Promoting Electric Public Transport

TROLLEY Project

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PART A:  
On-board energy storage with supercapacitors in Parma  
Author: TEP S.p.A.

PART B:  
Installation of the lithium-ion-battery for the combined on-board energy storage system for Europe’s first “Trolley-Hybrid-Bus”.  
Author: Barnimer Busgesellschaft mbH

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Table of Contents

PART A (TEP)
1. Introduction and Overview
   1.1 Trolleybuses in Parma
   1.2 Energy Storage with Supercapacitors
   1.3 Objectives
2. Optimising Energy Use
   2.1 On-board Storage System
   2.2 Market Overview (Example from Milan)
3. Analysis of tender offers
   3.1 Overview
   3.2 Supercaps
   3.3 Start-up stage of the supercap-equipped vehicle
   3.4 Braking stage of the supercap-equipped vehicle
   3.5 Specific energy consumption
   3.6 Supercap test in Milan
      ANNEX 1 - Data processing for the tests in Milan
   3.7 Supercap test in Parma
      ANNEX 2 - Data processing for the tests in Parma

PART B (BBG)
1. Installation of the lithium-ion-battery for the combined on-board energy storage system for Europe’s first “Trolley-Hybrid-Bus”
2. Status of realisation
3. Transnational added value
Introduction and Background

The INTERREG Central Europe project TROLLEY – Promoting electric public transport - contributes to an improved accessibility of, and within, Central European cities, focusing on urban transport. By taking an integrated approach the project has one main aim: the promotion of trolleybuses as the cleanest and most economical transport mode for sustainable cities and regions in Central Europe.

The Central Europe project TROLLEY (www.trolley-project.eu) is one consortium of 7 European cities: Salzburg in Austria, Gdynia in Poland, Leipzig and Eberswalde in Germany, Brno in the Czech Republic, Szeged in Hungary and Parma in Italy. Horizontal support for research and communication tasks is given by the University of Gdansk, Poland, and the international action group to promote ebus systems with zero emission: trolley:motion.

The project TROLLEY promotes trolleybus systems as a ready-to-use, electric urban transport solution for European cities, because trolleybuses are efficient, sustainable, safe, and – taking into account external costs – much more competitive than diesel buses. The project directly responds to the fact that congestion and climate change come hand in hand with rising costs and that air and noise pollution are resulting in growing health costs. Trolleybus systems are assisting with the on-going transition from our current reliance on diesel-powered buses to highly efficient, green means of transportation. Therefore, the TROLLEY project seeks to capitalise on existing trolleybus knowledge, which is truly rich in central Europe, where trolleybus systems are more widespread.

The following document “Transnational Manual on Advanced Energy Storage Systems” presents the results of feasibility and simulation studies as well as real-life evaluation reports of TROLLEY’s pilot studies and pilot investment in the area of advanced energy storage systems for trolleybus systems. The document exists of three parts: “Part 0” presents a general introduction to different energy storage systems available in the market. “Part I” describes on-board energy storage systems and shows the evaluation results of TROLLEY’s investment pilots “installation of supercaps on trolleybuses” in Parma and the “installation of a lithium-ion battery on a trolleybus” in Eberswalde. “Part II” illustrates the results of TROLLEY’s feasibility studies for network based energy storage systems. It describes the dimensioning of a network-based energy storage system on the basis of wayside installed super capacitors in the networks of TROLLEY’s partner cities Eberswalde and Gdynia
1. Introduction and Overview

1.1 Trolleybuses in Parma

TEP S.p.A. has been the Parma public transport company since 1948. In Parma it operates a trolleybus service covering approximately 20 Km of network, using 34 vehicles on 4 lines. There are 133 stops which on average are spaced approximately 250 meters apart. TEP carries approximately 7.5 m passengers a year and is one of the twelve Italian companies still using trolleybuses. Unlike other cities, Parma has decided to invest in its trolleybus fleet and is extending its network. Trolleybuses are likely to become one of the most important elements on routes carrying the heaviest traffic, creating an environmentally sustainable and energy-efficient alternative to other methods of urban transport.

1.2 Energy Storage with Supercapacitors

According to Kühne und Haase (2003¹), in order to achieve an energy-efficient operation of trolleybuses with little wear and tear of the catenary, there is a need for on-board energy storage systems that are able to quickly store the regenerated braking energy from the traction motors and to feed it back into the drive system when needed – for example in acceleration and phase and while driving up-hill. For such energy storage systems not only the energy density (measured in energy/mass or Wh/kg) is essential, but also the energy per unit of time that is provided, since for trolleybuses energy storage and power reinforcement (measured in energy/mass/time i.e. power/mass or W/kg) are required instantly. Figure 1 shows an overview of the different existing storage systems regarding their energy density and power density. As can be seen supercapacitors are highly efficient regarding both the energy density and the power density.

Overall, the main characteristics of supercapacitors are:

- Provision of recuperated braking energy for the next acceleration phase
- Energy input into the catenary of up to 35% due to a combination of brake energy regeneration and energy storage
- Current limiter for the power network of 100 A

### 1.3 Objectives

Optimising energy use: TEP plans to purchase 9 new trolleybuses equipped with supercapacitors as part of the Trolley project. The kinetic energy recovery system (KERS) of the supercapacitors, already installed and tested on a small fleet of trolleybuses, will optimise energy use by 25%. This proposed investment is a real technological highlight in on-board energy recovery and storage systems. The supercapacitors (“supercaps”) to be used in Parma are enhanced versions that can store a significant amount of energy. Furthermore, they are designed to recover kinetic energy during vehicle braking and release it back as the vehicle accelerates.
This pilot investment makes use of braking energy that often remains unused. The tests will significantly influence the Central European trolleybus market as other decision-makers will examine the results when deciding whether or not to adopt these devices in their fleet.

2. Optimising Energy Use

2.1 On-board storage system

A system of supercapacitors makes it possible to recover over 90% of the energy generated by the electric motor during vehicle braking.

The stored energy is then made immediately available for when the vehicle next accelerates, thus limiting the quantity of current absorbed from the overhead wire and consequently reducing energy consumption.

As well as providing energy savings, the use of supercapacitors makes it possible to avoid dissipating energy on brake resistance with obvious benefits for the environment, it reduces the possibility of generating electric arcs when the vehicle transits under switches and neutral wire sections, thus increasing life-expectancy, it reduces overloads in substations and significantly reduces failures affecting on-board components powered by electric motors (air compressors, air-conditioning systems, etc.).

The system may be used to power the auxiliary equipment when the supply from the overhead wires is momentarily interrupted due to separators, switches and crossings. Amongst other things, this could lead to a reduction in failures caused by frequent ON-OFF cycles in the network power supply; in fact all the on-board power users would remain permanently powered thanks to the supercaps’ batteries.

The supercaps are installed on the roof, on the second section, in front of the current take-up device.
The system is made up of modern capacitors which are charged during vehicle braking by means of the power electronics and release energy back during acceleration. In this way, the energy stored during braking is readily available for the next acceleration, thus reducing overall power consumption.

The supercapacitor has been designed specifically based on the common characteristics of a vehicle operating in urban traffic: it is capable of rapidly absorbing high current values and therefore can efficiently recover the energy generated during braking from high speeds.

Thanks to this device large amounts of power are available in a short time to provide fast acceleration of the vehicle without further overloading the overhead wire. These devices are capable of transferring significant current values between the Supercap system and the traction converter.

A special feature of supercaps is their efficiency in transferring input and output energy. This ensures that a large part of the energy generated during braking is stored with very low losses and in a similar way, a large amount of energy is made readily available, in a short space of time, for the next acceleration. In particular situations, peak values can be withstood without any problems.
The supercaps system is suitable above all for use in systems which have a low in-line recovery capacity or where it is not possible to increase the mains voltage to reduce absorption and hence voltage drops, especially in sections of line which are a long way from electric supply substations. With Supercaps current peaks are eliminated or drastically reduced.

