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Optimal Strategy to Innovate and Reduce energy consumption in urban rail Systems

D4.1. Smart grid system definition, system studies and modeling, technologies evaluation

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
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EXECUTIVE SUMMARY

This deliverable starts by presenting the OSIRIS project. It clarifies the global objectives of this project and focuses on the task 4.1 entitled “Smart grid solutions study and related simulations”. It describes the rail transportation process and the electrical requirements in order to provide the needed power with minimum rate of perturbations. In this approach, the regenerative braking energy is evaluated and different technologies that contribute in saving braking energy and reducing energy consumption are studied. In order to explore these solutions, the concept of integrating a smart grid in an electrical grid is then presented on multiple levels (production, transmission, distribution and customer level) and the possibility of applying this technology to the urban mass transit is suggested. A description of the control system details the smart grid’s functionality. Finally, to prove the efficiency of this solution, simulations were realized to study the benefits of integrating a smart grid in urban rail networks.

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1 ABREVIATIONS

CAES: Compressed Air Energy Storage

CHP: Combined Heat & Power

DoD: Depth of Discharge

ECC: Energy Control Center

FES: Flywheel energy storage

GHG: GreenHouse Gas

LRV: Light Rail Vehicle

Mtoe: Million tons of oil equivalent

OSIRIS: Optimal Strategy to Innovate and Reduce energy consumption In urban rail Systems

PHEV: Plug-in Hybrid Electrical Vehicle

PHS: Pumped Hydro Storage

Pkm: Passenger kilometer

PV: Photovoltaic

ROI: Return On Investment

SMES: Superconducting Magnetic Energy Storage

Tkm: Ton kilometer

TPS: Traction Power Substation

WP: Work Package

2 THE OSIRIS PROJECT

2.1 THE EU'S 20-20-20 PLAN CONTEXT

In December 2008 the European Union adopted the 20-20-20 plan. The goal is to get in 2020:

- Reduction of **20** per cent in greenhouse gas emissions (GHG) compared with the 1990 level
- Reduction of **20** per cent of primary energy consumption compared with a projection for 2020
- Increase until **20** per cent the part of renewable energies in the final energy consumption

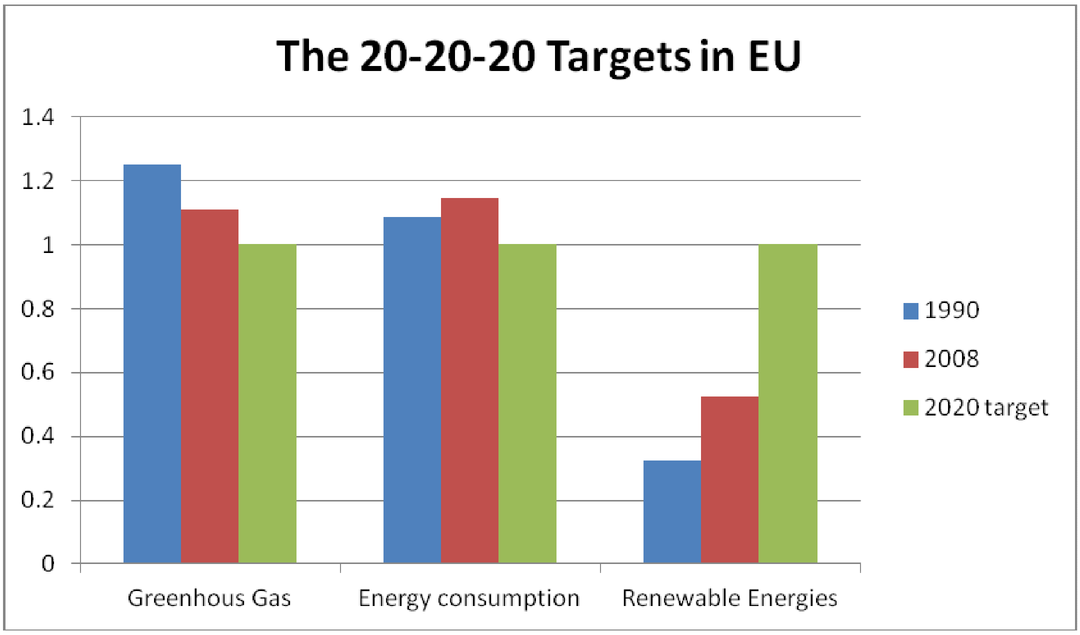


Figure 2-1: The objectives for 2020 and evolution during the time [1] [2] [3] [4] [5]

Our societies need services, industries and transport. If we want to reduce the energy consumption and greenhouse gas emissions we must improve the products' energy efficiency, have a smarter consumption, research new solutions …

For the realization of this plan all sectors have to take part of the change but industry and transport are the biggest contributors to the energy consumption and GHG emissions: in Europe, in 2007, the transport represented 33% (377.3 Mtoe) and industry 28% of the final energy consumption. The households were responsible for 25%, the services 12%, and the agriculture 2%.

Transport can be divided into road, air, waterborne and railways which consumed 2.5% of the final energy consumption in transport and 0.8% of the total (9.4 Mtoe).

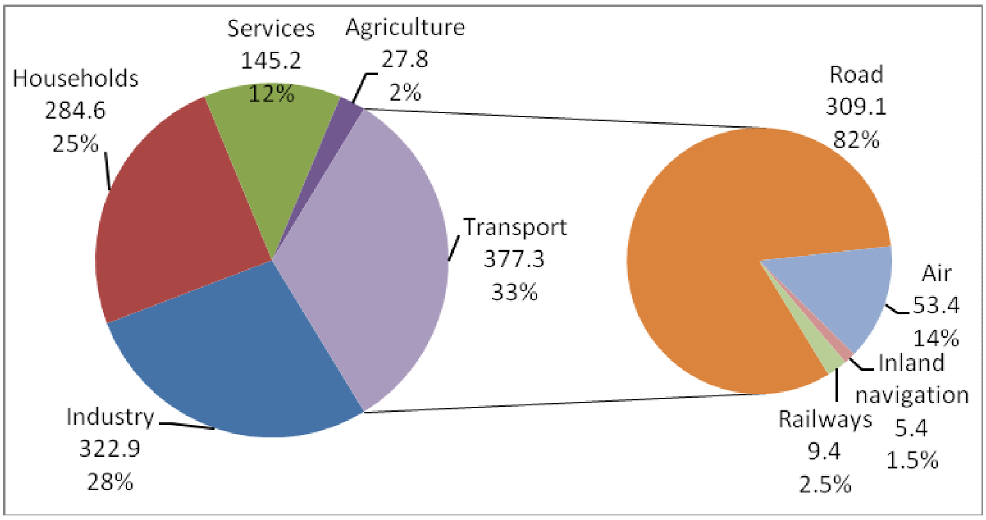


Figure 2-2: Final Energy Consumption in Mtoe (EU 2007) [6]

Note: the energy spent for the production of electricity isn't taken into account (electricity production in 2007: 57.7% with conventional thermal, 17.1% with nuclear, 18% with hydro and 7.2% with wind).

With regard to the GHG emissions in Europe in 2007 industry represented 52% of the total, transport 22% (1112.4 million tones CO2 equivalent), agriculture 10%, households 8%, services 3% and other 5% (emissions from fuel combustion, fugitive emissions from fuels, solvent and other product use, waste …). Railways are responsible for only 0.8% of the transport part and 0.2% of the total GHG emissions (8.7 million tones CO2 equivalent).

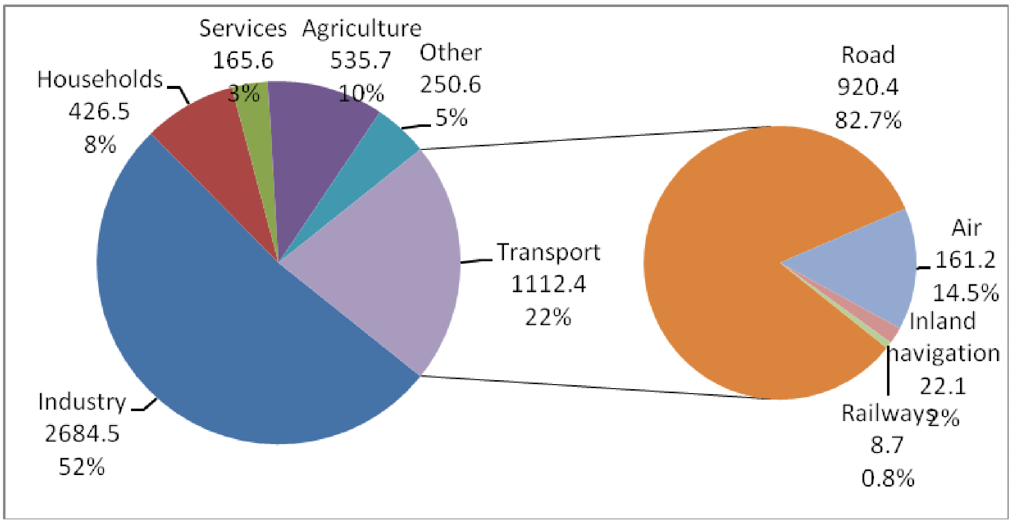


Figure 2-3: GHG Emissions in Million tonnes CO2 equivalent (EU 2007) [6]

Note: the GHG emissions due to the energy plants which supply railways with electricity are taken into account with industry and not with the transport sector.

The low energy consumption and GHG emissions of railways have to be compared to their part in passenger and freight transport in order to specify its energy efficiency.

Railways represent 8% of the passenger transport (498.2 billion passenger kilometers).

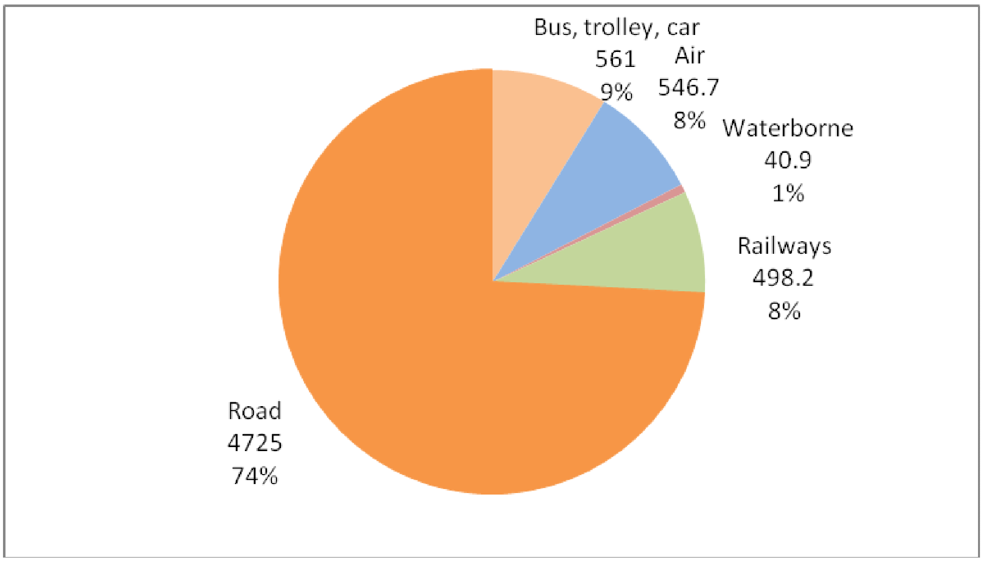


Figure 2-4: Passenger Transport in billion pkm (EU 2007) [6]

Note1: waterborne doesn't include international maritime freight.
Note 2: the air represents only the traffic intra-EU-27

For freight transport, railways represent 11% of the total (442.7 billion tones kilometers).

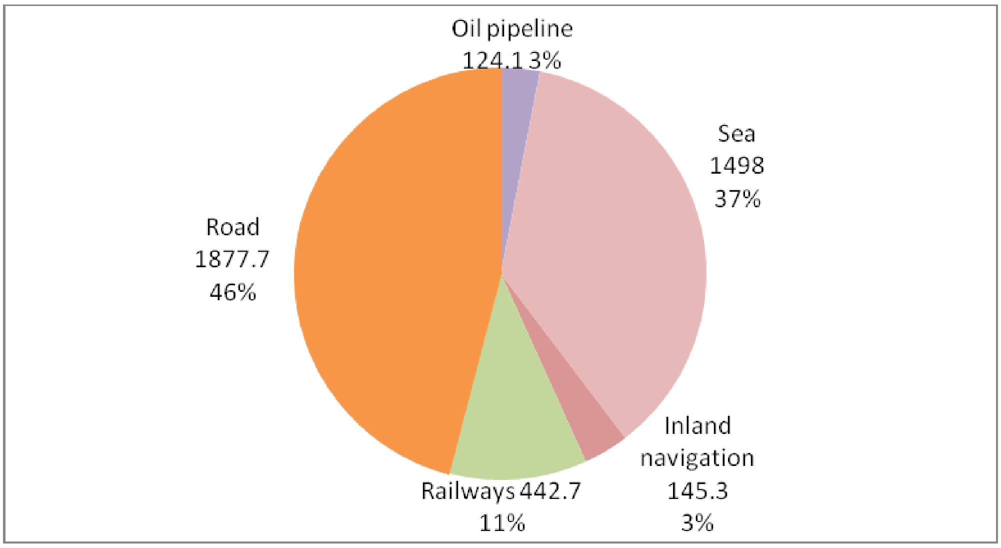


Figure 2-5: Freight Transport in billion tkm (EU 2007) [6]

Note: the air isn't represented because its part is 0.1% (2.7 billion tkm).

These 4 figures show the very high energy efficiency of the railways. In London, the total energy cost in 2006 of underground trains (traction and auxiliaries) was 15 kWh per 100 pkm which is five times better than baseline cars and the energy cost of buses was 32 kWh per 100 pkm. In addition to this low energy consumption and low pollution, underground trains run faster than buses and cars [7].

Railways seem to be the best transportation in order to achieve the 20-20-20 plan. However, there are lots of differences on the GHG emissions in several countries. Indeed, each country has different energy mixes: in France the emission of Paris metropolitan represents 4g of CO^2 per pkm [8] whereas in England the emission of London metro represents 80g of CO^2 per pkm [9]! The factor of 20 is due to the large use of nuclear, hydro and renewable power (90%) in France contrary to England where 35% of the electricity is produced with oil and coal. In England a little fuel-car with only the driver produce quite the same quantity of CO^2 than a metro per pkm. Then, a focus on the total energy consumption of traction units for mass transit systems shows that a little save of energy can represent lots of money: in Paris the annual consumption of metros, tramways and RER represents about 1 TWh [10]. Moreover cars will consume less energy in the future and GHG emissions from cars and road transport will decrease strongly with the likely increase of electrical vehicles. Keeping the actual technology in trains and railways architecture won't be sufficient. Railways must improve their performance (energy consumption) and their integration in the city (air and phonic pollution) thanks to innovations. In 2007 railways in Europe represented the energy consumption of Bulgaria and the GHG emissions of Latvia [6]!

2.2 OSIRIS Project

OSIRIS project is a way to innovate and achieve the 20-20-20 plan. OSIRIS means “Optimal Strategy to Innovate and Reduce energy consumption In urban rail Systems”. It is a 3-year European project started on the 1st of January 2012 and it will finish in December 2014. It aims at enabling a reduction of the overall energy consumption within Europe’s urban rail systems of 10% compared to current levels by 2020.

17 partners are taking part in the project: public transport operators, railway manufacturers and universities work together in order to improve railways with a global vision including the infrastructure to the trains. This global vision is necessary in railways because urban rail systems are complex environments and their energy consumption is characterized by a wide range of inter-dependent factors. That’s why the development of energy reduction can’t be studied only at the level of the train. In fact, the vehicle has to be integrated into the infrastructure and improvements on the vehicle can create decrease of the infrastructure’s performance. Finally the global performance won’t be as well as planned.

Benefits which are expected from OSIRIS are [11]:

- For the community:
  - Energy and CO2 savings thanks to progress in real tested technologies and solutions.

- For operators:
  - Common understanding with the manufacturers on energy savings and related innovative technologies (Key Performance Indicators, duty cycles, Technical Recommendations)
  - Decision Support Tool methodology: selecting optimum combinations of technical and operational solutions
  - Real experimental results from the field of innovative technologies to save energy (RS, Infrastructure & operational measures / thermal & electric energy)

- For manufacturers:
  - Clearly defined and harmonised requirements by operators
  - Extended electrical system simulations tools to integrate the new smart grid concept and new thermal simulation tool

The realization of OSIRIS is divided into 8 work packages:

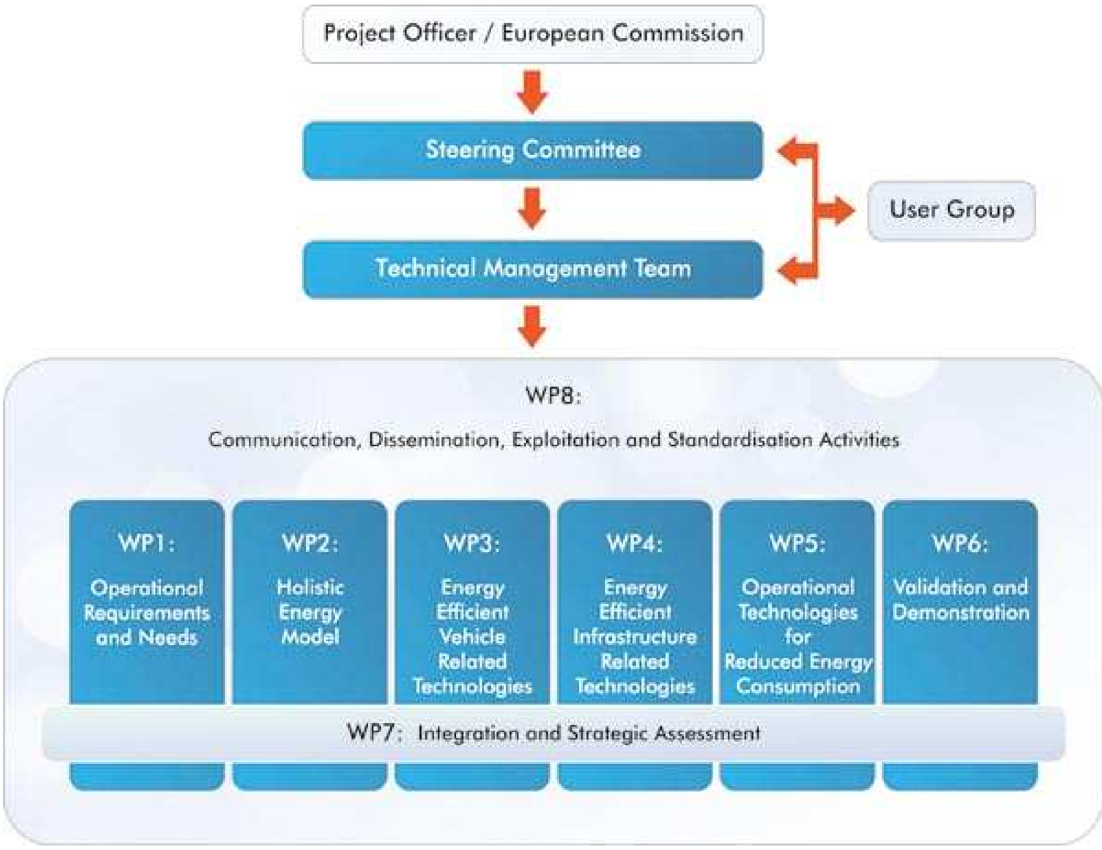


Figure 2-6: OSIRIS Organization [11]

We will focus on the work package 4 entitled “Energy Efficient Infrastructure Related Technologies”.

2.3 TASK 4.1 – SMART GRID SOLUTIONS STUDY AND RELATED SIMULATIONS

The work package 4 studies the impact on energy saving and CO2 emission of infrastructure recovery technologies in mass transit systems (i.e. LRV, Subway, Suburban systems).

The above defined objectives will be reached realizing different technical solutions. The technical objectives will be in the electrical and thermal domains and will include an eco-design approach in the whole system lifecycle.

The work package 4 is divided into 3 tasks:

- Task 4.1 : "Smart grid solutions study and related simulations"
- Task 4.2 : "Heat gaps evaluation and heat pump solutions to reduce the energy consumption of station and tunnel auxiliaries"
- Task 4.3 : "Thermal simulation and thermal management of infrastructure"

The task developed in this document is task 4.1.

The objectives are the following:

❖ Defining a smart grid management will allow to optimize the energy management of plants (including traction supply system, on ground auxiliaries and energy storage equipment) defining an optimized power supply architecture. In particular, ground plants, seen as intelligent nodes, will dynamically be considered to optimize the energy flow among loads and generators, such as several energy storage systems and renewable energy generators installed along a railway line. A smart management approach will consider plant operational cycles. Smart grid includes an intelligent monitoring system (including different types of sensors) to real-time monitor and manages the different intelligent nodes of the grid. The smart grid energy architecture will be used to manage the energy flow among upstream network, line feeders, storage systems, substations and auxiliaries to reach energy saving goals.

❖ Pushing the recovery of braking energy to its maximum potential (potentially 100% of receptivity of the line for DC systems) by recovery of energy braking on trackside for subway and suburban trains, running in what's called "close systems". Different technologies will be evaluated: line side energy storage systems such as batteries, super capacitors, fuel cells, etc. and DC reversible substations. A comparison among different technologies to recover and re-use braking energy will be done through the holistic model developed in WP2.

The final goal is to apply the concept of smart grid for electrical networks in the suburban and tramway network and to give a vision of what a smart grid should be. The improvements that a smart grid should achieve will be defined in terms of quality (perturbation or failure recovery, flexibility and interconnection) and quantity (energy savings, intelligent load sharing, lower impact on environment in terms of CO2 emissions).

It should treat of the following questions:

- Gap analysis: what are the goals to be achieved by a smart grid in the future compared to the current technologies, processes, regulations? The desired future state is compared to the current one and gap statements will be identified. Specific solutions that integrate new technologies and applications are identified
- Mass transit energy configuration and load profiles: The mass transit system engineering evaluation will be set up in order to give the appropriate energetic profile specific to different transportation systems (tramway/metro, etc.)
- Smart grid available technologies evaluation and component studies.

Simulations of urban rail systems based on different operational conditions and a sensitive analysis, concerning electrical characteristics, will be carried out to evaluate a preferred topology of a future smart grid for the different transportation systems.

