Assessment of energy savings on light rail vehicles and hybrid buses by using different super capacitor based energy storage systems

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Abstract

This article will assess the energy savings, at tram and substation level, that can be achieved on a 30m long tram by hybridizing its drive train with a supercapacitor based energy storage system. Different configurations of energy storage systems, ranging from 0.9 to 1.56kWh, will be proposed. Simulations of vehicle and feeding network, developed in Matlab/Simulink, lead to results on energy savings varying from 24 to 27.6% under the same driving cycle and auxiliaries' consumption. At the end-of-life of the supercapacitors the energy savings vary between 18.1 and 25.1% depending on the energy storage system used and vehicle load. The return on investment of opting for an energy storage system aboard a tram in Brussels has been assessed taking into account changes in several parameters.

Keywords: Energy savings, Supercapacitor, Efficiency, Energy Storage, Hybrid electric vehicle (HEV)

1 Introduction

Increasing concerns on the depletion of fossil fuels, environmental matters and especially the increasing cost of energy has led to investigations in alternative fuels and energy consumption reduction.
Transportation sector is one of the main consumers of fossil fuels and energy in general and it is looking into new technologies that can help ease the situation.
Public transportation is the core of mobility in urban areas, contributing to a better use of energy per passenger. Due to its role, it should be a showcase in the adoption of new technologies.
Several segments can be distinguished among the ground vehicles: buses or road vehicles, and rail vehicles such as trams, metro trains and heavy trains. In the middle of both, trolleybuses offer an alternative for zero emissions on the place of use. In large cities, rail vehicles form the main transport structural axes. They are emissions-free at the place of use due to their electric traction, but however, this energy is produced in many cases out of fossil fuels. As a consequence, it is also desired to reduce the energy consumption of this transport mode.
To achieve a higher energy efficiency on light rail vehicles, their drive train can be hybridized with the inclusion of an energy storage system (ESS) for energy recovery purposes [1,2].

Modern rail vehicles can feed back to the grid up to 40 % of the energy supplied to them [3]. This energy can be sent to other vehicles on the line provided that they will consume it simultaneously; but this is infrequent for tram networks where the light traffic density entails a small percentage of braking energy re-use.
Supercapacitor based ESSs are ideal for this kind of applications where high peak powers are frequent. Their low internal resistance makes possible a high charge/discharge cycle efficiency while their electrostatic nature allows for a long life time [4].
Hybridizing the tram drive train with supercapacitors can have several purposes, depending on the particular aims, such as: energy savings, peak power shaving, overhead line voltage stabilization [5,6], etc. According to this aim, a specific control strategy and a particular sizing will be needed. This study will focus on the development of an ESS oriented to energy savings.

2 Methodology

Many parameters influence the design of a supercapacitive ESS for a rail vehicle. Features such as tram weight, passenger load, maximum speed, driving cycle, altitude differences and supercapacitor characteristics need to be studied to determine the ESS in terms of energy capacity.
To evaluate the effects of all these parameters, a backwards looking simulation tool [7,8] has been developed in Matlab/Simulink with the objective of determining the power flow at tram level, line voltage and current, and power drawn from substations with and without on-board supercapacitors. Figure 1 shows a detail of the tram model inside the simulation program.
Starting from a predefined speed cycle, it calculates both the traction and braking power requested by the tram. Then, according to the requested power at the DC bus level, a power controller (blue), determines the amount of power to be provided by the supercapacitors and the remaining power to be provided from the net. The power split will depend on parameters such as the total power requested, the supercapacitors State of Charge (SoC), the tram speed, overhead line voltage, etc. This can be done in many different ways depending on the strategy used and the objective to achieve. In our case, since the aim is to recover the braking energy, the power controller will make sure that for a certain speed, the SoC of the supercapacitors will be appropriate to allocate the vehicle kinetic energy in case of sudden braking.
Other control strategies are possible, such as voltage stabilization focus. They are not considered in this article but it is of the interest of the authors as a subject of study in future work.
The model can simulate both conventional and hybrid drive train by switching the 'hybrid selector' block. The power requested from the overhead line is passed to a network model where the current and voltages are calculated at every iteration step.
The energy consumed from the net by the conventional tram and the hybrid version are compared and thus, the energy savings are determined.

