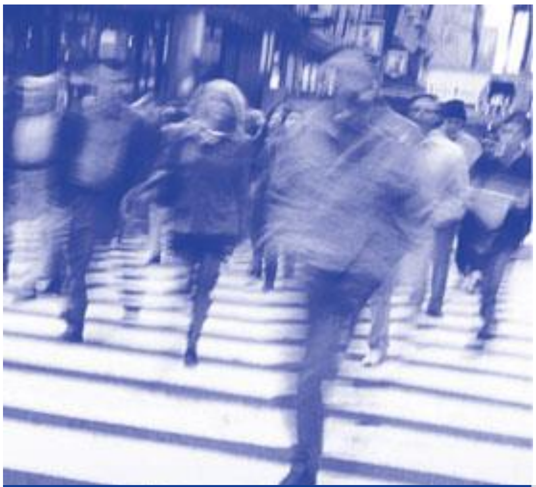

CIVITAS
Cleaner and better transport in cities

DYN@MO
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Report on the efficiency of Li-Ion traction batteries in PKT company in Gdynia

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Abstract

The idea of equipping trolleybuses with auxiliary drives in case of some emergencies on the road is not completely new in Gdynia. In 2010 the first trolleybuses with Nickel-Cadmium batteries started to be introduced in Gdynia when PKT purchased 28 modern Solaris vehicles within an EU project co-financed by the European Regional Development Fund under the Regional Operational Programme for the Pomorskie Voivodeship.

It should be emphasised that PKT had decided to go purely electric from the very beginning. As for auxiliary drives there is also diesel technology available and in fact it is quite popular with operators. However, the philosophy and strategy of PKT is to become greener and greener, which was the basis for the decision.

Officially, Nickel-Cadmium battery auxiliary drives allow a 12 metre vehicle to drive off the traction network with full passenger capacity and air-conditioning/ heating on for 5 km. In reality the distance proved to be much longer (up to 20 km). However the issue with Nickel-Cadmium cells is that they should not be discharged to more than 70% as otherwise their battery life decreases sharply. Fort this reason, Ni-Cd cells can only be used in case of emergencies.

Therefore, while preparing an proposal for CIVITAS DYN@MO project PKT decided to pursue a solution to overcome this problem and deploy the battery as an alternative drive that could be suitable and that would easily allow for regular off-traction courses to be covered by Gdynia trolleybuses. Within the project, PKT purchased two vehicles equipped with Li-Ion traction batteries and deployed them on an extended line, which has been operating since 1 May 2015 in the central area of Gdynia.

This report covers information on the process of introducing these vehicles and information on the evaluation results on the 18 months since the extended line is being operational.

Project Partners

Organization	Country	Abbreviation
PRZEDSIEBIORSTWO KOMUNIKACJI TROLEJBUSOWEJ	POLAND	PL
UNIVERSITY OF GDANSK	POLAND	PL
CITY OF GDYNIA	POLAND	PL

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1 Introduction

Within CIVITAS DYN@MO PKT, Gdynia public transport operator, implemented two measures. One of them was entitled: “Innovative Li-Ion trolleybuses on a new line” (measure G2.1). Within this measure PKT purchased and gained experiences with battery hybrid trolley buses. Two hybrid trolleybuses (Solaris Trollino 12M) with Li-Ion batteries were purchased and put into service on line 21 which thereby was extended by two km, running without wires on a non-electrified section of Kosciuszko Square street in both directions. This line started to be operational from 1 May 2015. When the DYN@MO project was set up, it was planned that the buses would be running as a test in the warm season from May until October only. However, due to the positive results of the battery tests as well as feedback from passengers it is now operated all year round.

Solaris Trollino 12M on Skwer Kościuszki Street. Photo by Marcin Czapnik

2 Objectives of measure G2.1 “Innovative Li-Ion trolleybuses on a new line”

The main objectives of this measure were to:

- increase the reliability and flexibility of the trolleybus system thanks to the deployment of alternative battery drive
- expand the operation of electric public transport vehicles in new highly populated city areas by extending off grid courses
- purchase two innovative Li-Ion hybrid trolleybuses and deploy them on a 2 km new line
- increase awareness of local community and stakeholders of other Polish cities in terms of trolleybuses being the most energy and cost efficient, clean and “ready to use” mean of PT
- set a national and international replicable example of ecological innovation in public transport

All of these objectives were successfully met.