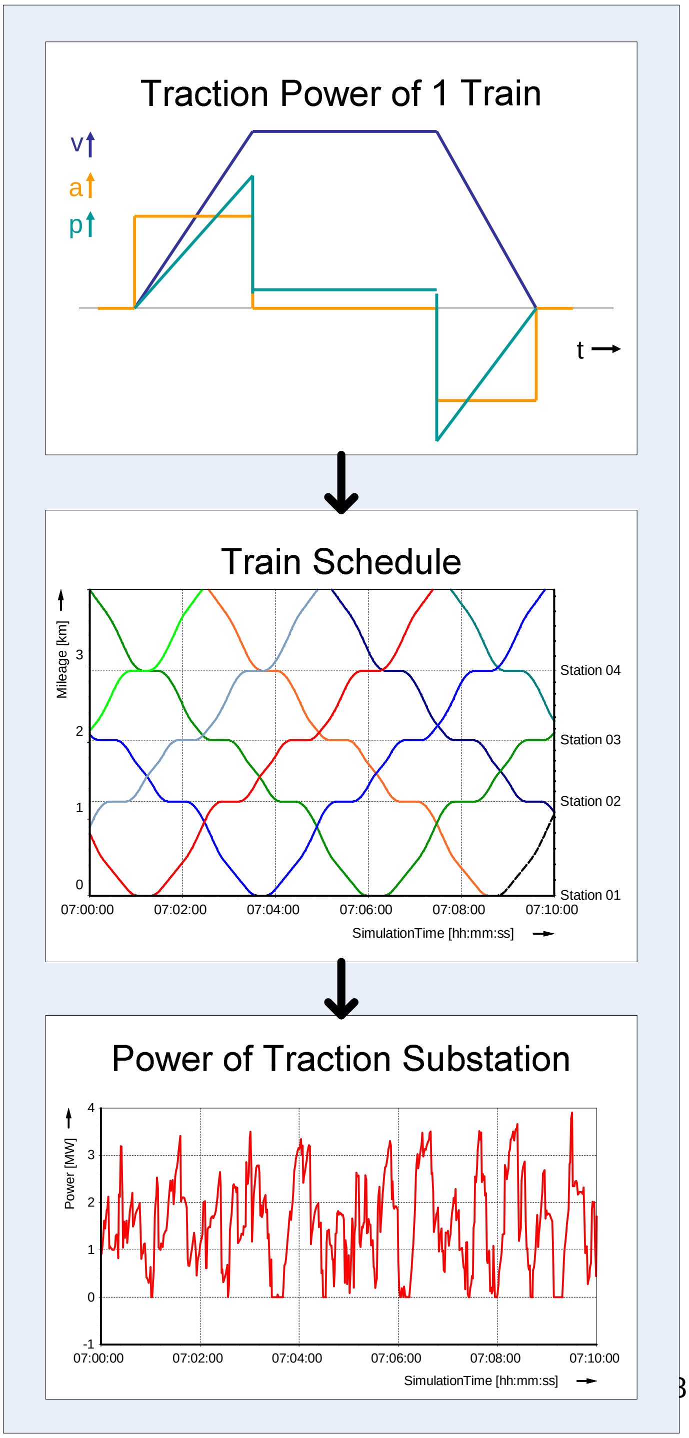
Electrical transportation systems are enabling the use of regenerative energy sources as a substitution of fossil energy use. Every measure increasing the acceptance of public transport is therefore welcome in order to reduce GHG emissions and other disadvantages of individual transport like noise space and dust. The acceptance can be increased by providing fast and comfortable transport.

All measures to improve the reliability of traction networks and increase the speed and the comfort are welcome. The power supply has to serve these requirements beneath the need for permanent increase of efficiency.

Better ambient conditions, faster transportation and higher reliability with same energy consumption are also welcome. Efficiency is only one point.

3 THE MASS TRANSIT NETWORK STATE OF THE ART

3.1 RAIL TRANSPORTATION PROCESS AND RESULTING REQUIREMENTS FOR THE ELECTRICAL NETWORKS



The basic task of an urban rail system is the transportation of passengers. Therefore trains require power to overcome mechanical resistances. Based on the physical principles, the required power can be calculated. The figure of the left represents the simplified power variation for one train running between two stations. Additionally, power for HVAC is needed. The Train acts as consumer during motoring and as producer of electrical energy during braking. Its power is pulse-shaped.

In a typical urban railway system, several trains participate in the transportation process, which is defined by the number of passengers, the headway, the topology, etc. A simplified train schedule is shown on the left. In urban railway systems, there are typically short driving cycles with accelerating, driving with constant speed, coasting and breaking. The trains are interacting via the contact line and exchanging energy.

The interaction of the trains leads to the resulting traction substation power. An example for the high fluctuation of this power is shown on the left with a typical ratio between peak power and average power of approx. 3. The traction power substations are the interface to the electrical network. Hence, the constraints and requirements for the electrical network can be derived from the characteristic power of the traction substations. Generally, for the transportation process service, a high availability and reliability of the electric network is necessary. Furthermore, the electric network has to provide the high fluctuating power for the railway system. The short circuit power at the point of coupling must be high enough in order to limit disturbances like harmonics and flicker even under the condition of the permanent heavy load change.

3.2 THE REGENERATIVE BRAKING ENERGY

3.2.1 Introduction

Before studying the smart grid solutions, we will focus on how an urban public transport works today:

- Metro and tramways drive along the line powered by the catenary or the third rail. The energy is delivered by Traction Power Substations (TPS) which are generally rectifiers distributed on different points of the line in order to ensure a good quality of power with a low voltage drop. These substations can be powered directly by the "national" electrical grid or by an internal electrical network of the train operator or infrastructure manager.
- Stations and auxiliaries (lights, signalisation, escalators, technical rooms ...) are powered by another electrical network which can be independent or connected to the traction network. In fact, energy storage systems can also be used as power suppliers to the station loads and to auxiliaries.
- When a train is braking, it regenerates energy: the kinetic energy is transformed into electrical energy. This electrical energy is directly consumed by the auxiliaries of the train (heating, air conditioning, lights ... representing 50 to 200kW) and the remaining energy is sent back to the feeder (3rd rail or catenary). If there is a train accelerating in the area of the braking train (highest is the line voltage, largest is the area), the accelerating train is powered by the braking train. Otherwise the voltage increases and the braking train dissipates the energy in the braking rheostats.

This kind of braking is generalized to all rolling stocks because of its ease of use in alternative or direct current. No additional component is required because of the natural reversibility of motors and converters by principle or by construction. Moreover this regenerative energy allows improving the energy efficiency of the traction system and it is the main research topic to decrease the consumption of electricity.

The state-of-the-art of power electronics and electrical machines provides the reversibility in today’s traction equipment. Older equipment (nowadays app. 50%) does not provide this feature. It will be replaced step by step and is not considered in this document. Nevertheless the replacement of this equipment will save energy in the future.

3.2.2 Available braking energy and power

❖ Energy study

As said before, the braking energy represents the kinetic energy of the train at his speed before the train begins to brake (with the hypothesis the power of motors allows an electrical brake until 5km.h^{-1} and the line is receptive at 100%). For a solid in translation, it is represented by the following equation:

$E_k = \frac{1}{2} m.v^2$ with E_k in Joules, m in kg and v in m.s^{-1}.

However the kinetic energy doesn't represent the total amount of energy which can be reversed to the network.

$$E_{braking} = [(E_{potential} + E_{kinetic} - E_{friction} - E_{aerodynamic}) \times \eta_{vehicle} - E_{auxiliaries}] \times \eta_{DC/DC}$$

With $E_{potential}$ the potential energy, $E_{kinetic}$ the kinetic energy, $E_{friction}$ the mechanical frictions, $E_{aerodynamic}$ the frictions with the air (more important in tunnels than outside because of the piston effect), $\eta_{vehicle}$ the efficiency of the drivetrain, $E_{auxiliaries}$ the energy reversed to the auxiliaries and $\eta_{DC/DC}$ the efficiency of the chopper.

The potential energy is equal to $m \times g \times h$ and the result is adapted in a descent with a factor of 0.9 (positive energy) and in climbing with a factor of 1.10 (negative energy). The potential energy can be counted as a real source of energy if the slope is negative (for a train of 200 tones with a slope of -4% the potential energy is equal to 19.62kWh/km).

This total energy braking for a train of 260 tones at a speed of 80 km.h^{-1} reversed to the line represents 9 kWh.

❖ Power study

The electrical braking curve characteristic of a rolling stock is generally composed by a first part without power at low speed (the braking is done mechanically) then a linear progression until high speeds (from about 70 km.h^{-1}) where the curve is constant at the maximum power. For a metro type the maximum braking power can be equal to 2MW.

Diode rectifier AC/DC substations are unable to recover the regenerative braking energy not being used after natural exchange of braking energy between trains. Also, the probability of having trains braking and trains accelerating close enough to each other to allow for an effective energy transmission and reuse is rather small, except in very dense urban networks. Consequently, a sizeable percentage of braking energy is lost in the braking rheostats.

As shown in Figure 3-1 : Energy balance for Mass Transit (based on 6 simulations)about 10% of the total energy consumption is lost in rheostatic braking and it represents about 15% of the total purchased energy.

This figure has been realized with the exploitation of 6 different simulations. 2 of them are metro simulations (750V and 1500V), 1 of them is a heavy tramway simulation (750V), and the 3 last are light tramway simulations (750V). All these simulations are based on an annual consumption and include all headways (peak hours, off-peak hours, week-end & nights ...): it enables to have a truthful simulation which is not limited to a specific headway. The auxiliary percentage was calculated from the auxiliary power, the losses percentage was calculated from the line losses and losses in the rolling stock (the efficiency was deduced from the division between the mechanical power P = F x v and the electrical power P = U x I), the braking percentages were deduced from the output data and the resistance to motion percentage was the complement to 100.

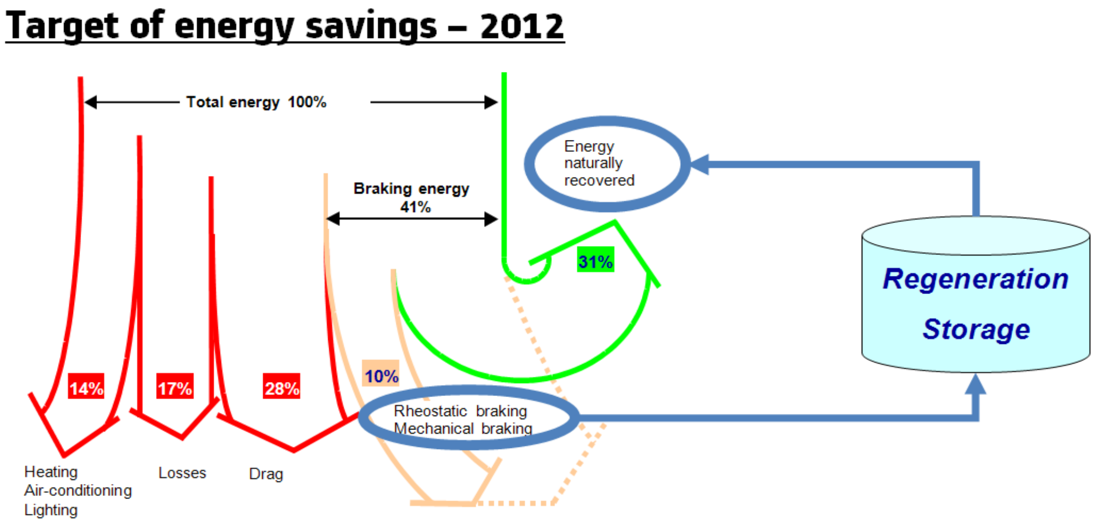


Figure 3-1 : Energy balance for Mass Transit (based on 6 simulations)

3.3 Solutions to recover the braking energy and reduce the energy consumption

A simple solution exists and consists in controlling the operation of trains in order to be sure than when a train brakes another is accelerating. But this solution is not acceptable for the transport process. A short introduction to other existing solutions is done thereafter (the main development will be done further).

3.3.1 Inverters

Another solution based on smart reversible inverters (as HESOP for Alstom [12]) exists. These converters let the natural exchange of energy between trains and if there is no train able to use the braking energy, the inverters recover the energy and distribute it to the electrical grid or transfer it to the upstream network where it is distributed to other consumers e.g. in stations. This solution captures at least 99% of recoverable energy but it isn't perfect. In fact, lots of auxiliary station networks are independent of the traction network and the unique solution is to sell the energy to the grid operator which will buy this energy at a low price compared to the selling price (when the consumption is very high it is possible to sell at a higher price). There is no obligation from the electricity provider to buy back the impulsional braking energy. Moreover, if the inverter do not allows the priority of energy exchange between trains and it only operates between fixed voltage levels it will not decrease the gross energy consumption of the mass transit network. The fraction of energy that could have been exchanged between trains without the action of the inverter is taken from the rectifier substation and paid on the energy bill. However if the operator owns a private medium voltage network which supply all the traction substations, another traction substation (or station substations if they are linked to the same private network) can consume the recovered energy and energy savings can be done.

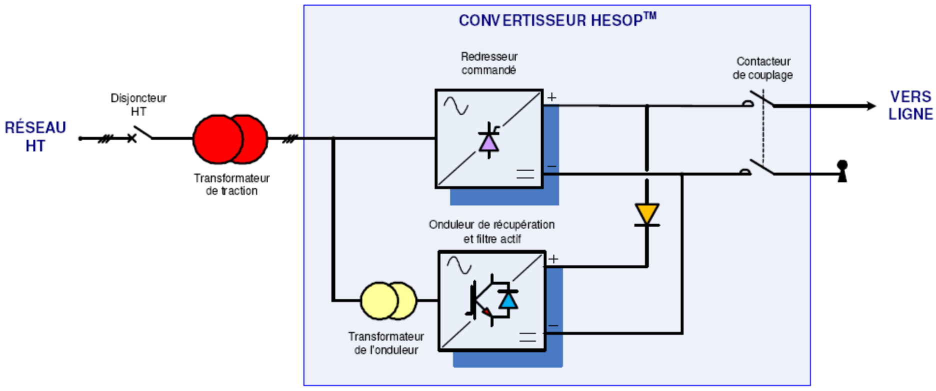


Figure 3-2: HESOP Traction Power Substation [12]

3.3.2 Storage systems integration

Lots of storage systems exist and a huge number can be used in urban transport. The best known are batteries (Li-ion, lead-acid or NiMH), super capacitors and flywheels. All storage applications present 2 basic characteristics:

- A storage system is specifically dedicated to power (supercapacitors), energy (batteries) or hybrid (flywheels) use.

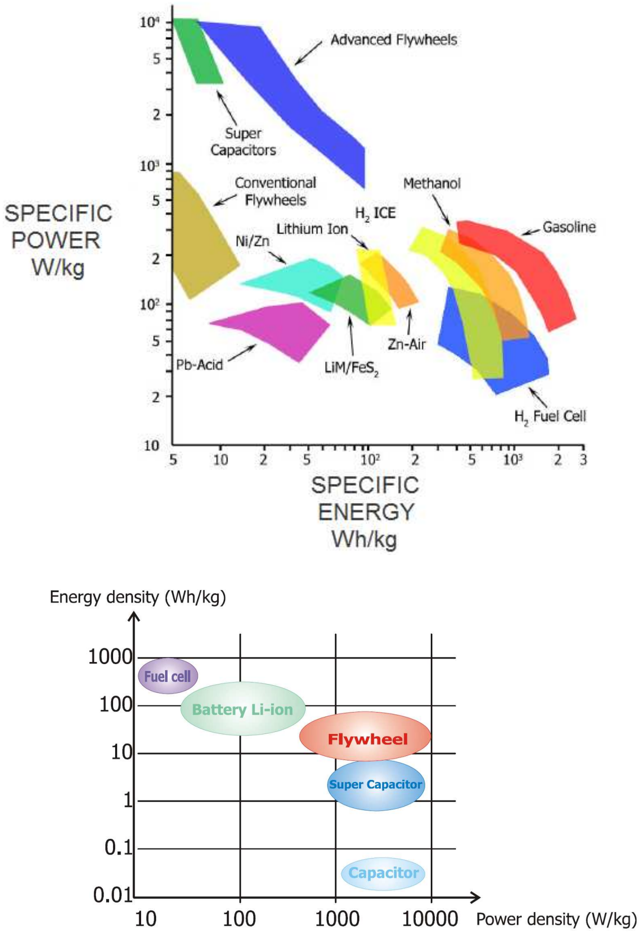


Figure 3-3: Energy and power densities of different storage systems [13]

- The storage system can be on-board or fixed. An on-board storage system stores the braking energy and delivers it during the acceleration. Thereby the peak of power at the TPS is limited during the acceleration and line losses decrease. However the train is heavier (the need of more power to move) and the rolling stock has to be studied in order to embark a storage system (problem of space).

Figure 3-4: Bombardier MITRAC on-board energy storage [14]

A fixed storage system allows operators to install a higher power or energy system without the problem of space.

Figure 3-5: Siemens SITRAS SES energy storage system for railway application [14]

3.3.3 Renewables integration

Another possibility to decrease the energy consumption on the electrical grid consists in increasing the local production of electricity of the operator. Thus the integration of renewables along the line is a possibility.

Some operators decided to install photovoltaic panels at the roof of high speed railway station (East Japan Railway Company in Japan, China, Belgium …). The Figure 3-6: 200 kW PV system at Takasaki Station (Japan) [15] shows 200kW of photovoltaic panels installed at Takasaki station.

Figure 3-6: 200 kW PV system at Takasaki Station (Japan) [15]

The same installation could be realized at the roof of urban railway stations. For example 2 roofs of 40 meters by 1.5 meter let to install 120 m² of panels. It represents a power of about 18kW and energy of 15 MWh/year. However this energy is variable during the day and the year with sunlight conditions and there is no correlation between the traction or station consumption and the photovoltaic production. Photovoltaic system's peak production is around noon while the station and traction's consumption peak is in the morning and in the evening as show the following measures (single-phase load contains lights of the station, three-phase load contains air conditioner, elevator and escalator). Therefore, local storage systems and/or energy management system, allowing power flow to other loads, need to be installed for better energy utilization.

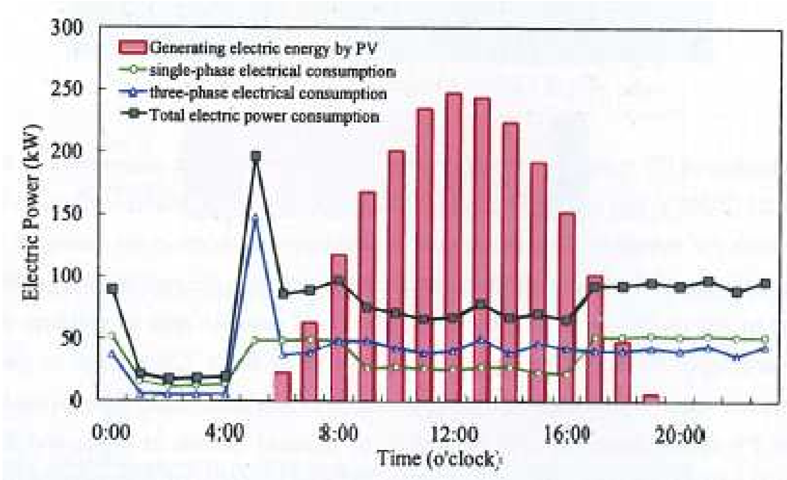


Figure 3-7: Relation between PV generation and station load at middle size railway station [15]

In depot and stabling areas a roof will provide shadow. In this case, a train under this roof is protected against solar radiation of about 1 100 W/m^2 warming up the train and its components. At hot days it reduces the use of air conditioning. The benefit is higher than the produced energy only.

These 3 solutions are only partial and taken alone cannot achieve the OSIRIS goal (reduction of the overall energy consumption within Europe's urban rail systems of 10% compared to current levels by 2020). They are actually used in a punctual way and not in global energy optics that is the base of smart grid concept. It's necessary to have a new view of the grid, in which all the actors (generators, loads, energy storage systems, and auxiliaries) are managed in an optimal power flow direction.

3.4 OTHER TECHNOLOGIES

The smart grid approach in railway systems is still at its beginning and is not clearly defined. There are several technologies and measures which can be seen as “smart”, in the way that they lead to an intelligent use of the energy in railway system. In the following, examples for smart technologies and measures are listed:

- Increase energy efficiency
  - Using energy efficient lighting in trains. This reduces the energy twice: for light and for air conditioning.

- Demand oriented consumption
  - Using variable-speed electric drives instead of those with constant speed, for e.g. ventilation, escalators. This is based on the fundamental principles of drive technology ($P \sim v^3$)
  - Defining a voltage depending current characteristic of the train as per EN 50388 leads to a reduction of the traction power of the trains in case of weak state of the railway grid.
  - Switch off unused consumers e.g. switch off the lighting in trains in depot, switch off information, entertainment and escalators if unused.

- Recuperate energy wherever it is possible
  - e.g. at escalators and elevators
  - The losses of consumers which can be used for heating can be used e.g. for domestic hot water

- Holistic energy consumption is more important than energy consumption of subsystems
  - Smart metering: Using smart meters in the railway system. Smart meters generate system know-how which can be used e.g. as input for energy-management-system. Generally the integration of information bears advantages.
  - If possible shift energy consumption to phases with energy surplus in the electric network. E.g. tunnel temperature has a relative high time constant. Hence the tunnel cooling can be done during phases with high power generation of wind energy plants.

- Use intelligent equipment which can be adapted according to the different situations
  - Inverters, energy storages, Controlled rectifiers. The communication medium for this equipment is the line voltage.

- Others
  - Use circuit breaker instead of fuses. Eliminate fuses. Fuses produce overvoltage with a potential to disturb other equipment

4 GLOBAL NETWORK SOLUTIONS: THE NOTION OF SMART GRID

4.1 THE SMART ELECTRICAL GRID

4.1.1 Why a new grid's architecture is needed?

Power grids were developed at the end of the 19th century. They responded to a need for local electricity production to provide the energy needed to power plants, lights of big cities or the electric rail. The networks were managed locally, so it was easy at that time to meet the production-consumption balance. Then grids were interconnected to each other; by using high voltage, it was possible to transmit power over long distances. This production was centralized and then had to support a power consumption steadily increasing (development of new uses, power switch from a non-electrical source to the electricity) with annual peaks of current (summer in warm climates, winter in cold countries ...) and daily peaks (19h in winter and 13h in summer in France ...). In parallel with this electricity consumption more and more important, power generation is increasingly decentralized with the integration of renewable energy which may require adding storage solutions. This new production is also difficult to predict as subject to the vagaries of weather (wind, brightness ...) and does not follow the curve of power consumption. The equilibrium consumption and production is increasingly complex to achieve and it is no longer possible to manage its centralized power generation based on consumption and a single way of power flows. Moreover while a century ago the electricity represented quite zero percent of the final energy consumption, it represents nowadays about 40% in the USA, as shown in Figure 4-1, and this percentage could grow up until 80% in developed world within 10-30 years. [16]

In addition, the dependency on fossil fuels is decreasing and the anti-nuclear movements are pushing governments to reduce nuclear energy production therefore it became necessary to increase the efficiency of power generation, reduce losses in transmission (5-10%), distribution and consumption of electrical energy and to ensure an effective integration of renewable power generation.

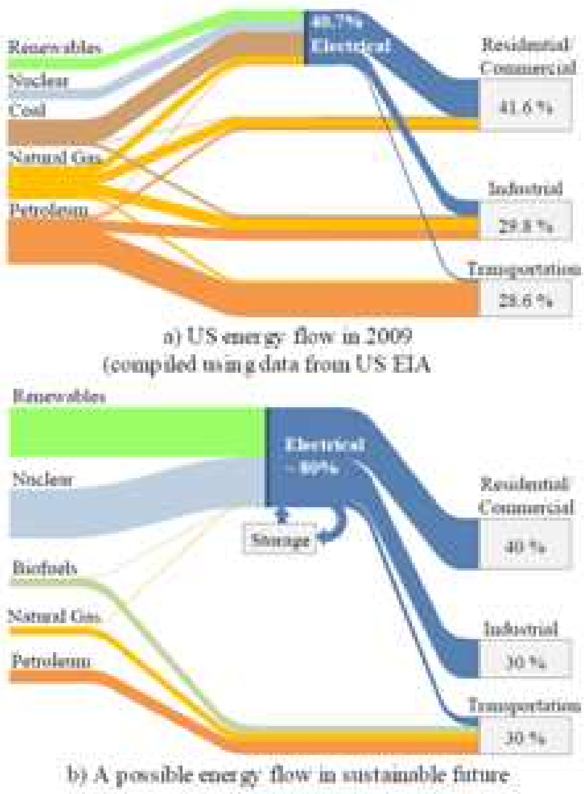


Figure 4-1: Total energy production and consumption in developed societies [16]

That is why, when a century ago the concept of smart grid had neither meaning nor technical tools available, it has now become essential for grids which have a hierarchical structure including supply generation, transmission network, and distribution networks (to which industrial, commercial and domestic user load is connected, generally involving unidirectional power flow between generation and loads). Although at transmission level, a well instrumented active network involving generally two-way power flows is already employed. At distribution level the network and connected loads are largely passive and power flows are unidirectional, with few intelligent appliances.