The distinctive aspects of double-layer capacitors, or SUPERCAPS, are their particularly high level of stability and at the same time their resistance to overcurrents. It is therefore possible to use the supercaps system for a long time, even along the most arduous routes through urban traffic. Given the reliability over time, the reduced maintenance requirements and the modular structure of the system (which facilitates servicing operations) the SUPERCAPS system appears to be a profitable investment for the vehicle's life-cycle.
The simplified diagram of the recovery system is illustrated below:

With:
- **DPU** – electronic inverter which powers the traction motor
- **HTS** - inverter for regulating and controlling supercap operation
- **BNU** – static converter for service power supplies.

### 2.2 Market Overview (Example from Milan)

Trials providing positive outcomes have recently been carried out in Italy by the Milan transport company (ATM S.p.A).

ATM S.p.A. purchased thirty 18-metre-long VAN HOOL AG300T trolleybuses equipped with supercapacitors with the following specifications:
The supercaps system installed on this fleet of trolleybuses is made up of two modules, each of which is composed of 76 double-layer high-performance capacitors for a total weight of 300 Kg.
The energy readings taken during operation highlight a reduction in consumption of approximately 25% compared to other types of trolleybuses not equipped with Energy Storage Systems.
3. Analysis of tender offers

3.1 Overview

The tender offers for the supply of “7 new articulated tram-look urban bimodal trolleybuses, class 1 of a length between 17.5 m and 18.75 m, with four doors and completely lowered floor” highlighted the following types of supercaps:

<table>
<thead>
<tr>
<th>DENOMINAZIONE DEL VEICOLO</th>
<th>BMB - AVANCITY PLUS HTB</th>
<th>HESS - BGT NZC</th>
<th>SOLARIS - TROLLINO 18</th>
<th>VAN HOOL V. KIEPE - AG300T TRL</th>
<th>VAN HOOL V. KIEPE - AG300T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supercapacitori:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- marca</td>
<td>Maxwell</td>
<td>Maxwell</td>
<td>LS Mtron</td>
<td>Maxwell</td>
<td>Maxwell</td>
</tr>
<tr>
<td>- tipo</td>
<td>n.5 mod. HTM Power Series 125V</td>
<td>Condensatori a doppio film HTM Power</td>
<td>LSUM 201RSP 0041F EA</td>
<td>Condensatori a doppio film HTM Power</td>
<td>Condensatori a doppio film HTM Power</td>
</tr>
<tr>
<td>- peso</td>
<td>300 kg + 5%</td>
<td>ca.300</td>
<td>4x80</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>- dimensioni</td>
<td>250x840x440 (singolo modulo)</td>
<td></td>
<td>453,2x683,2x257,5</td>
<td>4 moduli da 1500x670x300</td>
<td>4 moduli da 1500x670x300</td>
</tr>
<tr>
<td>- vita utile</td>
<td>10 (con riduzione 20% della capacità nominale o aumento del 100% della resistenza in serie equivalente)</td>
<td>11 anni Cid di carica ca. 1.000.000</td>
<td>1.000.000 ciddi, 80%</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>- risparmio energetico</td>
<td>%</td>
<td>16</td>
<td>ca. 26.2</td>
<td>11-16 in funzione delle condizioni di esercizio per il profilo di missione indicato dalla TEP</td>
<td>26.2 da linea aerea</td>
</tr>
</tbody>
</table>
3.2 Supercaps

On 21st December 2010 the TEP Board of Directors awarded the supply contract to VAN HOOLO NV (Belgium) in temporary joint venture with VOSSLOH KIEPE (Germany) for the bimodal articulated trolleybus, model AG300T TRL.

The bimodal articulated trolleybus, model AG300T TRL is equipped with MAXWELL supercapacitors whose characteristics adapt well to use in the city of Parma, and are the result of evaluations on the geometrical features of the overhead wires and the altimetric conditions of the same. The supercapacitors system is made up of 4 modules; the quantity of energy which can be stored during braking is 0.33 KWh. Therefore with 4 modules it is possible to store the energy generated during braking by a vehicle travelling at 40 km/h, a speed which is considered the most appropriate, statistically speaking, for the type of service operating in Parma. In fact, if the vehicle were to travel at 50 km/h and brake, it is possible to store energy only up to approximately 30 km/h in the supercapacitors to saturate the capacity of supercap storage. This is derived from the quadratic dependence of kinetic energy on speed. Optimization of the speed parameters, distance between the stops, type of traffic etc., makes it possible to maximize the final performance even taking into consideration the extra weight which installation of additional modules on board the vehicle entails.

Each module is made up of double film capacitors with a 2600 Farad capacity each. They are suitably arranged in series/parallel batteries in order to obtain the necessary voltage and capacity values. In particular there is an overall capacity equal to 9.1 Farad with a variable voltage between 300 – 700 V.

The corresponding power is 200 kW.

The energy flow in input and output from the modules is managed by the control software depending on selections with appropriate parameter settings for greater optimization according to the characteristics of the line.

The on-board diagnostics takes care of providing details on the values of energy absorbed from the mains and yielded as well as the energy absorbed from the system. Furthermore
the datum relative to the voltage and current values of the line provided by 5 regular measurements taken between two consecutive stops is made available.

3.3 Start-up stage of the supercap-equipped vehicle

Starting with a stationary vehicle, the power necessary to set the vehicle in motion (red $P_{DPU}$ curve) flows from the battery of the supercapacitors (blue $P_{HTS}$ curve) while the power from the overhead wire (green $P_{OL}$ curve) remains on zero and begins to be absorbed when the contribution from the supercaps, which remains constant, is no longer sufficient.
The vehicle increases speed and the voltage of the supercaps begins to drop: the supercaps begin the process of discharging; the necessary power for continuing acceleration is switched from the supercaps to the overhead wire.

3.4 Braking stage of the supercap-equipped vehicle

As soon as braking commences the control logic immediately switches the current from the electric motor, which acts as a generator, onto the battery of the supercaps which begin to charge; the voltage at their ends increases and the input current continues to flow until the vehicle has almost come to a complete standstill. The process is repeated every time energy is generated during vehicle deceleration.
3.5 Specific energy consumption

The energy consumption of current with a power supply from overhead wires in the presence of supercapacitors calculated from a traction diagram for a section of 300 metres of level and straight route with a full load is 343.1 kWh/100 km.

The mean consumption registered by the line, in real standard operating conditions, registered for vehicles running for other Italian transport companies, is approximately 260 kWh/100km.

The consumption of diesel fuel for normal operation in equal condition, in the presence of supercapcitors is 37.4l/100 km.

The percentage energy savings, calculated from the traction diagrams, of a supercap vehicle as opposed to a vehicle without supercapacitors is:

- with overhead wire power supply 26.2%
- running autonomously 22.1%
3.6 Supercap test in Milan

**Conditions requested for testing**

The vehicle must be ballasted and must run along ten typical straight routes with no gradients, 250 m in length, using power from the overhead line, in observance of the conditions indicated in the traction diagram.

Testing must be performed with the supercaps enabled and disenabled.

**Preparation of the vehicle:** The vehicle, with chassis number 62794 and service number ATM 703, was ballasted using sandbags along the whole length of the vehicle until an overall weight of 28,500 kg was reached in addition to the load of the four test personnel. Tyre pressure was checked to ensure nominal operating values were met.

**Instrumentation:** A personal computer was used complete with a diagnostics program for recording the various parameters. Energy consumption calculations were carried out by conversion of the diagnostic data using the MATHCAD analysis system.

**Personnel:** Four technicians were present - Martin Böh (Project Engineer, Vossloh Kiepe Düsseldorf), Torsten Schöne (Project Engineer, Vossloh Kiepe Düsseldorf), Laszlo Kiraly (Technical Assistance, Vossloh Kiepe, Italy), Roberto Barrera (Technical Assistance, Van Hool)

**Testing conditions:** Testing was performed on 23 -24 July 2009. The climatic conditions remained good for the whole period of testing with dry weather and a temperature of >35°C.
As a typical route the road running between Viale Liguria (Piazza Serafino Belfanti) to Viale Cassala / Via Carlo Torre was chosen (see the attached figure 1).

It must be underlined that the first difficulty encountered lay in the unfeasibility of travelling along 10 consecutive identical routes, due to traffic conditions and the traffic light system, therefore to run each following 250-m route the vehicle had to turn round and go back to where it started from.

Bearing in mind the difficulties caused by traffic conditions, the number of typical routes was reduced to 5 for each type of recording (5 recordings performed with the supercaps enabled and five without), having checked that the recording parameters did not vary for the different routes.

