First experiences of ethanol hybrid buses operating in public transport

Martina Wikström[1,*], Anders Folkesson[2], Per Alvfors[1]

[1] *Chemical Engineering and Technology, Division of Energy Processes, Royal Institute of Technology, Stockholm, Sweden*
[2] *Sustainable Solutions, Buses and Coaches, Scania CV AB, Södertälje, Sweden*
** Corresponding author. Tel: +46 8 790 65 51, Fax: +46 8 732 08 58, E-mail: marbjor@kth.se*

Abstract: With the ambitions to further increase its share of more sustainable vehicles, Stockholm Public Transport Authority (SL) carried out a project to evaluate the performance of ethanol hybrid buses together with bus manufacturer Scania and bus operator Nobina. Ethanol hybrid buses were operating in regular suburban public transport traffic in Stockholm between May 2009 and June 2010. The purpose of this paper is to evaluate the potential of the ethanol hybrid buses in general and their energy efficiency in particular. The evaluation is based on experimental data, mainly from standardised duty cycle tests, but also general experiences during the trail, for example error reports. The buses have a series hybrid powertrain with super capacitors as energy storage. At favourable conditions the fuel reduction is approximately 20 %. The potential additional fuel savings of the start/stop software has been tested and adds at least another 10 % fuel reduction. Not all of the hybrid system's components are yet robust enough, thus they need further development to fully commercial. Hybrid city buses have great potential but are currently not technically mature and proven, nor have the overall costs over the lifetime of the vehicle reached a commercial level as yet.

Keywords: *Ethanol hybrid bus, Series hybrid, Duty cycle, Urban public transportation, Energy analysis*

1. Introduction

Six ethanol hybrid buses and one reference bus were operated during a one-year field test to evaluate the robustness and energy saving potential of their hybrid powertrain. Partners in the project were the Stockholm Public Transport Authority (SL), the bus manufacturer Scania and the bus operator Nobina and it was carried out with funding from the Swedish Energy Agency. This is a unique project because it is one of the first times renewable-fuelled hybrid buses have been tested and operated in real traffic. The buses were operating in Stockholm's south suburban areas but were also taken out of traffic to perform standardised duty cycle tests on a test circuit, tests intended to better reflect inner-city driving. The objective of the field test from Scania's perspective was to test the hybrid powertrain in real traffic early in the development process in order to find weaknesses in the hybrid system. From SL's and Nobina's point of view the project aimed to evaluate the status and the potential of hybrid buses and was a way to enhance the development of even more environmentally friendly vehicles in their fleets. Already today (2010), SL has the world largest fleet of renewable-fuelled buses with more than 400 ethanol buses and 100 biogas buses in operation out of a fleet of around 2000 buses. The target is that 50 % of all buses should run on renewable fuels at the end of 2011 and 100 % by 2025 [1]. In this paper the general operational findings are presented with focus on evaluation of robustness of the powertrain (one-year field test) and the energy efficiency potential (duty cycle tests).

2. Methodology

The objectives are to evaluate the robustness and the energy efficiency potential of ethanol hybrid buses. In order to evaluate the robustness of the hybrid powertrain, the drivers and technicians filed error reports during the one-year field test. To attain reproducible experimental data in order to evaluate the energy efficiency potential, duty cycle tests were carried out. More details about the experimental set-up, see section *5. Experiments and results.*

3. Towards sustainable urban transportation

There are many reasons for promoting more sustainable urban transportation:

- To reduce emissions harmful to public health such as NOx, particulates and noise.
- To reduce emissions of greenhouse gases, most important fossil CO_2.
- To secure energy supply for the transport sector in the long term.

Additionally, by increasing the share of public transportation the problems with traffic congestion decrease. Traffic congestion becomes worse as the population in urban areas increases and cities become more densely populated while simultaneously more transports of people and goods must be carried out in the same or even less space than before.

The CO_2 emissions are, apart from increasing the share of public transport, tackled cost-efficient by shifting from fossil to renewable fuels. This has positive impact also on the energy security issue, especially if bio fuels may be produced locally. Bio fuels may sometimes be used as low-blends in fossil fuels, and sometimes as high-blends or pure fuels. There are political targets and also legislation for introduction of bio fuels in various regions, e.g. the EU is to have 10 % renewable fuels by 2020 [2]. A local example is the Swedish Government's vision that the Swedish transport sector should be independent of fossil fuels by 2030 [3]. Most widely spread renewable fuels are ethanol and biodiesel but other fuels, such as biogas are also getting increased attention in some markets [4].