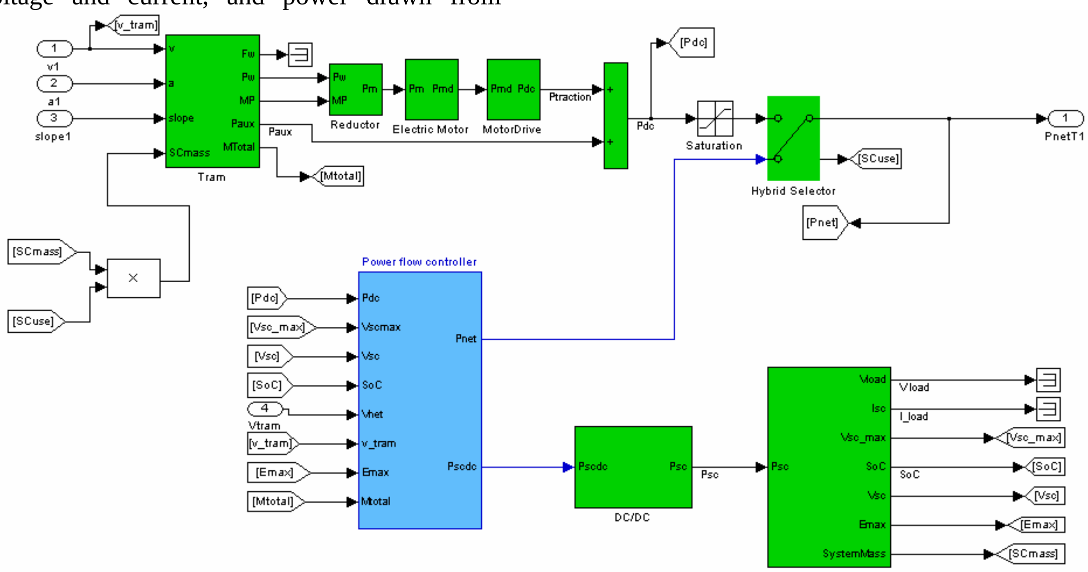

Figure 1. Detail of tram model in simulation program

3 Energy storage system sizing

There are different ways of determining the size of an ESS for hybrid vehicles. In the case of series hybrid buses and cars, the objective of hybridizing the drive train is to keep the Internal Combustion Engine working at the most efficient working point. Therefore the ESS is sized to cope with the remaining power. By analyzing the power flow from/to the ESS of the vehicle following a worst-case driving cycle, the ESS size is determined. It is also possible to reduce the ESS size by slightly modifying some of the settings of P_{ICE}. This is exposed and further analyzed in [9].

$$P_{Total} = P_{ICE} + P_{ESS} \qquad \textbf{Eq 1}$$

$$P_{ESS} = P_{Total} - P_{ICE} \qquad \textbf{Eq 2}$$

For electric powered vehicles such as trams, there is no big constraint regarding the most efficient working point. This will allow for extra freedom to design the ESS in terms of energy savings. In order to optimize the ESS size, the dynamic sizing method [9] is proposed. This will consider the energy variation in the supercapacitor ESS within one charging/discharging cycle, and will entail the use of a power flow controller in the tram [10]. This controller will manage the power split between the grid and the ESS according to several parameters such as vehicle speed, supercapacitors state of charge (SoC), requested traction power, etc.

Since the general aim is the recovery of braking energy, the control algorithm will tend to:

- Keep the supercapacitor SoC high at low vehicle speeds;
- Keep the supercapacitor SoC low at high vehicle speeds;
- Recharge the ESS when vehicle speed and power requested are low.

3.1 Design Criteria

-The voltage variation of the SC will be kept between 100% and 50% of its maximum voltage. Thus, the available energy of the SC will be 75 % of the total energy stored according to Eq 3.

$$E_{Total} = \frac{1}{2} \cdot C_{Total} \cdot (V^2_{TOTAL\max} - V^2_{TOTAL\min}) \qquad \textbf{Eq 3}$$

-The current of the SC cell will not go over the value $0.12 \cdot I_{ShortCircuit}$ [9].

-Power losses and end of life (EoL) of the SC will be taken into account for the energy saving calculation

-Maximum ESS voltage will be lower than network

3.2 Assumptions

-The driving cycle used for the saving calculation is based on the route of tram 23 in Brussels, taking into account the distance between stops, but neither the traffic conditions nor the altitude profile. Further measurements will be done to simulate an actual measured cycle.