At the beginning of each route the supercaps were manually charged to the level of “output” charge from the previous route. As requested by specification ATM ST 72, the air-conditioning circuit was kept on throughout testing.

In order to better simulate the traction diagram referred to in ST ATM an external electric brake was installed. The driver, once the requested speed had been reached, left the vehicle to coast while the brake was activated until a determined route was reached.

As can be seen from the line on the diagrams, line voltage during the vehicle acceleration phases went below the value of 550V, altering the project conditions and consequently reducing traction. The values recorded by the vehicle’s diagnostic systems were converted with the help of the MATHCAD program. Each route run was documented by a power and energy diagram as well as a traction diagram.
Test results: **Routes run with the Supercaps enabled** - Name of the diagnostics file:

- ZLG1_0703_Abnahmefahrt250m_32 [No.: 1]
- ZLG1_0703_Abnahmefahrt250m_33 [No.: 2]
- ZLG1_0703_Abnahmefahrt250m_34 [No.: 3]
- ZLG1_0703_Abnahmefahrt250m_35 [No.: 4]
- ZLG1_0703_Abnahmefahrt250m_36 [No.: 5]

### Table 1: Test results: **Routes run with the Supercaps enabled**

<table>
<thead>
<tr>
<th>Record No.</th>
<th>Absorption of energy from the line $E_{OL}$ [Wh/t x km]</th>
<th>Route [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>109</td>
<td>257</td>
</tr>
<tr>
<td>33</td>
<td>120</td>
<td>234</td>
</tr>
<tr>
<td>34</td>
<td>115</td>
<td>235</td>
</tr>
<tr>
<td>35</td>
<td>124</td>
<td>221</td>
</tr>
<tr>
<td>36</td>
<td>126</td>
<td>223</td>
</tr>
<tr>
<td>Ø1</td>
<td><strong>118.8</strong></td>
<td></td>
</tr>
</tbody>
</table>
Test results: Routes run without the Supercaps enabled - Name of the diagnostics file:
- ZLG1_0703_Abnahmefahrt250m_37 [No.: 6]
- ZLG1_0703_Abnahmefahrt250m_38 [No.: 7]
- ZLG1_0703_Abnahmefahrt250m_39 [No.: 8]
- ZLG1_0703_Abnahmefahrt250m_40 [No.: 9]
- ZLG1_0703_Abnahmefahrt250m_41 [No.:10]

Table 2: Test results: Routes run without the Supercaps enabled

<table>
<thead>
<tr>
<th>Record No.</th>
<th>Absorption of energy from the line $E_{OL}$ [Wh/t x km]</th>
<th>Route [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>172</td>
<td>233</td>
</tr>
<tr>
<td>38</td>
<td>155</td>
<td>246</td>
</tr>
<tr>
<td>39</td>
<td>167</td>
<td>227</td>
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<tr>
<td>40</td>
<td>167</td>
<td>238</td>
</tr>
<tr>
<td>41</td>
<td>171</td>
<td>224</td>
</tr>
<tr>
<td>Ø2</td>
<td>166.4</td>
<td></td>
</tr>
</tbody>
</table>

**Processing of the results**

**Specific energy consumption**

the mean specific energy consumption with the supercaps enabled was:

$E_{OL} = 118.8\text{ kWh} / \text{ t x km}$ (see Table 1)

**Energy savings**

Energy savings, defined as the difference in specific consumption when the supercaps are enabled and disenabled multiplied by vehicle weight and length of the route is:
\[(166.4 - 118.8)\text{[Wh / t * km]} * 28.5\text{[t]} * 0.25\text{[km]} = 339.15\text{Wh}\]

Referring to 10 routes

\[= 339.15 \text{[Wh]} \times 10 \text{ routes}\]

\[= 3391.5 \text{ Wh}\]

**Calculation of the percentage of energy savings**

The percentage of energy savings for a vehicle running with SC compared to a vehicle without SC is:

\[
\left(1 - \frac{118.8}{166.4}\right) \times 100 = (1 - 71.39) = 28.61\%
\]

**Comparison of results with contractual indications**

The recorded consumption (0.1188 kWh / t x km) is in keeping with the declared consumption (0.134 kWh / t x km)

The energy savings measured for a vehicle running with SC compared to a vehicle without SC over 10 routes with no gradient (3.21 kWh) is less than declared (3.391 kWh).
Attachments Part A

1. ANNEX 1
   a. Data processing for the individual routes 1 .. 10
   b. Analysis of the power and energy records: 
      ZLG1_0703_Abnahmefahrt250m_32 - 41
   c. Diagnostic records: ZLG1_0703_Abnahmefahrt250m_32 - 41

2. Traction diagram 071108 01

3. Route for execution of testing

Key to diagnostic records

UNPOL: Line voltage
MSFB: Moment of acceleration-braking
IOL+: Line current
MIST: IST torque
UDSK+: Supercap voltage
V: Speed
SFZ_FABR: Route
ANNEX 1 - Data processing for the tests in Milan

Annex 1.1: Data processing for the routes with supercaps, Milan

Data processing for route [No.: 1]
Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_32.mat"
Route length: $s = 257.2572$ m
Vehicle weight: $m = 28.5$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- $E_{DPU\ FA} = 1056.1208$ Wh
- $E_{DPU\ FA} = 144.046$ Wh/(km x t)

Energie HTS im Fahren (ENERGY SUPPLIED BY THE SUPERCAPS):
- $E_{HTS\ FA} = 345.6728$ Wh
- $E_{HTS\ FA} = 47.1469$ Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{BNU} = 145.1491$ Wh
- $E_{BNU} = 19.7971$ Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- $E_{OL} = 800.2729$ Wh
- $E_{OL} = 109.1505$ Wh/(km x t)

Energie DPU im Bremsen (ENERGY SUPPLIED IN BRAKING):
- $E_{DPU\ BR} = 610.0695$ Wh
- $E_{DPU\ BR} = 83.2083$ Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- $E_{HTS\ BR} = 374.1931$ Wh
- $E_{HTS\ BR} = 51.0368$ Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Figure 2: Energy balance
DIAGNOSTIC HELP

PROGRAM
Creation date: 07.11.06
Project: DGVANCOUVER_en
Name: Windg01_en.exe
Version number: 96.046317.1270

CURRENT FUNCTION
Name: Display

DATA, CURR. FUNCTION
Data origin: ZLG1_0703_Ablauftafel250m_0
Equipment number: 1
Version: Module software: ZLG_MID20070800
Coach number: 703
Transmission date: 24.07.2009
Print date: 01.10.2009

1 UNPOL 600W/div
2 MSFB 500Nm/div
4 IOL+ 150A/div

5 MIST 500Nm/div
6 LDSK+ 100V/div
7 V 10km/h/div
8 SFZ_FABR 1000m/div

Time base: 6s/div
Data processing for route [No.: 2]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_33.mat"

Route length: \( s = 234.2395 \) m

Vehicle weight: \( m = 28.5 \) t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):

- \( E_{DPU \text{ FA}} = 1054.2765 \) Wh
- \( E_{DPU \text{ FA}} = 157.9245 \) Wh/(km x t)

Energie DPU im Bremsen (ENERGY SUPPLIED BY THE BRAKE):

- \( E_{DPU \text{ BR}} = 573.6187 \) Wh
- \( E_{DPU \text{ BR}} = 85.9247 \) Wh/(km x t)

Energie HTS im Fahren  (ENERGY SUPPLIED BY THE SUPERCAPS):

- \( E_{HTS \text{ FA}} = 331.348 \) Wh
- \( E_{HTS \text{ FA}} = 49.634 \) Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):

- \( E_{HTS \text{ BR}} = 350.4179 \) Wh
- \( E_{HTS \text{ BR}} = 52.4906 \) Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):

- \( E_{BNU} = 121.9879 \) Wh
- \( E_{BNU} = 18.2731 \) Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):