4.1.2 What is a smart grid?

A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and "prosumers" who can do both) in order to efficiently deliver sustainable, economic and secure electricity supplies (EU SmartGrid Platform).

The smart grid’s goal is to provide global energy solutions using local actions to generate and distribute energy flows in a more efficient, economical and sustainable way than a classic grid and with a supply security. As said before the electrical production has to follow the electrical consumption. During the year and the day this consumption is changing a lot with peaks of consumption at the morning and the afternoon, a normal consumption during the day and a low consumption during the night. The smart grid will smooth this consumption during the day in order to limit the peaks of consumption. Then it will smooth the electrical production thanks to energy storage systems (as for the example shown in Figure 4-2): electrical production varies less and could stay constant all day (during off peaks the surplus of energy is stored and during peaks this energy is reversed to the grid to ensure the surplus of consumption).

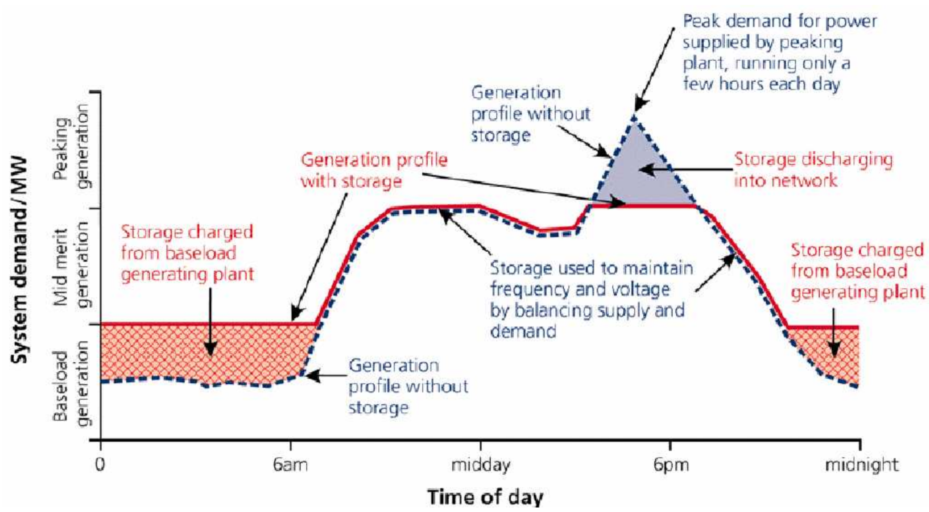


Figure 4-2: Example of smooth of production [17]

Finally the last goal of smart grid is to integrate renewables and decentralized production into the electrical system. It integrates and interconnects technologies (products and services) and innovating tools from the power production to the devices of the final users. This integration is realized thanks to the use of sensors and digital equipment of protection, measure and communication in interface with the centers of control and piloting. All these tools allowed stepping toward the smart grid; in fact, sensors and communication equipment led to an evolution of the grid from the classical electromechanical architecture to a digital grid as follows:

Table 4-1Comparison between the actual grid and the future smart grid

Actual Grid characteristics	Future Smart Grid characteristics
Analog	Numeric
Unidirectional	Bidirectional
Centralized Production	Decentralized Production
Communicating on one part of the grid	Bi-directional communication on the whole grid
Electrical system balance based on production	Electrical system balance based on consumption
Consumers	Prosumers

This evolution can be realized using a new architecture based on:

- Classic architecture providing basic electrical support (lines, transformers…)
- Communication architecture constituted by new technologies allowing to collect data from different sensors fixed on the electrical grid, such as the AMR (Automated Meter Reading) that gives energy distributors information about the power and energy profile of users; the AMI (Advanced Metering Infrastructure) that allows full real-time measurement, power outage notification, power quality monitoring and communication between the user.
- Applications and services such as troubleshooting systems and automatic programs responding to real time electrical demands.

So, by using these technologies, the next step is toward the smart grid: the smart grid offers to all consumers the possibility to obtain information on their own electrical usage. It allows them to manage their own consumption, their possible production and to improve their energy efficiency, in relationship with the grid and its operators.

The intelligence of the grid is mobilized to improve the continuity and the quality of the power supply, in a context of increased and versatile demand, and more decentralized and intermittent generation. It allows minimizing high investments for the infrastructures reinforcement of the grid.

A smart grid has different levels of integration [18] [19]:

❖ Energy production level

This level includes a centralized production (traditional power plants of coal, fuel, gas or nuclear) and a decentralized production (renewables). The production which was before realized using few large power plants will tomorrow be realized with much more distributed smaller power plants. Some controls and facilities on the grid have to be done in order to link this intermittent production with optimized level of reinforcement.

❖ Transmission system level

The transmission system permits the transmission of power from the power plants to the customers via the distribution system. It represents the high and very high voltage lines used to minimize the current and the energy losses. The notion of smart grid already exists in the transmission system. Indeed the power flow can move in both directions and circuit breakers can be opened and closed at substations to manage power line fault thanks to the protection switchgear. However other means and devices can be deployed to make the transmission of energy smarter. For example with FACTS (Flexible AC Transmission System) the parameters of the transmission line can be changed to better manage the power flow. FACTS combined to an autonomous control of switches can ensure that the power is transmitted where it is needed.

❖ Distribution system level

The distribution system represents the part of the grid directly connected to customers with a lower voltage than at the level of the transmission system. This voltage level differs from one country to another and even from one electric utility to another, yet a value of around 100 kV can be used generally used to differentiate between industrial solutions for transmission and distribution.

The distribution system undergoes strong and intermittent variations amplified by the fact that consumers can be producers too. In consequence, the distribution system has to be automated to counter a power fault and to avoid the loss of the entire distribution line. Grid reinforcement is usually needed as this system is mostly radial. Traditionally, to provide continuity of supply, paralleling upstream distributions lines with 100% redundancy has to be implemented. With the smart grid solutions, the energy can be routed to other consumers instead of upstream grid reinforcement. Additional automated solutions can decide to supply critical services and to not supply the others in case of loss of one part of the production or if the production can't follow the demand (to avoid a total blackout). Another possibility is to include the concept of islanding: customers who produce their own energy can be disconnected from the rest of the failing grid and ensure the electricity consumption in the local area.

❖ Customer level

The last level of integration is the customer level: customers in a smart grid are not only consumers but they can be producers, they receive information about their consumption and they communicate it back to the distribution substation. With smart meters the electricity distributor can know exactly the amount of energy consumed by each customer. The distributor can adjust the price policy to the real consumption (and not to hours which can't always be a real indicator of peaks of consumption) and inform its customers. If the customer gets an electrical vehicle he won't use, he can inform the grid that this source of energy can be reversed to the grid if necessary. The customer is important in the smart grid to ensure the production is equal to the consumption which can be adapted to the grid production too (a heating or cooling source can absorb an intermittent surplus of power for example).

Finally a smart grid is more like the Internet, so that control systems can route power to where people need it, when they need it, and from solar, wind, and other green sources as much as possible. It is a new system architecture which is able to transport energy and communicate in both directions, to integrate energy storage systems, to manage an intermittent production and prosumers who communicate with the grid, as depicted in Figure 4-3. The whole idea of the smart grid is to have enough computer intelligence to control the grid better and make it more autonomous and self-healing.

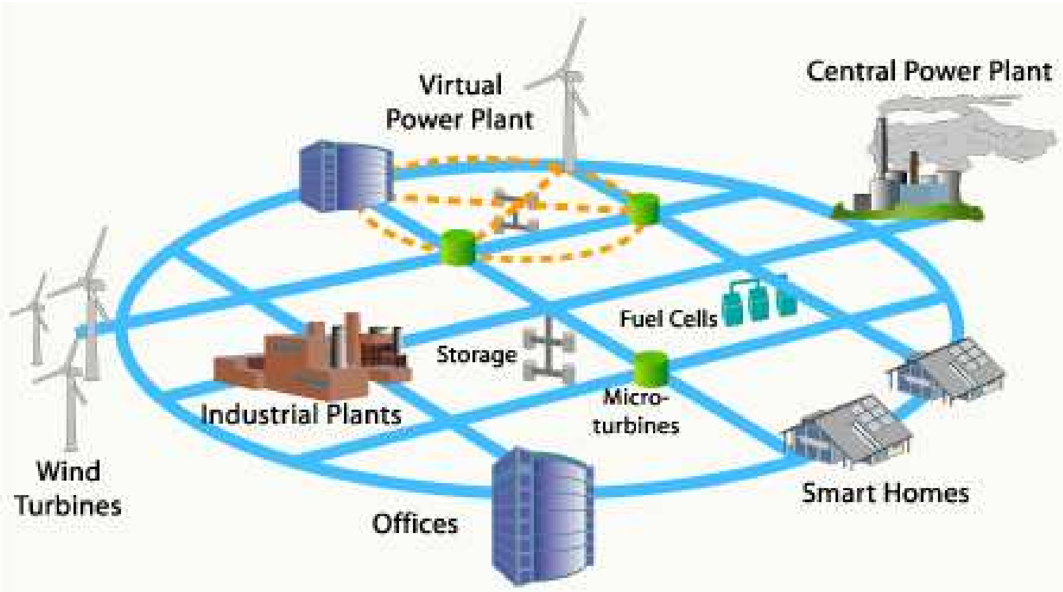


Figure 4-3: Global vision of the smart grid [20]

4.2 THE NEW ARCHITECTURE

Traditionally, the power architecture is built as a tree with branches. At the top, there is the power generation from where several transmission lines are stretched over long distances. Then each transmission line feeds into several distribution lines which are connected to the customers through distribution transformers. The interconnections in the grid are generally limited to the transmission system and the distribution system isn't interconnected. In addition the transmission system is meshed while the distribution system is radial, as shown in Figure 4-4.

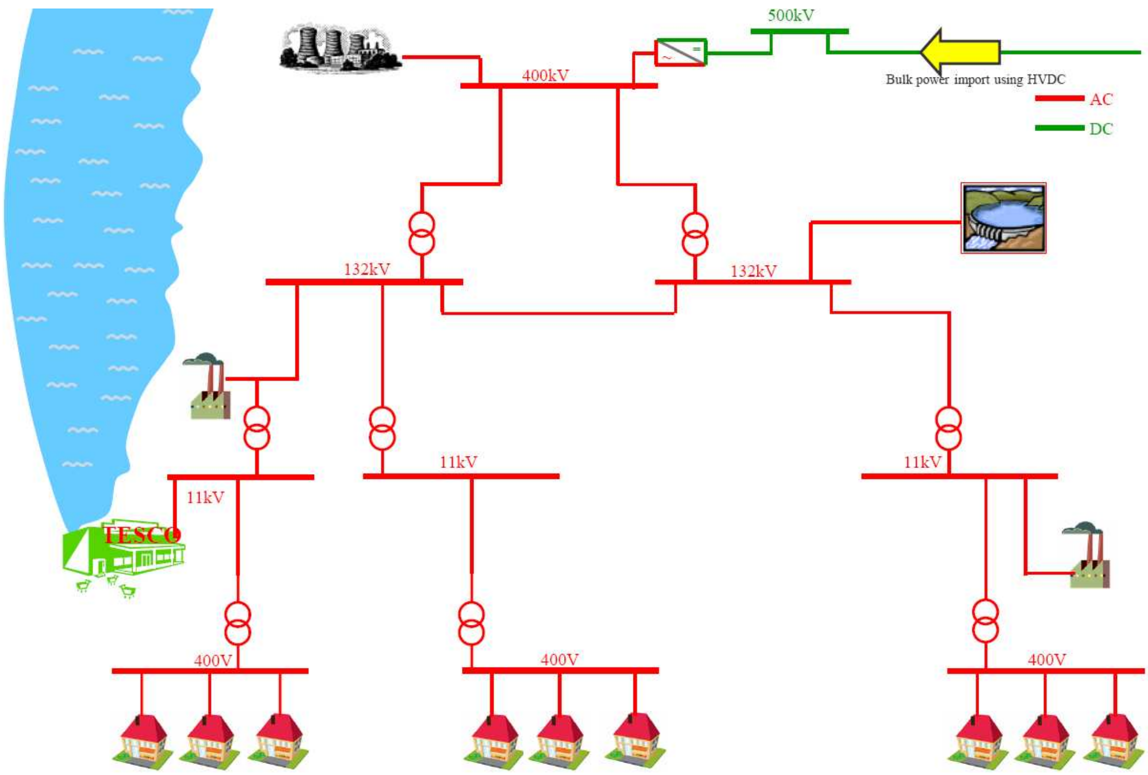


Figure 4-4: The grid of today [21]

This architecture of the distribution grid presents several limits:

- In case of fault the entire branch of the grid is disconnected.

- If a branch consumes more energy than the line can support during a long period the branch will be cut off electrically, and grid reinforcement measures should be done in order to secure the power supply to the users.
- Without energy storage system it's harder to integrate renewables and to smooth the production.
- This power system is slow because it is controlled with mechanical devices, tap changers for transformers, reactors and capacitors compared to a system with power electronic which is faster in the control of the energy flow.
- Limited control over power flow.
- Reverse power flow is not allowed and may impact the protective switchgear performance.

The main differences between transmission and distribution grids are:

- ➢ Distribution grids are not designed for interactive operation, as they have radial design as opposed to meshed design for transmission grids. Hence, grid reinforcement and grid codes are needed to accommodate generation units on distribution grids.
- ➢ The X/R ratio of distribution is less than that for transmission grids due to the use of cables rather than overhead lines. Hence compensation of power quality phenomena is required to be implemented through the control of both active and reactive powers.
- ➢ Distribution systems have limited or no use of SCADA, hence no coordinated control is feasible and only local control if at all allowed.
- ➢ Restricted grid codes for connecting active devices to the distribution systems.
- ➢ Power quality problems are more significant in the distribution systems.
- ➢ Stability problems (traditionally exist for only transmission grids) may arise in the distribution due to the integration of new sources of intermittent generation or loads; e.g. urban rail networks.

Hence, for tomorrow the new architecture (as depicted in Figure 4-5) will need to:

- Interconnect at several points the transmission and distribution lines
- Integrate a multitude of new electrical producers at all levels

- Integrate energy storage systems to allow for more distributed energy coming from renewables.
- Introduce a hybrid system with AC and DC interconnections in order to optimise energy utilisation and reduce reinforcement costs. This will also stabilise the distribution systems as DC connections provide firewalls to different power quality phenomena; as learnt from the experience of similar systems in transmission.

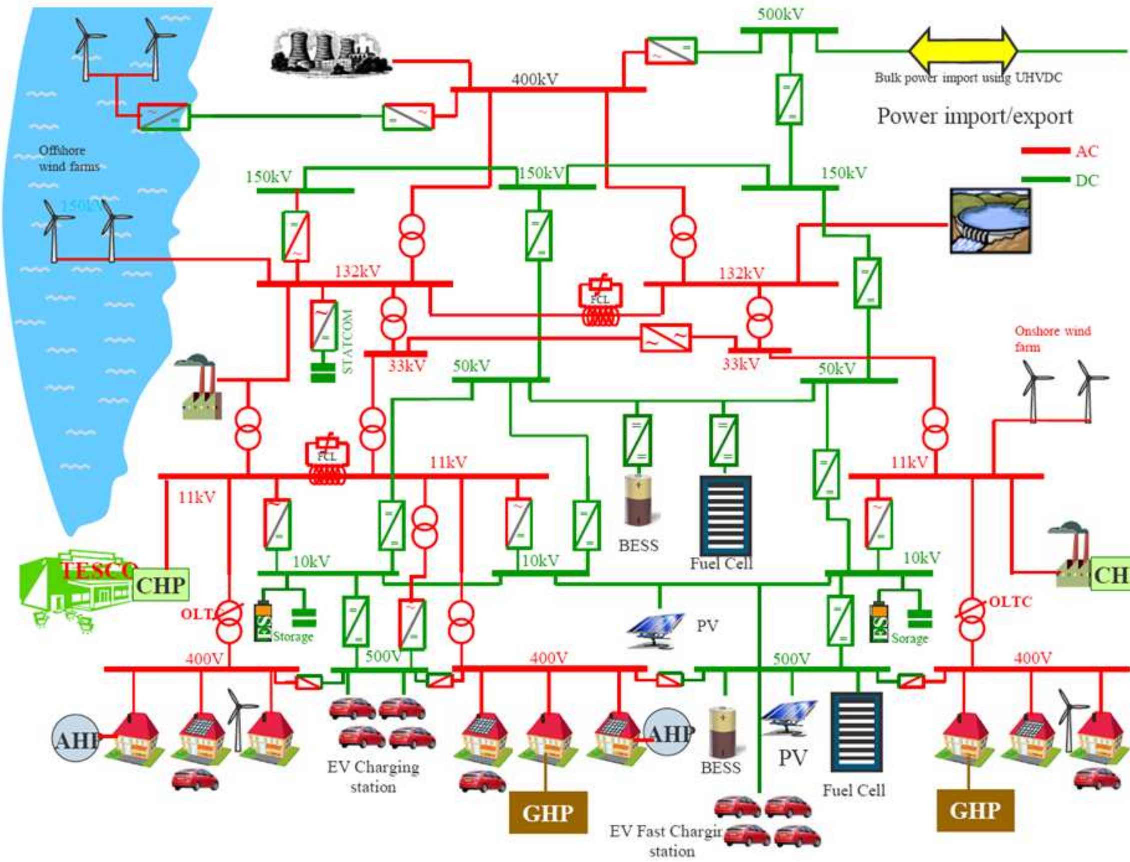


Figure 4-5: The grid of tomorrow [21]

This new power architecture allows better managing the electricity and energy flows.

Indeed with the multiplication of interconnections and CHP, the integration of renewables, energy storage systems and electrical vehicles connected to the grid make possible the consumption of a local energy production. Furthermore, it allows smoothing the production during the day thanks to the storage and it avoids a total blackout in a branch: the line where the fault is detected can be isolated from the rest of the grid and loads after this part of the line can be supplied thanks to interconnection with other branches (even at the distribution level) and/or the energy stored until the improvement of the situation. Without the energy storage, a degree of freedom is lost at the level of the energy management.

4.3 KEYLOCKS OF SMART GRID TECHNOLOGIES

The keylocks are important issues that must be solved in order to allow the development of an industrial sector. They could be political, social, economic, technological, or regulatory. Solving out these issues determines priority research directions.

4.3.1 Technological Keylocks

The most important technological keylocks for the sector are:

- Network equipment and technologies :
    - Development and integration of new technologies (transducers, actuators, protections, etc) in the existing energy systems
    - Maintenance of distributed new technology devices
    - Interaction between the different transport and distribution networks
    - Building large meshed networks (supergrids), potentially limited by the difficulty of introduction of DC grids better adapted for energy transport
    - Difficulty in building and designing systems for the management of EV charging networks
    - lack of experience and undefined impact on security of supply
- Storage technologies :
    - Costs and location in the network's architecture
    - Impact on the storage equipment lifecycle caused by the network charge/discharge solicitations
    - High footprint and maintainability cost
- Client technology :
    - Difficulty of driving devices already installed
    - Intelligent drive of equipment for an optimal level of end user comfort; capacity of large data processing
    - Interface standardization, communication protocol between loads, counting devices
    - Measurement of load flexibility for service valorisation

- Information systems :
  - Large data volumes manipulation
  - Data confidentiality
  - Cyber-security
  - Data processing architecture choice (centralized, or decentralized)

4.3.2 Economic and Regulatory Keylocks

- Complex billing system leading to a hard client acceptance
- Business models building in relation with regulation rules
- Distribution role for existing and new market actors such as aggregators or storage operators
- Data sharing with third parties: energy providers, service providers, etc.

4.3.3 Social Keylocks

- Acceptance of private data sharing and transmission
- Social acceptance of the proposed solutions and change of energy consumption habits
- End user interface ergonomics

4.3.4 The standardization in the smart grid

The development of the smart grid has to take into account several standards (which include communications, measurement systems, control systems, etc.), that allow to:

- avoid re-inventing the wheel
- learn from industry best practices
- specify requirements more easily
- reduce integration costs
- prevent single vendor "lock-in"
- share a much larger market

The use of standards in the electric network allows:

- the communication among the components in an efficient and rapid way

- controlling and monitoring the status of the network, as shown in Figure 6-1

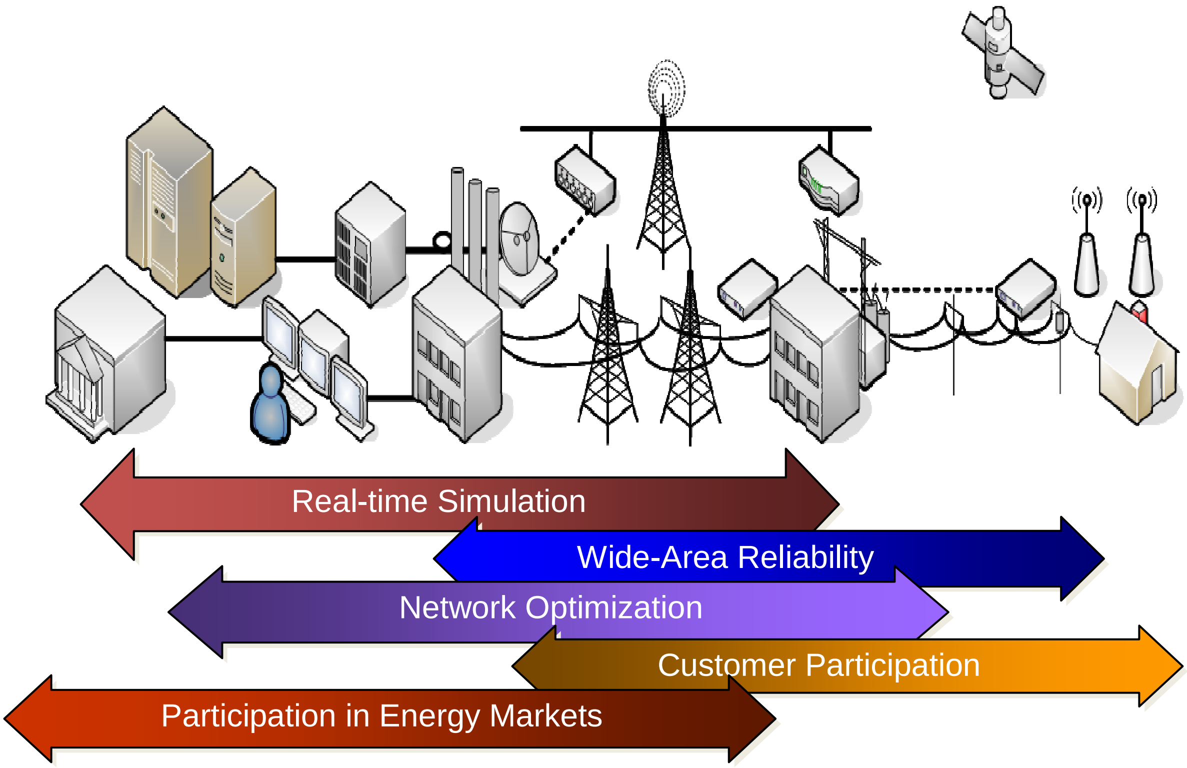


Figure 6-1: The use of standards in the smart grid

Starting from the general architecture showed in Figure 6-1, here we present the main standards proposed at international level for the different elements of the smart grid.