-The altitude differences are not considered at this time. They will be further studied, but it can be expected that the SC based ESS will not have enough capacity to store all the available potential energy.

-The simulated network is made up of substations connected to the overhead line every 1.5 km.

-Only one tram was running on the line. The possibility of feeding energy back to the network is being developed at the moment but its results are not included in this article.

-Unless it is specified in another way, the vehicle auxiliaries' power will be set up to 23 kW, corresponding to measured tram average values.

3.3 Energy requirements

The recoverable energy in the braking phase of the train will be its kinetic and potential energy given by Eq 4 and Eq 5.

$$E_{Kinetic} = \frac{1}{2} \cdot M \cdot v^2 \qquad \text{Eq 4}$$

$$E_{Potential} = M \cdot g \cdot h \qquad \text{Eq 5}$$

A general design criterion is that the ESS must be able to recover the kinetic energy of the vehicle. In the worst case, at maximum speed (70 km/h) and loaded with 4p/m^2 (51800 kg) the kinetic energy is 2.72 kWh.

However, the max speed of the tram, 70 km/h is hardly achieved. In surface driving the speed rarely goes over 50 km/h, being 60 km/h a reasonable limit for both surface and tunnel driving. Besides, part of the kinetic energy is used in overcoming the rolling resistance and aerodynamic drag as well as the internal vehicle losses. The recoverable energy is determined by simulations in a deceleration from 60 to 0 km/h in a full tram. The energy subject to be stored in the ESS under these conditions is 1.14 kWh. This is shown in Figure 2.

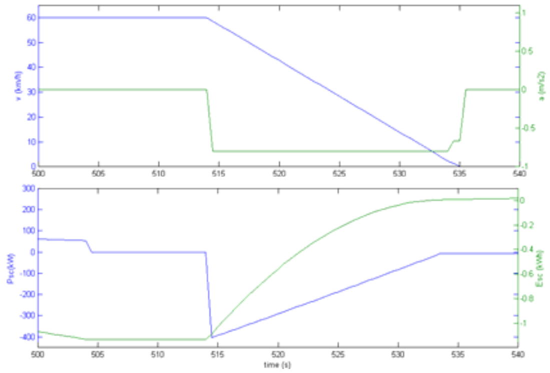

Figure 2. Detail of vehicle deceleration

3.4 Proposed Configurations for the Energy Storage Systems

There are plenty of possibilities to form the ESS, for a requested energy capacity, by combining different cell capacities, number of cells in series and number of parallel strings. The total usable energy of the supercapacitor modules is given by Eq 6 to Eq 9.

$$E_{usable} = \frac{1}{2} C_T (V_{T\max}^2 - V_{T\min}^2) \quad \textbf{Eq 6}$$

Where

$$C_T = \frac{C_{CELL} \cdot N_P}{N_S} \quad \textbf{Eq 7}$$

$$V_{T\max} = V_{CELL\max} \cdot N_S \quad \textbf{Eq 8}$$

$$V_{T\min} = V_{CELL\min} \cdot N_S = 0.5 \cdot V_{CELL\max} \cdot N_S \quad \textbf{Eq 9}$$

Where N_S is the number of cells in series per string and N_P is the number of paralleled strings.

Following the design criteria exposed in section 3.1, four possible configurations for the supercapacitor based ESS will be next proposed.

3.4.1 Option A

The criteria for this option consist on the fact that the system should be able to store all the braking energy generated in a deceleration from 60 to 0 km/h when the vehicle is loaded with 4 persons/m^2.

Cells:	C=*2000F, V_{max}= 2.5V.*
Configuration:	*4 strings x 232 cells in series*
Usable energy:	*1.2 kWh*
Max Voltage:	*580 V*
Cells weight:	*371kg*

Table 1. Option A module characteristics

3.4.2 Option B

The criteria is the same as the used in option A, but this time, instead of single cells, the configuration has been done with built-in Maxwell© modules.