At the same time as more bio fuels are introduced in the transport sector, vehicles must be as energy or fuel efficient as possible, irrespective of the fuels used, i.e. fossil and/or renewable.
Striving for fuel efficiency is an ongoing process and has been the single most important force of competition in the commercial vehicle industry for decades – fuel efficiency improvements are introduced when commercially feasible. Commercially feasible refers to the lifecycle cost of an improvement in comparison with its expected benefits. This is for fuel efficiency improvements the development and production costs, expected lifetime, replacement cost if the lifetime of a new component is short as well as additional repair and maintenance costs measured against fuel cost saving or CO_2 saving. Hybridisation is one proposed method for vehicle fuel savings. A hybrid powertrain also gives the potential to improve the vehicle by other means and to make it more attractive for the passengers, e.g. noise impact can be minimised during start and acceleration since the internal combustion engine is assisted by one or more electric motors. If the vehicle has a series hybrid powertrain, i.e. a completely electric propulsion system, the powertrain usually offers a completely step less, and thereby very comfortable, drive without any jerks at all due to gear shifts. In this powertrain, there are also possibilities to improve the vehicle design and layout because there are basically no restrictions imposed by a mechanical transmission, prop shafts, cardan angles etc [5]. Even though hybrid buses seem to have a good potential there is no production of hybrid buses in common commercial terms, only small series production as tests and demo fleets, or politically driven and heavily subsidised fleets. In North America there are a few thousands hybrid buses running in Seattle, New York City, San Francisco and Toronto among other cities, all heavily subsidised by the government or local municipalities. The extra cost for hybridisation is usually very high, in the range of 100,000 € or even more extra per vehicle [6] and the technology is not yet proven, especially the energy storage systems (e.g. battery). Even so, hybrid buses, if designed and implemented in a clever and cost-efficient way, may play an important role in a future sustainable transport system due to their potential for energy saving, especially if combined with renewable fuels.

4. The bus

The ethanol hybrid bus is a Scania OmniLink, a three axis, 13.7 meter long low-entry city/suburban bus with a rear boggie. The internal combustion engine (ICE) is a diesel engine slightly adapted (e.g. higher compression ratio) to combust ethanol according to the diesel combustion process. The renewable fuel (ED95) used for the engine consists of 95 % ethanol and 5 % additives (ignition improver, lubricating additive etc). This is the third generation of ethanol engines from Scania since start of production in the late 1980s. So far around 700 ethanol buses have been delivered, mainly to Stockholm but also to number of cities worldwide.

The hybrid buses are equipped with a series hybrid powertrain, i.e. with fully electric propulsion. A 150 kW electric motor propels the mid axle of the bus. A high power and high torque generator is mounted on the internal combustion engine. The electric motor, generator and power electronics are delivered by Voith. The energy storage system in the hybrid powertrain consists of super capacitors, not batteries. Four 125 V modules from Maxwell connected in series offer total usable storage capacity of 400 Wh.

Fig 1. The Scania OmniLink ethanol hybrid bus and a schematic illustration of the series hybrid powertrain [Photo: Stefan Wallin, SL]

A reference bus with an identical ethanol engine but equipped with a conventional six-speed hydraulic automatic gearbox with retarder from ZF was also operated during the field test. The reference bus has the same identical exterior dimensions (excluding the roof hood containing the energy storage) and interior design as the hybrid bus. The only difference is that the hybrid buses have one seat missing in front of the rear door of the bus due to a conduit for cabling and coolant pipes to the power electronics and the energy storage system mounted on the roof. The hybrid bus is approximately 1.5 tonnes heavier than the reference bus.

Type: Scania OmniLink Low-entry city bus	Description
General	
Dimensions (*L* × *W* × *H*)	13.7 m × 2.55 m × 3.54 m
Kerb weight	16 tonnes
Max weight	26 tonnes
Passenger capacity	115 (40 + 75) (minus one seat in hybrids)
Internal Combustion Engine	Diesel ethanol engine
Fuel	ED95
Maximum Power output	198 kW (270 hp)
Maximum Torque	1 250 Nm
Emission level	Euro V / EEV
Hybrid components	
Type	Series hybrid
Electric motor	Voith TFM
Maximum Power	150 kW
Maximum Torque	2 750 Nm
Generator	Voith TFM
Maximum Power	220 kW
Maximum Torque	1 250 Nm
Energy Storage Unit	Maxwell Super Capacitors
Number of modules	4
Total capacity (useable)	400 Wh
Maximum voltage per unit	125 V
Maximum voltage in total	500 V

Fig 2. Technical description of the ethanol hybrid bus

5. Experiments and results

The one-year field test generated considerable experience as regards the robustness of the hybrid powertrain. In order to evaluate the energy efficiency potential, duty cycle tests were carried out to obtain experimental data representing various traffic situations. The nature of the suburban route did not produce data relevant for an energy flow analysis for city traffic.