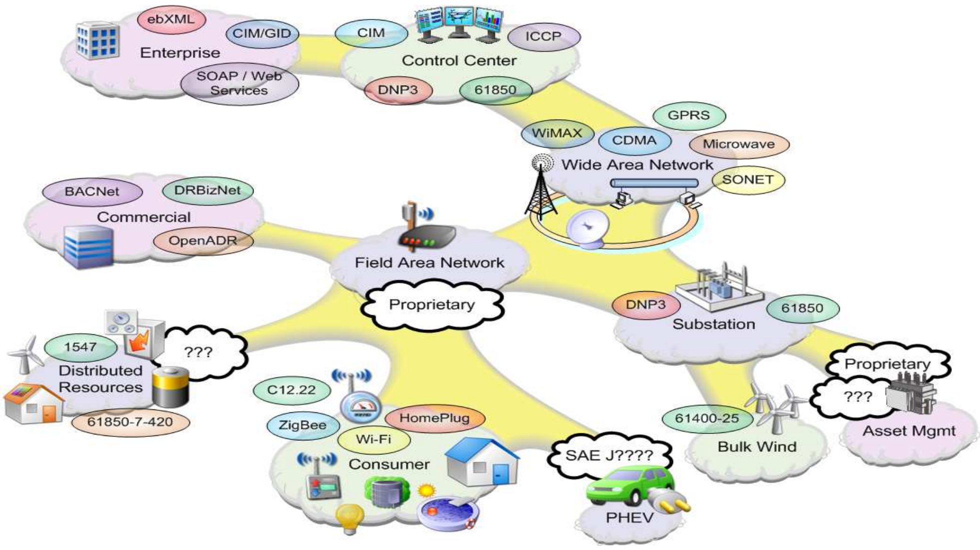


Figure 6-2 -Domain of standards in the smart grid

- enterprise and control centre:

Name / No.	Description	Status
IEC 60870-6	*Inter-Control Center Protocol*	*Widespread*
IEC 62325	*ebXML for Power Systems*	*In development*
IEC 61970	*Common Information Model / Generic Interface Definitions (CIM/GID)*	*In use; mostly single-vendor*
IEC 61968	*Interfaces for Distribution Management*	*Mostly still in development*
Multispeak	*NRECA Enterprise web services*	*In use, not flexible*

Figure 6-3 -Standards in enterprise and control centre

- wide area networks:

Name	Notes
Frame Relay	*Packet-switched, no reliability guarantee*
SONET	*Campus or city backbones*
WDM	*Wavelength Division Multiplexing – follows SONET*
Microwave	*Proprietary, used in geographically difficult areas*
Satellite	*Various proprietary technologies, costly*
Trunked Radio	*Licensed, one broadcast channel, one return*
Spread-Spectrum	*Unlicensed frequencies, more efficient*
IP Radio	*Like trunked radio but with IP addressing*

Figure 6-5 -Standards in wide area networks

- substations:

Name / No.	Description	Status
IEC 61850	*Object models, self-describing, high-speed relaying, process bus*	*Widespread in Europe, beginning here*
DNP3	*Distributed Network Protocol*	*Most popular in NA*
Modbus	*Evolved from process automation*	*Close second*
COMTRADE	*Fault Capture file format*	*Widespread*
PQDIF	*Power Quality file format*	*In use*
IEC 62351	*Security for power systems*	*Recently released*

Figure 6-6-Standards in substations

- access wide area networks:

Name	Notes
PSTN	*Public Switched Telephone Network – dial-up, leased lines*
DSL	*Digital Subscriber Line - Telco IP-based home access*
Cable	*DOCSIS standard for coax IP-based home access*
WiMAX	*Wi-Fi with a backbone, cellular-type coverage*
Cellular	*Various technologies e.g. GSM/GPRS or CDMA/EVDO*
FTTH	*Fiber to the Home. Passive Optical Networks (PONs)*
PLC	*Narrowband Power Line Carrier – the "old stuff"*
Access BPL	*Broadband over power line to the home*
Paging	*Various proprietary systems, POCSAG*

Figure 6-7-Standards in wide area networks

- home area network:

Name	Number	Notes
Ethernet	*IEEE 802.3*	*Substation LANs, usually fiber optic*
WiFi	*IEEE 802.11*	*Access by field tool, neighborhood AMI net*
ZigBee	*IEEE 802.15.4*	*Customer premises automation network*
HomePlug	*1.0, AV, BPL*	*Power-line comms, in and outside premises*
6LowPAN	*IEEE 802.15.4*	*The "approved" IPv6 wireless interface*
OpenHAN	*HAN SRS v1.04-2008*	*Power Industry requirements definition*

Figure 6-8-Standards in home area networks

- distributed resources:

Name / No.	Description	Status
OPC	*Application interface*	*Widespread in industry*
IEC 61400-25	*Wind Power*	*In use; turf war*
DRBizNet	*California initiative*	*In development*
BACNet	*Building automation*	*In use; many profiles*
OpenADR	*Automated Demand Response*	*In development*
IEEE 1547	*Basic principles of DER*	*In use*
IEC 61850-7-420	*Information models for DER*	*Just released*

Figure 6-9-Standards in distributed resources

These standards will be considered in the definition of technological solutions. At the end of the project, TecRec will be provided to select the more suitable standards for a smart grid system applied to a railway network.

4.4 SMART GRID'S COMPLIANCE WITH THE STANDARDS

4.4.1 Assurance of compliance today

The primary function of the electric grid is to ensure that acceptable reliability and high quality of power is delivered to all network users (consumers or producers); with as low intervention as possible with unplanned power flows that may result from the evolving electricity market.

Hence, traditionally, the energy provider main aim was to ensure delivering high quality power to the customers. In this sense the energy provider has an active role while the electricity customers have a passive role in maintaining high power quality of the grid.

Most of the connection standards were then developed taking this assumption into account and consequently limit the impact of the grid connected equipment.

This is changing however, due to the fact that customer equipment is becoming more active by using power electronics interfaces. This equipment can improve or degrade the quality of power depending on its function. This in turn has forced a new scenario today where both the energy provider (or grid operator) and the electricity customer do have active roles in the electricity grid compliance with standards and connection codes.

Grid codes and standards compliance methodology can then be split into two main categories as shown in Table 4-1; equipment compliance and grid compliance.

Table 4-2: Standards compliance methodology today.

Compliance category	Assurance of Compliance	Prevention of non-compliance
Equipment	■ Factory testing and equipment certifications ■ All regulatory standards are identified and mapped into processes, controls, activities and even documentations – companies are audited ■ Commissioning (on-field tests)	■ Businesses monitor non-compliance to ensure business continuity ■ Penalties may apply in case of non-compliance
Grid (aggregated impact measurement)	■ Planning levels higher than compatibility levels higher than equipment immunity ■ Monitoring (performance indicators)	■ Grid reinforcement (common practice) ■ Dynamic operation (test cases – limited to dispatcheable equipment) ■ Penalties may apply in case of non-compliance

Equipment compliance

To assure continuation of the business, manufacturers usually identify all regulatory standards related to their market and required by their customers (the grid operator in this context); and map such regulations into all processes, controls, activities and even documentations.

Products are tested, in the manufacturers own test labs or sent to independent test labs, and certified before being commissioned. In any case, the certifications should be approved by an accredited organization.

Certificates of conformance, calibration and test are supplied as requested/necessary to customers, and the equipment supplier usually provides summary details of standards to which products comply, or processes to which samples or equipment have been subjected.

Conformance marks are usually stamped on the product enclosure (e.g. CE marking for compliance with EU product safety regulations), following predefined procedures.

Upon commissioning, all required markings and documentations are inspected by the hosting grid operator. Also, pre-defined field tests are carried out. These requirements vary from one operator to the other, and also vary depending on the intended use of the equipment.

Penalties usually apply if non-compliance has been experienced after commissioning.

Grid Compliance

Ensuring product compliance with electromagnetic interference (EMI) directives, for instance, does not result in overall grid compliance. Accepted voltage quality level (which is a measure of EMC) at an equipment connection point may penetrate through the grid and build up unwanted EMI levels at other locations of the grid, resulting in degraded services to other grid users.

The first measure to ensure overall grid compliance is done at the planning stage. Planning levels are usually selected higher than equipment compatibility levels, which in turn are higher than equipment immunity levels (to ensure that other grid users are less affected by the aggregated EMI levels – this is again the traditional role where the grid operator is being active and customers are passive towards keeping a clean grid).

The second measure is done through monitoring performance indicators. Traditionally, the continuity of supply and voltage quality are used as performance indicators of how well the grid performs its aim. These indicators are also used to help the grid operator making the right investment decision for grid reinforcement if not satisfied.

Audits are usually conducted by different authorities (depending on the country) of the distribution companies. The auditing authority usually informs the audited company of what indices will be audited. Generally, the audits result in fines in cases of non-compliance.

More information about how different EU countries carry out audits is available from the Council of European Energy Regulators (CEER). Periodical surveys and analysis of the quality of supply in the EU is also carried out and publically available [63].

4.4.2 Assurance of compliance tomorrow

With the evolution towards the Smart grids, the performance indicators used today will not ensure that the grid performs its aim. This is mainly because of the new core functionalities of the smart girds.

The European Energy Regulators have proposed 34 performance indicators in a position paper on Smart Grids [64]. These indicators will be used by national regulatory authorities to assess the performance of network operators. But also these indicators can be used to assess the R&D and demonstration projects on smart grids as a first step towards the compliance of the smart grids.

It is worth here highlighting one group of these performance indicators, as they reflect the smart grid core functionalities: “Enhanced customer awareness and participation in the market by new players”. There are six indicators under this group; as follows:

1) Demand side participation in electricity markets and in energy efficiency measures

2) Percentage of consumers on time-of-use/critical peak/hourly pricing

3) Measured modifications of electricity consumption patterns after new pricing schemes

4) Percentage of users available to behave as interruptible load

5) Percentage of load demand participating in market-like schemes for demand flexibility

6) Percentage participation of users connected to lower voltage levels to ancillary services.

To monitor the above indicators, the Smart Grid needs to incorporate distributed functionality where controllers need to discover, add or remove actors as the grid evolves.

To implement this, Smart grid solutions may require:

- More real time information
- Bi-directional communication of data to multiple actors
- Distributed autonomous solutions
- Market regulations that incentivize the contribution of network users

Figure 4-6 below represents a generic compliance methodology regarding the grid, where actors (to the right of the figure), actions (to the left of the figure) and implementation (arrows) are dependent on the country.

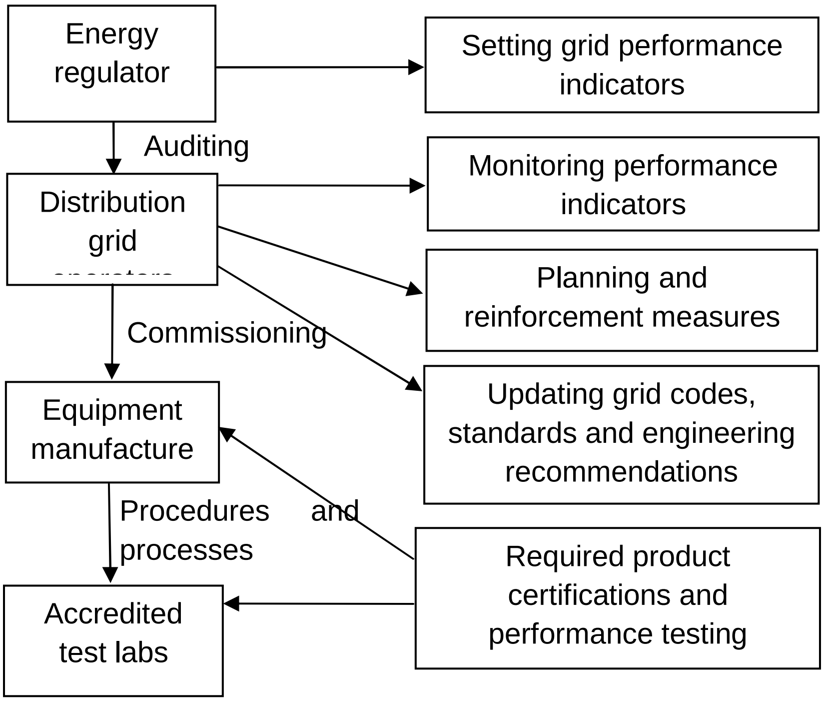


Figure 4-6: Smart grid compliance methodology.

4.5 Research priorities

In order to unlock these keylocks, new research directions and priorities are proposed.

4.5.1 Technological Research priorities

- Network equipment development
  - Very high voltage and DC equipment
  - Power electronics and semiconductors (e.g. Bidirectional DC/DC converters)
  - More efficient and more environment friendly equipment
  - Equipment accepting a larger number of operating cycles
  - Intelligent and communicating equipment (Metering for supervision and control using RTUs, PLCs, SCADA…)
  - Network components development such as mobile or stationary storage, new protections, transducers, etc.
- Network management technology development
  - Real time distribution network management
  - Decentralized production integration in real time

- Very high voltage and DC network management
- EV integration as a new mean of flexibility in the offer and demand process
- Coupling with heat and gas networks: such as temperature regulation for lower level during the night when the station is closed…

- Customer equipment development
  - DC network for home and tertiary end users
- Information systems development
  - Intelligence and self-learning information systems for maintenance, fault detection and decision making
  - Forecast and planning tools for the decentralized production and intermittent generators and loads
  - Interoperability of information and communication protocols
  - Complex systems design engineering tools
- Safety and security
  - Transducers and remote operation protection devices
  - Cyber security and anti-intrusion protection
  - Adapting the protection to decentralized production units
  - Blackout prevention

4.5.2 Economical and Regulatory priorities

- Regulatory and business models for all the actors participating to the new technological effort, especially storage and EV development

- Favourable pricing policy for new technology integration payback and protection of vulnerable persons (social energy pricing)

- Valorisation of renewable energy production

- Acceptance by the end user of an intrusive management of his energy resources for rewarding energy efficient behaviours

4.6 AVAILABLE ENERGY MONITORING AND MANAGEMENT PRODUCTS

In order to manage energy consumption, efficient monitoring systems should be able to recuperate real-time measurements, such as current and voltage, then analyse these data and give the needed information to evaluate the consumed energy and its cost (variable price depending of the consumption hour).

Many energy saving products are nowadays used in the residential sector. They can be divided into three categories: Portable plug-in energy monitor, Full building energy monitor and Full building energy management with individual device control.

4.6.1 Portable Plug-in Energy monitor

These are the simplest energy monitoring devices that measure the power usage of any electronic device. Using these portable devices, the consumed power (in watts), the cost (euros per KWh) and the amount of carbon dioxide produced can be monitored. The power can be measured in both instantaneous and average modes. The average power is calculated on a time period starting from the second the device was plugged in.

In addition, for some products, wireless communication is possible between the power meters and the display panel (433MHz radio frequency channel). For others, access to power usage can be made by internet using a portable computer.

Figure 4-7 Portable Plug-in monitors

4.6.2 Full building Energy Monitors

In this case, a sensor is fixed on the electrical energy meter (analog or digital) to measure and give a live feed of the energy consumption on a web or on your phone. The hardware and the software are generally fully integrated so the setup process is easy. All it needs is a wireless Internet connection and access to the power meter. An included gateway (the white box in figure 4-7) is connected to the sensor using a wire. It sends the energy use data, including the hourly cost, to the web or to a mobile device. The measurements are updated every 10 seconds.

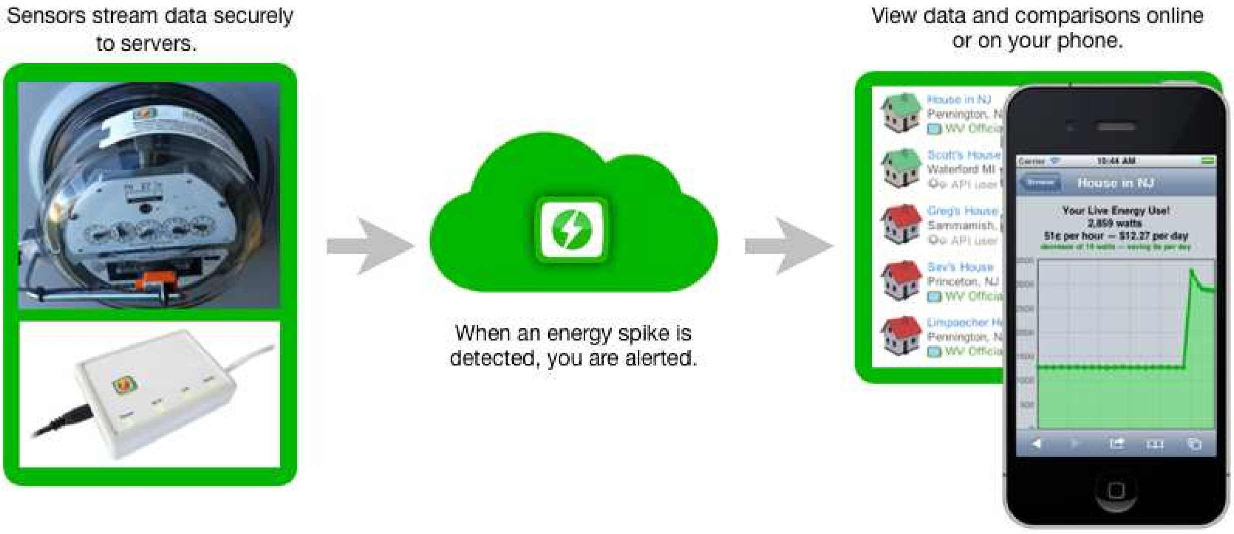


Figure 4-8 Full building energy Monitor

4.6.3 Full building energy management with individual device control

These devices are built to monitor, control and manage the power consumption using smart meters and wireless sensors distributed through the building. Its role is to inform the users with important and detailed information on the power consumption of full building to individual loads and propose power saving plan.

Figure 4-9 Energy management systems

Below, a flow chart describes the functionality of an energy management device that can identify different units requiring power using communicating devices (smart plugs) or by NIALM (Power signal processing), determine the expected amount of power required for each unit, and calculate the cost of the power requirement. Based on the importance and the priority of the requesting units, and the expected power cost, it provides power, delays or cancels a process to ensure that the power cost of the device remains within preset boundaries (e.g., the power cost of the device or of a home network of devices does not exceed a maximum cap).

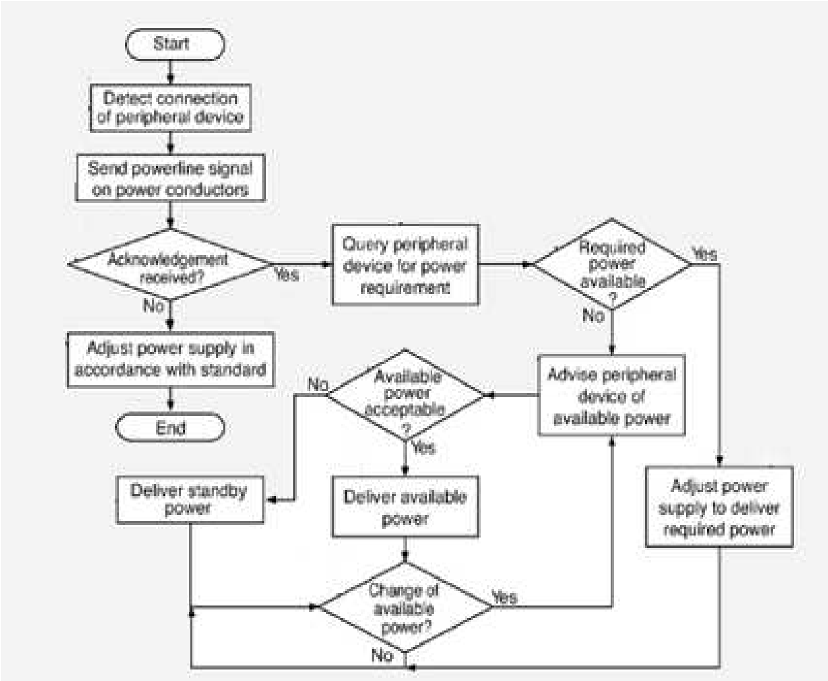


Figure 4-10 Flow chart determining the amount of power for a device

In summary, the Energy Management Devices' characteristics are presented below:

Plug-in Energy Monitoring devices	Full building Energy Monitor	Full building Energy Manager
• Direct sensing through AC line • Total power usage of connected devices • Communication: ZIGBEE/ WIFI • Price: 15 – 219 $	• Circuit by circuit categorized load • Sensor fixed on the energy meter • Communication: Sensor to Display: wireless Remote data access: WIFI • Price: 100 – 250 $	• Smart metering infrastructures • NIALM • Communication: System: WIFI/ ETHERNET Device to Device: ZIGBEE • Price: 200 - 1300$

5 INTEGRATION OF URBAN MASS TRANSIT IN A SMART GRID ARCHITECTURE

5.1 REMINDER OF THE URBAN RAIL REQUIREMENTS

The characteristics of urban rail systems inherently result in a number of requirements that may impact the design of the smart grid architecture. The most significant performance indicators are these related to the quality, reliability and safety of rail service.

The urban mass transit system is determined by the service provided to passengers. Reducing the energy consumption of transport should not compromise the quality of service and trip-duration shall not be increased. The solution lies to maintain the quality of service and has to be robust to any problem. Moreover, if there is an electrical disturbance on the traction network, it should not affect the station auxiliary service network and vice versa.

A traction network is composed by a number of connecting points linked to substations which supply the energy delivered to a multitude of trains. These trains are accelerating, braking, rolling, coasting ... and moving along the line. As a consequence, the electrical properties of the trains and of the electrical network change a lot in time. Moreover, when trains are braking they are not considered as loads but as power sources. Moreover, the situation won't be the same the next day at the same time. This physical fluctuation of the electrical network is the second topic.

The third topic is the peaks of power. In fact, another characteristic of the urban rail system is the peak of consumption when the train accelerates and the peak of power when it brakes. The acceleration and the deceleration are really short in the time. The electrical network and all devices which could improve the network have to be able to support and follow these power consumption and production. The braking energy is not continuous; it is one form of intermittent green energy sources (due to random braking).