Built-in modules:	*C=63F, V_{max}= 125 V.*
Configuration:	*3 strings X 4 modules in series*
Usable energy:	*1.23 kWh*
Max Voltage:	*500V*
Modules weight:	696 kg (cells, packaging, cooling,etc)

Table 2. Option B module characteristics

3.4.3 Option C

This option consists of a higher capacity module, designed to be able to store the braking energy of a tram loaded with 6 persons/m2 decelerating from 63 km/h to 0. [another criterion that leads to similar results is that of option A considering SC end of life].

Cells:	C=*3000F, V_{max}= 2.5V.*
Configuration:	*4 strings x 200 cells in series*
Usable energy:	*1.56 kWh*
Max Voltage:	*500 V*
Cells weight:	*440 kg*

Table 3. Option C module characteristics

3.4.4 Option D

This smaller sized system has a capacity which allows for a recovery of the braking energy of a tram in a deceleration from 50 km/h to 0 km/h assuming a load of 4persons/ m^2.

Cells:	C=*1500F, V_{max}= 2.5V.*
Configuration:	*4 strings x 234 cells in series*
Usable energy:	*0.91 kWh*
Max Voltage:	*585 V*
Cells weight:	*300 kg*

Table 4. Option D module characteristics

4 Energy saving results

The cycle used for the simulations is built based on tram line 23 route in Brussels. The route include surface and tunnel sections covering a total distance of 20.4 km. Max speed of 60 km/h is assumed for tunnel sections while a maximum speed of 50 km/h and 30 km/h is reached in surface depending on the distance between stops; the average speed of the cycle is 23 km/h. Stop times of 20 s are implemented. Further measurements in the coming months will allow the simulation of a real driving cycle.

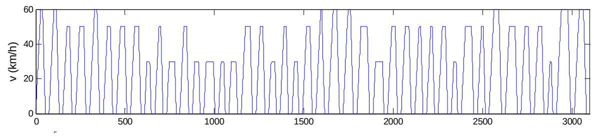

Figure 3. Tram driving cycle

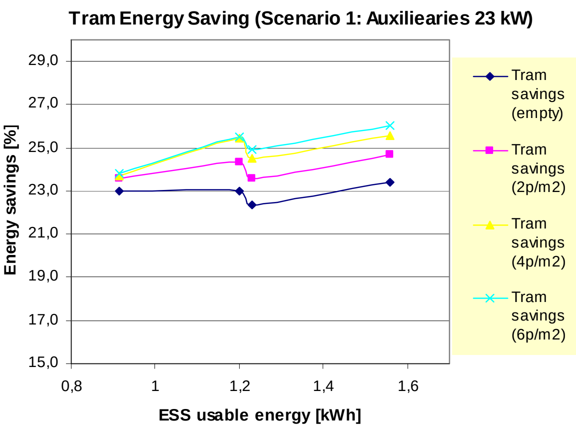

Figure 4. Energy savings vs. ESS size

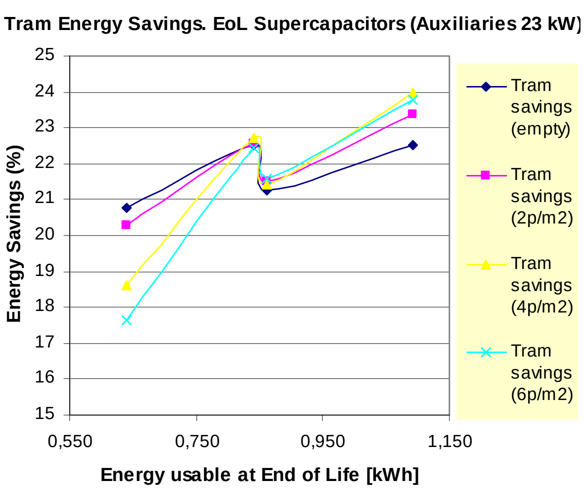

Figure 5. Energy savings vs. ESS size at supercapacitor end of life.

It is observed in Figure 4 that on an empty tram, the energy savings are around 23%, almost independently of the energy storage used; while for a tram loaded with 6 persons/m2 the energy savings will vary from 23.8% (using option A; 0,91 kWh) to 26% (using option C; 1,52 kWh). The difference between option A and option B is also marked. Although they have almost the same energy capacity, the results differ significantly. This is due to the fact that option A has a higher efficiency than option B. The current through the cells of option A is lower than in option B, due to the module configuration. This makes option A more efficient than option B and shows that the SC module topology has an important influence on the result. ESS size has a higher impact at the EoL of supercapacitors due to the drop of capacitance as shown by Figure 5.

