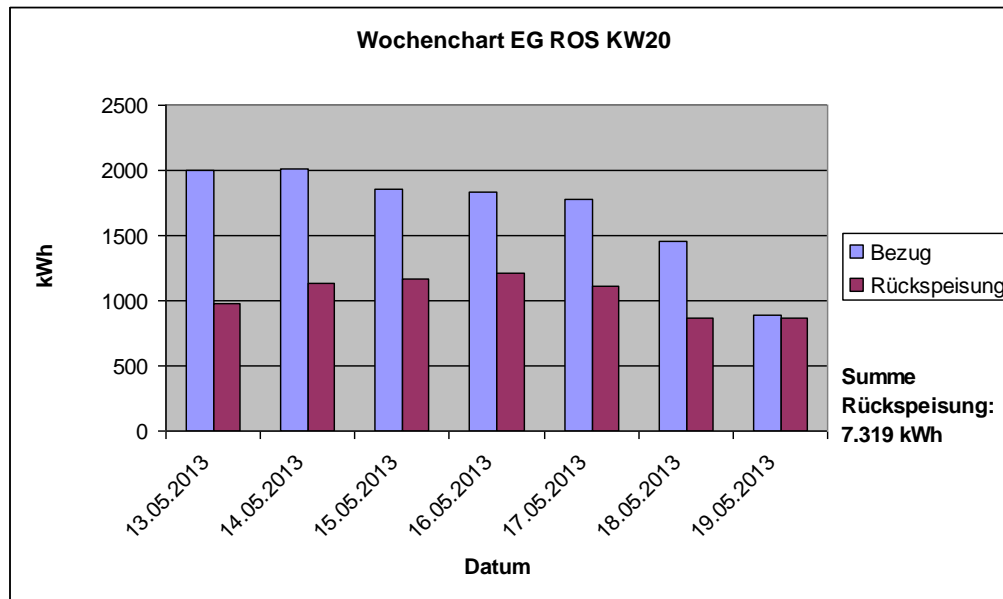


Figure 32: Results of supply and feeding back over a week; measured on calendar week 20/2013 in substation Rosenhöhe

5.2.5 Results

The energy recovery results of the different systems have been continuously collected.

The weekly energy recovery values are given in Figure 33 and are correlated to the average temperature. moBiel has noticed a strong influence of the outside temperature on the braking energy recovery results. During the winter period, energy savings are much lower due to the fact that the vehicle uses a part of the recovered energy directly for heating requirements. This happens also during summer months but to a lesser extent for cooling requirements. moBiel is also analysing how the fluctuating number of passengers is impacting the results.

The figure shows also that the results of the first semester 2014 are much better than the ones from the previous semester. This is due to the fact that all systems have been fine-tuned to optimize the energy recovery.

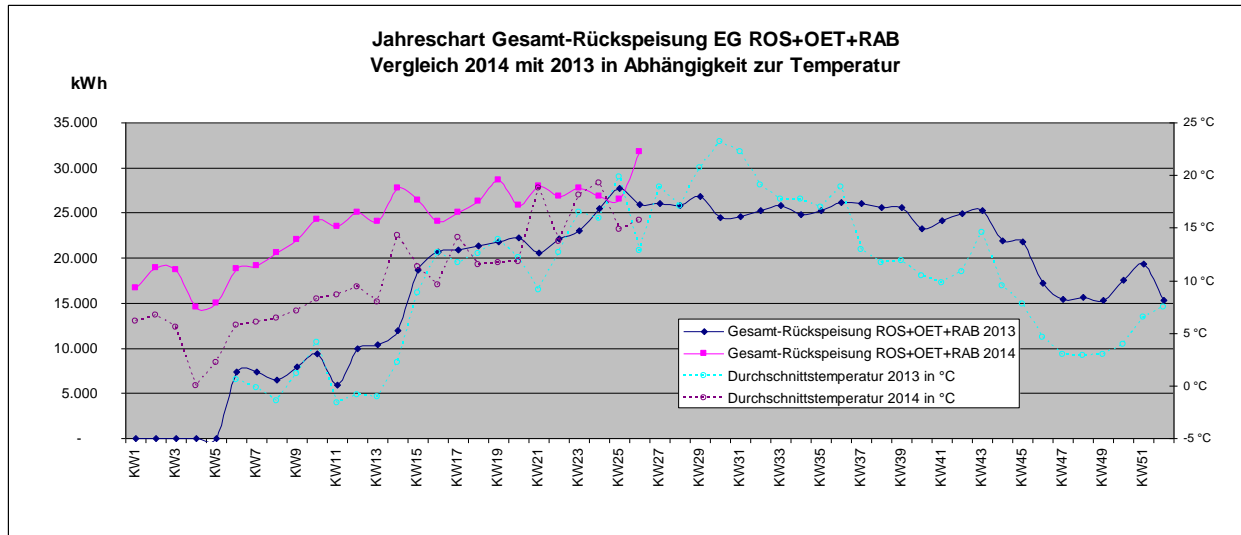


Figure 33: Overview of feeding back results of all substations with energy recovery systems in correlation with average temperature

The in-depth analysis of the results has shown that the overall efficiency of the inverter is 98% compared to 85% for the flywheel. The lower efficiency of the energy storage system results from the losses at the motor and generator levels as well as the friction losses of the flywheel.

However, the annual results of the flywheel exceeded the expectations based on the network study. The results of both inverters are in line with expectations. All systems are currently fine-tuned to optimize energy savings. The global energy consumption reduction amounts to around 6% of the tram traction energy. The payback time is 10 years without funding.

Type (location)	Calculation for 2014 based on real measurements	Expectations based on simulations
Flywheel system (Rabenhof)	360,000 kWh	220,000 kWh
Inverter (Oetkerhalle)	320,000 kWh	346,000 kWh
Inverter (Rosenhöhe)	350,000 kWh	295,000 kWh

Inverter (Universität)	70,000 kWh	50,000 kWh
TOTAL	1,100,000 kWh	911,000 kWh

Table 18 : Overview of the results based on real measurements and simulations

The global energy consumption reduction amounts to around 7% of the tram traction energy. The payback time is 10 years without funding.

Investment costs (€)	1,1 Mio Euro
Energy savings (%)	7%
Energy savings (kWh/year)	1,1 Mio kWh/a
Annual CO₂ savings (TCO₂)⁴	570 TCO ₂
Payback time (years)	5 years with funding 10 years without funding

Table 19 : Overview of costs and energy savings

5.2.5.1 Maintenance costs

moBiel expects maintenance costs of approximately 3,525€/ year for the flywheel system and of about 2,300€/ year per system for the inverters.