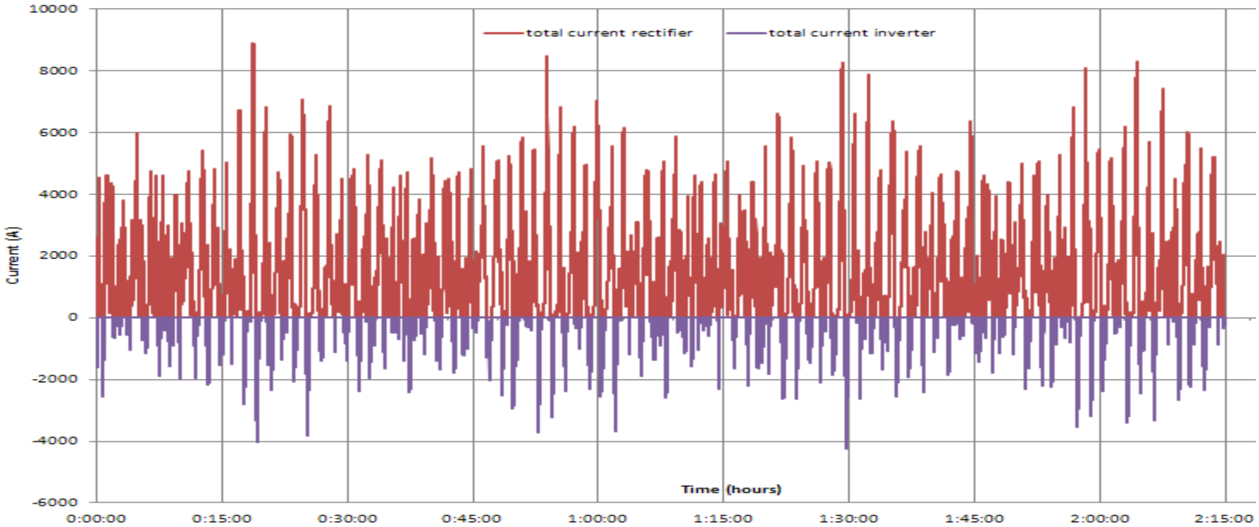


Figure 5-1: Traction current (red) and braking current (blue) at a reversible traction substation

5.2 TYPICAL LOADS OF URBAN RAILWAY SYSTEMS

In this section, we will give a list of the main subsystems used in a typical urban railway network, considering their involvement into the smart grid. The characterization of the components of a rail network allows analyzing of energy flows and the energy management to optimize the energy consumption of the network.
A list of possible components of an urban railway network could be:

Power traction subsystems:

- vehicles
- electrical substations
- rectifiers
- UPS and batteries
- braking recovery technologies

Low current subsystems:

- communication systems
- Signalling systems

Auxiliary systems:

- HVAC
- lightings
- passenger conveyors
- platform doors
- pumping systems
- tunnel ventilation systems

Each one of the indicated elements contributes to the energy consumption of the whole system. Therefore it is important to consider the consumptions of each element and its impact on the global consumption in order to define the best energy strategies to reduce the consumption.

In particular, in the WP1, the vehicle and infrastructure characteristics of the components are defined as power installed and energy consumption. To provide some examples of installed power and of the energy used in the various subsystems, here are some numeric data, provided by the operator involved in the project:

Subsystem	Power Installed [kW]	Annual Energy Consumption [kWh]
ATAC SSE - point of distribution – Line A - Cinecittà	24000	20700000
ATM – Tunnel Ventilation – Line M1 – Sesto F.S End of Line	40	210240
RATP – Escalators – Metro 8 – Balard -	30	219000
ATAC – Lighting – Line A - Battistini	51.3	299592

Starting from these data, the smart grid for an urban railway network will be designed and defined.

5.3 SMART GRID INTEGRATION

The electrical network study requires reviewing the available energy storage systems to be able to select the storage technology that best fit for urban rail application. The integration of these technologies in a traditional grid at generation, transmission and distribution levels represents a real challenge. An energy storage system can be considered, depending of its usage, as load or source which makes it difficult to evaluate the total profit in order to convince utilities to invest in this new technology. Before studying the electrical network, a focus will be done on the energy storage systems.

5.3.1 Energy storage systems

There are many kinds of energy storage systems.

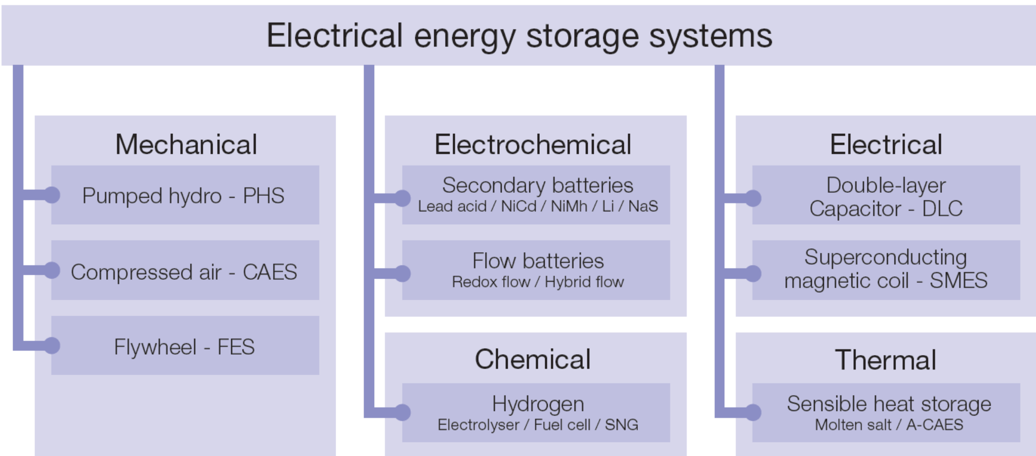


Figure 5-2: Classification of electrical energy storage systems according to energy form (Fraunhofer ISE) [22]

However, some of these storage systems cannot be applied to railway domain or does not have the optimal characteristics in term of energy efficiency, energy or power density, cycle life or time of (dis)charge and response. The most known are developed after.

5.3.1.1 Pumped Hydro Storage (PHS)

PHS consists of two water reservoirs at different elevations. When the energy isn't required during off peak hours, the water from the lower reservoir is pumped to the upper reservoir. During peak hours, the water is reversed to the lower reservoir and generates electricity using a turbine and a generator. This system presents a good efficiency of 80% and a long life time but a low energy and power density. Whereas PHS is the largest used storage system (99% of the total electrical stored and 3% of the total electrical production) can't be applied to urban rail systems because of the lack of energy and power in a limited space. A PHS with an height of 10 meters and a rate of flow of 1 $m^3.s^{-1}$ delivers a maximum power of 100 kW (equivalent to the auxiliaries consumption) and a battery AA contains the same amount of energy than 100kg of water falling from 10 meters. However this solution is possible for other rail solutions: for example SNCF becomes the owner of a hydro energy production network in the south of France.

5.3.1.2 Compressed Air Energy Storage (CAES)

The principle of this storage system is to compress air or gas into reservoirs thanks to a compressor supplied by an electrical motor. The energy stored will be delivered thanks to the rotating machine driven by the expansion of the air.

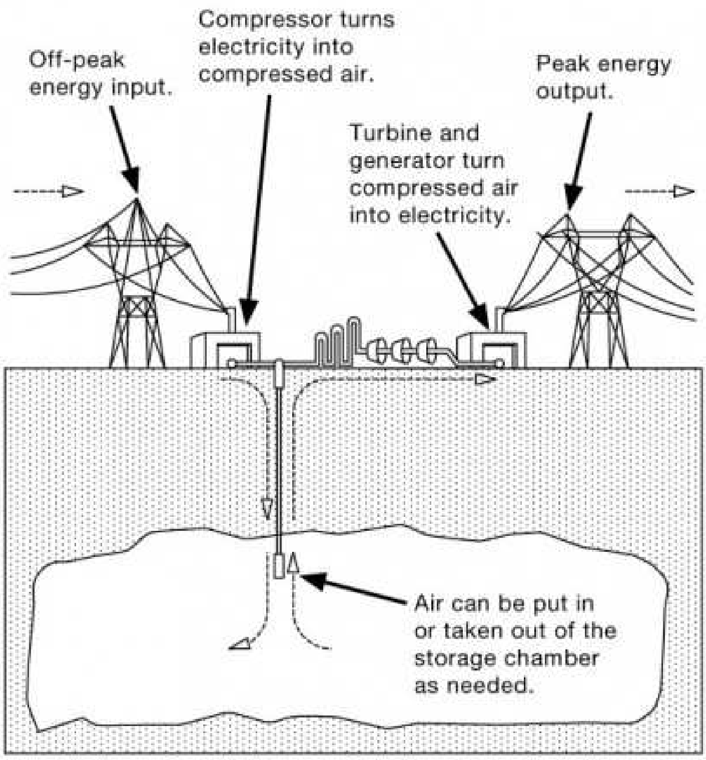


Figure 5-3: Underground CAES [23]

This system gets an energy efficiency of only 50%. Added to the constraints of security because of the high pressure needed (higher is the pressure, bigger is the energy stored - the power depends on the motor/generator) this storage system isn't adapted to the urban rail system.

5.3.1.3 Superconducting magnetic energy storage (SMES)

SMES system works because the energy is stored in a constant magnetic field created by the flow of direct current in a superconducting coil which is kept below its superconducting critical temperature. The density of current is higher than in copper (10 to 100 times) and there is no Joule heating in a constant electromagnetic field. However if the electromagnetic field varies during the time some AC losses appears. Moreover the refrigeration system (liquid helium at 4K for SMES low temperature and liquid nitrogen at 77K for SMES high temperature) needs energy to keep the system at a "superconducting temperature" and longer storage times are limited by the energy demand.

SMES gets very high energy efficiency but it decreases during the time because of the refrigeration system consumption. This technology is still at research stage and maybe it will be a possibility of storage for urban rail systems in the future.

5.3.1.4 Flywheel energy storage (FES)

A flywheel system is formed by a rotating mass and converters. As the train in translation stores a kinetic energy, a mass in rotation stores a kinetic energy too. The equation is similar and equal to: $E_k = \frac{1}{2} J.\omega^2$ with J the moment of inertia (J depends of the mass and at the square of its radius) and ω the rotating speed in rad.s-1.

The coupling with the electrical network is realized thanks to an electrical rotating machine and converters. The discharge is realized with the generator function of the machine in order to produce the electricity from the rotating energy. Two kinds of flywheels exist: flywheels for on-board application with a high rotating speed and a low mass and flywheels for fixed applications with a low rotating speed and a high mass.

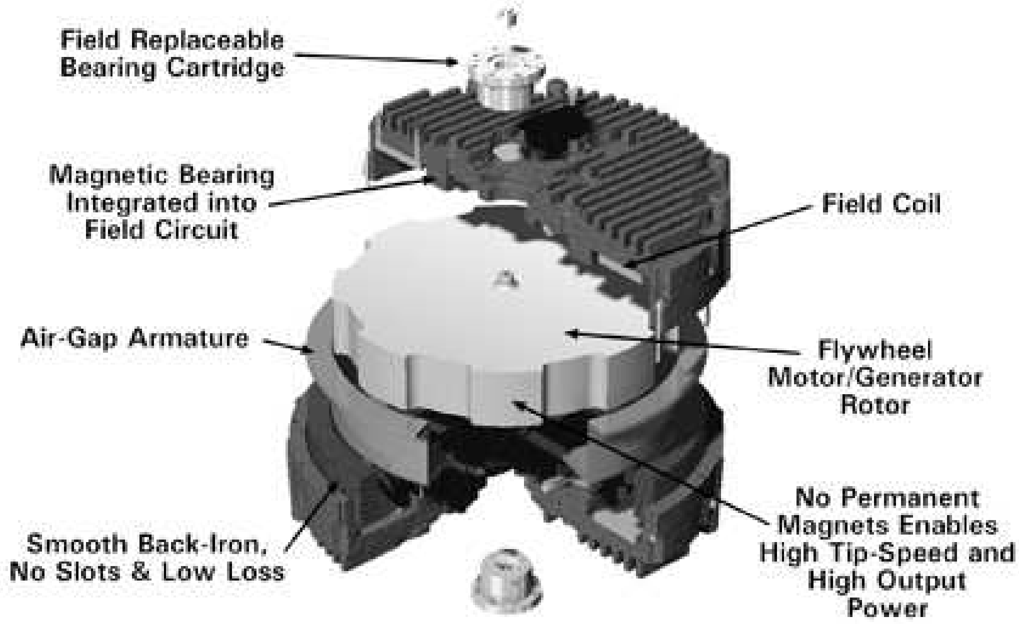


Figure 5-4: Flywheel [22]

In a flywheel it is not interesting to discharge totally the energy stored. Indeed, the maximal power can be delivered only above a minimal speed represented by Ω_b in the following figure.

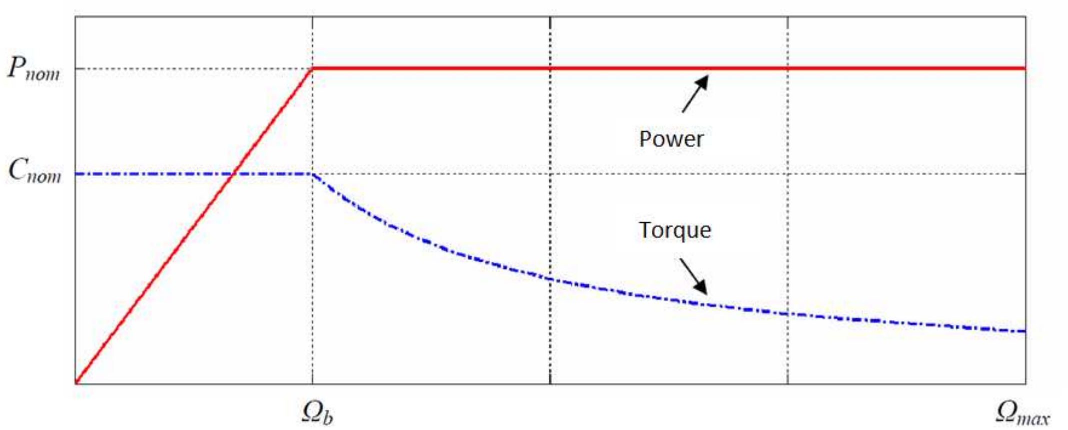


Figure 5-5: Variation of power and torque with the speed [17]

The characteristics of the flywheel depend of the machine characteristics especially for the power density. Flywheel presents the advantage to get a good power density compared to other storage systems (about 5kW/l), high energy efficiency (about 90%) and a long lifetime.

5.3.1.5 Batteries

Batteries are another possibility to store the energy even with a low power density. A battery is composed by a multitude of electrical accumulators connected in series or in parallel. This storage mode is the most common storage system because of its simplicity, its maturity and its good energy density.

Batteries with lead-acid, which are the most common batteries because of their price, get a capacity of 30Wh/kg whereas other batteries get a higher capacity (150Wh/kg for Lithium-ion, 300Wh/kg for lithium-sulphur, lithium-vanadium or 500Wh/kg for lithium-air). These last batteries aren't competitive due to their price but research should allow improving their efficiency and reducing their production price. However, the power density of batteries is really limited (about 2 kW/kg) but with fixed energy storage. The weight isn’t a huge problem. Moreover their cycle life is limited from hundreds to a few thousands of cycle life but its life time will depend on the depth of discharge (DOD) applied to it (lowest is the DOD longer is the lifetime).

5.3.1.6 Supercapacitors

The majority of supercapacitors are formed by collectors of current in aluminium and electrodes generally in active coal soaked in an aqueous or organic electrolyte. In the case of aqueous electrolytes, the operating voltage is equal to 1.2V whereas with organic electrolytes the operating voltage grows up until 2.3V to 2.85V. The operating principle of a supercapacitor is based on the energy storage by distribution of the ions coming from the electrolyte near to the surface of the two electrodes. It is an electrostatic storage without any chemical reaction between the charge and the discharge. The phenomenon is reversible which explains their very high cycle lifetime. Supercapacitors are known to get a very high power density and a low energy density. So this storage system is perfect for applications which require a high power in a short time. However, the problem with using supercapacitors is the high cost.

5.3.1.7 Conclusion about the energy storage systems for a urban rail network use

PHS is not adapted to an urban application because of the lack of space. CAES presents a very low efficiency and SMES isn't enough mature but both could in the future be used to store the braking energy of urban trains. Supercapacitors for a power management, batteries for an energy management and flywheels for a hybrid management could be used in the near future. Here are their principle characteristics:

EES White Paper - IEC 2011	Flywheel	SuperCapa	Batt Li-ion
Energy density (Wh/l)	20-80	10-20	200 - 400
Power density (W/l)	5 000	40 000 – 120 000	1 300 – 10 000
Time of (dis)charge / of response	Sec / <Sec	Sec / <Sec	Hours / <Sec
Self discharge	2-5% per minute	50% per month	<10% per month
Maximum Depth of Discharge (DoD)	None	None	80-90%
Cycle life	2*10^4–10^7	10^4-10^5	500 – 10^4
Energy efficiency (%)	80-90	85-98	85-98
Cost per Wh	1$	20$ (Power dimensioning)	0.5-1$
Remarks	High energy losses Dngerous if failure	Low energy storage	High cost

Table 5-1: Characteristics of different energy storage systems [22]

5.3.2 Renewables

For an urban application, renewable energy is limited to the solar energy. The solar energy is due to the photons in solar radiation and equal to: $E = h.v = \frac{h.c}{\lambda}$ [24] with h the constant of Planck and c the light celerity. A photovoltaic cell converts this solar energy into electrical energy: it is based on a semi-conductor pn-junction. When sunlight strikes the PV cell, electrons are released from their atoms by photons (with energy higher than the band gap energy). The free electrons are directed toward the front surface of the solar cell. It creates a current flow between the negative and positive sides. However, photons which get energy lower than the band gap energy won't be used and those which get energy higher than the band gap energy will be able to shock a free electron but the surplus of energy will be lost too. Thus the photovoltaic cells get low efficiency depending on the technology:

- Monocrystalline solar cells get the better efficiency (about 16%)
- Polycrystalline solar cells get the best value for money and are the most used (about 14% of efficiency)
- Amorphous solar cells get the lowest efficiency (about 12%) but these modules present a good future because of their flexibility and their good production with a low light.

For the final user, a photovoltaic cell is generally represented as a diode in parallel with a current generator.

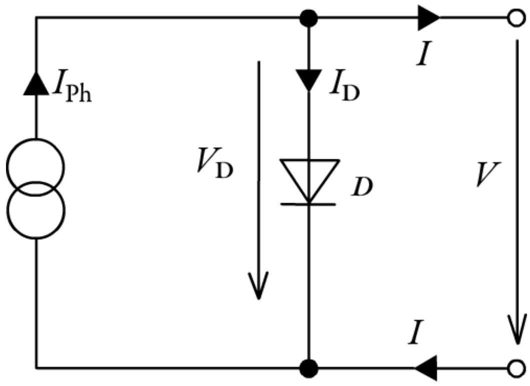


Figure 5-6: Simple equivalent circuit of a solar cell [25]

This solar cell produces a direct current and its characteristics are shown after.

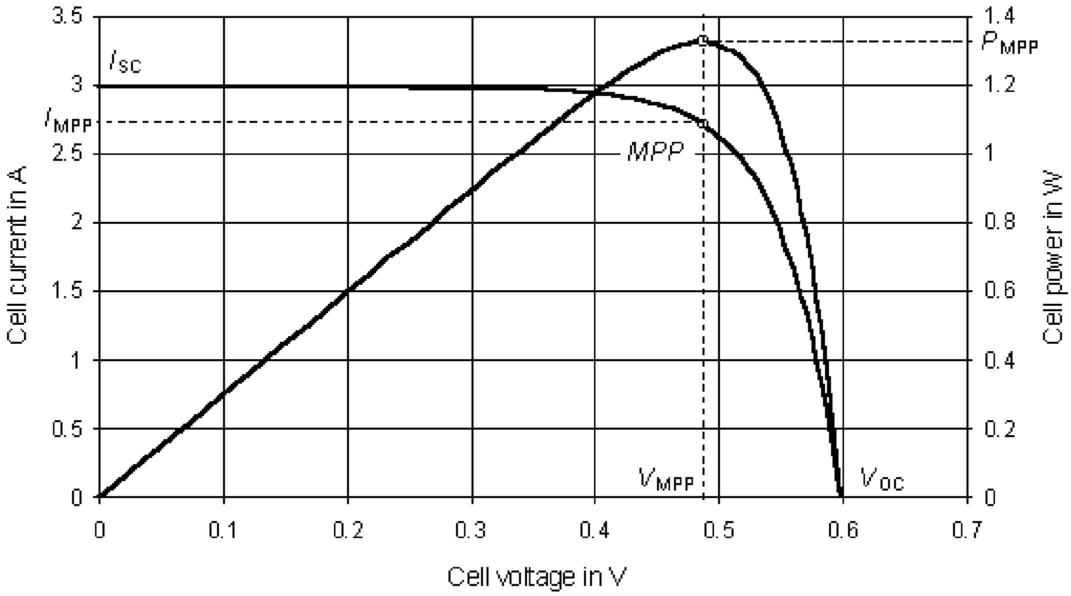


Figure 5-7: Operating characteristics of a PV module [25]

V_{OC} represents the open-circuit voltage of the module with zero-input current (the open-circuit voltage of the module increases when sun irradiance energy is captured by a PV module). I_{SC} represents the short-circuited current with zero-output voltage (the maximum short-circuit current can be measured if the module is short-circuited. The maximum power (P=U x I) can be extracted at a current I_{MPP} and a voltage V_{MPP}. In this example, a solar cell generates a maximum power of 1.3 Watts. To increase the voltage solar cells are connected in series and to increase the current they are connected in parallel (both connections increase the power). It forms a solar module which can generate a power of a few hundred watts. Then these modules are associated in parallel and series to increase the power and it forms the solar array with a power of a few thousand watts. In the same manner the association of solar arrays allows to increase the power delivered to in some cases (and large areas) a few megawatts. The amount of energy produced by the PV array is directly proportional to the area of the array.

Finally power electronics converters are added at the interface between PV arrays and the electrical network. They allow increasing or decreasing the output-voltage of PV arrays and ensuring that arrays delivers the adequate voltage of the grid and the maximum power. Indeed the maximum power delivered is a variable point which changes with the sunlight and the temperature.

For an urban rail application the power is limited by the lack of space to install PV arrays. In the case of an underground station, it's not possible to install PV arrays. In the case of outside stations, there are the station roofs (about 120 m²). Below are presented characteristics of power and price of some PV arrays.

Module	Type 1	Type 2	Type 3	Type4
Power max, W	190	200	170	87
V_{MPP}, V	54.8	26.3	28.7	17.4
I_{MPP}, A	3.47	7.6	5.93	5.02
V_{OC}, V	67.5	32.9	35.8	21.7
I_{SC}, A	3.75	8.1	6.62	5.34
Efficiency	16.4%	13.10%	16.8%	16%
Price, €	696	556	440	317.6
Area, m²	1.16	1.46	1.48	0.66

Table 5-2: Characteristics of different PV modules [26]

A short business study can be realized with a lifetime of 25 years and an area of 120 m².

Module	Type 1	Type 2	Type 3	Type4
Power for 120 m², kW	19.7	16.5	12.9	15.9
Energy for 120 m²	16.4 MWh/year	13.7 MWh/year	10.7 MWh/year	13.2 MWh/year
Price for 120 m², k€	72.1	45.8	33.5	58
Energy produced for 25 years	410.4 MWh	343.7 MWh	268.7 MWh	331.2 MWh
Price of the energy for a balanced investment	0.176 €/kWh	0.133 €/kWh	0.125 €/kWh	0.175 €/kWh
Price of the energy for a ROI after 10 years	0.439 €/kWh	0.333 €/kWh	0.312 €/kWh	0.438 €/kWh

Price of the energy for a ROI after 20 years	0.220 €/kWh	0.167 €/kWh	0.156 €/kWh	0.219 €/kWh

Table 5-3: Business study of PV arrays

There are two possibilities to use the energy with different costs of use:

First, all the energy is reversed and sold to the grid. This solution can allow to earn until 0.30€/kWh. In this case it is possible to earn money after 10 to 17 years but this price depends on the renewables policy of each country and it can be lower.

Second, all the energy is consumed and the consumption from the national grid is decreased. This solution can allow to earn 0.135€ per kWh not consumed on the national grid. It means there's quite no return on investment and it can be negative.

So without governmental policies which valorises the integration of PV arrays this solution isn't financially viable today. However lots of research are improving the efficiency of PV cells and let in a near future to multiply PV arrays installations with a good return on investment.