- \( E_{OL} = 799.2047 \) Wh
- \( E_{OL} = 119.7162 \) Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Figure 2: Energy balance
<table>
<thead>
<tr>
<th>PROGRAM</th>
<th>CURRENT FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creation date: 07.11.06</td>
<td>Name: Display</td>
</tr>
<tr>
<td>Project: DIGVANCOUVER_en</td>
<td>Data origin: ZLG_M124070900</td>
</tr>
<tr>
<td>Name: WinDg61_en.exe</td>
<td>Equipment number: ZLG_M124070900</td>
</tr>
<tr>
<td>Version number: 96.045317.127D</td>
<td>Cost: 703</td>
</tr>
<tr>
<td>DEVICE DEFINITION</td>
<td>Transmission date: 24.07.2009</td>
</tr>
<tr>
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<td>Print date: 01.10.2009</td>
</tr>
<tr>
<td>Object number: ZLG_M124070900</td>
<td></td>
</tr>
<tr>
<td>Device: ZLG1</td>
<td></td>
</tr>
<tr>
<td>Module: MZE1</td>
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</tbody>
</table>

**Graph:**

- **Axes:**
  - Y-axis: R, G, B
  - X-axis: Time base: 5s/div

- **Scales:**
  - 1 UNPOL: 600W/div
  - 2 MSFB: 500N/m/div
  - 3: 100W/div
  - 4 4OL+: 150A/div
  - 5 MIST: 500Nm/div
  - 6 UDSK+: 100V/div
  - 7 V: 10km/h/div
  - 8 SFZ_FABR: 1000m/div

---

**Page 1**
Data processing for route [No.: 3]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_34.mat"

Route length: \( s = 235.2112 \text{ m} \)
Vehicle weight: \( m = 28.5 \text{ t} \)

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- \( E_{\text{DPU FA}} = 1034.8073 \) Wh
- \( E_{\text{DPU FA}} = 154.3677 \) Wh/(km x t)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- \( E_{\text{DPU BR}} = 615.3265 \) Wh
- \( E_{\text{DPU BR}} = 91.7916 \) Wh/(km x t)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- \( E_{\text{HTS FA}} = 344.8907 \) Wh
- \( E_{\text{HTS FA}} = 51.4492 \) Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- \( E_{\text{HTS BR}} = 379.024 \) Wh
- \( E_{\text{HTS BR}} = 56.541 \) Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- \( E_{\text{BNU}} = 126.6686 \) Wh
- \( E_{\text{BNU}} = 18.8958 \) Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- \( E_{\text{OL}} = 769.9639 \) Wh
- \( E_{\text{OL}} = 114.8596 \) Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Figure 2: Energy balance
Data processing for route [No.: 4]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_35.mat"

Route length: \( s = 221.4219 \, \text{m} \)

Vehicle weight: \( m = 28.5 \, \text{t} \)

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- \( E_{\text{DPU,FA}} = 999.9726 \, \text{Wh} \)
- \( E_{\text{DPU,FA}} = 158.4611 \, \text{Wh/(km x t)} \)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- \( E_{\text{DPU, BR}} = 598.6338 \, \text{Wh} \)
- \( E_{\text{DPU, BR}} = 94.8628 \, \text{Wh/(km x t)} \)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- \( E_{\text{HTS, FA}} = 310.9599 \, \text{Wh} \)
- \( E_{\text{HTS, FA}} = 49.2764 \, \text{Wh/(km x t)} \)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- \( E_{\text{HTS, BR}} = 373.5045 \, \text{Wh} \)
- \( E_{\text{HTS, BR}} = 59.1876 \, \text{Wh/(km x t)} \)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- \( E_{\text{BNU}} = 161.6381 \, \text{Wh} \)
- \( E_{\text{BNU}} = 25.6141 \, \text{Wh/(km x t)} \)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- \( E_{\text{OL}} = 784.5263 \, \text{Wh} \)
- \( E_{\text{OL}} = 124.3203 \, \text{Wh/(km x t)} \)
Figure 1: Power absorbed and released by the vehicle

Figure 2: Energy balance
DIAGNOSTIC HELP

PROGRAM
Creation date: 07.11.09
Project: DIGVANCOUVER_en
Name: Windg61_en.exe
Version number: 98.048517.1271

DEVICE DEFINITION
Name: ZLG_MSL.pf
Object number: ZLG_M24090000
Device: ZLG
Module: MZE1

CURRENT FUNCTION
Name: Display

DATA CURR. FUNCTION
Data origin: ZLG1_0703_Abahnmetahrt250m_T1
Equipment number: ZLG_M24079000
Cost number: 703
Transmission date: 24.07.2009
Print date: 01.10.2009

Diagram with various measurements and parameters, including:
- 1 UNPOL 600W/div
- 2 MSFB 500N/m/div
- 4 IOL+ 150A/div
- 5 MIST 500N/m/div
- 6 UDSK+ 100V/div
- 7 V 10km/h/div
- 8 SFZ_FABR 1000m?/div

Time base: 5s/div
Data processing for route [No.: 5]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_36.mat"
Route length: \( s = 223.4827 \, \text{m} \)
Vehicle weight: \( m = 28.5 \, \text{t} \)

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- \( E_{\text{DPU FA}} = 1036.6584 \, \text{Wh} \)
- \( E_{\text{DPU FA}} = 162.7597 \, \text{Wh/(km x t)} \)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- \( E_{\text{DPU BR}} = 571.7006 \, \text{Wh} \)
- \( E_{\text{DPU BR}} = 89.7594 \, \text{Wh/(km x t)} \)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- \( E_{\text{HTS FA}} = 310.9938 \, \text{Wh} \)
- \( E_{\text{HTS FA}} = 48.8273 \, \text{Wh/(km x t)} \)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- \( E_{\text{HTS BR}} = 357.7338 \, \text{Wh} \)
- \( E_{\text{HTS BR}} = 56.1657 \, \text{Wh/(km x t)} \)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- \( E_{\text{BNU}} = 117.0667 \, \text{Wh} \)
- \( E_{\text{BNU}} = 18.38 \, \text{Wh/(km x t)} \)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- \( E_{\text{OL}} = 801.3856 \, \text{Wh} \)
- \( E_{\text{OL}} = 125.8209 \, \text{Wh/(km x t)} \)
Figure 1: Power absorbed and released by the vehicle

Figure 2: Energy balance
DIAGNOSTIC HELP

PROGRAM
Creation date: 07.11.05
Project: "DGVANCOUVER_en"
Name: "WinDg61_en.exe"
Version number: 99.040317.1271

DEVICE DEFINITION
Name: "ZLG_M1x.ppt"
Object number: "ZLG_M124070900"
Device: "ZLG"
Module: "MZE1"

CURRENT FUNCTION
Name: "Display"
DATA CURR. FUNCTION
Data origin: "ZLG1_0703_Abannahmefahrte290m_1"
Equipment number: "ZLG_M124070900"
Cost number: 703
Transmission date: 24.07.2009
Print date: 01.10.2009

Graph with various lines and annotations.
Annex 1.2: Data processing for the routes without supercaps

Data processing for route [No.: 6]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_37.mat"

Route length: $s = 233.0824$ m

Vehicle weight: $m = 28.5$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- $E_{DPU\ FA} = 1061.6405$ Wh
- $E_{DPU\ FA} = 159.8171$ Wh/(km x t)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- $E_{DPU\ BR} = 535.808$ Wh
- $E_{DPU\ BR} = 80.6594$ Wh/(km x t)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- $E_{HTS\ FA} = 0.46976$ Wh
- $E_{HTS\ FA} = 0.070716$ Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- $E_{HTS\ BR} = -0.0037111$ Wh
- $E_{HTS\ BR} = -0.00055866$ Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{BNU} = 102.0115$ Wh
- $E_{BNU} = 15.3566$ Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- $E_{OL} = 1140.2672$ Wh
- $E_{OL} = 171.6534$ Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Abbildung 2: Energieumsatz des Fahrzeugs
DIAGNOSTIC HELP

PROGRAM
Creation date: 07.11.06
Project: DIGYVANCOUVER_en
Name: WinDg61_en.exe
Version number: 55.045317.127D

CURRENT FUNCTION
Name: Display

DATA CURR. FUNCTION
Name: ZLG1_0703_Abahnmetafahrt250m_1
Data origin: 250m
Equipment number: ZLG_M24070900
Version: Module software: 703
Coast number: 24.07.2009
Transmission date: Print date: 01.10.2009