Figure 6 and Figure 7 show a comparison between the ESS (option A, C and D) under different load conditions at the beginning and at the end of life. Option C is the most efficient in all conditions but for loads smaller than 4 p/m2, there is no big difference between option A and C. At the end of life this differences have increased.

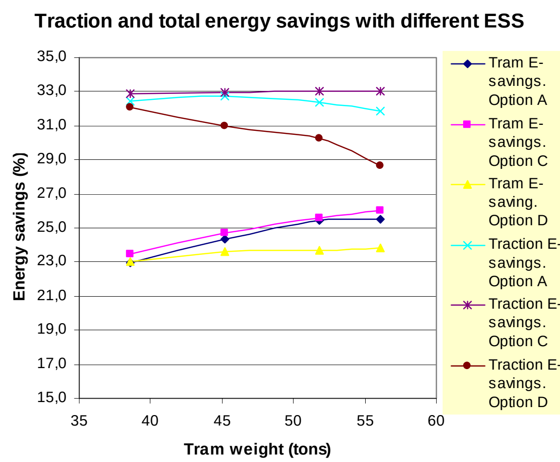

Figure 6. Energy savings vs. vehicle load

Another fact to notice is the influence of the auxiliaries' consumption on the end results. The smaller the value of the auxiliaries' consumption, the higher the energy savings will be because this energy can not be recovered.

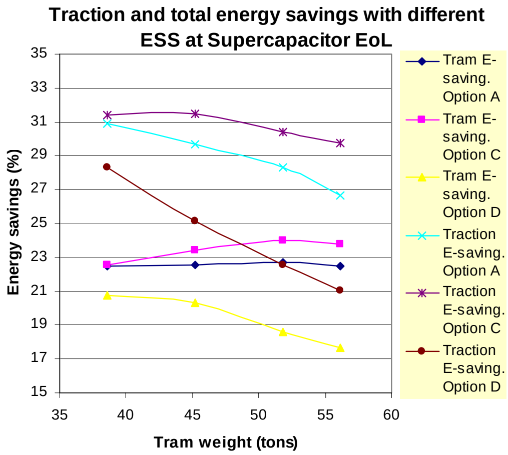

Figure 7. Traction and total energy savings vs. weight

Energy savings shown in the figures correspond to the savings at tram level. Due to the losses on the line, the energy savings at substation level are between 1 and 2% higher considering only 1 tram running on the line. In the next step, the net will be simulated with several trams on it, as it happens daily. In this case, the savings on the line will also be higher due to the higher current flowing through it.

5 Economic assessment

5.1 Market analysis

The supercapacitors market has increased from approximately $130 million in 2003 to some $272 million in 2006. The largest growth sector has been industrial electronics, primarily in applications requiring burst power or rapid start. The market is expected to see continued growth [11] at an average annual growth rate of 15.3% through 2011, to reach $560 million in 2011[12]. However, the evolution of the supercapacitors market has been hampered by the high costs of manufacturing double layer cells. The labor-intensive manufacturing processes have now been replaced by more recent automated assembly techniques that have significantly decreased these costs. In 2006, the cost of supercapacitors has reached some 0,01€ per Farad for very large quantities and around 0,03€ per Farad for smaller quantities. The main obstacles for a broader use of the supercapacitors in both hybrid and full-electric vehicles are the price of the cells that lengthens the payback time as well as the low customer awareness of this relatively recent technology. Moreover, the costs of supercapacitors will not only have to come down to allow this technology to gain a substantial market share but the devices will also need to prove their efficiency and reliability on a day-to-day basis before entering new markets.

5.2 Return on Investment evaluation

Based on the four supercapacitors modules configurations presented in 3.4., the return on investment (ROI) of fitting the Brussels line 23 trams with an energy storage system will be evaluated. The return on investment is the ratio between the cost of an ESS and the annual energy and emissions savings. For these ROI calculations, all the scenarios were not taken into account, only the closest to the realistic operational conditions were analyzed. The different parameters of the scenario used for the economic calculations are detailed hereafter:

5.2.1 Evaluation parameters

Vehicle load: the weight of the tram has been fixed to 45,2 tons which corresponds to an average of 2 persons/m^2. It is assumed that this value is an average of the daily passengers load factor on this line.