5.3.3 The control and metering systems (PMU, AMR, AMI)

The development of Smart grid involves the use of new intelligent technologies, able to allow the control and monitoring of electrical parameters of the network.

These new devices are measuring systems, which carry out the synchronized control of voltage and current. Thanks to the synchronization based on satellite navigation systems (Global Navigation Satellite System - GNSS) and in particular of the GPS, the PMU device (Phasor Measurement Unit) implements algorithms that can calculate not only the module, but also the phase of the phasor quantities (voltage and current). Currently WAMS installations (Wide Area Monitoring System) with monitoring functions are in development. However the applications are limited because of several problems, such as: reliability of the PMU device, conditioned also by the problems of synchronization, absence of a standard on the requirements of the device in response to transient conditions of the network, opportunity to enter additional features in the device of phasor measurement, complexity in the identification of appropriate functions of monitoring and control, reliability of the communication systems.

The diffusion of Information and Communication Technologies (ICT) and the exercise of the power system require a more precise synchronization of the measurement units and their precise positioning in the networks.

The first application of time synchronized infrastructure network concerned the telecommunications industry, but then the same mechanisms have been applied to the field of electrical system. Initially, the synchronization was based on a hierarchical approach in which the master clock was placed at the highest level of the network and the synchronization of the nodes followed a waterfall approach from layer 1 to layer 2 up to the network nodes. In the 60s and 70s, there were no reliable methods for transferring in a precise way the temporal signals and the only way to transfer information was through a hierarchical structure.

This structure was also used for the time synchronization. However, due to the increased requirements of temporal accuracy and the advent of GPS, the first Global Satellite Navigation Systems (GNSS), which ensures accuracy in the distribution of time and the economy of devices, are causing a shift from hierarchical structure to wide area distribution by satellite. Thanks to GNSS systems the time can be disseminated simultaneously to all nodes without the degradation associated with the hierarchical structure.

In this sense, the main change has been the elimination of the hierarchical structure and the replacement of the Master Clock on Earth with a satellite one, a solution which has the advantage of simplicity and offers significant guarantees of accuracy.

In despite of the practical point of view, this change is quite limited. The consequences have been far more extensive than we had expected initially: the performance of network infrastructure can be based on a clock that keeps track of time in a synchronous way across the globe, which allows to shoot with great precision the status of the network: the GPS provides in fact the Universal Coordinated Time (UCT) in all corners of the Earth with great accuracy.

The global coverage of GPS has ensured that all nodes of wide area networks can be synchronized instantaneously by the same reference signal without being subject to problems of disruption or latency stability (due to different routes of signals) and then provided considerable economies and ease of operation.

The time and space can be seen as key elements to characterize the measures and control of the power supply. The time can be a reference to:

- correlate events
- sample the signals (measurements)
- represent the waveforms (via phasors)
- identify control actions

while the space can be a reference for:

- locating of the devices (generators, stations, loads, ...)

- fault locating
- monitoring and controlling devices

The first level of monitoring, which uses spatial and temporal information, consists in identification and localization of critical phenomena or disturbances in nodes, lines, or specific areas of the network. Pushing timing capacity at the level of the *[ms]* is possible in order to sample the waveforms, analyze the signals, monitor, control and protect the synchronism among the generators in case of disruptions in the system.

The localization of faults requires a precision better than *[ms]* in the time synchronization, in order to detect faults by determining the difference between the arrival times of disturbances at the measuring points. The interruption of a transmission line can be localized accurately evaluating the timing associated with the induced noise (Fig 5-10). The effects of the fault in the form of sudden disturbances are propagated through the network and are identified by measurement devices. The precise timing of these units allows to associate a temporal tag to the noise and, if the defect is propagated through the network and generates a chain of "failures", this approach allows to discriminate between causes and effects based on their time and space correlation . To allow distinguishing between "cause and effect", a high accuracy is necessary at level of *[ms]*.

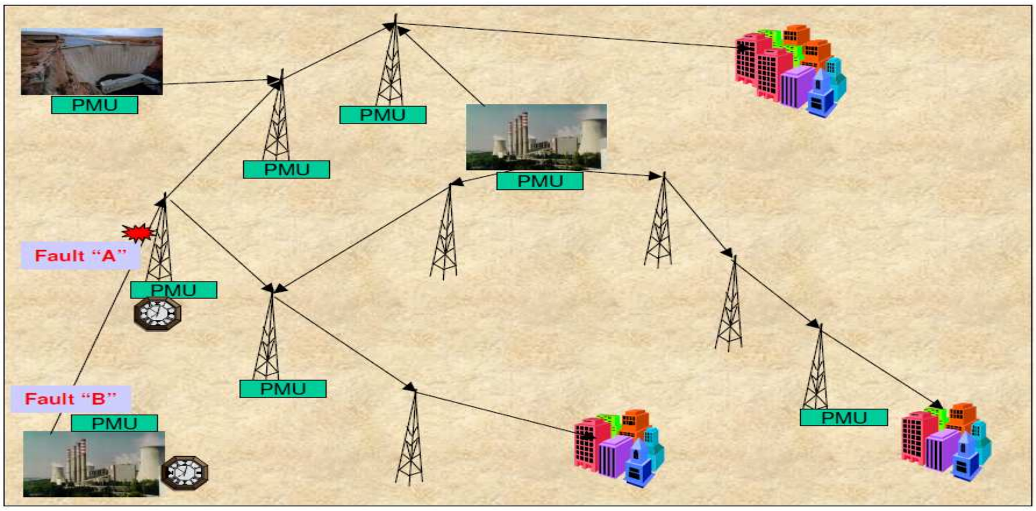


Figure 5-10: Fault propagation in the electric network

The phasors are one of the basic tools for the analysis of electrical circuits in alternative regime and were introduced to represent in a simple way sinusoidal waveforms with a certain fundamental frequency.

Formally, it is possible to apply the concept of phasor not only under static conditions, or almost static, but also for transient conditions during which the electrical quantities evolve quickly enough. In these cases, the variable of the phasors (voltage and current) are calculated in a mobile time window of a period or multiples of the fundamental period.

An on-line use of phasor measurements is an indispensable efficient method of calculation, carried out by microprocessors, to process in timely measures and to provide information of amplitude, phase, and frequency directly usable to monitor and control the whole network. This aim can be achieved using different techniques that involve estimators and digital filters of various kinds. Currently the methodology followed is based on the use of Discrete Fourier Transform (DFT).

The Phasor Measurement Unit (PMU) is a digital device operating to provide measures of synchronized phasors from inputs of voltage and current via a synchronizing signal. Synchronizing the sampling processes for different signals, separated by hundreds of kilometers, they can reproduce the magnitudes on the same phasor diagram. The phasor measurements are obtained individually for each phase, usually only as regards the direct phasor sequence.

This is how a PMU works: the analog inputs of the voltage signals and / or current, suitably transduced, are previously filtered and subsequently sampled and converted into digital signals. A typical sampling rate is 12 samples per cycle (equal to 720 Hz in systems with nominal frequency of 60 Hz), but values even quadrupled can be reached (2880 Hz). In this phase it is necessary to acquire a synchronized signal to ensure that the sampling is made at exact intervals. Subsequently, the signal is processed by a microprocessor normally programmed to provide the values of amplitude and phase of the sequences of positive voltage and current (Fig 5-11). If we exclude the synchronization feature, the hardware of a PMU in principle is equal to that of a digital recorder of failure (Digital Fault Recorder - DFR) or a digital relay.

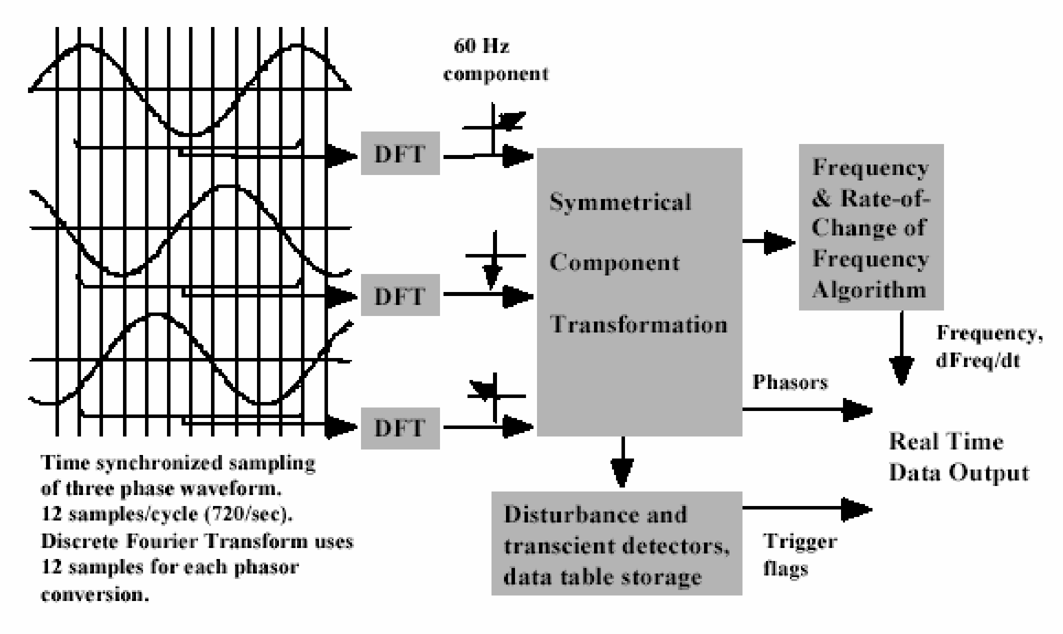


Figure 5-11: Phasor measurement process

The monitoring of the electrical system is classically achieved via the SCADA system, characterized by delays, inaccuracies and a refresh rate of the order of seconds. The measured variables are only some of those of interest and are also asynchronous to each other. Therefore errors and inaccuracies in the estimation of the static state of the system are introduced and the uncertainty on the results of safety analyzes (indices of security assessment by SSA - DSA) increases. In particular, with the acquisition through the conventional SCADA, we can't study the electromechanical transient neither some significant elements of the state of stress of the system, as the phase shifts between the nodal voltages (calculated in the procedure of load flow).

A significant feature of WAMS (Wide Area Monitoring System) is their ability to integrate devices for the measurement of phasors (Phasor Measurement Unit, PMU). The PMU, arranged in strategic positions within the system, instead of measuring only the traditional effective values of voltage and / or current, measure the voltage and current phasors, that is the amplitude and the phase of the quantities. The synchronization in time provided by GPS signals ensures that the measures in the various points of the network are carried out at the same time allowing a reliable reconstruction of the state of operation of the network and to monitor the angular differences between the phasors of the electrical quantities (voltages and currents) in remote points of the system.

The development of WAMS technologies can make them available for off-line analysis, but also real-time, and to carry out accurate and synchronized measurements, allowing a comprehensive understanding of the behavior of the electrical network and enabling innovative applications for monitoring and control: the user benefits of a more comprehensive monitoring while control systems can effectively counteract the global problems receiving as input global signals. By searching in this direction, safety can be ensured by acting on two fronts: on one hand, time detection of phenomena; on the other hand, disturbances prevention to propagate.

At the international level, there are several examples of wide area systems in operation, with different features and work areas. The wealth of information collected by a WAMS is used for direct monitoring of the network or off-line studies, but the ultimate goal is to increase the reliability during operation. The areas of application of the information obtained with the WAMS can be separated into the categories shown in Figure 5-12.

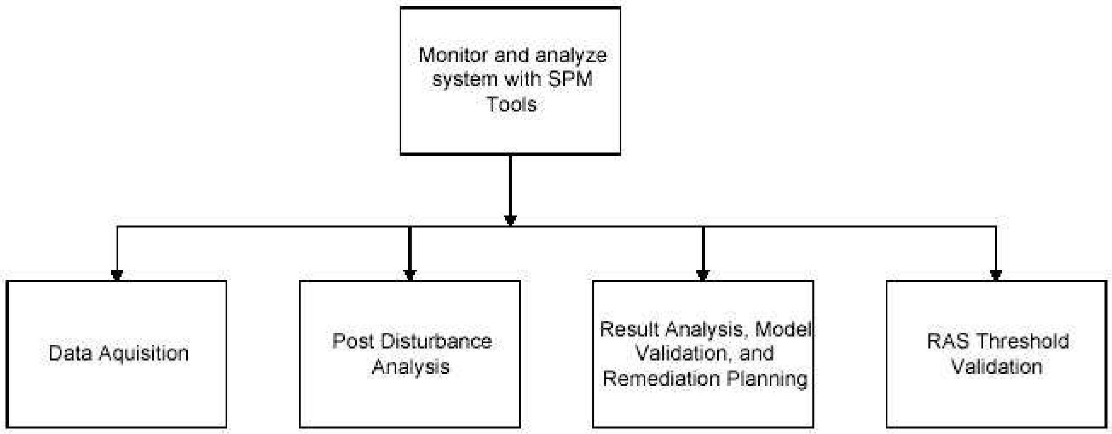


Figure 5-12 Areas of application of the synchronized measurement

The PMU can be inserted in a WAMS according to the typical architecture shown schematically in Figure 5-13: more phasor measurement apparatuses are connected to concentrators (Phasor Data Concentrator, PDC).

They send the aggregated data of PMU to the centers for different applications of processing, viewing, and archiving. The latest architecture is based on direct links with the center of the PMU, without passing through the concentrator. This is the scheme implemented also for Italian WAMS.

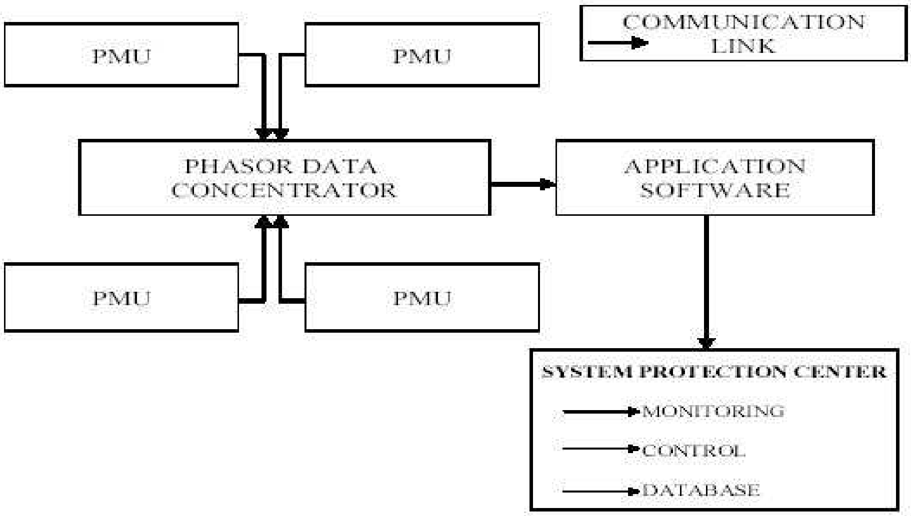


Figure 5-13: WAMS structure with PMU

The communication channels that can be used are telephone lines, microwaves (analog or digital systems), and optic fiber cables. The fiber offers the highest performance. The requirements for reliability and speed limit the WAMS from entering the management and control of the system. In particular, the reliability and performance become critical, when the WAMS provides input to control systems and protection. Also for these reasons this type of application are still not common, because the technology is still in a relatively early stage.

Digital systems such as the optical fiber are much faster than analog modem. The connections via a telephone line or via Internet at the moment are not reliable enough for continuous control systems in real time, but may be adopted in the future. In general, however, the eligible delays are very low when compared with those of a SCADA system.

The figure 5-14 shows the layout of a PMU.

Figure 5-14: Layout of a PMU

The integration of PMU in the electric network is one of the most important aspects of a smart grid. The aim of the research is to introduce this concept in the distribution network too, and not only in transmission one, considering the problems linked to the DG (Distributed Generation). In fact, we must consider the decentralized energy flows and the intermittency of renewable energy sources.

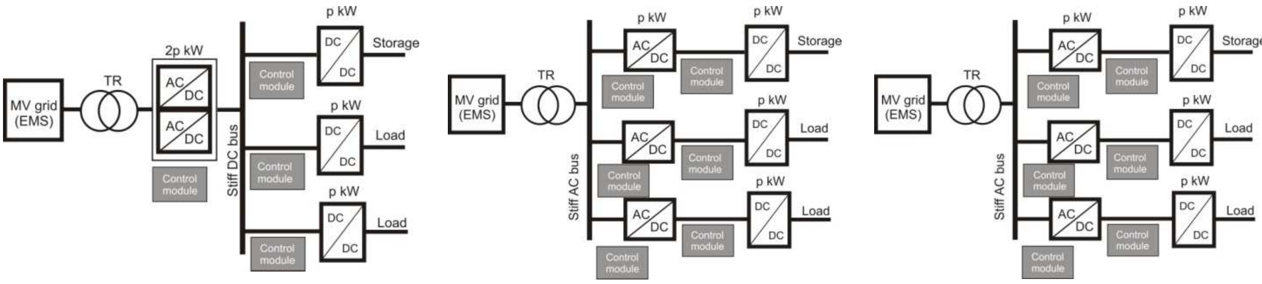
Smart Grid is the synonym of flexibility, i.e. the ability to send the surplus energy of certain areas, for other areas that are currently in deficit, all in real time and in a dynamically way.

In logic of evolution to the Smart Grid, the AMR (Automated Meter Reading), which allow distributors to know the status of their remote clients and therefore consumption or any fault conditions but without allowing corrective measures, have been replaced by the AMI (Advanced Meter Infrastructure). The latter, thanks to the two-way communication with the meters, allow not only to obtain instantaneous information on the individual customer or aggregates of them, but also to impose limitations in consumption of the same and to implement all the logical managements aimed at reducing costs.

5.4 THE FUTURE URBAN RAIL NETWORK

After studying energy storage systems and PV arrays we will focus on the most important part: What could be the architecture of the future urban rail network? We saw PV arrays will become financially interesting in a near future and energy storage systems are essentials to exchanges and manage power flows. Both will take part in this new architecture like power electronics and communication between the different devices.

In general, DC-bus based systems are superior for hybrid and intermittent energy systems with local energy management. An illustrative simple example is shown in Figure 5-8. In the example a p kW storage is assumed along with two intermittent loads of p kW each. The advantages and disadvantages of the three possible architectures are listed in Table 5-1. The only disadvantage of a DC based smart grid architecture is the immaturity of the technology, which can be overcome through building up various demonstration projects.



(a) DC-based architecture (b) LV-AC-based architecture (c) HV-AC based architecture

Figure 5-8. Possible systems architecture with local energy management (note: EMS stands for energy management system).

Table 5-1. Comparison between three possible architectures for integration of urban rail in a smart grid.

	DC-based system	LV-AC based system	HV-AC based system
Advantages	✓ TR potentially smaller ✓ Lower number of conversion units ✓ Lower footprint and higher efficiency ✓ Warm redundancy of the grid converter ✓ higher reliability /availability and lifetime ✓ Circulating power goes through DC-bus(two conversion units)	✓ TR is potentially small ✓ AC protection and metering	✓ DC / DC converter potentially small (for low power applications) as HF transformer can be eliminated ✓ AC protection and metering
Disadvantages	Technology not mature	× More conversion units × more losses × higher footprint × No redundancy × shorter lifetime and availability	× Higher losses × More conversion units × Less life time and availability × No redundancy × Power recycling at HV bus – another Grid TR will be needed

The main AC grid won't directly supply the traction or station network but a local area including buildings and other city loads via an energy control center (ECC). This first micro grid gets energy storage systems, PV arrays and PHEV or electrical buses connected to it. For each device a converter will be the interface with an AC or DC distribution. The energy control center and converters will manage the energy flow which can be bidirectional. These converters allow isolating from the rest of the grid any part in the network which could be in fault. They allow giving preferential use of local energy then using the main supply energy.

A second micro grid including PV, energy storage systems, PHEV and electrical buses, traction and auxiliaries is connected to the first one via another energy control center. Each device is dependant from the others thanks to converters and the principle is the same than at the superior level: managing a bidirectional energy flow, isolating any part in fault and giving a preferential use to a local use of energy. Several second level of grid can be connected to the same first level of micro grid. Each level of micro grid will give the priority of consumption to any surplus of power from the inferior level. It exchanges the energy with other devices of its level and then delivers or consumes energy from superior levels.

In the figure below the future architecture should let the network exchange energy between the different loads connected thanks to a common DC bus (left part) or an AC bus (right part):

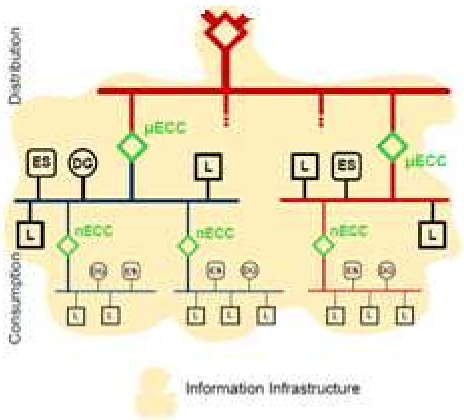


Figure 5-9: Micro grid concept [16]

Specifically in the case of a DC bus, the architecture could be as follow:

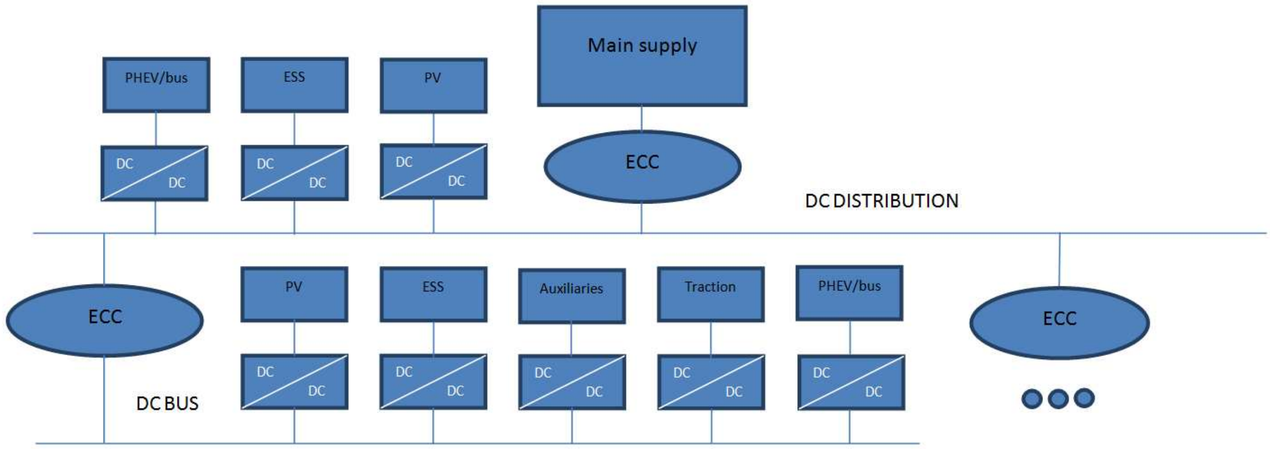


Figure 5-10: Future urban rail grid architecture

The idea is to integrate the urban rail network in the city grid to maximize the direct reuse of the regenerative braking energy without any energy storage system (it avoids to lose a fifth of the total energy because of the efficiency of storage systems). The surplus of power will be stored in energy storage systems. Other possibilities existed with this smart grid: it is possible to store the maximum of energy and using the surplus of power to supply the local grid because the company prefers keeping the energy for the acceleration of the train or mainly to sell it later at a high price.