5.1. Evaluation of powertrain robustness from one-year field test

Based on error reports filed by the drivers and technicians during the field test, the main malfunctions were divided into three categories: 1) ICE, internal combustion engine 2) the bus in general and 3) hybrid powertrain-related errors. To further evaluate the hybrid powertrain, this section is divided into four subgroups (a – d) to evaluate the robustness of its main areas. Compilation of results from error report is shown in Figure 3.

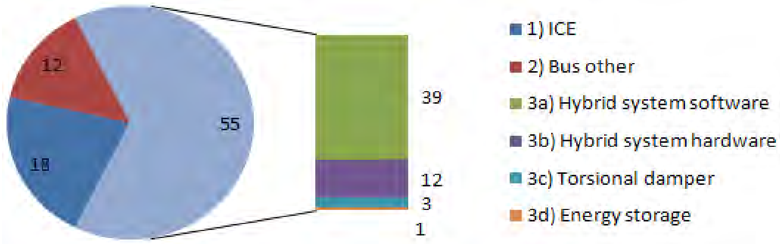

Fig 3. Error reports filed during the one-year field-test.

The robustness of the hybrid powertrain is the focus for this paper, but just to mention something about the other two categories, also the internal combustion engine underwent development during the field test period, e.g. the fuel injections system was improved. Upgrading the engine eliminated many of the errors reported during the first part of the test period. The hybrid software is still under development; during the field test it was too sensitive to interference from e.g. abnormal parameter values sent from other hybrid components as well as the 24 V system voltage level. Through maintenance charging of the 24 V start battery; the number of software reports was reduced. Malfunctions due to hardware are caused predominantly by three components: the direction sensor on the electric motor, the electric motor itself and the torsional damper between ICE and generator. Due to the hybrid management road safety system, incorrect indication of torque to the direction sensor will immediately shut down the system. Some sensors were malfunctioning and therefore replaced and other reported errors were just false alarms. The construction of the electric motor in the tested version was not durable enough for this 3-axle hybrid bus application and had a life of about 15 000 – 20 000 km in several buses causing many filed error reports. This problem arose rather late in the project and was not yet resolved when the field test ended, but is defined and considered possible to tackle with further development. The torsional damper (3c) was initially too weak and when replaced by a stronger one the problem was solved. The only problem reported concerning the energy storage was a fan failure and therefore not caused by the super capacitors. The super capacitors may, as far as this one-year field test is concerned, be regarded as suitable energy storage for the application as regards robustness.

5.2. Evaluation of energy efficiency potential by standardised duty cycle test

In order to evaluate the potential of the hybrid powertrain, standardised duty cycle tests, according to SORT – Standardised on-road tests cycles (developed by the International Association of Public Transport, UITP), were carried out. The key parameters in a traffic situation are the average speed and the number of stops per kilometre, see Table 1. Variations due to topography are neglected to make the test repeatable, hence duty cycles are assumed to be completely flat.

Table 1. Characteristics of the three SORT duty cycles, from UITP 2004 [7]

	SORT 1	SORT 2	SORT 3
Average speed [km/h]	12.6	18.6	26.3
Stops per kilometre	5.8	3.3	2.1
Time idling [%]	39.7	33.4	20.1
Cycle type	Urban	Mixed	Suburban

Figure 4 shows the three performed duty cycles' continuous velocity profile coupled with the energy content in the super capacitors expressed as the state-of-charge (SOC) where 100 % is fully charged and the lowest level is restricted to 25 % (half nominal voltage) to decrease the risk of chemical side reactions and thereby increase capacitor service life. Experiments show that the super capacitors obtain a high round-trip efficiency, generally above 90 %. Super capacitors have high power density [8] and are therefore a suitable energy storage units for heavy vehicles equipped with regenerative braking. The kinetic energy accumulated during deceleration, is converted in the electric motor into electric power charging the super capacitors. If not stored in the super capacitors, it will be used to propel the ICE via the generator or, last of all, dumped in the resistor as heat to the cooling system, see Figure 1. SORT 1 tests show dynamic energy storage management without long time periods of completely charged or empty super capacitors. As seen in Figure 4 already during the SORT 2 test the energy storage will be restricted in terms of size (400 Wh), i.e. the energy storage system is fully charged. During SORT 3 tests, the charge oscillates between its extreme values. The capacity of the energy storage system is therefore a limiting factor for a bus in driving situations similar to SORT 2 and 3 but feasible for SORT 1, urban operation.