Off grid tests. Photo by Marcin Czapnik

3 Preparation for and implementation of Li-Ion trolleybuses at PKT

After the start of DYN@MO, PKT analysed the options of Lithium traction batteries for trolley vehicles and, in December 2013, an internal working document ("Concept for Li traction batteries for trolley vehicles") was prepared

On the basis of the data gathered on the batteries from the Lithium group and with reference to their technical capabilities and legal exploitation possibilities the "Specification of essential terms of order" were prepared for the tender procedure.

The original plan within CIVITAS DYN@MO was to purchase two chassis of used diesel buses, convert them into trolleybuses and equip them with Lihium batteries acquired from the market.

Thus, in January 2014 a public tender was announced for the purchase of two Li traction batteries. A detailed explanation of the "Specification of essential terms of order for bidders" was also placed online. However, in February 2014 the tender was annulled due to the lack of any offers and no response from the market. A protocol from the tender procedure was drawn up. It turned out that the manufacturers were simply not interested in producing separate, unique and very specifically designed batteries for PKT in the batch of only two of them. Apparently it was not economically viable or profitable. The fact that PKT didn't receive any offers from the market for purchasing two separate batteries lead to the decision to buy new trolleybuses already equipped with Li-Ion batteries instead of installing separately purchased batteries in converted trolleybuses. In order not to fall behind the measure time schedule the Measure Leader decided to invest more financial resources on PKT's part and to obtain from the market new vehicles with Li-Ion batteries. The decision was taken in February 2014 and it was dictated by the market conditions.

In March 2014 PKT published a new tender on the purchase of two new trolleybuses with an alternative drive based on Lithium-Ion batteries. "Specification of essential terms of the order for the bidders" accompanying the procurement together with detailed explanations were issued alongside. The new tender received a considerable response and after having analysed the offers the manufacturer was chosen and a contract was signed with Solaris Bus&Coach on 23 May 2014. Two 12 metre trolleybuses were purchased for the price of €400,000 each, which was only slightly more than for the previously bought trolleybuses with Nickel-Cadmium batteries. In March 2015, well in accordance with the terms of the contract, the two innovative vehicles were delivered to PKT, which allowed PKT to achieve all measure G2.1 objectives within the lifetime of the project. One month later the technical approval for the operation was obtained and numerous off-traction test rides on batteries were conducted with the new Li-Ion trolleybuses, which aimed at exploring and analysing the technical parameters and possibilities of the new vehicles. The tests continued for a month and they proved that the trolleybus can easily run on the battery for ca. 15 km in any conditions.

In April 2015, after a thorough analysis lasting for several months, the final decision of the most appropriate location for the pilot extended trolleybus route was taken in cooperation with the University of Gdansk. It was decided to make this extension in the central, most touristy and very popular area of Gdynia, on Skwer Kościuszki Street, where so far no public transport had been used. The 2 km line started on 1 May 2015 and is being operated successfully since then. The trolleybuses get off the traction network, drive on batteries to the popular Gdynia Aquarium by the Baltic Sea shore, they pass the Naval Academy and automatically switch back to the traction network on 10 Luty street.

4 Monitoring and evaluation results

4.1 Analyses during operation of trolleybuses

The Li-Ion traction battery is an integral part of the two trolleybuses that have been purchased by PKT. The traction batteries used in the Solaris trolleybuses Trollino 12M subject to the analyses described below are:

Type of the battery cell: Li-ion; Manufacturer: WAMTECHNIK; Two parallel blocks 638 V; 35.5 Ah; rated power at 38 kWh; 27 kWh approximately available.

This is the type of traction batteries used in previous versions of the Solaris Trollino 12M trolleybus (comparisons are made against these batteries):

Type of the battery cell: Ni-Cd; Manufacturer: SAFT; 2 sequential batteries 100.6 V; 80 Ah; 7x12 STH800; total of 16 kWh.

During the operational phase, not only the battery but the functioning of all vehicle components was monitored and analysed closely. Particular attention was paid to the electric energy parameters of the trolleybuses. Based on the data recorded in the period from 1 May 2015 to 30 April 2016 a set of technical parameters was designated for each day. This chapter contains the collected and processed data, which are presented in the form of tables and descriptions. In addition, data from the daily operation of both trolleybuses were being reviewed on an ongoing basis in order to detect anomalies and defects in these trolleybuses, and then they were qualified or disqualified for further processing. As little as 9% of the daily data was disqualified, mostly due to the lack of operation on a given day.

