Energy recuperation and storage on the Brussels tram network

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INTRODUCTION

The increasing levels of greenhouse gases are changing the natural climate cycles while the depletion of fossil fuels is leading to an increase in the energy costs, requesting developments in alternative fuels and energy consumption reduction. As urban areas increase, emissions from transport significantly contribute to the greenhouse effect. However, public transport performs the best at densely populated areas, where it is able to reduce the carbon footprint. In large cities, light rail vehicles form the main transport structural axes. To achieve a higher energy efficiency on light rail vehicles, the drive train can be hybridized with the inclusion of an energy storage system (ESS) for energy recovery purposes [1,2]. Recent studies have shown that up to 40 % of the energy supplied to electrical rail guided vehicles could be recovered through regenerative braking [3]. Furthermore, the nature of city driving, where low speeds, frequent acceleration and sudden braking occur, implies that the public transportation sector is an ideal candidate to benefit from an ESS. In most cases, supercapacitors form an optimal option for this purpose. They can accept high power peaks from regenerative braking, have a long lifetime, need no maintenance and work at a wide temperature range without suffering from a negative effect on their lifetime.

ENERGY STORAGE ASSESSMENT ON THE TRAM NETWORK

Objectives

This paper aims to assess the costs and benefits of using a supercapacitor based energy storage system aboard a tram on the Brussels public transport network operated by the STIB/MIVB. Supercapacitors are light weight and high power energy storage devices which have an operational life typical equal to that of a vehicle and they allow energy recuperation during the braking phase of a vehicle or when driving downhill.

Methodology

To evaluate the energy consumption of a light rail vehicle, a backwards looking simulation tool [4,5] has been developed in Matlab/Simulink with the objective of determining the power flow at tram level, the line voltage and current, and the power drawn from substations. The energy consumed from the net by a conventional tram and a version fitted with an ESS is then being compared to determine the energy savings. Based on these results, economic calculations can be done to see the financial impact on the annual energy consumption of the vehicle. The reduction of the air pollution and the greenhouse gases is also evaluated and monetized. Those financial results are then used to measure the return on investment of hybridizing one vehicle with a supercapacitive system to see if the technology is mature enough and competitive from a societal point of view. The objective of this paper is to evaluate the potential energy savings and reduction of the impacts of air pollution in a tram network by installing a supercapacitor ESS. Then, an economic analysis will be carried out to determine whether the technology is mature and whether it is worth investing at this stage in a supercapacitive system for the Brussels light rail network.

Energy storage system

Many parameters influence the design of a supercapacitive ESS for a rail vehicle. Features such as vehicle 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. There are plenty of possibilities to configure the ESS for a requested energy capacity by combining different cells, number of cells in series and number of parallel strings. Four different options have been identified and tested as shown in Table 1. The details about the design criteria of the ESS are deliberately omitted in this extended abstract but can be found in [6].

Table 1. Energy storage systems options

<table>
<thead>
<tr>
<th>Option A</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria: The system will have a minimum size in terms of energy equal to that needed to store all the available braking energy of a tram, loaded with 4 persons/m², in a deceleration from 60 to 0 km/h. The minimum energy is 1.13 kWh.</td>
<td></td>
</tr>
<tr>
<td>Built-in modules: 125 V, C=63 F.</td>
<td></td>
</tr>
<tr>
<td>Configuration: 3 strings X 4 modules in series</td>
<td></td>
</tr>
<tr>
<td>Max Voltage: 500 V</td>
<td></td>
</tr>
<tr>
<td>Usable energy: 1.23 kWh</td>
<td></td>
</tr>
<tr>
<td>Modules weight: 696 kg (it includes cells, connection inside the modules, Voltage balancing circuits, packaging and cooling)</td>
<td></td>
</tr>
<tr>
<td>Cells: C=2000 F, $V_{max}$= 2.5 V.</td>
<td></td>
</tr>
<tr>
<td>Configuration: 4 strings x 232 cells in series</td>
<td></td>
</tr>
<tr>
<td>Usable energy: 1.22 kWh</td>
<td></td>
</tr>
<tr>
<td>Max Voltage: 580 V</td>
<td></td>
</tr>
<tr>
<td>Cells weight: 371 kg</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Option C</th>
<th>Option D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria: The system will have a minimum size in terms of energy equal to that needed to store all the available braking energy of a tram, loaded with 6 persons/m², in a deceleration from 65 to 0 km/h. The minimum energy is 1.52 kWh.</td>
<td></td>
</tr>
<tr>
<td>Cells: C=3000 F, $V_{max}$= 2.5 V.</td>
<td></td>
</tr>
<tr>
<td>Configuration: 4 strings x 200 cells in series</td>
<td></td>
</tr>
<tr>
<td>Usable energy: 1.56 kWh</td>
<td></td>
</tr>
<tr>
<td>Max Voltage: 500 V</td>
<td></td>
</tr>
<tr>
<td>Cells weight: 449 kg</td>
<td></td>
</tr>
<tr>
<td>Cells: C=3000 F, $V_{max}$= 2.5 V.</td>
<td></td>
</tr>
<tr>
<td>Configuration: 4 strings x 234 cells in series</td>
<td></td>
</tr>
<tr>
<td>Usable energy: 0.91 kWh</td>
<td></td>
</tr>
<tr>
<td>Max Voltage: 585 V</td>
<td></td>
</tr>
<tr>
<td>Cells weight: 309 kg</td>
<td></td>
</tr>
</tbody>
</table>