---

1 UNPOL
2 MSFB
600W/div
500N/m/div

4 10L+
150A/div

5 MIST
500N/m/div

6 UDSK+
100V/div

7 V
10km/h/div

8 SFZ_FABR
1000m²/div

Time base: 5s/div

---

Page 1
Data processing for route [No.: 7]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_38.mat"

Route length: $s = 246.1251$ m

Vehicle weight: $m = 28.5$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- $E_{DPU\ FA} = 1024.4955$ Wh
- $E_{DPU\ FA} = 146.0526$ Wh/(km x t)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- $E_{DPU\ BR} = 584.641$ Wh
- $E_{DPU\ BR} = 83.3467$ Wh/(km x t)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- $E_{HTS\ FA} = 0.44778$ Wh
- $E_{HTS\ FA} = 0.063835$ Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- $E_{HTS\ BR} = -0.031133$ Wh
- $E_{HTS\ BR} = -0.0044384$ Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{BNU} = 81.3471$ Wh
- $E_{BNU} = 11.5969$ Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- $E_{OL} = 1084.723$ Wh
- $E_{OL} = 154.6387$ Wh/(km x t)
Auswertung Abnahmefahrt: Leistung

Figure 1: Power absorbed and released by the vehicle

Auswertung Abnahmefahrt: Energie

Abbildung 2: Energieumsatz des Fahrzeugs
Data processing for route [No.: 8]

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_39.mat"

Route length: $s = 227.1349$ m
Vehicle weight: $m = 28.5$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- $E_{DPU\ FA} = 988.4688$ Wh
- $E_{DPU\ FA} = 152.6983$ Wh/(km x t)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- $E_{DPU\ BR} = 574.1479$ Wh
- $E_{DPU\ BR} = 88.6942$ Wh/(km x t)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- $E_{HTS\ FA} = 0.57569$ Wh
- $E_{HTS\ FA} = 0.088932$ Wh/(km x t)

Energie HTS im Bremsen (BRAKING ENERGY):
- $E_{HTS\ BR} = -0.23784$ Wh
- $E_{HTS\ BR} = -0.036742$ Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{BNU} = 123.6596$ Wh
- $E_{BNU} = 19.1029$ Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- $E_{OL} = 1078.4938$ Wh
- $E_{OL} = 166.6054$ Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Abbildung 2: Energieumsatz des Fahrzeugs
Data processing for route [No.: 9]

Name of the .lac file: "ZLG1_0703_Abnahmfahrt250m_40.mat"

Route length: \( s = 237.9769 \) m

Vehicle weight: \( m = 28.5 \) t

Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):
- \( E_{DPU\ FA} = 1059.4847 \) Wh
- \( E_{DPU\ FA} = 156.2122 \) Wh/(km x t)

Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):
- \( E_{DPU\ BR} = 552.9261 \) Wh
- \( E_{DPU\ BR} = 81.5244 \) Wh/(km x t)

Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):
- \( E_{HTS\ FA} = 0.29902 \) Wh
- \( E_{HTS\ FA} = 0.044088 \) Wh/(km x t)

Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):
- \( E_{HTS\ BR} = -0.11902 \) Wh
- \( E_{HTS\ BR} = -0.017549 \) Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- \( E_{BNU} = 83.8089 \) Wh
- \( E_{BNU} = 12.3569 \) Wh/(km x t)

Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):
- \( E_{OL} = 1129.6212 \) Wh
- \( E_{OL} = 166.5533 \) Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Abbildung 2: Energieumsatz des Fahrzeugs
**Data processing for route [No.: 10]**

Name of the .lac file: "ZLG1_0703_Abnahmefahrt250m_41.mat"

Route length: \( s = 223.9355 \) m

Vehicle weight: \( m = 28.5 \) t

**Energie in DPU im Fahren (ENERGY CONSUMPTION FOR TRACTION TO THE MOTOR):**

- \( E_{\text{DPU FA}} = 998.956 \) Wh
- \( E_{\text{DPU FA}} = 156.5231 \) Wh/(km x t)

**Energie DPU im Bremsen (ENERGY PROVIDED BY THE BRAKE):**

- \( E_{\text{DPU BR}} = 593.6939 \) Wh
- \( E_{\text{DPU BR}} = 93.0239 \) Wh/(km x t)

**Energie HTS im Fahren (ENERGY PROVIDED BY THE SUPERCAPS):**

- \( E_{\text{HTS FA}} = 0.20657 \) Wh
- \( E_{\text{HTS FA}} = 0.032366 \) Wh/(km x t)

**Energie HTS im Bremsen (ENERGY TO RECHARGE THE SUPERCAPS):**

- \( E_{\text{HTS BR}} = 0.0213 \) Wh
- \( E_{\text{HTS BR}} = 0.0033374 \) Wh/(km x t)

**Energie in BNU (ENERGY CONSUMED BY AIR-CON):**

- \( E_{\text{BNU}} = 137.7917 \) Wh
- \( E_{\text{BNU}} = 21.5901 \) Wh/(km x t)

**Energie aus Oberleitung (TOTAL CONSUMPTION OF OVERHEAD LINE ENERGY):**

- \( E_{\text{OL}} = 1089.8741 \) Wh
- \( E_{\text{OL}} = 170.7688 \) Wh/(km x t)
Figure 1: Power absorbed and released by the vehicle

Abbildung 2: Energieumsatz des Fahrzeugs
## DIAGNOSTIC HELP

**PROGRAM**
- **Creation date:** 07.11.06
- **Project:** DIGVANCOUVER_en
- **Name:** WinDgpt1_en.exe
- **Version number:** 96.043517.127D

**DEVICE DEFINITION**
- **Name:** ZLG_MI.ppt
- **Object number:** ZLG_M240T0900
- **Device:** ZLG
- **Module:** MZE1

**CURRENT FUNCTION**
- **Name:** Display

**DATA CURR. FUNCTION**
- **Data origin:** ZLG1_0709_Abnahmefahrt250m_
- **Equipment number:** 1
- **Version Module software:** ZLG_M240T0900
- **Cost number:** 703
- **Transmission date:** 24.07.2009
- **Print date:** 01.10.2009

---

### Graph

<table>
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<tr>
<th>1</th>
<th>UNPOL</th>
<th>2</th>
<th>MSFB</th>
<th>4</th>
<th>IQL+</th>
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<td>600 W/div</td>
<td>500 Nm/div</td>
<td>150 A/div</td>
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<td></td>
</tr>
</tbody>
</table>

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<table>
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<tr>
<th>5</th>
<th>MIST</th>
<th>6</th>
<th>UDSK+</th>
<th>7</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 Nm/div</td>
<td>100 V/div</td>
<td>100 km/h/div</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Time base:** 5 s/div
**ATM MAILAND**

**DIAGRAMMA DI TRAZIONE**

**PENDENZA 0% - 250m CON SUPERCAPACITORI**

- **PESO DEL VEICOLO A VUOTO**: 19.00t
- **PESO DEI PASSENGERI**: 10.60t
- **TENSIONE TRA/FREI**: 600.00V / 750.00V
- **PENDENZA**: 0.00%
- **TRATTA**: 250.00m

**TECNOLOGIA**: TROLLEY

- **SPARROW**: 1,386,000W
- **HIGHER**: 932,000W

**ACCELERAZIONE MAX**: 1.11 m/s²

- **Vel. CALMA**: 1.1 m/s²
- **Vel. CAM**: 0.97 m/s²
- **Vel. CIRCA**: 2.63 km/h

**CORRENTE ERP DEL MOTORE**: 392.4kA

** POTENZA DEL GENERATORE**: 7,590kW / 425.000W

**CONSOMMA URTO DI FRENO**: 779.2kWh / 245.000W

**CONSOMMA URNA**: 517.0kWh / 145.000W

**RISERTEUR ENERGY IN CIRCUIT**: 203.5kWh / 203.5kWh

**CONSOMMA ACCELERATORI**: 10.4kWh / 40.4kWh

**CONSOMMA ENERGIA TOTAL**: 926.3kWh / 125.100kWh

**CONSOMMA ENERGIA PER KM**: 475.18kW / 117.800W

---

**Diagramma di trazione**:

- **M**: Corrente del motore
- **v**: Velocità
- **s**: Tratta
- **t**: Tempo

---

**TROLLEY Transnational Manual on Advanced Energy Storage Systems**

54 of 85
3.7 Supercap Test in Parma
Aim: The purpose of testing is to measure specific energy consumption of the vehicle when running at full load with power provided by the overhead line, both with active energy recovery devices (supercapacitors) enabled and with said devices disenabled.