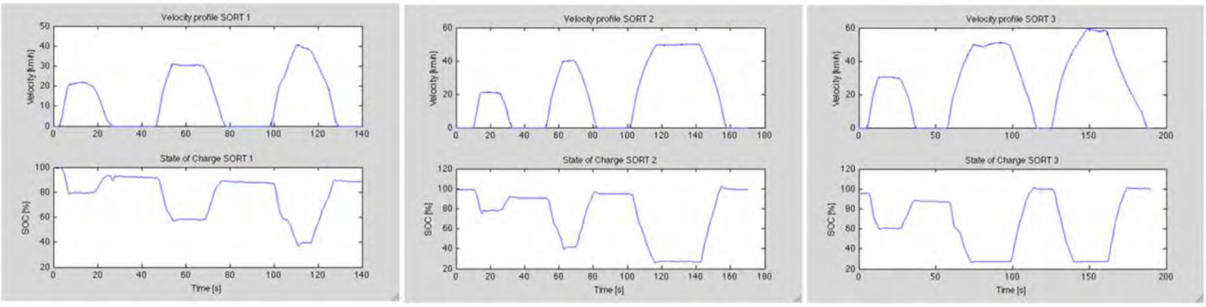

Fig 4. Velocity profile (top) and corresponding SOC profile (bottom) for SORT 1-3 test cycle

Performed SORT cycle tests with the reference bus enable quantification of the absolute fuel consumption reduction generated by the hybridisation, see Table 2.

Table 2. Fuel consumption SORT duty cycles.

	Reference Fuel consumption [litre/ 100 km]	Ethanol hybrid bus Fuel consumption [litre/ 100 km]
SORT 1	89.5	72.5
SORT 2	79.0	63.0
SORT 3	71.0	63.0

A significant fuel consumption reduction is attained for the cycles SORT 1 and SORT 2, 19 %, and 20 %, from 89.5 to 72.5 l/100 km and 79 to 63 l/100 km, respectively. The fuel consumption reduction for SORT 3 corresponds to 11 %, from 71 to 63 litre/100 km. In order to increase the level of detail, the energy spent per driving mode was explored, see Figure 5.

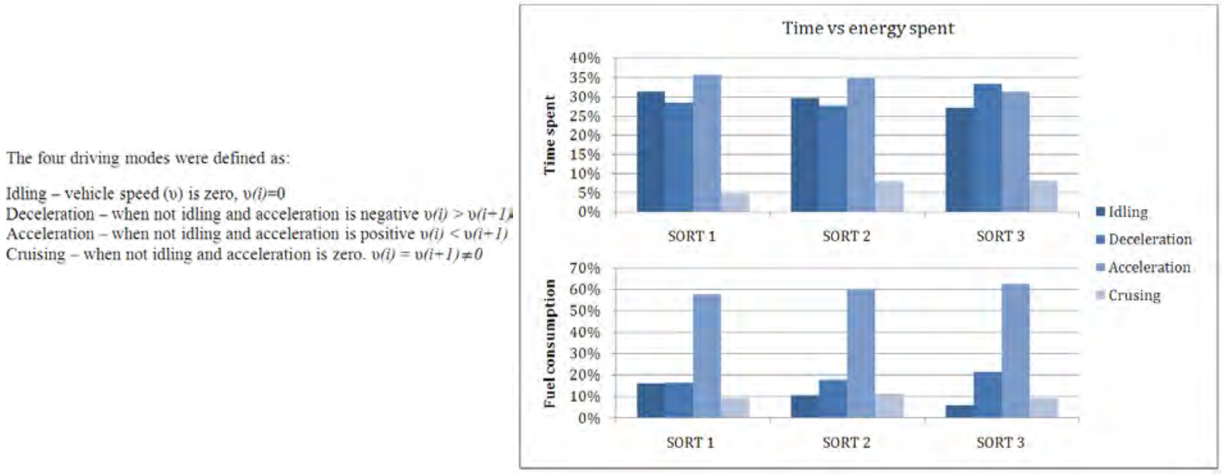

Fig 5. The energy and time spent per driving mode for duty cycle tests with hybrid bus according to the three SORT-cycles

Even though a large time is spent idling (about 1/3 of the time), the fuel consumption during this driving mode is moderate (between 5 and 15 %). The most fuel-consuming driving mode is acceleration where approximately 60 % (varies between 57.7 and 62.8 %) of the total fuel consumption is utilised during about 30-35 % of the time.