5.2.5.2 Additional consumption of the neighbouring substations

When determining the energy savings results, the consumption of the neighbouring substations has to be considered. This consumption must be subtracted from the energy recovery values. The total consumption of all the neighbouring substations has been monitored at different seasons, each time during a complete day. The values have been compared with the values when the braking energy recovery systems were switched off. moBiel came to the conclusion that the additional consumption of the other substations was in the range of a few percents. This extra consumption comes from the

⁴ In Germany, the CO₂ emission factor was 522g/kWh in 2013. The CO₂ emission factors are different for every country. This was thoroughly analysed within the T2K project. (See www.tickettokyoto.eu)

fact that some power on the network is recovered and cannot be used by other vehicles anymore.

5.2.5.3 Reduction of power peaks

In addition to the energy savings, the reduction of the 15min-power peaks allows a further cost advantage in the power price determination.

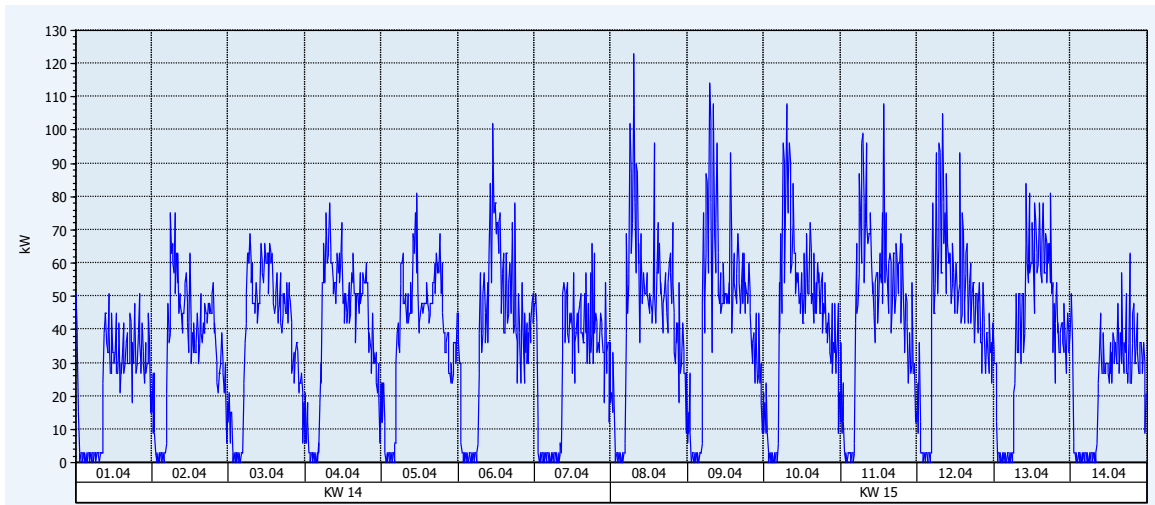


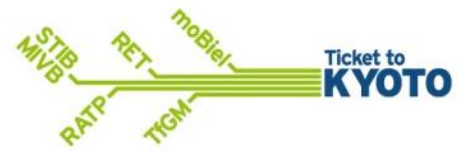
Figure 34: Reduction of power peaks, energy storage system switched on in calendar week 14 (left), and switched off in calendar week 15 (right)

5.2.5.4 New inverter at the University substation

Following the results of the pilot phase, a third inverter has been purchased and installed at the University substation, at the end of line 4. After completion of the line extension, an annual braking energy recovery of 310,000 kWh is expected. The results so far are above expectations. The installations located at the ends of the network yield better results than those situated in the downtown area. This can be explained by the fact that the line receptivity in the downtown area is better due to the higher density of vehicles.

5.2.6 Conclusion

moBiel expects in 2014 energy savings of around 1,1 GWh, which corresponds to 6.8% of the global tram traction energy and a reduction of around 570 CO₂ tons. The systems



performed very well and few failures occurred. moBiel is very satisfied by the braking energy recovery concept and wishes other companies will decide to invest in this field.

5.3 RET – Rotterdam

5.3.1 Context

RET is the public transport company that provides public transport services in the city of Rotterdam and its periphery. It operates five metro lines, 10 tram lines, 58 bus routes and a fast- ferry service. Its predecessor was founded in 1878. RET is the main operator in the area and also maintains the rail infrastructure. On a daily basis, almost 600,000 people use RET's public transport services. Rotterdam is the second largest city in the Netherlands and largest maritime port in Europe. The population of the city was around 615,000 inhabitants in 2012, whereas the greater Rotterdam area is home to more than 1.2 million people.

5.3.1.1 Past experience

In the past, RET has performed a test with a flywheel on-board of a tram. The results of that test were not very promising and a flywheel came loose, which resulted in quite some damage. Luckily it happened in a workshop and not while the tram was in service. RET therefore considers flywheels as a dangerous system.

RET has also tested a supercapacitors-based storage system along its tram network. The system is still running but initially the savings were below expectations and the system was not very reliable and must be regularly switched off. Today there are hardly any faults and the savings are within the range of expectations. One key issue is also the noise produced by the system. The installation was built in a special container to reduce the noise level to the environment.



Figure 35: View of the container hosting the supercapacitors storage system, RET

During the commissioning noise level measurements were performed. The results are given below

Distance	A SES off, ventilation off	B SES off, ventilation on	C SES active, ventilation on
0 mtr.(inside the container)	48 dB(A)	72 dB(A)	75 dB(A)
1 mtr	58 dB(A)	64 dB(A)	66 dB(A)
10 mtr	56 dB(A)	58 dB(A)	59 dB(A)

Table 20: Results of the noise measurements of the supercapacitors system, RET

The noise inside the container is very high and the damping of the walls of the container is significant. The container is located in a light-industrial area, what means that there are no people living in the near area of the container. For dense inhabited areas the

The average number of trains on the D line are given in the table below.

	Rotterdam CS – Slinge (7 km)	Slinge – Akkers (14 km)
07:00h – 09:00h	16 – 18	12
09:00h – 16:00h	12	6
16:00h – 20:00h	16 - 18	12

Table 21 : Average number of trains on RET metro line D, RET

5.3.1.3 Electrical network

40 substations feed the electrical network. Braking energy recovery systems have been studied for the D line between the Rotterdam Central Station and “De Akkers” station at the end of the line. The traction part of the Rotterdam metro network is identical to that of Brussels, consisting of different segments, which are electrically connected through the substations. The nominal voltage is 750VDC with a maximum of 900VDC.

The feeding of the substations is different, each substation is connected to a 10 kV or 23 kV grid which is owned by RET. This grid is connected with the energy supplier on a few locations. The figure below shows the 10 kV configuration of the D-line.