Annual distance: An average annual distance of 50.000 km has been considered although some vehicles may drive up to 65.000 km per year.

Energy consumption: The annual energy consumption is based on the technical simulations presented above and depends on the vehicle's weight. For this economical assessment, only the consumption at the substation level of a 45,2 tons tram with 23kW auxiliaries'consumption has been considered.

Energy price: In 2006, the STIB paid its electricity **74€/MWh**. However, the energy prices are expected to rise considerably in the coming years.

Emissions**:** The emissions from the production of electricity are greater than for the production of other fuels. However, electric vehicles have the advantage of producing zero emissions locally so that their environmental impact in urban areas is smaller than equivalent combustion engine vehicles. The energy consumption reduction of electric vehicles has a direct impact on the pollutants emitted since less energy is consumed and produced. The emissions in Belgium, and their evolution, depend on the types of fuels used and the technical equipment of the electric power plants. Since 2005, the decrease in the consumption of coal resulted in a significant reduction of sulphur dioxide (SO_2) and considerable decrease in dust emissions. The CO_2 emissions are particularly low in Belgium, compared to other European countries, due to the large proportion of nuclear power generation. The Table 5 shows the values of the different pollutants per kwH produced in Belgium.

Pollutant	Emissions
CO_2	248 g/kWh
SO_2	360 mg/kWh
NO_x	298 mg/kWh
CO	28 mg/kWh
CH_4	4,03 mg/kWh
VOC	3,56 mg/kWh
N2O	1,34 mg/kWh
PM 2,5	5,36 mg/kWh

Table 5: Environmental results of electricity generating facilities in Benelux and in Belgium[13]

At this stage, only the savings in CO_2 emissions will be measured. The authors envisage developing an in-depth environmental analysis that will cover all pollutants of the electricity production mix as shown in Table 5 to weigh up their impact on investments. The CO_2 ton is here valuated at 27€, value taken from the French Commissariat Général du Plan report which evaluates the costs of transport emissions[14]. This value is relatively low compared to other studies such as IWW/INFRAS which values a CO_2 ton at 135€. Today, however, there seems to be a consensus among the scientists to fix the price of a CO_2 ton between 20€ and 30€.

Supercapacitors price: The prices of the supercapacitors cells presented in Table 6 are based on estimations.

Model	**<100 cells**	**>25k cells**
BCAP1500	**70€**	**30€**
BCAP2000	**90€**	**40€**
BCAP3000	**100€**	**45€**
HTM Power	**4200€**	**3500€**

Table 6: Maxwell cells price estimations

The Brussels Public Transport Company (STIB) has 68 new generation Bombardier trams (49 T3000 and 19 T4000) in service and 102 in order. If we assume that each vehicle would be fitted with an energy storage system (ESS) and that each ESS requires around 1000 cells, 170.000 cells will be needed. This can be considered as a large order so that we based our economical calculations on the “large order” prices.

Power converter price: Beside the supercapacitors cells, power converters are necessary for ensuring that the supercapacitors are correctly used, efficiently charged and discharged and prevent them from damages. A DC/DC bi-directional power converter will be required to convert the variable supercapacitor DC voltage to a controlled DC output with a desired voltage level. It seems that standard products do not exist for this type of applications. Consequently, the prices for a specific device will certainly be high. Since the authors could not find reliable figures for this type of devices, they considered that a power converter would cost some 50% of the supercapacitors cells and fixed the price at 20.000€ per vehicle. Further investigations will be necessary to confirm this figure.

Packaging, cooling & voltage stabilization: Other devices are also necessary to stabilize the voltage level and monitor the temperature inside the system. The cost of interconnections, packaging, cooling and voltage stabilization will add about 20% to the system unit cost [15].

The Table 7 indicates the price of each option as developed in 3.4.

Option A	**64.544,00€**
Option B	**70.400,00€**
Option C	**63.200,00€**
Option D	**53.696,00€**

Table 7: ESS options prices

5.2.2 Return on investment vs. vehicle weight

The Figure 8 shows clearly that the weight of the vehicle has a strong impact on the ROI since more energy can be recovered during the braking when the vehicle is heavier.