Energy savings simulations

The cycle used for the simulations has been built based on the route of tram line 23 in Brussels. This route includes surface and tunnel sections covering a total distance of 20.4 km and consisting of 44 stops. A maximum speed of 60 km/h is assumed for tunnel sections while a maximum speed while 50 km/h is the maximum speed at surface sections. When the distance between stops is smaller than 300m, then the maximum speed is set to 30 km/h. The duration of the stops is 20 seconds and the average speed of the route is 23 km/h. It is also assumed that only one tram is running on the line and the vehicle auxiliaries’ power is set to 23 kW, corresponding to measured tram average values. The tram occupancy varies between an empty tram (0 persons/m² – 38.6t) and a fully loaded tram (6 persons/m² – 56,1t). It is assumed that the average occupancy rate throughout the year is around 2 persons/m2.

Figure 1. Tram energy savings results
Figure 1 shows the potential savings of the tram in function of the energy storage used and its occupancy. For an empty tram, the energy savings are around 23% almost independently of the energy storage used while for a fully loaded the energy savings vary from 23.8% (using option A; 0.91 kWh) to 26% (using option C; 1.52 kWh). There is also a significant difference between option A and option B although they have almost the same energy capacity. This is due to the fact that option A has a higher efficiency than option B. For the environmental and economic assessments an average energy saving rate of 24% is considered which corresponds to a tram occupancy of 2 persons/m² and equals to 45.2 tons. Simulations developed show that the energy consumption of one tram, in this particular scenario, at the substation level (i.e. the tram energy consumption plus the energy lost in the overhead line), is 5 kWh/km.

Environmental assessment

Although electric vehicles are more environmentally friendly than fuel-powered vehicles, the production of electricity is not emission-free and better energy efficiency could avoid harmful emissions. These emissions are directly linked to the types of fuels and the technical equipment used in the electricity generating facilities. The CO₂ emissions of the Belgian electricity production mix are low compared to other European countries, due to the large proportion of nuclear power generation. The Table 2 shows the values of the different pollutants per kWh produced in Belgium.

Table 2 Environmental results of electricity generating facilities in Belgium in 2006[7]

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>248 g/kWh</td>
</tr>
<tr>
<td>SO₂</td>
<td>360 mg/kWh</td>
</tr>
<tr>
<td>NOx</td>
<td>298 mg/kWh</td>
</tr>
<tr>
<td>CO</td>
<td>26 mg/kWh</td>
</tr>
<tr>
<td>CH₄</td>
<td>3.76 mg/kWh</td>
</tr>
<tr>
<td>VOC</td>
<td>3.32 mg/kWh</td>
</tr>
<tr>
<td>N₂O</td>
<td>1.25 mg/kWh</td>
</tr>
<tr>
<td>PM</td>
<td>25 mg/kWh</td>
</tr>
</tbody>
</table>

Based on the simulations of the energy savings, the emissions reduction could be calculated as shown in Table 3.

Table 3. Emissions reduction due to the energy savings

<table>
<thead>
<tr>
<th>Average annual distance (km)</th>
<th>Annual consumption (MWh)</th>
<th>Energy savings rate (%)</th>
<th>Energy saved (MWh)</th>
<th>CO₂ emissions avoided (tons)</th>
<th>SO₂ emissions avoided (tons)</th>
<th>NOx emissions avoided (tons)</th>
<th>CO emissions avoided (tons)</th>
<th>CH₄ emissions avoided (tons)</th>
<th>VOC emissions avoided (tons)</th>
<th>N₂O emissions avoided (tons)</th>
<th>Particulate matters emissions avoided (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45000</td>
<td>225.00</td>
<td>24.00%</td>
<td>54.00</td>
<td>13392.00</td>
<td>19.44</td>
<td>16.09</td>
<td>1.40</td>
<td>0.20</td>
<td>0.18</td>
<td>0.07</td>
<td>1.35</td>
</tr>
<tr>
<td>50000</td>
<td>250.00</td>
<td>24.00%</td>
<td>60.00</td>
<td>14880.00</td>
<td>21.60</td>
<td>17.88</td>
<td>1.56</td>
<td>0.23</td>
<td>0.20</td>
<td>0.08</td>
<td>1.50</td>
</tr>
<tr>
<td>55000</td>
<td>275.00</td>
<td>24.00%</td>
<td>66.00</td>
<td>16368.00</td>
<td>23.76</td>
<td>19.67</td>
<td>1.72</td>
<td>0.25</td>
<td>0.22</td>
<td>0.08</td>
<td>1.65</td>
</tr>
<tr>
<td>60000</td>
<td>300.00</td>
<td>24.00%</td>
<td>72.00</td>
<td>17856.00</td>
<td>25.92</td>
<td>21.46</td>
<td>1.87</td>
<td>0.27</td>
<td>0.24</td>
<td>0.09</td>
<td>1.80</td>
</tr>
<tr>
<td>65000</td>
<td>325.00</td>
<td>24.00%</td>
<td>78.00</td>
<td>19344.00</td>
<td>28.08</td>
<td>23.24</td>
<td>2.03</td>
<td>0.29</td>
<td>0.26</td>
<td>0.10</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Economic analysis