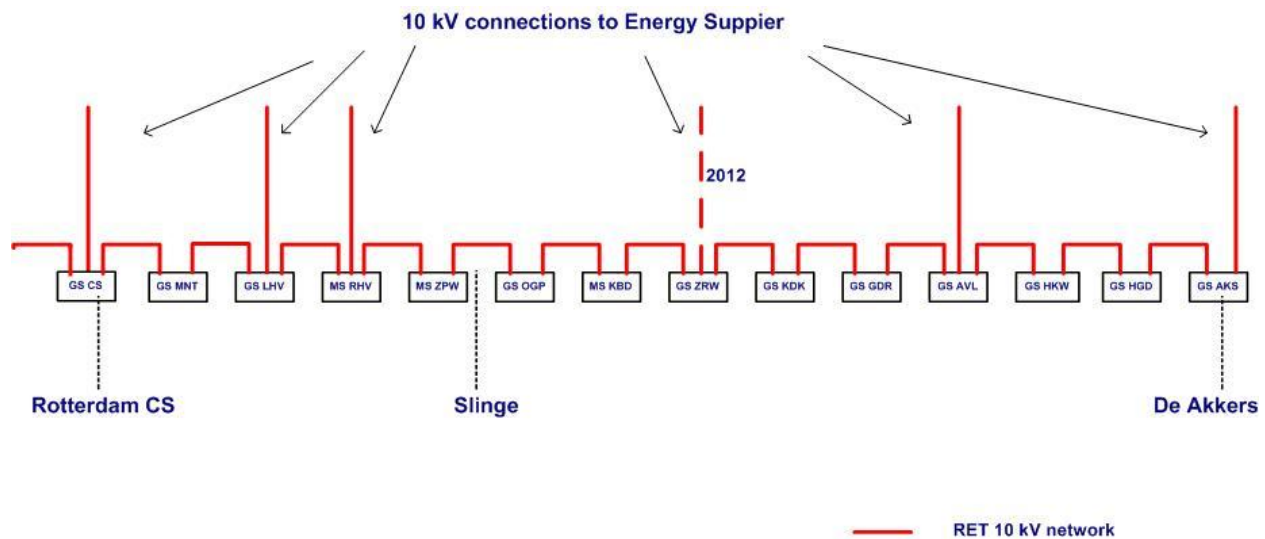


Figure 37 : View of the 10 kV configuration of the RET D-line

Medium Voltage network	10 kV
Nominal Traction voltage	750 Vdc
Zero Load Traction voltage	850 Vdc
Maximum Traction voltage when braking	900 Vdc
Rated power of substations	most 2 x 1440 kVA. Some higher.
Average distance between substations	appr. 2.0 km
Feeding system	3rd rail

Table 22 : metro electrical network characteristics, RET

5.3.1.4 Vehicles

RET has two types of vehicles on their metro network, both are able to recover braking energy and to send it back to the 750 VDC grid to be used by other vehicles.



	Type SG2	Type RSG3
		
Weight	44.3 t	65 t
Length	30 m	45 m
Acceleration	max 1.0 m/s ²	max 1.0 m/s ²
Braking	max -1.5 m/s ²	max -1.5 m/s ²
Braking power	max 1200 kW	max 1800 kW
Trains on D-Line	2, 3 or 4 cars coupled	1 or 2 cars coupled

Table 23 : Overview of vehicles on the RET D-line

5.3.2 Decision making

5.3.2.1 Business case

RET identified braking energy recovery as a great opportunity to reduce the energy used by its metro system. The company has previous experience with braking energy recovery technologies. A supercapacitors-based storage system has been implemented along the tram network, but the results were below expectations. The installation was also very noisy and had to be encapsulated in a container. RET also has some doubts about flywheels. It has experienced a number of failures with an on-board flywheel system on a tram: the flywheel worked loose and destroyed the installation. The company made an assessment of this situation, taking into account the history of other energy recovery systems, investment and operational costs, space requirements and the risks of each technology.

A reversible substation was seen as the best option for the metro network in the Rotterdam area. As a result, RET decided to invest in two inverters, where no storage is needed and energy can be used directly on the 10kV network. To determine the best location for these inverters on the network, a network simulation was done with different timetables. This led to the recommendation to place them on two different lines.

For the RET internal business case, the ROI and NPV were calculated for 2 reversible substations.

Calculation ROI en NPV

Investment	€ 477.894	
T2K contribution	€ 219.960	
Contribution RET	€ 257.934	
Yearly costs	€ 2.972	
Savings / year	€ 54.780	
Interest rate	15%	
Lifetime [Years]	10	
Year	Net present Value	Cumulated
0	-€ 257.934	-€ 257.934
1	€ 45.050	-€ 212.884
2	€ 39.174	-€ 173.709
3	€ 34.065	-€ 139.645
4	€ 29.621	-€ 110.023
5	€ 25.758	-€ 84.266
6	€ 22.398	-€ 61.868
7	€ 19.477	-€ 42.391
8	€ 16.936	-€ 25.455
9	€ 14.727	-€ 10.728
10	€ 12.806	€ 2.078
NPV (10 jr/15%)	€ 2.078	
ROI	5,0 years	

Table 24 : Business case for braking energy recovery system, RET

5.3.2.2 Simulation

RET asked the consultancy MOVARES to develop a simulation tool to assess the potential savings on the D metro line and to rank the best substations for installing braking energy recovery systems. The simulation tool allowed selecting the two optimal locations for implementing an inverter, the best location for the Benelux line and the best location for the Erasmus line.