Description of the recovery system: The vehicle is equipped with a supercap system which makes it possible to recover 100% of the energy generated by the electric motor during braking.

The energy flowing into and out of the modules is managed by control software in accordance with parameters which can be selected to ensure maximum optimization depending on characteristics of the line.

The on-board diagnostics system provides details on the energy values absorbed from the overhead lines and released by the vehicle as well as the value of the energy absorbed from the supercap system. Furthermore data is also made available relative to line voltage and current values provided by 5 measurements taken at regular intervals between two consecutive stops.

Test parameters:

Date: 29.01.2013
Weather conditions: Damp, temperature 1°C
Vehicle type: VanHool ExquiCity 18
Place: Straight section of a trolleybus line in Parma

Instrumentation: Notebook computer with diagnostics cable; diagnostics program for the electrical drive system of the Exquicity Parma vehicle.

Tester: Björn Wagner
**Test preparations:** the vehicle was ballasted with sandbags with an overall weight of 9.0 t

<table>
<thead>
<tr>
<th>Description</th>
<th>Weight (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare weight of the vehicle:</td>
<td>20.66 t</td>
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<tr>
<td>Testing personnel: 5 people</td>
<td>0.34 t</td>
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<tr>
<td>Ballast</td>
<td>9.00 t</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>30.00 t</strong></td>
</tr>
</tbody>
</table>

**Additional information:** The vehicle travelled along the same route a number of times with the supercaps enabled and disenabled. At the beginning of each route the supercaps were manually charged to the level of “output” charge from the previous route.

Traffic conditions meant it was impossible to make recordings on routes which were totally identical. In fact it can be seen that the length of the routes taken into consideration vary between a minimum of 280 m and a maximum of 328 m. However diagnostics provide us with a specific consumption datum (Wh/t x km) so consumption values can easily be compared.
**Records with Supercap enabled:**

- ZLG_5104_Prova SC energia.2.laz [No.: 1]
- ZLG_5104_Prova SC energia.6.laz [No.: 2]
- ZLG_5104_Prova SC energia.7.laz [No.: 3]
- ZLG_5104_Prova SC energia.13.laz [No.: 4]
- ZLG_5104_Prova SC energia.14.laz [No.: 5]

<table>
<thead>
<tr>
<th>Record No.</th>
<th>Absorption of energy from the line $E_{OL}$ [Wh/t x km]</th>
<th>Route [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>111,16</td>
<td>280</td>
</tr>
<tr>
<td>2</td>
<td>109,63</td>
<td>292</td>
</tr>
<tr>
<td>3</td>
<td>110,66</td>
<td>306</td>
</tr>
<tr>
<td>4</td>
<td>110,41</td>
<td>298</td>
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<tr>
<td>5</td>
<td>113,59</td>
<td>320</td>
</tr>
<tr>
<td>Ø1</td>
<td>111,09</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1

**Records with supercap disabled:**

- ZLG_5104_Prova SC energia_noSC.3.laz [No.: 6]
- ZLG_5104_Prova SC energia_noSC.4.laz [No.: 7]
- ZLG_5104_Prova SC energia_noSC.6.laz [No.: 8]
- ZLG_5104_Prova SC energia_noSC.13.laz [No.: 9]
- ZLG_5104_Prova SC energia_noSC.15.laz [No.: 10]

<table>
<thead>
<tr>
<th>Record No.</th>
<th>Absorption of energy from the line $E_{OL}$ [Wh/t x km]</th>
<th>Route [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>151,58</td>
<td>323</td>
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<tr>
<td>7</td>
<td>155,54</td>
<td>314</td>
</tr>
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<td>8</td>
<td>148,22</td>
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<td>153,26</td>
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<td>295</td>
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<td>Ø2</td>
<td>151,48</td>
<td>-</td>
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</tbody>
</table>

Table 2
Processing of the results

Energy consumption:
The mean specific energy consumption with the supercaps enabled and disenabled was (respectively):

\[ E_{OL\ (with\ SC)} = 111.09 \text{ Wh} / \text{t x km} \quad \leftrightarrow \quad 3.3327 \text{ kWh/km} \]

\[ E_{OL\ (without\ SC)} = 151.48 \text{ Wh} / \text{t x km} \]

Energy savings over a 300-m route:

\[
\text{Energy savings} = (\phi_{\text{energy absorption without SC}} - \phi_{\text{energy absorption with SC}}) \times \text{vehicle weight} \times \text{route length}
\]

\[
= (151.48 - 111.09) \text{ Wh} / \text{t x km} \times 30.00 \text{ t x 0.3 km}
\]

\[
= 363.51 \text{ Wh (per 300m)}
\]

Referring to 10 routes

\[
= 363.51 \text{ Wh x 10 routes}
\]

\[
= 3,635.1 \text{ Wh}
\]

Calculation of the percentage of energy savings:
The percentage of energy savings for a vehicle running with SC compared to a vehicle without SC is:

\[
\left(1 - \frac{111,09}{151,48}\right) \times 100 = \left(1 - \frac{73,34}{73,34}\right) = 26.66\%
\]

Key to diagnostic records

- **UNPOL**: Line voltage
- **MSFB**: Moment of acceleration-braking
- **IOL+**: Line current
- **MIST**: IST torque
- **UDSK+**: Supercap voltage
- **V**: Speed
ANNEX 2 - Data processing for the tests in Parma

Annex 2.1  Diagnostic records with Supercaps enabled:

Testaufnahme ZLG_5104_Prova SC energia.2
Testaufnahme ZLG_5104_Prova SC energia.6
Testaufnahme ZLG_5104_Prova SC energia.7
Testaufnahme ZLG_5104_Prova SC energia.13
Testaufnahme ZLG_5104_Prova SC energia.14
Annex 2.2  Diagnostic records with Supercaps disabled

Testaufnahme ZLG_5104_Prova SC energia_NO SC.3
Testaufnahme ZLG_5104_Prova SC energia_NO SC.4
Testaufnahme ZLG_5104_Prova SC energia_NO SC.6
Testaufnahme ZLG_5104_Prova SC energia_NO SC.13
Testaufnahme ZLG_5104_Prova SC energia_NO SC.15
Example of diagnostic records data processing

Data processing for route No. 2 with SC:

File name: "ZLG_5104_Prova SC energia_6"
Route length: \( s = 293.5022 \text{ m} \)
Vehicle weight: \( m = 30.00 \text{ t} \)

**Energie in DPU im Fahren (ENERGY CONSUMPTION IN TRACTION):**

- \( E_{\text{DPU FA}} = 1228.616 \text{ Wh} \)
- \( E_{\text{DPU FA}} = 141.4207 \text{ Wh/(km x t)} \)

**Energie DPU im Bremsen (BRAKING ENERGY):**

- \( E_{\text{DPU BR}} = 612.4565 \text{ Wh} \)
- \( E_{\text{DPU BR}} = 70.4973 \text{ Wh/(km x t)} \)

**Energie HTS im Fahren (CAPACITOR ENERGY USE):**

- \( E_{\text{HTS FA}} = 342.8173 \text{ Wh} \)
- \( E_{\text{HTS FA}} = 39.4602 \text{ Wh/(km x t)} \)

**Energie HTS im Bremsen (BRAKING ENERGY):**

- \( E_{\text{HTS BR}} = 419.0424 \text{ Wh} \)
- \( E_{\text{HTS BR}} = 48.2342 \text{ Wh/(km x t)} \)

**Energie in BNU (ENERGY CONSUMED BY AIR-CON):**

- \( E_{\text{BNU}} = 134.1385 \text{ Wh} \)
- \( E_{\text{BNU}} = 15.4401 \text{ Wh/(km x t)} \)

**Energie aus Oberleitung im Fahren (TOTAL ENERGY CONSUMPTION):**

- \( E_{\text{OL FA}} = 927.1926 \text{ Wh} \)
- \( E_{\text{OL FA}} = 106.7252 \text{ Wh/(km x t)} \)