Based on the four supercapacitors modules options presented here above, the return on investment (ROI) of investing in an ESS has been evaluated taking into account various parameters:

Energy price: In 2006, the Brussels public transport company paid its electricity 74€/MWh. However, the energy prices are expected to rise considerably in the coming years and up to a 100% increase remains highly possible.

Supercapacitors price: The evolution of the supercapacitors market has been hampered by the high costs of manufacturing double layer cells. The labour-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.

**Power converter price:** Beside the supercapacitors cells, power electronic devices will also be 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 adapt the variable supercapacitor voltage to the higher and stable overhead line voltage and to manage the bidirectional power flow through the supercapacitor bank. Standard products do not exist for this type of applications so that the power converter price has been estimated to cost some 50% of the supercapacitors cells. A constant price of 20.000€ per vehicle is considered.

**Packaging, cooling & voltage stabilization:** Other devices are also necessary to stabilize the voltage level and monitor the temperature and due to their small size, the cells must be paralleled to achieve a functional system. The cost of interconnections, packaging, cooling and voltage stabilization will add about 20% to the unit cost [8].

### Table 4. ESS options prices

<table>
<thead>
<tr>
<th>Option</th>
<th>Supercapacitors</th>
<th>Power converter</th>
<th>Packaging</th>
<th>Total price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option A</td>
<td>37.120,00€</td>
<td>20.000,00€</td>
<td>7.424,00€</td>
<td>64.544,00€</td>
</tr>
<tr>
<td>Option B</td>
<td>42.000,00€</td>
<td>20.000,00€</td>
<td>8.400,00€</td>
<td>70.400,00€</td>
</tr>
<tr>
<td>Option C</td>
<td>36.000,00€</td>
<td>20.000,00€</td>
<td>7.200,00€</td>
<td>63.200,00€</td>
</tr>
<tr>
<td>Option D</td>
<td>28.080,00€</td>
<td>20.000,00€</td>
<td>5.616,00€</td>
<td>53.696,00€</td>
</tr>
</tbody>
</table>

**Emissions valuation price:** Only the savings in CO₂ emissions are monetized in this paper and is valuated at 27€/ton. This value is taken from the French Commissariat Général du Plan report which evaluates the costs of transport emissions. This value is relatively low compared to other studies such as INFRAS which values a CO₂ ton at 135€. Today, however, there seems to be a consensus among the scientists to fix the price of a CO₂ ton between 20€ and 30€. In the future, an in-depth environmental analysis that will cover all pollutants of the electricity production mix will be developed.

### Return on investment vs. annual distance

The Figure 2 shows the influence of the increase of the annual distance covered by one vehicle in one year. The use of the vehicle has a direct impact on the payback time since the energy storage system is more used and its cost is more rapidly recouped.

![Figure 2: Return on investment (years) vs. annual distance](image)

### 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. Figure 3 shows the impact of a 25% (92,5€/MWh), 50% (111€/MWh) and 100% (148€/MWH) increase in energy prices.
The increasing awareness of the environmental issues among politicians and citizens will help taking policies in favor of more sustainable choices. CO$_2$ emissions will have to be cut drastically by imposing carbon taxes and emissions quotas. The energy efficiency will be encouraged and expensive technologies will become more affordable. Table presents different valuation prices for a CO$_2$ ton based on international studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>CO$_2$ valuation price</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITE</td>
<td>20€/ton</td>
</tr>
<tr>
<td>Comm. Gén. du Plan</td>
<td>27€/ton</td>
</tr>
<tr>
<td>ETSAP</td>
<td>55€/ton</td>
</tr>
<tr>
<td>INFRAS / IWW</td>
<td>135€/ton</td>
</tr>
</tbody>
</table>

CONCLUSION

The assessment of the Brussels tram network indicates undoubtedly that supercapacitor energy storage systems can markedly contribute to reduction on energy consumption in the public transport. This research gives similar results to other studies in this field or results reported by vehicle prototypes running in other cities [9]. However, not only technical issues, but also economic considerations have a crucial role when it comes to invest in a new technology. Due to the relatively high price of supercapacitors, the return on investment is longer than 10 years, hence the expected lifetime of supercapacitors. Thus, this fact would, from a strict economic point of view, advice against investing in supercapacitive technologies at present time. Nevertheless, considering that the prices of supercapacitors are going down, the cost of energy is constantly increasing and penalty on emissions become acceptable due to the raising environmental awareness among citizens and politicians, some scenarios could open a door for investment.
AKNOWLEDGEMENTS

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