5.2.1. Start/stop

To further decrease the fuel consumption it is possible to install a software start/stop feature, which automatically turns of the ICE when idling. Analogous to the time spent as in Figure 5 the fuel consumption when the start/stop software operated was measured. The fuel consumption during idling drops drastically, now only consuming between 2.97 % (SORT 1) and less than 1 % (SORT 2 and 3). Decreasing the fuel demand during idling (which for the SORT cycles, corresponds to approximately 30 % of the time and in real traffic sometimes up to 60 % or more) has a significant impact on the overall fuel consumption, seen in Table 3:

Table 3. Fuel consumption during SORT duty cycles with the buses

	Reference [litre/ 100 km]	Ethanol hybrid bus [litre/ 100 km]	Ethanol hybrid bus with start/stop [litre/ 100 km]
SORT 1	89.5	-19 %	-33 %
SORT 2	79.0	-20 %	- 21 %
SORT 3	71.0	-11 %	- 13 %

5.2.2. Energy flow analysis using Sankey diagram

The energy flows through the electrified powertrain, see Figure 1, for the urban SORT cycle are illustrated in Figure 6 by a Sankey diagram. The Sankey diagram presents an average overview of the energy flows, and is not representative for a specific time during the cycle but is illustrative for the complete cycle. The energy flows in and out of key hybrid components are on-board measured data. The total power input is calculated from the instantaneous amount of fuel injected, in gram per stroke, using the lower heating value and density of ED95, 26.8 MJ/kg and 820 g/l, respectively. Losses for the ICE correspond to energy losses such as heat, mechanical and transmission losses. The energy consumption for running the auxiliary systems is also accounted for as an energy loss over the ICE. The efficiency in the generator is defined as the ratio between electrical power output and mechanical input. The generator and its inverter has experimentally proven to have an average efficiency of around 92 %.The energy storage efficiency, when SOC-balanced just as the round-trip efficiency, is calculated as the ratio between the total energy storage output and total energy storage input.

The energy storage efficiency is consistently about 90 % for all the three cycle tests. When decelerating, the electric motor operates as a generator and recovers brake energy. The share recovered brake energy almost exceeds 20 % of total power input. The efficiency of the electric motor is defined as the ratio between the average power input from the powertrain and the mechanical power output. The experimental average efficiency of the electric motor is approximate 92%. The share of power dumped upon the resistor during the SORT 1 cycle is small which indicates adequate energy storage size. The share, which is not regenerated, constitutes the term of losses due to aerodynamic drag, rolling resistance, transmission losses and wheel brakes.

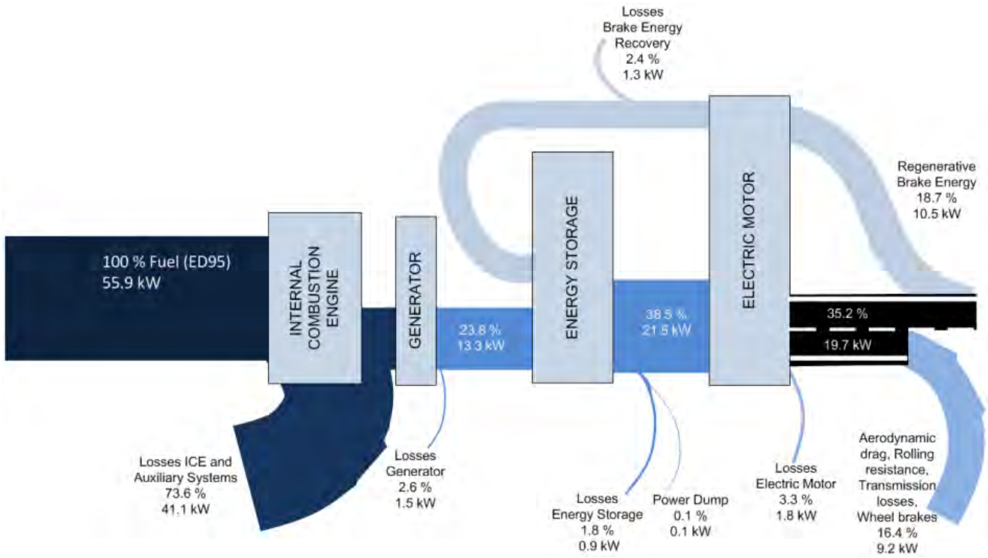

Fig 6. Sankey diagram of average, experimental power (energy) flows for the SORT 1 cycle