Off grid tests. Photo by Marcin Czapnik

Off grid tests. Photo by Marcin Czapnik

4.2 Key data and conclusions concerning the operation of Li-Ion traction batteries

Energy parameters while the buses were driving with power from the catenary are just as expected because they are similar and work in similar conditions as the Solaris trolleybuses Trollino 12M with Ni-Cd traction batteries which PKT already owns. What is more important, however, is the study of the whole trolley operation when supplied from Li-Ion traction batteries. The following tables show the most important parameters of solely Li-Ion traction batteries as well as the entire trolleybus powered by Li-Ion traction batteries.

Location of Lithium-Ion battery at the back of the vehicle. Photo by Mikolaj Bartlomiejczyk

Table 1: Traction batteries, average energy parameters

<table>
<tr><th colspan="6">TRACTION BATTERIES – average energy parameters</th></tr>
<tr><td colspan="2">Number of cycles with minimal state of charging in relation to working capacity</td><td colspan="4">Traction battery energy (kWh):</td></tr>
<tr><td colspan="2"></td><td colspan="3">Charged</td><td>Discharged in TB mode</td></tr>
<tr><td>Min. state of charging</td><td>Number of cycles</td><td>From the traction network</td><td>In stationary conditions</td><td>While braking in TB mode</td><td></td></tr>
<tr><td><0 ; 20></td><td>3</td><td>5,548.9</td><td>8.8</td><td>1,411.3</td><td>6,905.3</td></tr>
<tr><td>(20 ; 40></td><td>14</td><td colspan="4">Balance of traction battery energy (minus values mean energy loss in TB)</td></tr>
<tr><td>(40 ; 60></td><td>26</td><td colspan="2">- 63.7</td><td colspan="2">(kWh)</td></tr>
<tr><td>(60 ; 80></td><td>123</td><td colspan="2">- 0.91</td><td colspan="2">(%)</td></tr>
<tr><td>(80 ; 100></td><td>2,195</td><td colspan="4">Efficiency of only traction battery TB</td></tr>
<tr><td>Total</td><td>2,361</td><td colspan="2">99.1</td><td colspan="2">%</td></tr>
</table>

Table 2: Energy parameters of the drives and the entire trolleybus while being powered from traction batteries

<table>
<tr><td colspan="9">Energy parameters of drives and entire trolleybus in TB mode (power supply only from traction battery)</td></tr>
<tr><td>Energy absorbed by trolleys in TB mode</td><td>Energy given out by trolleys in TB mode</td><td>Energy absorbed by drives in TB mode</td><td>Energy given out by trolleys in TB mode</td><td>Braking energy dissipated in braking resistors, in TB mode</td><td>Distance in TB mode (km)</td><td>4,050.4</td><td colspan="2">Non-drive needs: heating, compressor, support, TB charging 24V, energy losses</td></tr>
<tr><td>6,905.3</td><td>1,411.3</td><td>5,371.8</td><td>1,827.3</td><td>47.5</td><td colspan="2">kWh</td><td>1,949.5</td><td>kWh</td></tr>
<tr><td>1.705</td><td>0.348</td><td>1.326</td><td>0.451</td><td>0.012</td><td colspan="2">kWh/km</td><td>0.481</td><td>kWh</td></tr>
<tr><td colspan="2">Energy absorbed by trolleys in TB mode decreased by braking recovery energy (usage)</td><td colspan="2">Energy absorbed by drives in TB mode decreased by braking recovery energy (usage)</td><td colspan="3">Efficiency of braking energy recovery by drives in TB mode (possibility of not dissipating energy in braking resistors):</td><td colspan="2">Coverage by braking energy recovered</td></tr>
<tr><td colspan="2">5,494.0</td><td colspan="2">3,544.5 kWh</td><td colspan="3" rowspan="3">97.5 %</td><td colspan="2">415.9 kWh</td></tr>
<tr><td colspan="2" rowspan="2">1.356</td><td colspan="2" rowspan="2">0.875 kWh/km</td><td colspan="2">0.103 kWh/km</td></tr>
<tr><td colspan="2">21.3 %</td></tr>
<tr><td colspan="9">These calculations did not take into account energy consumption by additional devices required for proper TB operation.</td></tr>
</table>