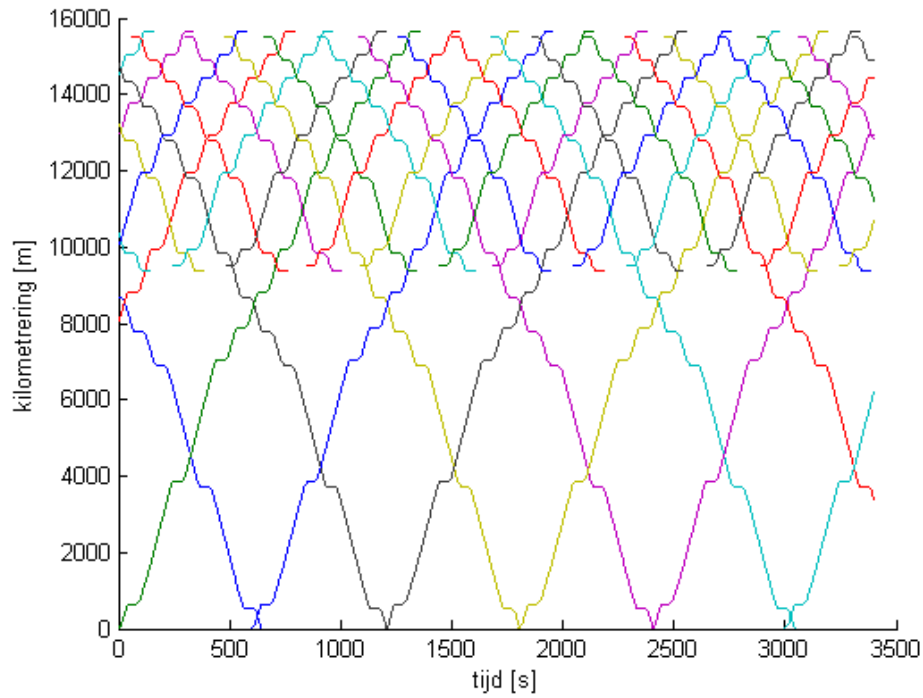


Figure 38 : View of the simulated timetable for the Benelux line C, Movares

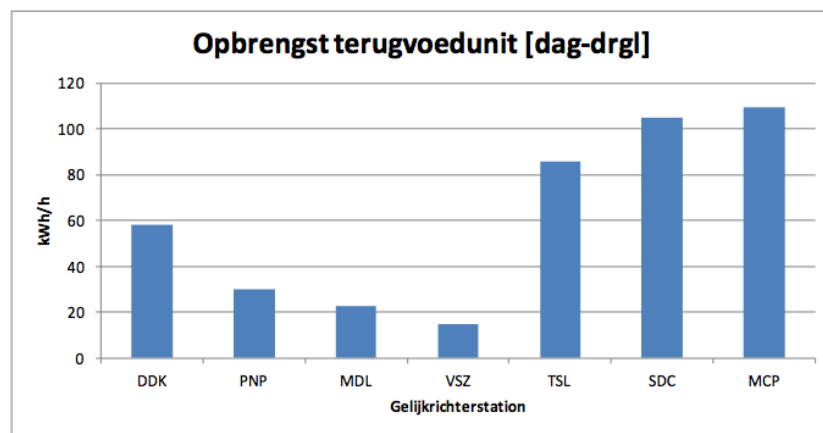


Figure 39 : Simulated savings [kWh/h] per weekday for Beneluxline, Movares

Although substation Marconiplein (MCP) has a slightly higher savings, RET has chosen substation Schiedam Centrum (SDC) for the location of the inverter because of operational reasons. The yearly savings of SDC were calculated at 663 MWh/y.

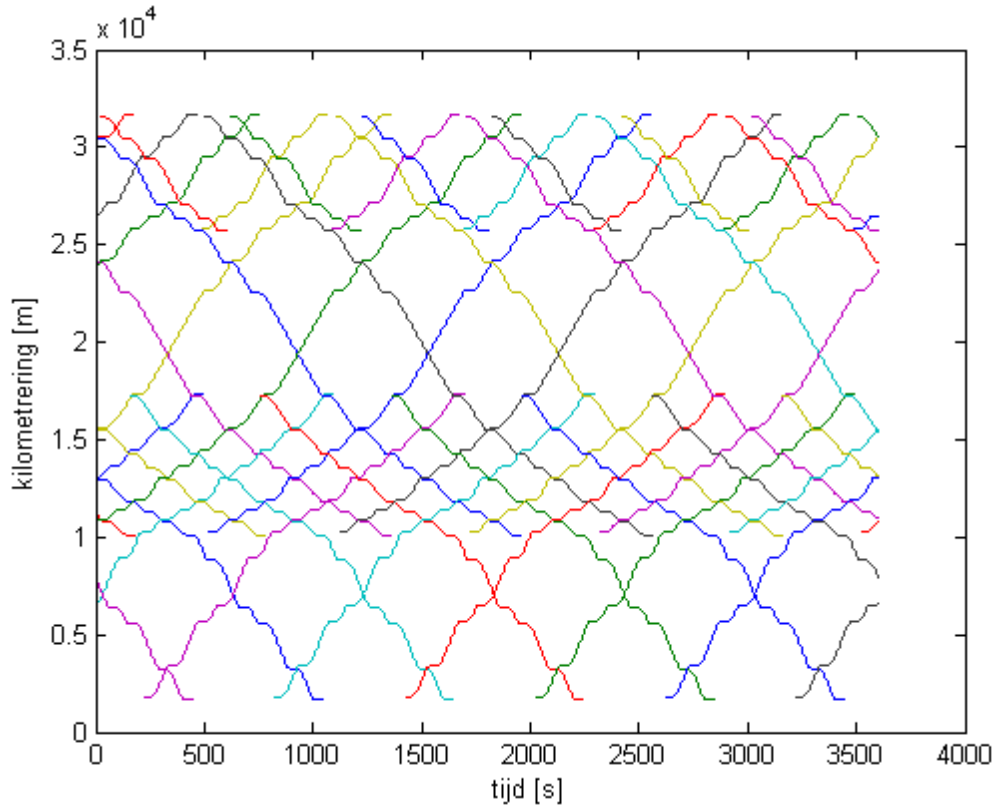


Figure 40 : View of the simulated timetable for the Erasmus line, line D, Movares

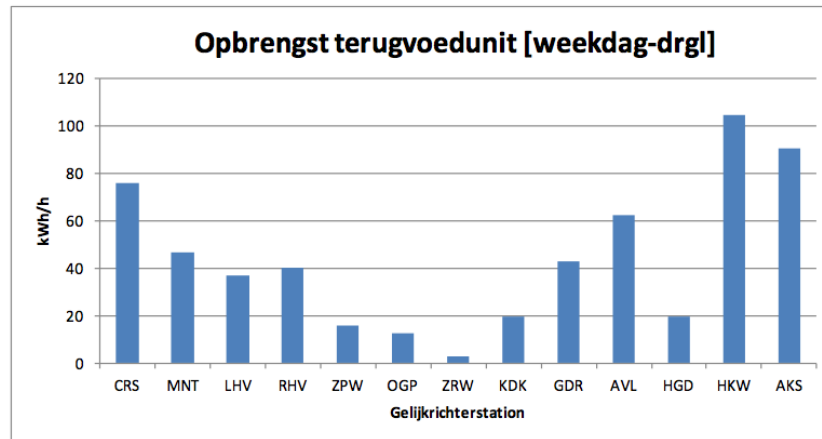


Figure 41 : Simulated savings [kWh/h] per weekday for Erasmus Line, Movares

Because it has the highest savings, RET choose substation Hekelingsweg (HKW) for the location of the 2nd inverter. The yearly savings of HKW were calculated at 560 MWh/y.