However this architecture can exist only with a very good communication technology. It includes sensors to measure system status, communications infrastructure to collect sensor information and send control signals, control algorithms to generate controls to change system state if needed and actuators to provide the desired change in the physical system. All these points involve the use of a high-speed protocol bidirectional. In this future network, sensors and actuators would be based at substations, energy control centers, on-board electric trains at PVs arrays and energy storage systems: it allows to manage the grid in the best way and to anticipate the flows of energy with a good algorithm.

Thus the energy delivered by PV arrays and the braking trains can be used to feed the station (lights, signalization, escalators), to be stored in batteries, supercapacitors ... (before reusing it when the train accelerates for example), supply local consumers directly (PHEV for example, refrigerated warehouse) or be sold to the local energy distributor in charge of the electricity network and distribution. This architecture should allow recovering all the braking energy.

6 SMART-RAIL SYSTEM STUDIES

The following studies simulate the case of a metro line and evaluate the impact of a smart reversible substation on one hand and flywheel energy storage system integration on the other hand. The aim is to evaluate the energy savings made by these technologies.

6.1 REQUIRED SYSTEM STUDIES

In order to study the benefit of integrating an energy storage system or a reversible substation in urban rail network, it is interesting to simulate a real case of a metro line and studying the impact of these technologies insertion on the energy consumption. Energy savings can then be evaluated.

Therefore, the following cases are studied:

- Integration of a smart reversible converter in an existing line to reverse the braking energy to the grid (AC)
- Integration of a flywheel in an existing line to study the storage of braking energy (DC)

Simulations are realized using the program system ELBAS-SINANET®, a simulation system for the traction simulation and electrical network calculation of DC railways electrification.

6.2 INTRODUCTION TO SIMULATIONS

This software requires several input data of the rolling stock (top speed, length, tare weight, passenger load, rotating mass, resistance to motion, maximal acceleration and deceleration, auxiliary power, curve of traction and braking effort with speed, curve of traction and braking current with speed and the curve of line limitation with the voltage), the topography of the line (location of stations, part of the line in tunnel to readjust the resistance to motion because of the piston effect, gradients and turns), operation line (speed restriction, headways, dwell times), traction electrical network (longitudinal conductors characteristics, traction substations characteristics, severing, negative and positive equipotentials). In order to avoid always having the same situation during the simulation, a shift is added to headways on each track as shown in figure 7.2. A positive shift time of a few seconds is realized on track 1 and a negative shift time of a few seconds is realized track 2. In this way a maximum of possibility is simulated and the worst case can be studied (several trains braking together for a storage system or accelerating together for the network).

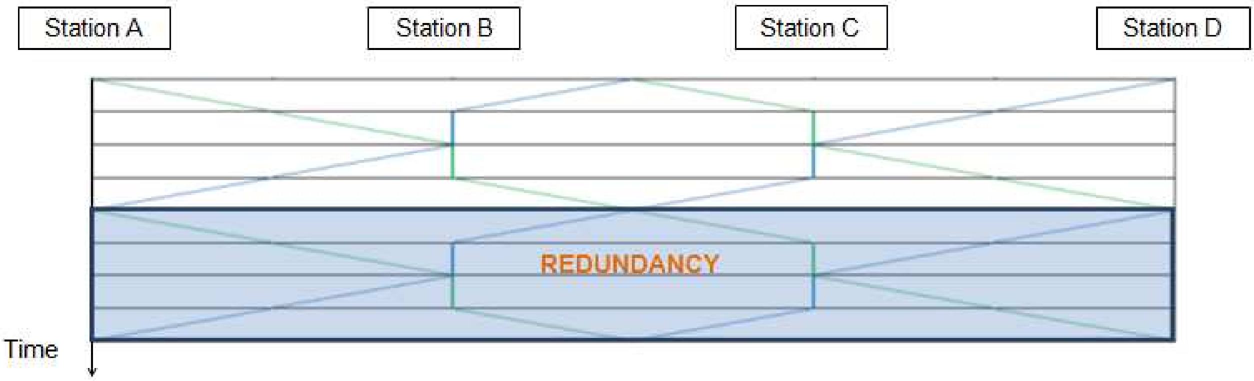
After the simulation, the software edits several files for each device of the line. For example the timetable of trains is edited; there is a file per train, substation and feeder to study the current, voltage, power and energy. For example you can get the available, used and losses braking energy.

```
>>>>> brake energy

  available              1344.1 kWh  (100.0 %)
  used                   1165.4 kWh  ( 86.7 %)
    recuperation         1062.6 kWh             ( 79.1 %)
    auxiliaries           102.8 kWh             (  7.7 %)
  losses                  178.7 kWh  ( 13.3 %)
    br.resist.            178.7 kWh             ( 13.3 %)
```

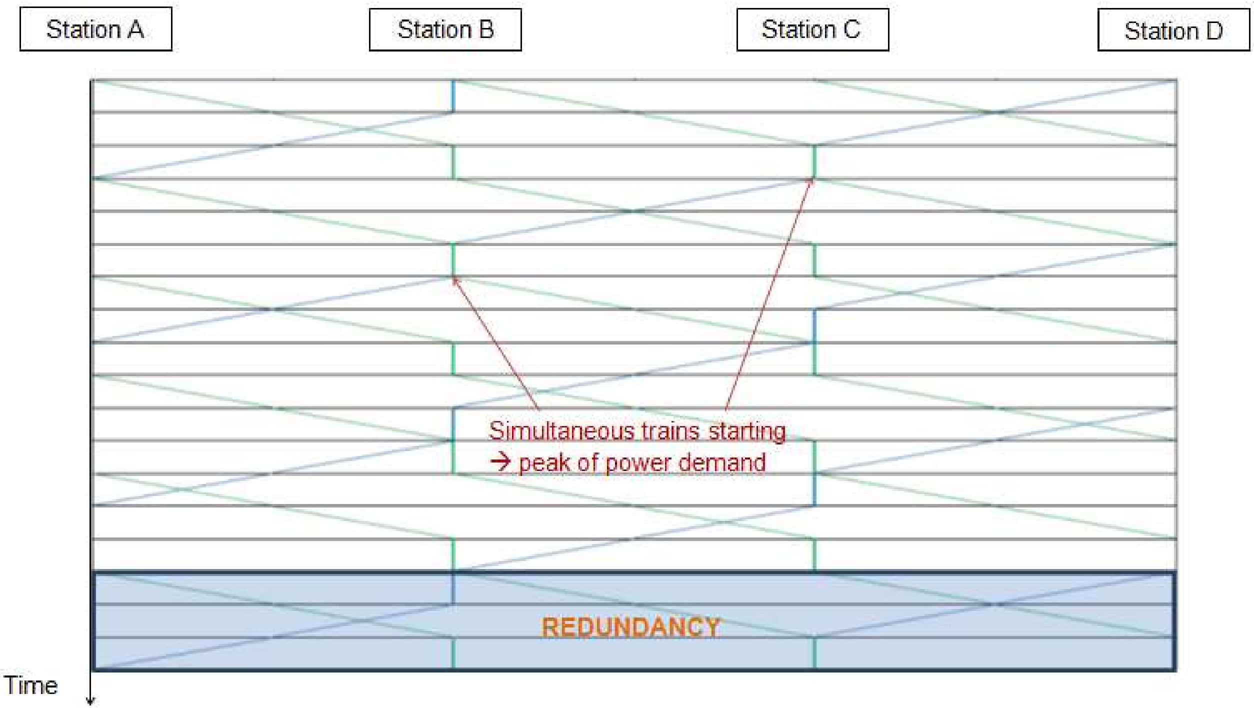
Figure 7-6-1: Braking energy simulation

Example with 4 stations without headway shift:



There is no simultaneous trains starting.

Same example with headway shift:



There are 2 simultaneous trains starting.

Figure 7-6-2: Example of headways in a simulation

Without headway shift between tracks 1 and 2 the simulation time can stop after a time equal to the headway length. The train positions are the same as at t=0. There is a chance that the simulation does not capture some simultaneous train accelerations on both tracks, like it could happen in the real line operation. With a slight different headway between track 1 and 2 the simulation will last longer until the trains will have the same positions as at t=0. Therefore there are more chances to capture in the simulations simultaneous accelerations and consumption peaks.

6.3 INTEGRATION OF AN INVERTER IN AN AC PRIVATE MEDIUM VOLTAGE

6.3.1 Line A

A generic heavy metro line was simulated with the following main characteristics:

- 16 km length
- 26 stations
- 14 traction substations, nominal voltage 750 V
- Headways :
    - o Peak hours : 6 minutes
    - o Off-peak hours : 7.5 minutes
    - o WE & Nights hours : 10 minutes

This simulation consists in the integration of an inverter on an existing line and studying the impact of this inverter in recovering this energy.

Before installing the inverter a simulation was realized without it in order to discover the best electrical area where trains brake without the inverter and burn the most of energy within.

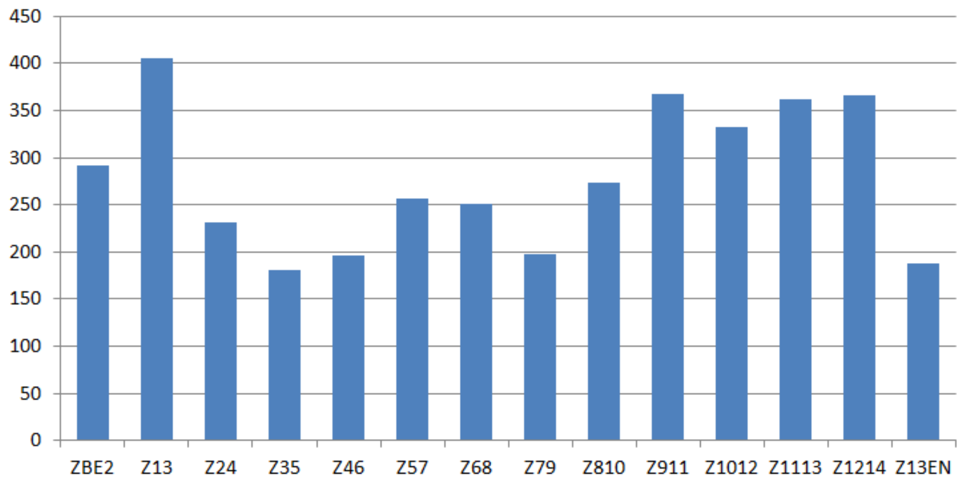


Figure 7-6-3: Energy in braking rheostats (in MWh/year) without inverter

We deduce from the simulation that the inverter should be added in the zone Z13 which the center is the substation 2.

With the inverter the energy in the braking rheostats decreased in the first electrical zones.

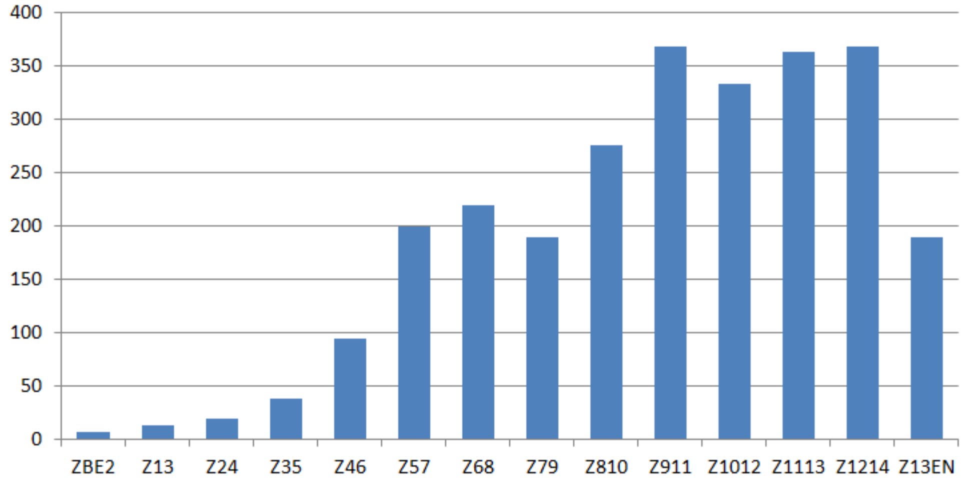


Figure 7-6-4: Energy in braking rheostats (in MWh/year) with an inverter

Adding an inverter helps to decrease the rheostatic braking energy

Whole year	Without inverter	With inverter
	MWh/year	MWh/year
TPS7	2823	2847
TPS6	4448	4521
TPS9	6988	7010
TPS1	1544	1546
TPS8	3650	3674
TPS3	1638	1641
TPS14	4653	4656
TPS5	3228	3282
TPS13	620	619
TPS2	3734	3744
TPS4	4508	4615
TPS10	3000	3001
TPS12	2031	2033
TPS11	1553	1556
INV1		-985

Figure 7-6-5: Energy consumption of each substation during the year

We note that during one year 985 MWh could be saved with the integration of only one inverter. However we observe the consumption of each traction substation increased. Indeed the inverter can be activated because of the increase of the voltage whereas a train accelerating could be supplied by this energy. So this lack of energy has to be supplied by the traction substations ... which increase consumption.

The final energy balance shows one inverter allowed to preserve 658 MWh/year which represents 1.5% of the total consumption. By adding two other inverters at substations 9 and 12, this percentage could be increased.

6.3.2 Line B

Another simulation with the adding of an inverter was realized. As in the first simulation, this second simulation was divided into a first part without the inverter and a second one with the inverter. For this second simulation, the inverter reversed the energy to the AC grid from 785V (770V is the no load voltage of the substation + 15V to let the exchange between trains). Moreover the rectifier of this converter has a resistance slope very low (0.0001 Ω/km) contrary to traditional rectifiers (0.0125Ω/km). It allows reducing the line losses and especially to keep the line voltage near the no-load voltage and ensure the quality of power.

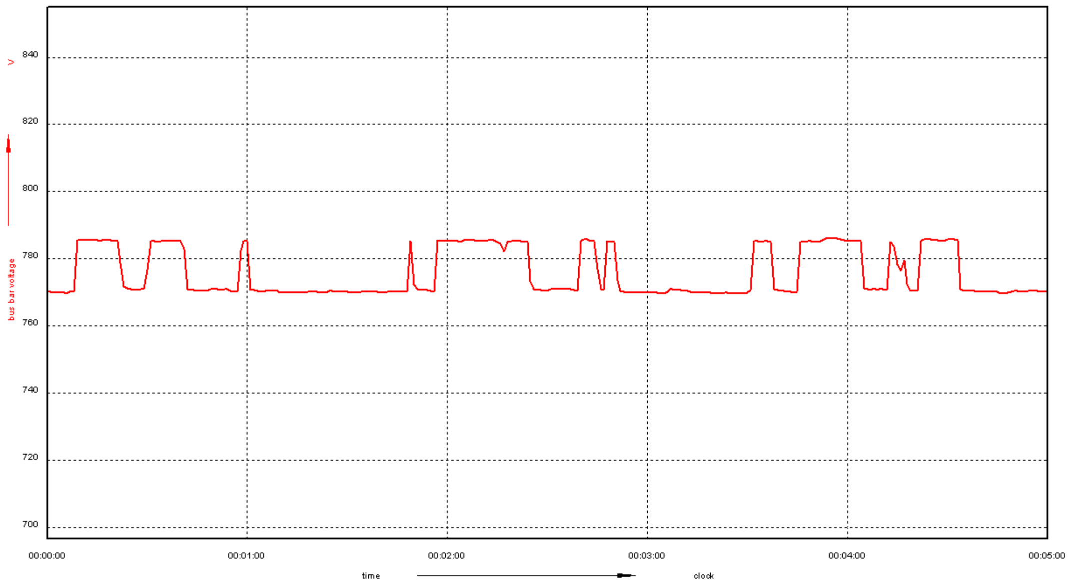


Figure 7-6-6: Line voltage at the smart converter during the 5 first minutes

Without the inverter the losses represent 13.3% of the available braking energy and with the inverter the braking energy losses decreased until 1.2% of the same amount. It allows regenerating 164.7kWh during 30 minutes of a peak hour simulation. With 4 hours of peak hours during 5/7 of the year it could regenerate 343.5MWh/year during only peak hours. If the price of electricity is 10c€/kWh the company could earn 34,350€/year.

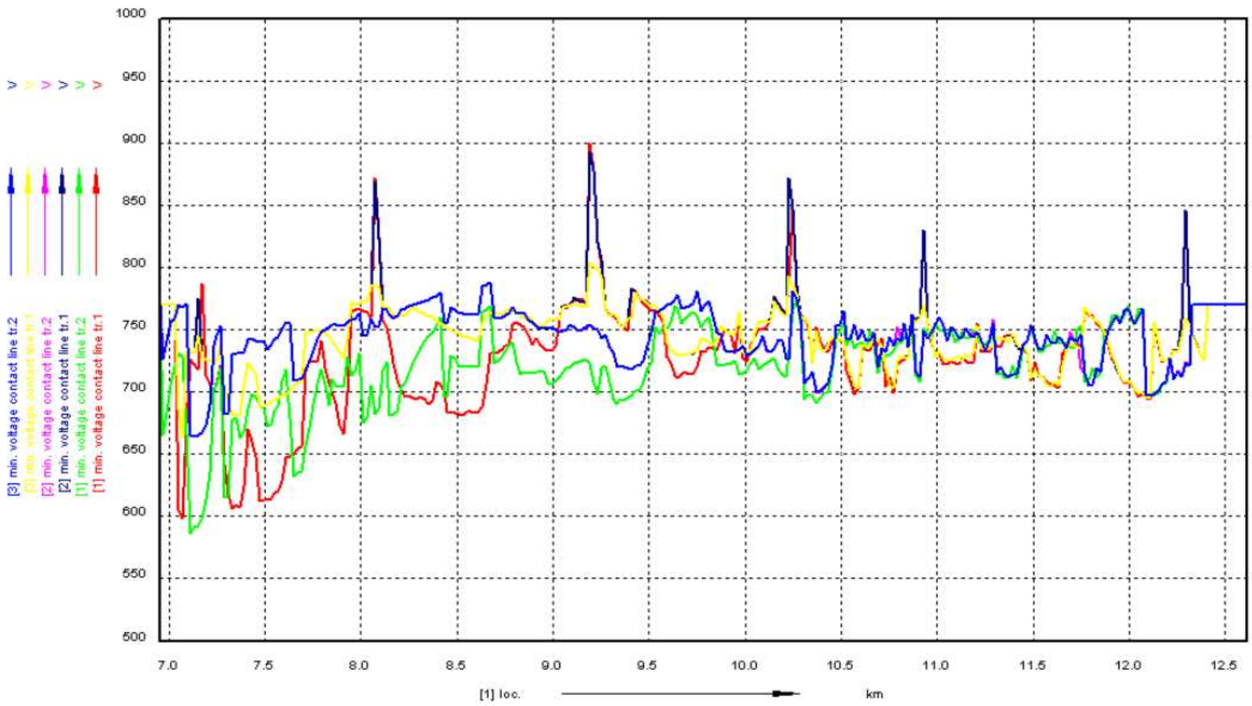


Figure 7-6-7: Minimum line voltages with HESOP (yellow and blue) and without (green and red)

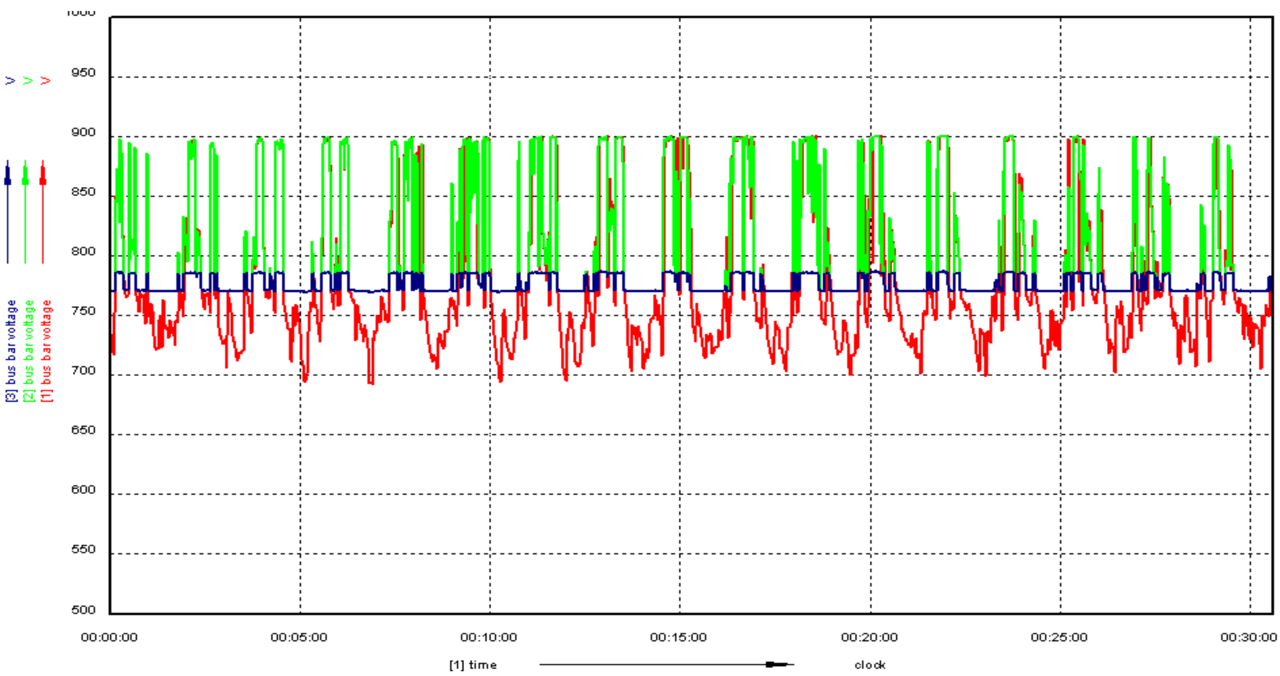


Figure 7-6-8: Line voltage at the substation with HESOP (blue) and without (red)

6.4 INTEGRATION OF A FLYWHEEL

ELBAS allows integrating an energy storage system to the network. However this module is limited to batteries and supercapacitors so the model of a flywheel is ideal in this simulation.

For this second simulation, the flywheel was defined with a maximum chargeable energy amount of 7.3kWh, an efficiency charge and discharge of 0.95 (0.9025 of total efficiency), a maximum power charge and discharge of 1MW, a maximum current charge and discharge of 1,500A and linear losses from 3.120kW to 9kW. The strategy was to charge the flywheel until 0.25 of the total energy until 785V (same value with the inverter) and after the braking energy charges the flywheel until its maximum. When the voltage of the line is inferior to 750V the flywheel discharges its energy and help to maintain the line voltage at 750V.

Without the flywheel, the losses represent 13.3% of the available braking energy and with the flywheel this lost braking energy decreased until 8.2% of the same amount. It allows regenerating 60kWh during 30 minutes of a peak hour simulation. With 4 hours of peak hours during 5/7 of the year it could regenerate 125MWh/year during only peak hours. If the price of electricity is 10c€/kWh the company could earn 12,500€/year.

The next figure shows a flywheel has a low impact on the minimum line voltage of the line contrary to a smart inverter.