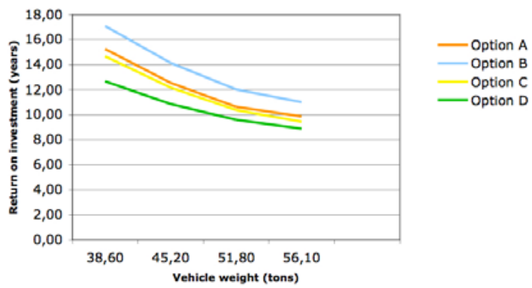

Figure 8: Return on investment vs. weight of the vehicle

In the next figures, we will only consider that the tram weighs 45,2 tons which corresponds to an average of 2 persons/m^2.

5.2.3 Return on investment vs. annual distance

The Figure 9 shows the influence of the increase of the annual distance covered by one vehicle in one year. It influences notably the payback time since the EES is more used and its cost is more rapidly recouped

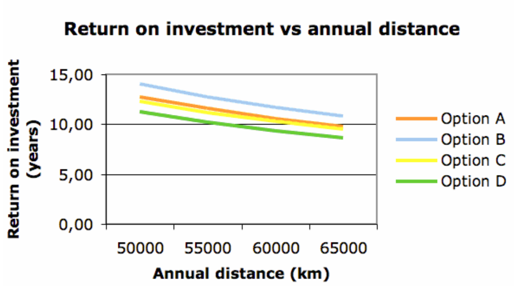

Figure 9: Return on investment vs annual distance

5.2.4 Return on investment vs. energy price

There has been a considerable increase in the energy prices the last years and most experts agree on the fact that the energy cost will continue to rise at a substantial rate. The Figure 10 shows the impact of a 25% (92,5€/MWh), 50% (111€/MWh) and 100% (148€/MWH) increase in energy prices.

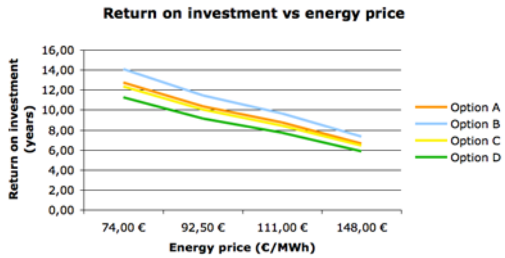

Figure 10: Return on investment vs. energy price

5.2.5 Return on investment vs. CO_2 emissions valuation price

The increasing awareness of the environmental issues among politicians and citizens will help taking policies in favor of more sustainable choices. As an example CO_2 emissions will have to be cut drastically by imposing carbon taxes and emissions quotas. The energy efficiency will be highly encouraged and expensive technologies will become more affordable. Table 8 presents different valuation prices for a CO_2 ton based on international studies.

Studies	CO_2 ton valuation price
UNITE	20€
C. général du Plan	27€
ETSAP	+/- 55€
INFRAS / IWW	135€

Table 8: Valuation prices for a CO_2 ton according to various studies [16]

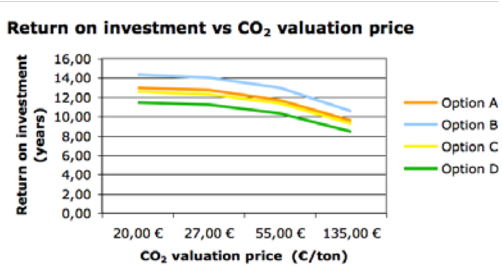

Figure 11: Return on investment vs. CO_2 ton valuation price

6 Next Steps

The methodology developed for the tram assessment will be further improved and utilized

for a similar assessment on the metro fleet. Higher energy savings are expected from the latter due to the higher speed and weight of the metro trains.
The assessment of the bus fleet will distinguish between conventional buses and diesel electric buses. Conventional buses can be retrofitted to micro parallel hybrids by installing an integrated starter alternator (ISA) as shown by Figure 12.

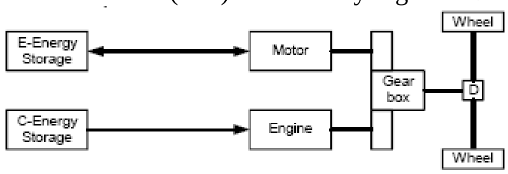

Figure 12. Micro-parallel hybrid propulsion system [17]

Therefore, a start/stop system will be implemented. The purpose is to switch the engine off when it is idling, i.e. at traffic lights, traffic jams, etc. Significant savings can be achieved in city driving environment.