5.3.3 Tender

The tender process was performed in two steps. The first was a prequalification selection of the suppliers. The suppliers have to meet the regular RET requirements. The second step was a tender process with the prequalified suppliers. First they had to make an offer and a description of the proposed systems and installation process. With these offers there was a meeting with each supplier regarding problems or issues they face, because the technology is relative new for them as well as for RET.

After these meetings, the suppliers were invited to make a Best And Final Offer (BAFO). Out of these BAFO's RET chose the best option by reviewing the offers through the standard RET appraisal system, reviewing costs, technical compliance, legal aspects etc.

The company IMTECH Traffic & Infra B.V. (Netherlands) was selected to deliver and install two inverters.

5.3.4 Implementation

To determine the best location for these inverters on the network, a network simulation was done with different timetables. This led to the recommendation to place them in two existing substations: one in Schiedam centrum and one in Hekelingseweg.

Technical data of the inverters

- Technology: IGBT
- Voltage range: 400-1000 V DC
- Maximum power: 1MW
- Feedback current : 58A AC
- Efficiency rate: 98%
- Weight: 3.6 tons
- Noise : <65dB(A)



Figure 42: View of the IMTECH inverter

The building works for the two inverters were finished in March 2014 but the systems are not fully operational yet (September 2014). The new installations needed to be adapted to the existing RET electrical equipment. During the first test, RET encountered malfunctioning with the existing installations and one transformer was burned at the station Schiedam Centrum. Also the transformer at Hekelingseweg was damaged due to a short circuit in the inverter. To prevent and fix this, RET and IMTECH are working on improvements of the equipment.

5.3.5 Results

Given the systems are not functioning yet, no results are available.

5.4 TfGM – Manchester

5.4.1 Context

Transport for Greater Manchester (TfGM) is the organisation responsible for implementing local transport policy, set by the Greater Manchester Combined Authority. The Greater Manchester area has some 2.5 million inhabitants. TfGM is the delivery arm for the elected body, responsible for investment in improving transport services. TfGM is responsible for providing the facilities and infrastructure to support efficient transport systems and to enable people to make sensible choices regarding their transport options. It manages 22 bus stations around Greater Manchester, 12,500 bus stops and over 4,000 bus shelters, 76 tram stops and 77 km of tram tracks.

5.4.1.1 Past experience

TfGM had no previous experience in the braking energy recovery field.

5.4.1.2 Line topology and headways

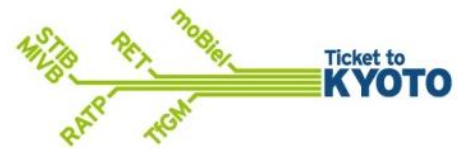
The Metrolink network has principally developed from former railway lines and as a result is largely characterized by longer average stop spacings with some several sections where the maximum line speed of 80km/h is sustained for a significant period. However other parts of the system involve street running with much closer stops, notably the City Centre section where average speeds are low.

In terms of gradients the lines to the north of the city are hilly whilst those to the south are flat. Whilst the steepest gradient on the system is 6.5%, the hilly lines tend have long gradients but not as steep, as would be expected given their railway origins.

The Manchester system generally operates with routes on a twelve-minute headway. However, the pattern of services operated is such that most lines are served by two routes to give a six minute headway during the peak (0700-1900, Monday to Saturday) reducing to a twelve minutes outside those hours. This further reduces to a fifteen-minute headway in the early morning and late at night.

5.4.1.3 Electrical network

When the system expansion is complete, 45 substations will provide the traction power supply for Manchester Metrolink. Each of these has its own independent connection to the energy supplier and there is no internal power grid.



The nature of the network is that is radial from Manchester City Centre. There is therefore no possibility to link the different routes electrically outside the City Centre area, in which speeds are low due to a shared environment with other traffic (including pedestrians), leading to little in the way of regenerated energy to recover.

The tram network is supplied at a nominal 750V d.c. with regeneration permitted up to a maximum of 900V d.c.

5.4.1.4 Vehicles

The Metrolink tram fleet has always had a capability for regeneration. The only difference with the new vehicles is the ability to regenerate down to lower speeds as there is no need to blend with an air brake as on the older vehicles. All trams have approximately the same passenger-carrying capacity, but the new M5000 trams are approximately 10 Tonnes lighter, which reduces both the energy consumed and regenerated.

5.4.2 Decision making

As part of the T2K project, TfGM proposed to install a lineside energy storage system (ESS), which would enable the energy regenerated, while there is no other vehicle available to use it, to be stored and subsequently drawn on when an accelerating vehicle enters the relevant electrical section. The use of the ESS should therefore maximise within the relevant electrical section the use of regenerated energy and reduce the overall demand on the electrical supply thereby helping to minimise CO₂ generation.

5.4.2.1 Simulation

Mott MacDonald had previously developed a simulation model of the Metrolink power supply system as part of an earlier investigation and this had been validated by TfGM. This package, known as TRAIN, was then further developed to take into account changes in the power supply system and to assess the performance of energy storage systems. For the initial assessment two levels of service were assumed, a peak and an off-peak service.

The simulation analysed the potential savings for a supercapacitors-based energy storage system (ESS). To evaluate the performance of the ESS, the following simulation runs were undertaken: a 2-hour peak service model simulation and a 2-hour off-peak service model simulation. All simulations were of normal operating conditions

i.e. with all substations operating normally and all services operating to their timetabled headways. The analysis and hence results are based on the use of the Siemens Sitras SESS. Other devices (possibly using an alternative technology) may yield different results.

ESD	Time Period	Likely Energy Saved In			
		1 hour (kWh)	1 week (kWh)	1 year (kWh)	15 years (kWh)
Hagside	Peak	29.3	2,110	109,720	1,645,800
	Off-Peak	12.4	645	33,540	503,100
	Subtotal	N/A	2,755	143,260	2,148,900
Brooklands	Peak	36.4	2,620	136,240	2,043,600
	Off-Peak	12.4	645	33,540	503,100
	Subtotal	N/A	3,265	169,780	2,546,700
Total Energy Saved			6,020	313,040	4,695,600

Table 25: Results of the simulation for a supercapacitors-based ESS, Mott McDonald

5.4.2.2 Business case

Based on the information received from different suppliers, TfGM concluded that the business case was not profitable due to a long payback time, despite significant energy savings. As a result, TfGM did not invest in a braking energy recovery system within the Ticket to Kyoto project.