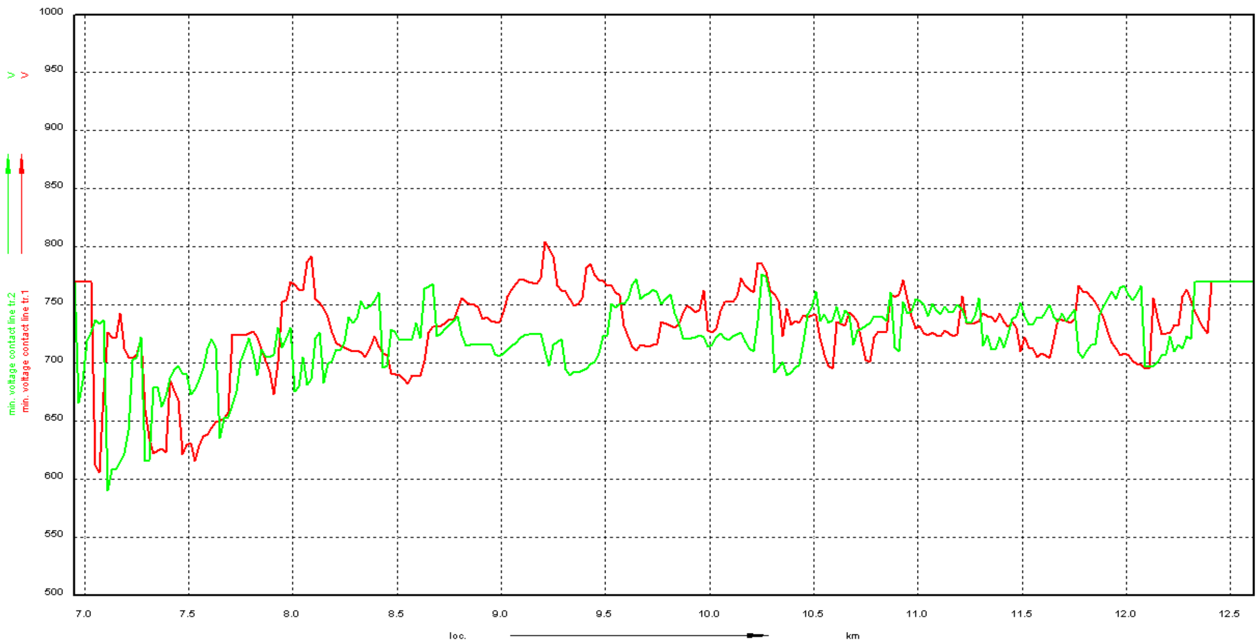


Figure 7-6-9: Minimum line voltages with the flywheel

The two following pictures show the voltage, power and energy of the flywheel.

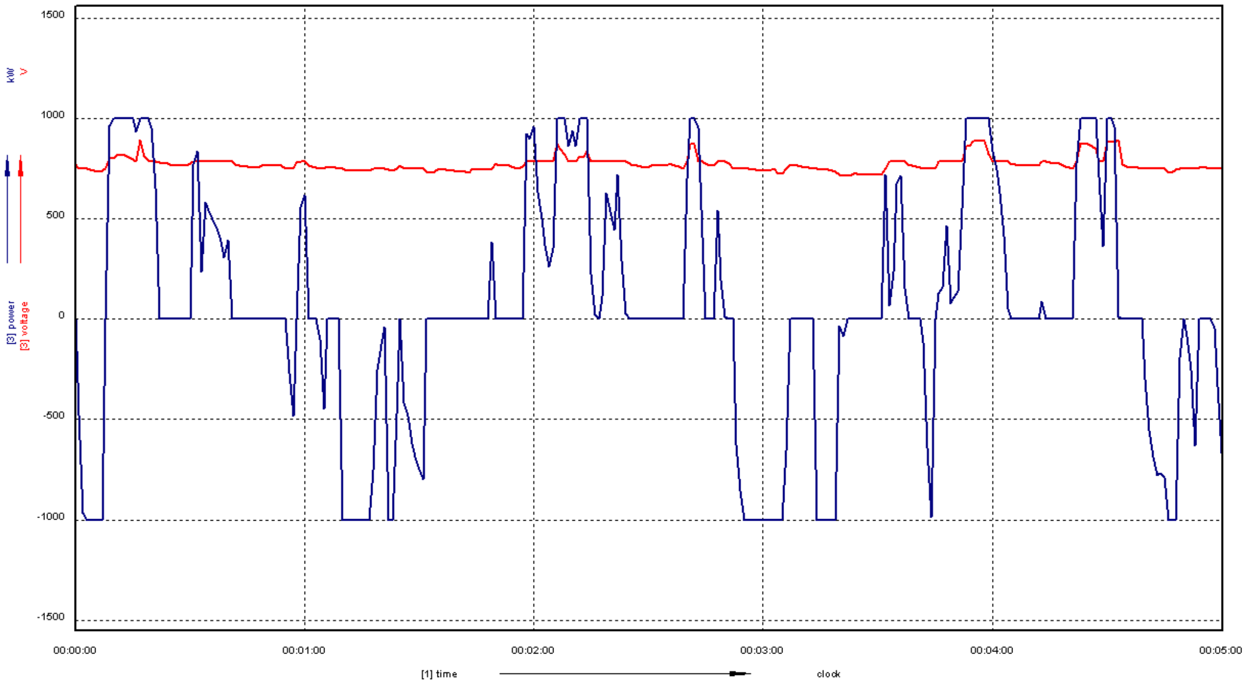


Figure 7-6-10: Voltage and power of the ideal flywheel during the first 5 minutes

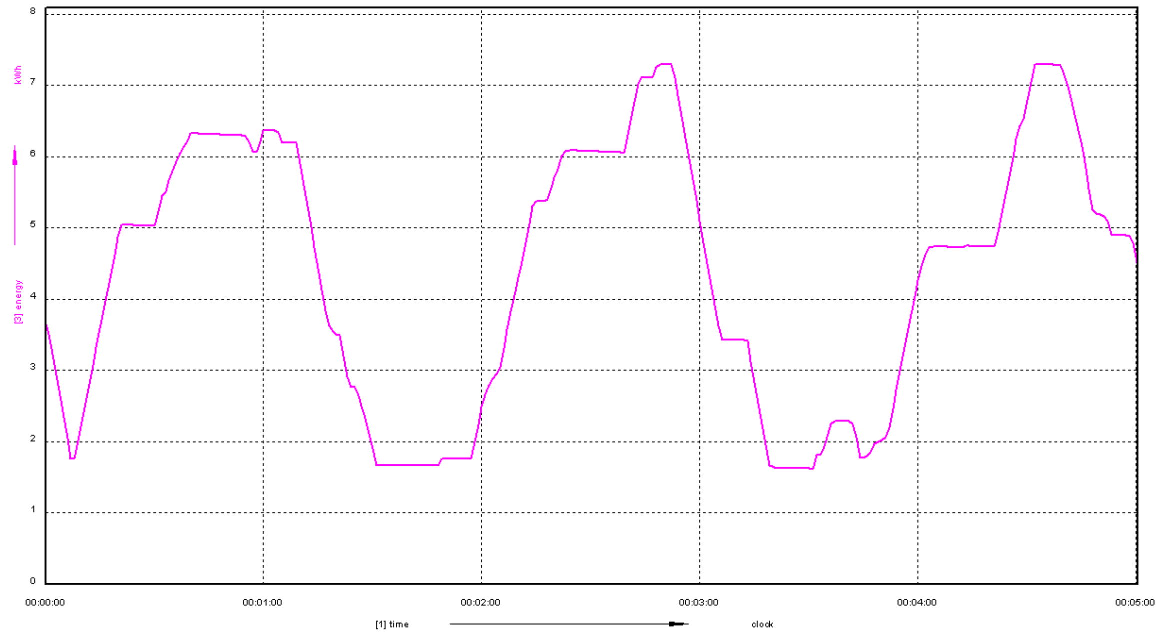


Figure 7-6-11: Energy of the ideal flywheel during the first 5 minutes

The two following figures show the impact of the flywheel on the line at the nearest substation.

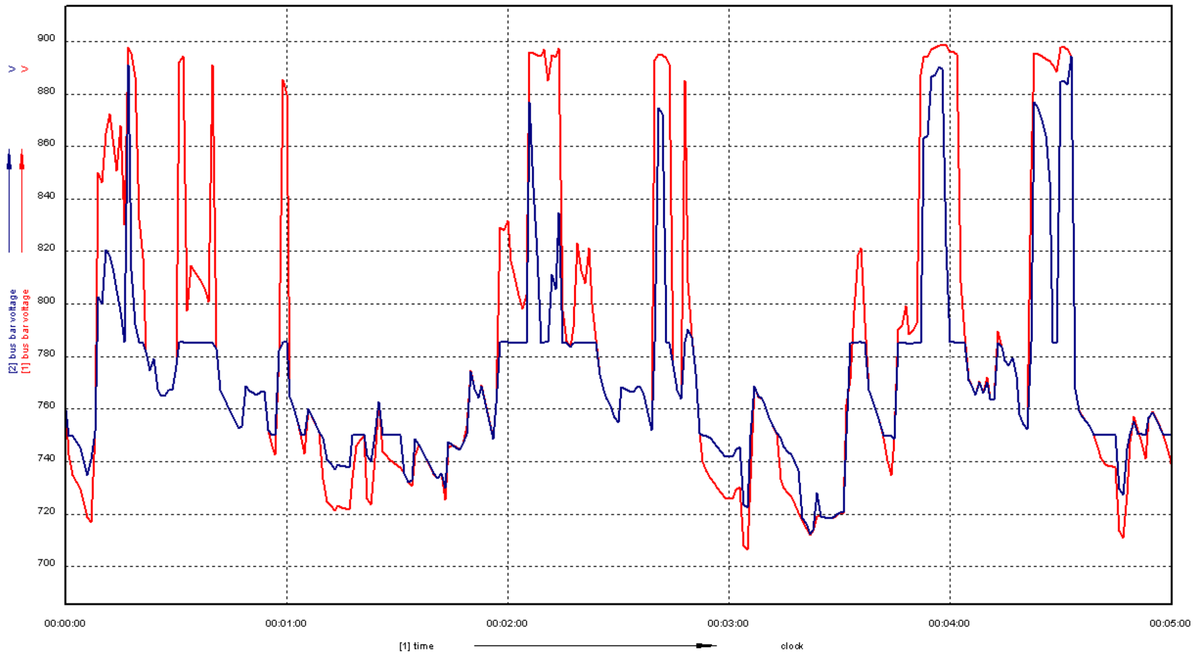


Figure 7-6-12: Voltage on the line without flywheel (red) and with flywheel (blue)

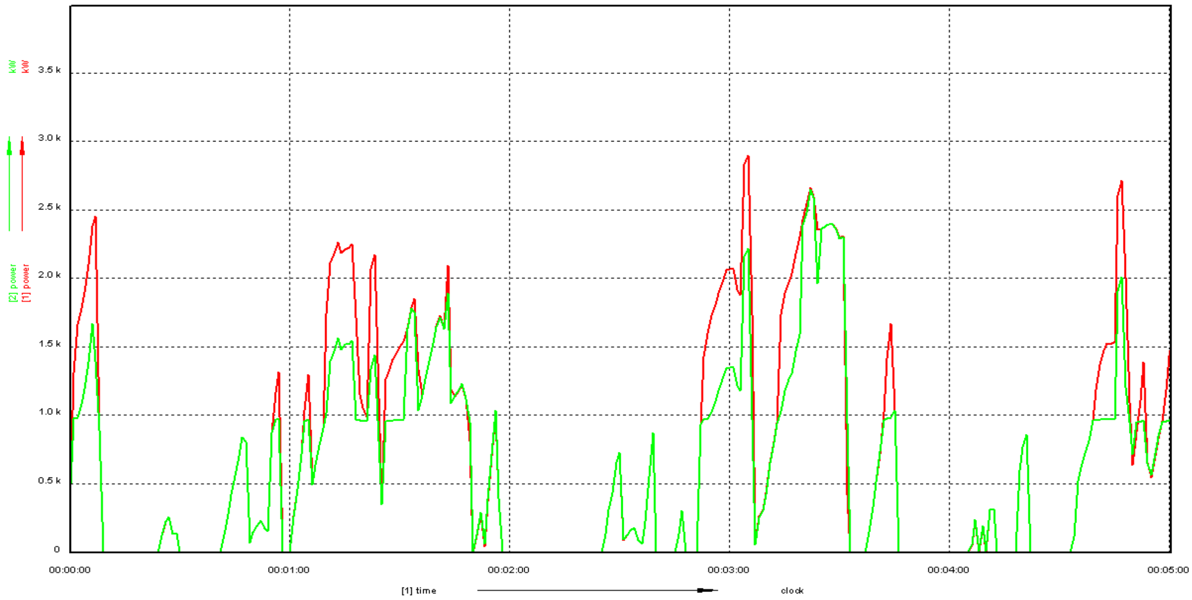


Figure 7-6-13: Power delivered by the nearest substation without flywheel (red) and with flywheel (green)

In the last figures, we can observe the flywheel helps to maintain the voltage on the line, and limits the peaks of power (and so of current).

However, the storage isn't sufficient alone. For example if two trains brake together near the flywheel, it isn't enough powerful to recuperate all the power and energy. The figure 7-14 shows that the used brake energy stops following the usable brake energy when a second train starts to brake whereas the flywheel isn't totally charged in energy as shows the figure 7-15. The losses are due to the limitation of power (figure 7-16). That's why it's necessary to integrate storage systems in a network capable to deliver the energy to other sources of power.

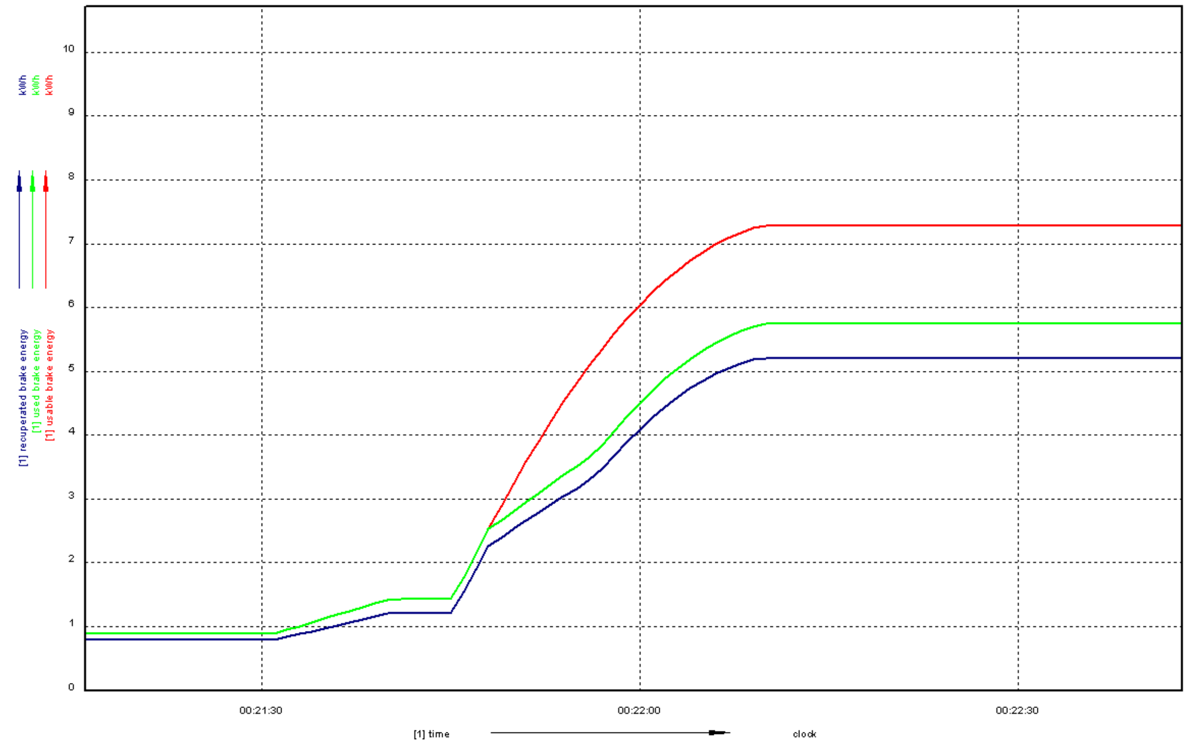


Figure 7-6-14: Braking energy (usable in red - used in green - recuperated in blue) and limit of the flywheel

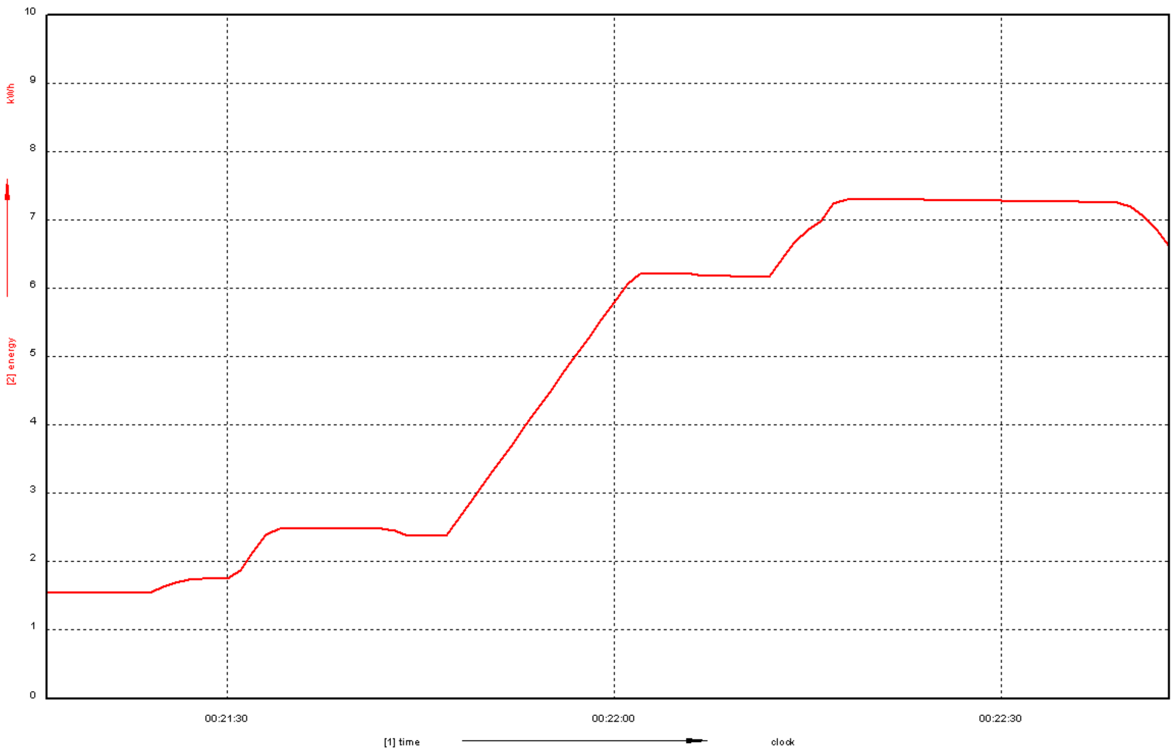


Figure 7-6-15: Energy of the flywheel and its limits

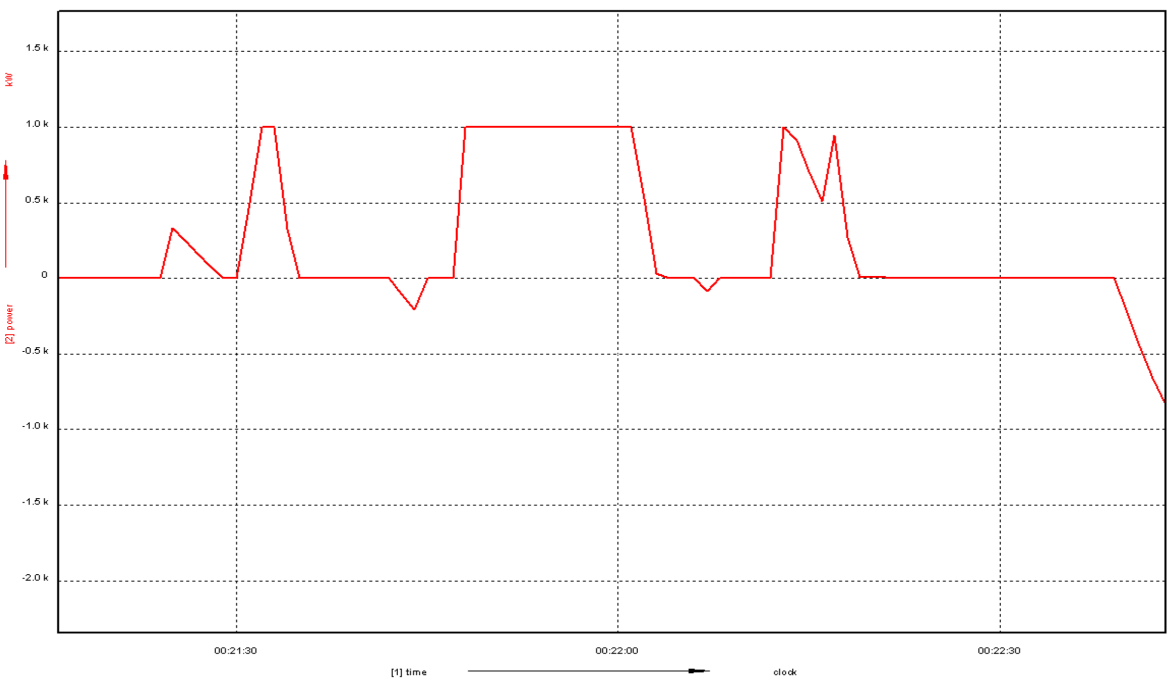


Figure 7-6-16: Power of the flywheel and its limits

7 CONCLUSION

The goal to decrease the total consumption of 10% can be achieved only with the recuperation of all the braking energy. Added to this recuperation, renewables are another way to decrease the electricity bill. All this system will be realized by a new architecture of urban rail networks inspired from the smart grid. The rail network communicates to the urban grid via an energy control center and a micro grid is installed in order to achieve the electrical interface between the 2 grids. Inside this grid a DC bus allows to interconnect different loads (station auxiliaries, traction, storage systems, PV arrays, PHEV and electrical vehicles ...). Thus if there is a load which produces electricity in an intermittent manner, an energy flow from this load to the others via DC bus allows to use this energy and not to lose it. Storage systems can be used to smooth these peaks of energy (in the case of renewables and traction) and help in this research of total recovery. However more the micro grid interconnects loads and distributed generators, more the design of the storage systems can be optimized and the price of the global architecture decreases. If necessary, the surplus of energy can be sold to the local grid (PHEVs, refrigerated warehouses) or to the electrical distributor if desired.

After this study, the energy control center has to be defined: definition of protocol, functions, services and algorithms will be in development in a versatile manner to accommodate it for as many use cases as possible. Moreover the power electronic will be studies. In the same development the bidirectional communication protocols and hardware have to be designed.

The development of smart grid is necessary to the achievement of energy consumption in mass transit systems but it can't be applied to the old networks in several cases. The simulations realized in the last chapter compare two different possibilities (smart converter and flywheel) which can be integrated without many constraints on an existing network. Considering only peak hours the return on investment for each solution is studied below

- The cost of the flywheel used is approximated to 200k€ and the system saves 125MWh/year so the return on investment is realized after 16 years.
- The cost of an HESOP converter is approximated to 725k€, the over cost compared to a traditional rectifier is approximated to 125k€ and the system saves 343.5MWh/year. The return on investment is realized after 21 years for a new converter and 4 years for a replacement which was mandatory (end of lifetime).

This return on investments (realized only for peak hours) show the best solution is to integrate a smart converter on an existing line if the replacement of the substation is needed. Otherwise the flywheel is more interesting.

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