5.3. Field test – Urban Stockholm

The SORT 1 cycle tests indicated that the series hybrid system has high potential for significant fuel consumption savings. This lead up to a one-day field test in central Stockholm, during rush hour, to evaluate the potential of transferring the SORT results onto public transportation. Both the ethanol hybrid bus and the reference bus operated two routes: 2 and 66. To perform only a one-day test results in statistically uncertain values but still generates data that hopefully may indicate potential for urban regular transport. Due to organisational and legal reasons, since the bus operator participating in the project was not responsible for the inner-city bus routes, the city field test could not be prolonged.

Table 4. Characteristics of routes 2 and 66 in Stockholm

	Route 2	Route 66
Average velocity [km/h]	12.2	12.4
Stops per kilometre	6.15	5.0
Time idling [%]	25.4	22.36

The fuel consumption reductions are not of the same order as for the SORT tests. For route 66 the hybrid powertrain gives an insignificant (less than 1%) fuel consumption reduction. The fuel consumption may be reduced by 9.3 % for route 2. An explanation to the poor result might be related to the test method used, that the buses were operated nose-to-tail, a method that normally works well in a controlled environment such as a test track. However, in dense real traffic when, apart from consider the other bus, other vehicles and pedestrians as well as traffic regulations, the bus is subjected to weak accelerations and decelerations, which results in poor brake-recovery for the hybrid bus.

5.3.1. London Hybrid Bus Trials

The results from both the duty cycle tests and the field test are similar to the results of an extensive diesel hybrid bus trail in London, hosted by Transport for London (TfL), which also had difficulties in obtaining the significant fuel consumption reduction achieved during duty cycle test for regular public transport [6]. Based on the Millbrook proving ground's London Transport Bus (MLTB) test cycle the average fuel consumption reduction was 31 %, an average attained from series, parallel and mixed hybrid buses, both single and double-decked. During the hybrid bus trail in London, 56 hybrid buses operated 10 routes. The results were scattered between almost reaching the TfL 30 % reduction target and an actual increase in fuel consumption. For all vehicle manufactures, the results indicated a much smaller (or non-existing) fuel consumption reduction than expected. This indicates that fuel consumption reductions due to the hybridisation, when operating on public urban routes oscillate depending on the prevailing traffic situation since there are parameters in real-life traffic which can not be transferred to a test situation. A general conclusion from operation of hybrid buses in London is that the overall costs over the lifetime of a hybrid vehicle are not on a commercial level yet, i.e. the fuel savings do not equal the extra cost of the vehicles.

6. Experiences and conclusions

The series hybrid powertrain have experimentally shown potential for reducing the fuel consumption in urban traffic by up to 20 % and additionally 10 % when utilising the start/stop software. In conformity with similar experiments with hybrid buses, it is not evident that the fuel reduction potential may be realised on real life routes since the fuel reduction potential is dependent on the route characteristics. A recommendation for the next project is that the real inner-city fuel saving potential should be validated in real operation on inner-city bus routes. Some components of the hybrid system still need some development as regards robustness. The super capacitors did work consistently during the whole field test and may so far be considered to be suitable as energy storage for this hybrid vehicle application.

References

[1] Stockholm Public Transport (SL) web page, www.sl.se, accessed 2010-12-18

[2] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Brussels

[3] The Swedish National Action Plan for the promotion of the use of renewable energy in accordance with Directive 2009/28/EC and the Commission Decision of 30.06.2009

[4] REN21, Renewables 2010, Global Status Report. Available at <www.ren21.net>, accessed 2010-12-14

[5] L. Overgaard, Scania hybrid concept – with robust technology into the future, Proceedings of 57th UITP World Congress, 2007

[6] Mike Weston, London Hybrid Bus Trials, Proceedings of Low Carbon Vehicle Partnership (LowCVP) Conference 2010, available at < www.lowcvp.org.uk >

[7] UITP, International Association of Public Transport, SORT – Standardised on-road test cycles, 2004. Available for purchase at < www.uitp.com >

[8] V. Paladini, T. Donateo, A. de Risi, D. Laforgia, Super-capacitors fuel-cell hybrid electric vehicle optimization and control strategy development, Energy Conversion and Management, Volume 48(11), 2007, Pages 3001-3008