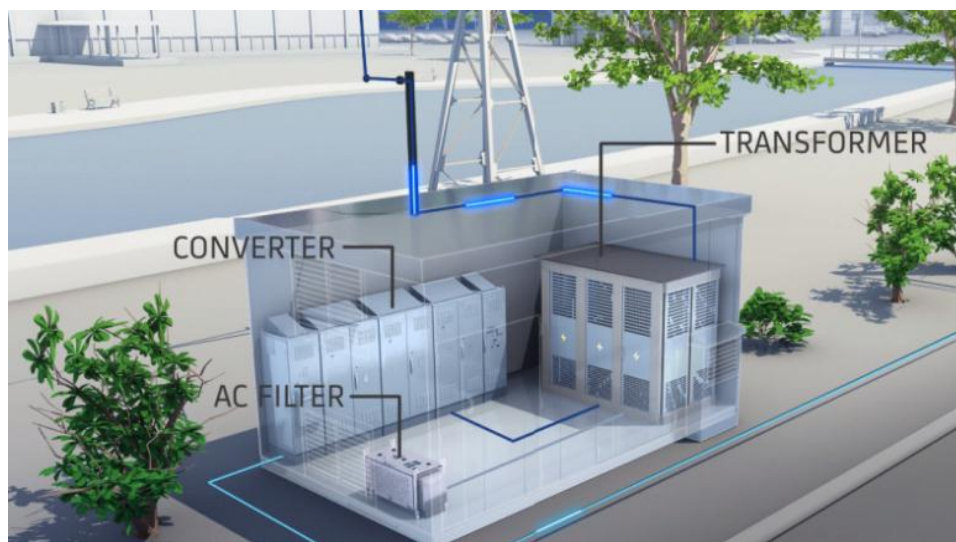
6 Industry insights

6.1 ALSTOM



As a response to operators’ economical and environmental concerns, Alstom designed HESOP™, an advanced power-supply substation designed to deliver the best energy efficiency and reduced infrastructure cost, for urban and suburban rail transport networks. HESOP™’s novelty lies in its specific single converter with dynamic regulation which optimizes the power required for traction and captures more than 99% of recoverable energy during braking mode.

HESOP™ is the only “all-in-one” solution that offers both traction and recovery functions within the same equipment.



HESOP™ has benefits in numerous fields and at all project stages, from construction to operation and maintenance. HESOP™ enables to increase the distance between

substations and thereby reduces their number: 5 to 7 conventional substations can be replaced by only 4 to 6 HESOP™ substations, depending on the layout and operating data. This results in less infrastructure investment, i.e. real estate and civil works.

Unlike inverters or stationary storage solutions (fixed voltage set point), HESOP™ is equipped with dynamic voltage regulation, which allows the capture of over 99% of the energy usually lost during braking, without stopping the natural exchange of energy between trains. The energy recovered can be re-injected into the electricity network or re-used through the station electro-mechanical equipment: lifts, escalators, lighting and ventilation. This implies traction energy savings by up to 40%, depending on the network’s operational specificities.



HESOP™ guarantees high energy quality and thereby avoids penalties or allows cheaper subscription from power supplier. The recovered energy can also be easily re-sold, if not completely used within the network.

Thanks to full recovery of available braking energy which leads to high line receptivity, HESOP™ limits train heat dissipation. This leads to less tunnel and in-station ventilation or air-conditioning; and to the removal of on-board brake resistors. The train’s weight is reduced which contributes to further traction energy savings.



HESOP™ addresses 600V to 1,500VDC metro, tramway and suburban networks, new or existing.

HESOP™ has been in operation on Paris Tramway T1 (France) since July 2011 and is currently under commissioning on London Underground’s Victoria Line (UK). Other deployments include Milan Metro, Milan Tramway (Italy) and Riyadh Metro (Saudi Arabia).

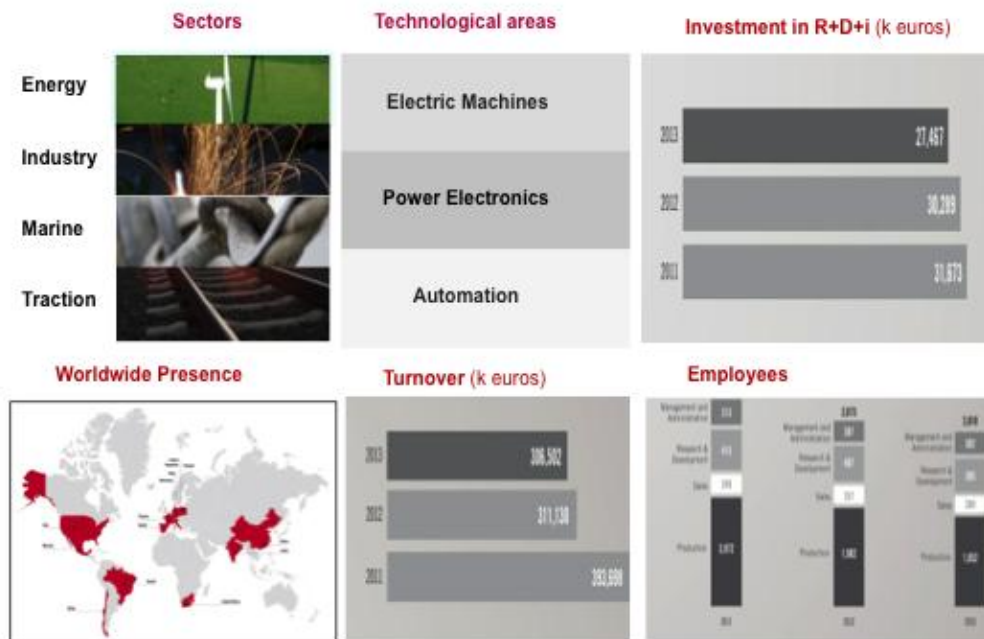


Jointly with ATM (Azienda Trasporti Milanese), the operator of the Milan Metro, Alstom has initiated the development of a new 1,500 V version of HESOP™ for metro lines and suburban trains that are high energy consumers. This project has been selected by the LIFE+ programme of the European Commission whose objective is to promote environmentally-friendly actions. Its development is 50% funded by the European Union.