**Energie in Oberleitung im Bremsen (...):**

- \( E_{\text{OL BR}} = -16.5448 \text{ Wh} \)
- \( E_{\text{OL BR}} = -1.9044 \text{ Wh/(km*t)} \)
Figure 1: Energy absorbed and released by the vehicle

Figure 2: Vehicle energy balance
Data processing for route No. 3 with SC:

File name: "ZLG_5104_Prova SC energia_7"
Route length: $s = 307.5142$ m
Vehicle weight: $m = 30.00$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION IN TRACTION):
- $E_{\text{DPU FA}} = 1307.2942$ Wh
- $E_{\text{DPU FA}} = 143.6205$ Wh/(km x t)

Energie DPU im Bremsen (BRAKING ENERGY):
- $E_{\text{DPU BR}} = 650.3845$ Wh
- $E_{\text{DPU BR}} = 71.4518$ Wh/(km x t)

Energie HTS im Fahren (CAPACITOR ENERGY USE)
- $E_{\text{HTS FA}} = 305.9485$ Wh
- $E_{\text{HTS FA}} = 33.6118$ Wh/(km x t)

Energie HTS im Bremsen (BRAKING ENERGY):
- $E_{\text{HTS BR}} = 341.518$ Wh
- $E_{\text{HTS BR}} = 37.5195$ Wh/(km x t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{\text{BNU}} = 63.8105$ Wh
- $E_{\text{BNU}} = 7.0103$ Wh/(km x t)

Energie aus Oberleitung im Fahren (TOTAL ENERGY CONSUMPTION):
- $E_{\text{OL FA}} = 1016.2808$ Wh
- $E_{\text{OL FA}} = 111.6495$ Wh/(km x t)

Energie in Oberleitung im Bremsen (...):
- $E_{\text{OL BR}} = 1.318$ Wh
- $E_{\text{OL BR}} = 0.14479$ Wh/(km*t)
Figure 1: Energy absorbed and released by the vehicle

Figure 2: Vehicle energy balance
Data processing for route No. 8 with SC:

File name: "ZLG_5104_Prova SC energia_NO SC_6"
Route length: $s = 315.696$ m
Vehicle weight: $m = 30.00$ t

Energie in DPU im Fahren (ENERGY CONSUMPTION IN TRACTION):
- $E_{\text{DPU FA}} = 1335.5515$ Wh
- $E_{\text{DPU FA}} = 142.9222$ Wh/(km x t)

Energie DPU im Bremsen (BRAKING ENERGY):
- $E_{\text{DPU BR}} = 639.7352$ Wh
- $E_{\text{DPU BR}} = 68.4604$ Wh/(km x t)

Energie HTS im Fahren (CAPACITOR ENERGY USE)
- $E_{\text{HTS FA}} = -2.2438$ Wh
- $E_{\text{HTS FA}} = -0.24012$ Wh/(km x t)

Energie HTS im Bremsen (BRAKING ENERGY):
- $E_{\text{HTS BR}} = 1.6113$ Wh
- $E_{\text{HTS BR}} = 0.17243$ Wh/(km*t)

Energie in BNU (ENERGY CONSUMED BY AIR-CON):
- $E_{\text{BNU}} = 110.1625$ Wh
- $E_{\text{BNU}} = 11.7889$ Wh/(km x t)

Energie aus Oberleitung im Fahren (TOTAL ENERGY CONSUMPTION):
- $E_{\text{OL FA}} = 1371.9409$ Wh
- $E_{\text{OL FA}} = 146.8164$ Wh/(km x t)

Energie in Oberleitung im Bremsen (...):
- $E_{\text{OL BR}} = -1.4414$ Wh
- $E_{\text{OL BR}} = -0.15424$ Wh/(km*t)
Figure 1: Energy absorbed and released by the vehicle

Figure 2: Vehicle energy balance
Auswertung Abnahmefahrt Nr. 9 ohne SC:

Name der .lac-Datei: "ZLG_5104_Prova SC energia_NO SC_13"
Streckenlänge: \( s = 329.1673 \text{ m} \)
Masse Fahrzeug: \( m = 29.6 \text{ t} \)

**Energie in DPU im Fahren (ENERGY CONSUMPTION IN TRACTION):**
- \( E_{\text{DPU FA}} = 1460.906 \text{ Wh} \)
- \( E_{\text{DPU FA}} = 149.9388 \text{ Wh/(km x t)} \)

**Energie DPU im Bremsen (BRAKING ENERGY):**
- \( E_{\text{DPU BR}} = 585.792 \text{ Wh} \)
- \( E_{\text{DPU BR}} = 60.1222 \text{ Wh/(km x t)} \)

**Energie HTS im Fahren (CAPACITOR ENERGY USE):**
- \( E_{\text{HTS FA}} = -2.1921 \text{ Wh} \)
- \( E_{\text{HTS FA}} = -0.22498 \text{ Wh/(km x t)} \)

**Energie HTS im Bremsen (BRAKING ENERGY):**
- \( E_{\text{HTS BR}} = 1.5632 \text{ Wh} \)
- \( E_{\text{HTS BR}} = 0.16043 \text{ Wh/(km x t)} \)

**Energie in BNU (ENERGY CONSUMED BY AIR-CON):**
- \( E_{\text{BNU}} = 56.8132 \text{ Wh} \)
- \( E_{\text{BNU}} = 5.831 \text{ Wh/(km x t)} \)

**Energie aus Oberleitung im Fahren (TOTAL ENERGY CONSUMPTION):**
- \( E_{\text{OL FA}} = 1464.2582 \text{ Wh} \)
- \( E_{\text{OL FA}} = 150.2828 \text{ Wh/(km x t)} \)

**Energie in Oberleitung im Bremsen (...):**
- \( E_{\text{OL BR}} = 1.2791 \text{ Wh} \)
- \( E_{\text{OL BR}} = 0.13128 \text{ Wh/(km*t)} \)
Figure 1: Energy absorbed and released by the vehicle

Figure 2: Vehicle energy balance
**TROLLEY Transnational Manual on Advanced Energy Storage Systems**

### Traction diagram

**FILOBUS PARMA**

**Diagramma di Trazione**

<table>
<thead>
<tr>
<th>Parametro</th>
<th>Valore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posizione del Veicolo A Vuoto</td>
<td>19.00 m</td>
</tr>
<tr>
<td>Posizione dei Passaggi</td>
<td>16.00 m</td>
</tr>
<tr>
<td>Posizione Tra/Tras.</td>
<td>550.00/770.00 W</td>
</tr>
<tr>
<td>Pendenza</td>
<td>0.00°</td>
</tr>
<tr>
<td>Tratta</td>
<td>200.00 m</td>
</tr>
<tr>
<td>Tramite di S-area</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Diametro delle Route</td>
<td>940.00 mm</td>
</tr>
<tr>
<td>Raggio di Trasmissione</td>
<td>1.050/1</td>
</tr>
<tr>
<td>Accelerazione Massa</td>
<td>1.20 m/s²</td>
</tr>
<tr>
<td>Decelerazione Massa</td>
<td>1.00 m/s²</td>
</tr>
<tr>
<td>Velocità Commerciale</td>
<td>13.80 km/h</td>
</tr>
<tr>
<td>Corrente Eff.Del Motore</td>
<td>260.00 A</td>
</tr>
<tr>
<td>Corrente Eff.Di Linea</td>
<td>280.00 A</td>
</tr>
<tr>
<td>Consumo Energia di Trazione</td>
<td>1918 kwh</td>
</tr>
<tr>
<td>Recupero Energia del Fren.</td>
<td>516.00 Wh</td>
</tr>
<tr>
<td>Consumo Energia Total</td>
<td>596.8 Wh, w...1322 Wh/(100 km)</td>
</tr>
</tbody>
</table>

![Graph](image-url)
PART B

1. Installation of the lithium-ion-battery for the combined on-board energy storage system for Europe’s first “Trolley-Hybrid-Bus”

With the delivery of a new Solaris/Cegelec bus in June 2012, PP03 BBG from Eberswalde (Germany) received an innovative and far unique vehicle: a Trolley-(battery)-Hybrid-Bus, the first of its kind in Europe!