A small portion of the Brussels transportation company (STIB/MIVB) bus fleet consists of diesel-electric buses represented by Figure 13. The advantage of these buses over conventional ones is that the internal combustion engine (ICE) is not coupled to the wheels so it can work in a broader speed range. Thus, the efficiency of the ICE is improved by letting it work at more efficient points. On the other hand, the multiple energy conversion processes and the extra weight of the vehicle increase the fuel consumption.

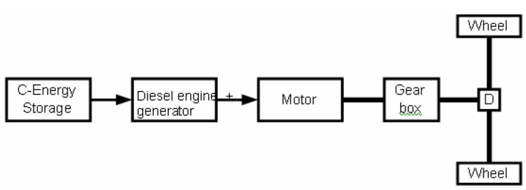

Figure 13. Diesel electric buses topology

Nevertheless, these vehicles are not hybrid and their performance is not optimal due to the lack of an ESS that can introduce savings linked to the braking energy recuperation.

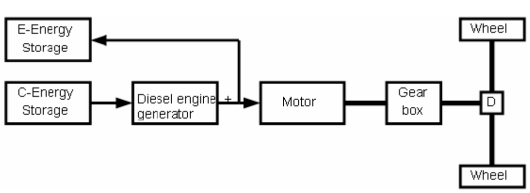

Figure 14. Series diesel-electric hybrid [17]

Hybridizing the vehicle, in the manner represented by Figure 14, will allow not only for braking energy recovery but will also provide an extra degree of freedom to set the ICE working point in a higher efficiency region, as shown by Figure 15.

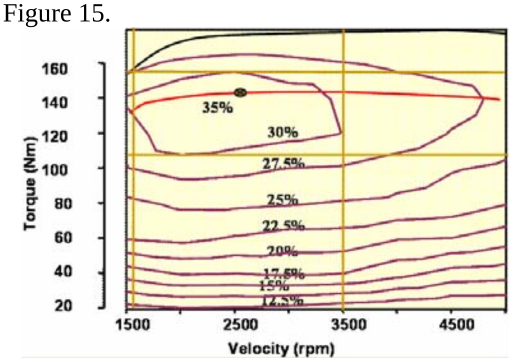

Figure 15. Example of ICE efficiency map

Preliminary simulations show energy savings at DC bus level in the order of 17-22% upon different driving cycles and vehicle loads. These values can be improved with a good management of the ICE. An ICE strategy will be developed in further work.
The sizing of the ESS for this kind of hybrid buses will not only depend on the recoverable braking energy but will also depend on the strategy used.

7 Conclusion

The assessment of the tram fleet indicates undoubtedly that supercapacitor energy storage systems can markedly contribute to reduction on energy consumption in the public transport. An analysis of the metro fleet has not yet been done, but it is expected to have better results due to the higher speeds and higher weight of the vehicles. The tendency in trams indicated that the higher the speed and the weight of the vehicle the higher the savings.
However, economic considerations have a crucial role to invest in new technologies.
It is generally assumed that the lifetime of supercapacitors cells is more or less 10 years depending on the number of cycles. The return on investment for an energy storage system should then be lower than 10 years to be economically viable. Considering the previous parameters, it seems that the investment is not profitable enough today to invest in the supercapacitive technology for a tram network. However, the previous figures have clearly

shown that some parameters have a considerable influence on the payback time of the whole system. If some parameters were to change simultaneously, e.g. an increase in the energy prices together with a fall in the supercapacitors cells prices, the payback time would be significantly reduced and the technology would then become more affordable. The inclusion of an ESS alsoconsumption entails a reduction of power peaks demanded fom the line. It may also have benefits such as the opportunity to increase the number of trams operating on the line without investing in new substations, voltage drops reduction and get better rates for the electricity consumed.
Another interesting element is that the large size option (Option C) is slightly cheaper than the medium size option (option A). This is due to the fact that cells used in option C (3000F) have a lower price (in terms of energy, €/Joule) than in option A (2000F). The future investigations will allow gathering more accurate data and improving the economic assessment.

NOMENCLATURE

ESS	Energy Storage System
SoC	State of Charge
SC	Supercapacitor
ISA	Integrated Starter Alternator
ICE	Internal combustion engine

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