6.2 INGETEAM

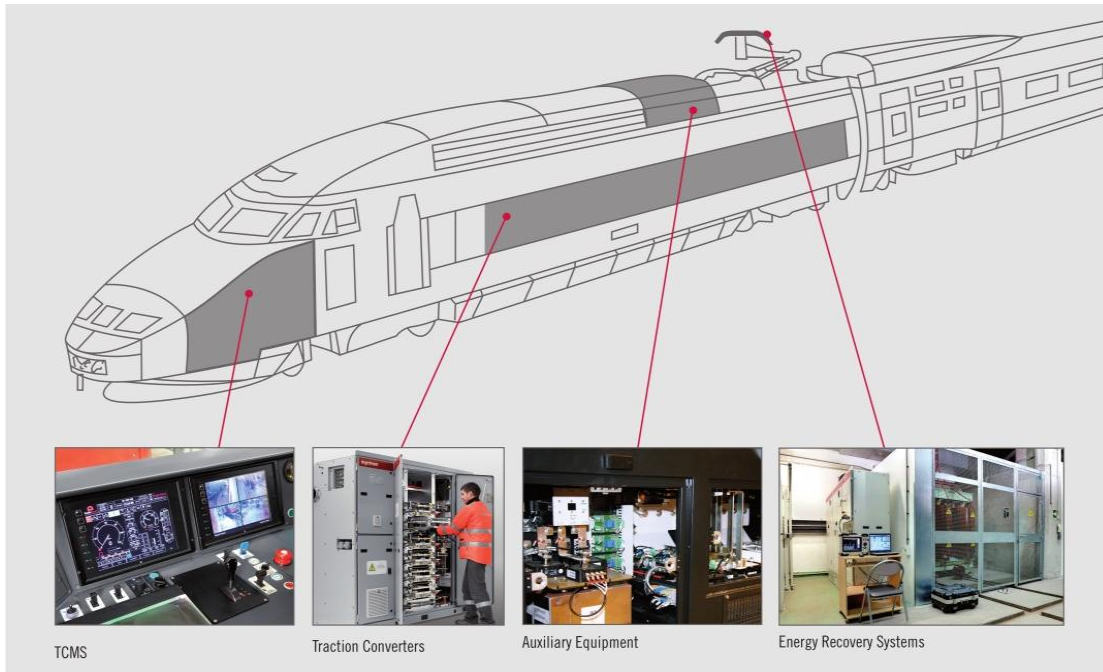
Ingeteam

6.2.1 Overview



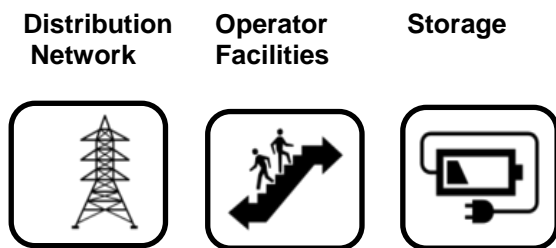
6.2.2 Portfolio

The development of solutions and systems for the efficient exchange of energy in different sectors, combined with our know-how on rolling stock engineering and rail operations, allow us to offer solutions that allow all parties actively involved in this sector to implement significant improvements. Our solutions and systems are mainly centred on improving aspects that for operators are key factors, like exploitation costs, reliability, availability, maintainability and energy efficiency.



6.2.3 INGEBER: the proved kinetic energy recovery system

It is now normal for rolling stock to incorporate regenerative braking systems: However in d.c. systems the kinetic energy regenerated can not be used to the optimum degree, since they are equipped with unidirectional electrical substations, the use of energy is limited to the cases where there is another vehicle whilst the non-recoverable energy is burnt off in the brake resistors of the vehicle. INGEBER fits into the current substation, enables all the limitations associated with the return of energy form the units to be overcome by optimizing the energy recovered and making it available.



6.2.4 A turn-key solution with previewed savings

The step preceding installation of the system is an analysis of the existing network with software developed by Ingeteam, taking into account the system's characteristics so that the systems to be installed can be defined both from the technical point of view and from the point of view of the return on investment. The INGEBER system developed by Ingeteam enables all the limitations associated with the return of energy from the units to be overcome.

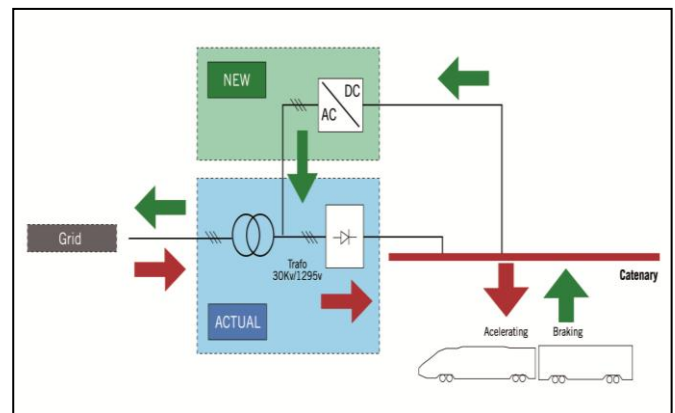
The system consists of power electronics equipment installed in the substation and connected to the main equipment that already exists in the substation, such as the transformer and rectifier. The system continuously monitors the catenary until it detects the point at which there is braking energy from one vehicle that is unable to be used by another vehicle. At this time the system extracts this energy from the catenary and transforms it according to the quality parameters of the supply grid so that this energy can be injected into the grid.

+ Advantages:

- ✓ Can be installed on new & old substations
- ✓ Transparent to the substation system
- ✓ Low maintenance costs & easy control
- ✓ Improves quality of power

References

750 Vdc	1,500 Vdc	3,000 Vdc
Brussels Bielefeld	Bilbao	Malaga (ADIF)



6.3 MOVARES



Movares B.V. is part of the Movares Group and is one of the leading Dutch consulting and engineering companies, providing services to public transport companies, local authorities and other clients. In recent years we have expanded from traditional railway engineering to generating solutions for capacity, safety and integration problems. From this perspective we help our clients inside and outside the railway sector, providing advice and innovative designs for projects in the field of guided transport. We operate from five offices in the Netherlands, including our head office in Utrecht.

One of the railway engineering consultancy teams covers the field of Traction Power and Electromagnetic Compatibility. We advise on Traction power solutions from 600V to 3000VDC and 25kV with or without autotransformers.

Focusing on 600/750V Movares is the preferred supplier of the metro and tram operating companies of Rotterdam, Amsterdam, The Hague and Utrecht because their extensive knowledge and experience in simulations, specifications and technical support.

The main components in an existing the substations are medium voltage transformers, rectifiers and a distribution unit. The medium voltage comes directly from the public grid or is delivered by a medium voltage distribution cable owned by the operating company or the municipality. The traction power system has been fully optimized to supply all the vehicles as efficiently as possible. This had led to a DC current as low as possible to maximize the voltage to each passenger car and minimize the losses in the catenary or third rail and the touch voltage between the tracks and earth. This has been done by choosing a high no-load voltage of the rectifier. These settings decrease the possibilities of recovery electrical energy to the grid while the tram or metro is braking. If the traction power supply is newly built, with maximum ability for recovery of braking energy, the rectifier is replaced by a mutator. The mutator can act as a “standard” rectifier or as a reverse rectifier or inverter.

Movares is able to simulate the most profitable no-load voltage for the inverter depending on location of substations, stops and timetable. The transition from an existing power supply with rectifiers to a supply with mutators is more complex.

Interaction between main components in the substation has to be taken into account and when several substations shares the same medium voltage cable, an extra electrical connection is created between the substations (parallel to the catenary or third rail).