The new bus is different from existing hybrid trolleybuses that run on electricity and diesel – some in addition being equipped with supercapacitor batteries. The diesel engine has been replaced by a lithium-ion battery, the system is now featuring two fully electric drive systems. The bus can receive power either via the catenary or the lithium-ion battery. On short distances, for example in the depot, the bus can additionally run on supercapacitors – the third electric drive system. All three systems have in common that they make the bus 100 % emission-free.

In test mode the new bus was able to run over a distance of 18 km – powered only by the battery. In theory a distance of even 28 km could be reached. In daily operation, however, the bus will be able to cover a wireless distance of approx. 5 km. Charging energy for this distance – via the catenary – takes ca. 20 minutes.

A series of tests carried out in January 2013 to evaluate the performance of the lithium-ion-battery demonstrate that the bus saves approx. another 25% of energy consumption compared to a “conventional” trolleybus (equipped with supercaps and auxiliary diesel engine in Eberswalde). Based on the tests conducted in Eberswalde, it can be said that investing in a hybrid trolleybus is worthwhile in terms of operating costs and environmental aspects for changes in routing or expansion of the trolleybus network. The current dimensioning of the battery capacity (72 kWh) for distances of approx. 4 km battery operation at a total line distance of approx. 18 km (the network in Eberswalde consists of two lines: line 861 with 18.8 km and line 862 with 18.1 km) is optimal for Eberswalde for a maximum life expectancy of the installed lithium ion battery. BBG will now examine the route network once more concerning possible expansion, keeping this aspect in mind.
2. Status of realisation

The realisation of the investment 3.2 “Costs of the lithium-ion-battery for the combined on-board energy storage system for Europe’s first “Trolley-Hybrid-Bus” of the TROLLEY project is 100% fulfilled.

Note: The pre-(feasibility)study of the Fraunhofer Institute for Transportation and Infrastructure Systems revealed that an installation of supercapacitors (supercaps) in a substation does not seem to be useful and economic, when energy can already be stored on the vehicle via supercaps (the energy consumption could already be decreased by 17 % due to the installation of on-board supercaps in Eberswalde; see also Part II of the “Transnational Manual on Advanced Energy Storage Systems”). The pre-study, which has been carried out between January 2011 and May 2012 by the external expert Fraunhofer Institute for Transportation and Infrastructure Systems (IVI), Germany, will become a part of the core output 3.3.10 “Section B: Transnational Manual on Energy Storage Part 2”. Thus, all other TROLLEY partners and interested parties beyond TROLLEY will benefit from the simulated use cases since they can use the knowledge gained in Eberswalde.

However, due to the pre-study results, PP03 BBG searched for another possibility to realise an investment for the optimisation of the energy use for the trolleybus system (WP3) and planned a combined on-board energy storage system including both a supercap (already installed on the roof of the new trolleybus fleet in Eberswalde) and an additional new battery storage unit. Such a combined on-board storage system is a “Europe's first”.

PP03 BBG decided to realise the newly planned investment 3.2 though, as the last delivery of the last and 12th trolleybus of the new trolleybus fleet was scheduled for June 2012 and therefore the last possibility to get a trolleybus with a combined on-board energy storage system was given for the next 17 years (timeframe for the operation of the new trolleybus fleet until renewal of the 12 trolleybuses).
Figure 1: Trolley-Hybrid-Bus equipped with a lithium-ion-battery – the investment 3.2 in Eberswalde

The TROLLEY investment refers to the purchase of the additional on-board storage lithium ion battery as a new element in a trolleybus from Eberswalde and thus resulted only in a change of focus with regard to the former planned TROLLEY investment 3.2 (WP3; from off-board to on-board energy storage system). PP03 BBG tendered the newly innovative combined energy storage system (Europe-wide tender) from mid-April to mid-May and received two bids for such a system. The tender included the additional on-board storage unit (lithium ion battery) and its instalment and integration into the existing on-board energy storage system (supercaps) of the trolleybuses in Eberswalde.

The innovative Trolley-Hybrid-Bus has two fully adequate electric drive systems and is able to drive without producing emissions as it can obtain its traction current either from the catenary or from the lithium ion battery. In both cases, energy supply is supported by the additionally installed supercaps, which can, over short distances (at the depot for example) even serve as a third drive option.

The cost for such an innovative combined storage system or the additional on-board storage (lithium ion battery) respectively amounted to 113,740 EUR. The investment was paid by PP03 BBG mid-June 2012 and the expenditure on the investment has been checked by BBG’s First Level Controller for the 5th payment claim. The PP03 BBG also carried out a testing phase and evaluation (supported by the external expert Cegelec) of the test runs of this
vehicle. The vehicle has arrived in June 2012 in Eberswalde and was officially introduced/presented in August 2012 to the public.

In general, the lithium ion battery has a total capacity of 70.4 kWh and energy consumption is at approximately 2.5 kWh per kilometre. With this power supply, it is, in purely mathematical terms, even possible to cover a distance of more than 28 km. In practice, this figure will not be accomplished, as if the discharge is too deep, life expectancy of the battery is shortened considerably. In the end, the total capacity in normal operation will level off at 42.2 kWh, which corresponds to a state of charge of 85%.

The lithium ion battery in the Trolley-Hybrid-Bus for Eberswalde was tested extensively in Ostrava (CZ) in June 2012 before its delivery to Eberswalde. Ostrava’s topography is similar to that of Eberswalde and in test operation even a distance of more than 18 km was covered. In practice, a maximum distance of 5 kilometres should be travelled in order to achieve approximately 12,000 loading cycles. For a distance of 5 km, a loading time of about 20 minutes is required and the battery is being recharged via the collectors at the catenary.

The tests in Eberswalde in January 2013 were also quite promising and a test series shall be repeated during summer time 2013 (with the additional energy consumption of a cooling instead of a heating system). The new Trolley-Hybrid-Bus of Eberswalde reached a sing of approx. 25% of energy consumption compared to a trolleybus equipped only with supercaps (and an auxiliary diesel engine).
Figure 2: Trolley-Hybrid-Bus test results for optimised load cycle of the lithium-ion-battery and with regard to energy consumption compared to a “conventional” trolleybus in Eberswalde.
In summary, it can be said on the basis of the tests conducted in Eberswalde, that investing in a hybrid trolleybus is worthwhile in terms of operating costs and environmental aspects for changes in routing or expansion of the trolleybus network. The current dimensioning of the battery capacity (72 kWh) for distances of approx. 4 km battery operation at a total line distance of approx. 18 km (the network in Eberswalde consists of two lines: line 861 with 18.8 km and line 862 with 18.1 km) is optimal for a maximum life expectancy of the installed lithium ion battery. BBG will now examine the route network once more concerning possible expansion, keeping this aspect in mind.

3. Transnational added value

The trolleybus in Eberswalde equipped with the “combined on-board energy storage system” is a “Europe’s first” and therefore of a high interest to other Public transport (PT) operators as a pilot “hybrid-trolleybus”. The results of the testing demonstrate the possibility to ride partially overhead-wire free for several kilometers and furthermore, could lead to a replacement of the additional diesel-engine with alternator, with which nearly all trolleybuses are still equipped. Thus, this “hybrid-trolleybus” would be a crucial element on the way to pure ebuses considering further developments of trolleybuses.

The potential impact of the “combined on-board energy storage system” in Eberswalde includes firstly, less energy consumption in the region, which will also contribute to meet the “Zero-Emission” target of the Barnim district. Secondly, due to the lower energy consumption the public transport system raise its competitiveness in general. Thirdly, public transport operators will benefit because the investment will lead to savings in energy costs and due to lower operation costs the public transport costs would be stabilised. This would make public transport more competitive.

The catenary-free operation and thus gained flexibility of a trolleybus system could be important for network extensions to urban areas in which catenaries are undesired regarding urban development aspects. Additionally, further development on the trolleybus network could be tested without any risks of investing in infrastructure firstly.

The Trolley-Hybrid-Bus from Eberswalde with its on-board storage system is a “Europe's first” and already raised awareness across Europe. The trolleybus cities of Esslingen (DE) and
Landskrona (SE) and also the TROLLEY partner city Gdynia (via PKT Gdynia) will purchase and test such a battery system for catenary-free operation on short distances (up to 5 km) in the framework of national or European (Gdynia as CIVITAS-DYN@MO partner) funding programs.