Introduction of inverters in a standard traction power supply system can be implemented in three commonly-used ways:

1. The first option is an inverter parallel to the existing rectifiers, where both are in service. An “extra inverter” parallel to existing rectifier(s) requires a decrease of the no-load voltage of the rectifier to enable recovery of braking energy. This leads to a higher touch- voltage and more losses in the DC part of the power system.
2. The second option is either one rectifier in service **or** one inverter. Both components are placed in parallel but operate independently and in optimal circumstances. The disadvantage is that standard substations do not support a double rectifier and a double inverter, so the reliability of this kind of substations is reduced.
3. The third option is replacement of the rectifier for a mutator. In this case the mutator alternates as supply rectifier or as recovery rectifier or inverter. If needed, the medium voltage level is taken into account.

A thorough simulation task starts with investigating all of the requirements: performance, passenger cars, substation and medium voltage grid. All these inputs are needed to base the selection of a cost-effective supply the metro or tram transportation system.

Contact

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6.4 Adetel

Adetel is a company specialized in design, industrialization and manufacturing of electronics and software systems in harsh environments. Adetel has developed several products regarding braking energy recovery in public transport.



Energy Saving

Patented technology



Benefits

- ✓ Reduced energy consumption up to 40%
 - ✓ Reduced carbon footprint
 - ✓ Reduced operating costs

Infrastructure assets

- ✓ Ultra long supercapacitors lifetime (15 years)
- ✓ Modular storage capacity to meet network specific requirements
- ✓ Original system installation can easily be extended with the addition of bays of 0.33kWh to meet updated operations
- ✓ Optimized storage availability thanks to a redundant system design
- ✓ Quick maintenance with no disruption to traffic
- ✓ Very high number of charge/discharge cycles rate



Services

- | | |
|--------------------|-------------------|
| ✚ Network analysis | ☰ Data processing |
| ✚ Delivery | 🔧 Maintenance |
| ✚ Installation | 👤 Training |
| ✚ Commissioning | |



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Energy Saving

Patented technology

Economical advantages

- ✓ Reduction of energy consumption
- ✓ 15 years lifetime supercapacitors

Modular advantages

- ✓ Adjustable storage system
- ✓ Evolving possibilities
- ✓ Operating reliability

FOR SUPPLYERS
ELECTRICITY CHALLENGE

GRAND PRIX AWARDS WINNER
2013

2013 ENERGY CHALLENGE

NeoGreen

Ground Regenerative Electricity for Economic Network Power

Based on our latest supercapacitor management technology, Adetel now offers NeoGreen, a highly efficient energy storage system, designed to maximize the railway transportation performance.

Storing surplus braking energy generated by vehicles, NeoGreen returns energy to the line when vehicles accelerate, optimized according to operational conditions, to reduce energy consumption.

Specifications

Input voltage	750VDC or 1500VDC (EN 50163)
Available energy	0,33 to 4 kWh
Peak power	110kW to 1,3 MW
Max. energy saving per hour	50 to 200 kWh/h
Ambient temperature	-20 to +50 °C
Internal safety	Isolating switch, High Speed Circuit Breaker
External communication	Ethernet 100 Mbps
Auxiliary power	400VAC 3ph+N / 48Vdc
Dimensions Master	880 x 980 x 2250mm, < 950kg
Dimensions Slave (1kWh)	840 x 2000 x 2100mm, < 1520kg



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Voltage Stabilization

Patented technology



Why NeoStab?

- ✓ When implementing a substation is not feasible
- ✓ When the distance between substations is too important
- ✓ When the line voltage is unstable
- ✓ When the operation increases in frequency or capacity
- ✓ When a line extension is performed

Risks without NeoStab:
 Risk of over/under voltage ▶ Loss of vehicles traction ▶ Operation disrupted



Benefits of NeoStab solution

- ✓ Low cost alternative to substation upgrades
- ✓ Ultra long supercapacitors lifetime (15years)
- ✓ Modular storage capacity to meet network specific requirements
- ✓ Original system installation can easily be extended with the addition of bays of 0.33kWh to meet updated operations
- ✓ Optimized storage availability thanks to a redundant system design

Options

- ✓ Integration inside a container (may be designed to meet customer requirements).

Container (1kWh)	6000 x 2600 x 2500 mm
Master	880 x 980 x 2250mm, < 950kg
Slave (1kWh)	840 x 2000 x 2100mm, <1520kg



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Voltage Stabilization

Patented technology

Economical advantages

- ✓ 15 years lifetime supercapacitors
- ✓ Alternative to the construction of additional substation

Modular advantages

- ✓ Adjustable storage system
- ✓ Evolving possibilities
- ✓ Operating reliability

2015 BUSINESS TRANSPORTATION CHALLENGE
TECHNOLOGY AWARD WINNER 2015
RESISTANCE TO CHANGE

NeoStab

Voltage Stabilization

Based on our latest supercapacitor management technology, Adetel now offers NeoStab, a highly efficient energy storage system, designed to maximize the railway transportation performance.

Connected to the railway electrical network, NeoStab maintains line voltage to avoid vehicle failures in distant areas of power supply and ensures smooth operations.

Specifications

Input voltage	750VDC or 1500VDC (EN 50163)
Available energy	0.33 to 4 kWh
Peak power	110kW to 1.3 MW
Max. energy supplied per hour	30 to 120kWh/h
Ambient temperature	-20 to +50 °C
Internal safety	Isolating switch, High Speed Circuit Breaker
External communication	Ethernet 100 Mbps
Auxiliary power	400VAC 3ph+N / 48Vdc



NeoStab - Product Sheet - EN - 2014/06

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7 Conclusion

The experience led during the Ticket to Kyoto project (T2K) regarding braking energy recovery technologies in the public transport has shown that the concept can offer significant energy savings and carbon reduction. This is the first time that several transport operators cooperate in this field and exchange their mutual experience about the technological choice and the implementation issues.

This unique opportunity has allowed all partners including STIB in Brussels, RET in Rotterdam, moBiel in Bielefeld and TfGM in Manchester to develop a very good understanding of the topic. Such investment requires a holistic approach to best determine what are the potential benefits and how these can be properly achieved. The pragmatic approach followed by the T2K partners will give useful insights for any transport operator considering the implementation of braking energy recovery systems along its network. This report will also be of interest for power electronics manufacturers who wish to better apprehend the complexity of this innovation and better understand the public transport needs and constraints.

Braking energy recovery is certainly one of the most promising technologies for improving the energy efficiency of rail transport systems and this was demonstrated within this project. Hopefully, many other transport companies will follow this trend to allow the public transport sector to fight jointly against energy scarcity and climate change.