Tables 1 and 2 contain the most crucial data concerning the exploitation of traction batteries in trolleybuses. Based on this data several conclusions have been drawn:

a. Li-Ion traction batteries have a very high energy efficiency: above 99%. For comparison, the estimated but not documented efficiency of Ni-Cd batteries is approximately at 80%. Due to the intended occasional use, the lower efficiency of Ni-Cd battery is not a major flaw, however when taking regular scheduled operation into account the higher performance Li-ion battery indeed is a major advantage. Energy losses while converting energy in the ZBBT (Zasilacz Buforowy Bateriii Trakcyjnej – Traction Battery Buffer Power Supply) resonant inverter have not been accounted but according to the manufacturer the efficiency of the device is about 98%, which is confirmed by the lack of noticeable heating even at a relatively high power.

b. A considerable advantage of the Li-Ion battery is that while using this kind of battery the capacity to recover braking energy to the traction battery is higher than in case of Ni-Cd batteries. In the Solaris trolleybuses Trollino 12M the applied Li-Ion traction batteries can charge and store energy from regenerative braking at a power capacity of approximately 120 kW which equals 50 kW for Ni-Cd batteries. In practice, most regenerative braking is done with a peak power of 100 kW to 150 kW whereas the most intensive results reach 220 kW. For the energy needed for other aspects than mere driving and the operation of the function enforcing the heating of the trolleybuses during braking, if the heating is on, with Li-Ion batteries there is little need to dissipate the excess of braking energy in braking resistors. From the recorded and processed data it turns out that, while the power is provided from the Li-Ion traction battery, 97.5% of the regenerative braking energy is actually used. In contrast, the amount of this energy in the trolleybuses equipped with Ni-Cd traction battery, the use of recuperated energy is estimated at around 30%. All in all, the higher recovery rate of braking energy of the Li-Ion traction batteries compared to the Ni-Cd ones in practice leads to an additional increase in the km range the trolleybuses can drive off traction.

Attention! When ordering electric vehicles with traction batteries based on lithium cells one should remember that not all types of cells, even those including conventional Li-ion batteries, have equally good capability of receiving energy from regenerative braking as the batteries purchased within the CIVITAS DYN@MO project and discussed here. Some types of Li-ion batteries do not have the possibility of receiving full braking energy at higher level of charge. Sometimes, however, one may deliberately select Li-Ion cells with restricted ability to take of regenerative braking energy at higher level of charge in return for greater energy capacity or longer life span. PKT recommends to take the above into account while preparing an order specification for a Li-Ion battery electric vehicle.

c. PKT noticed an improvement in operating parameters of Li-Ion batteries in comparison to Ni-Cd ones. The power consumed by the trolleybus from the Li-ion battery is approximately 120 kW, out of which about 100 kW are needed for traction drives. In contrast, the power derived from the battery and consumed by the trolleybus with Ni-Cd battery is approximately 50 kW, out of which about 45 kW are needed for traction drives. Having considered losses in engines and traction inverters, the increase in the mechanical power output by the engine is even more beneficial for power feeding when using the Li-ion battery. By increasing the power available for traction drives the trolleybuses powered by Li-Ion traction battery – although they give the impression of being slightly weaker than at times when they are powered from the catenary – they very easily reach the speed of 50 km/ h without obstructing the traffic in the city. For comparison, when fed from the catenary the power available for the trolleybus is a peak power of around 220 kW, yet typically 180 kW is used in fact.

d. While feeding trolleys from Li-Ion traction batteries it is possible to switch on the air conditioning or heating, which was impossible in the trolleybuses with Ni-Cd traction batteries. This contributes to maintaining the comfort of the journey for the trolleybus passengers regardless of the power source.

e. By improving the operating parameters and maintaining passenger comfort during the journey with the trolleybus regardless of the way the power is fed, trolleybuses equipped with Li-Ion traction batteries can serve most of the diesel bus lines that are also being offered within PKT's bus network. This is a perfect solution as it also allows for charging traction batteries during regular passenger transport when the power is fed from the catenary, which clearly is a significant advantage as compared to electric buses.

f. Trolleybuses powered from Li-Ion traction batteries have lower power consumption than feeding power from the catenary. However, this is not a reliable indicator because it is a completely different way of operation. Probably if trolleybuses fed from the network were operated in exactly the same way as trolleybuses fed from the battery the energy consumption would be comparable. In addition, the decrease in energy consumption by drives powered by the traction battery results from power limitation. Asynchronous drives have the highest energy efficiency with a load of approximately 60% of rated power, which occurs exactly during power being fed from Li-Ion traction batteries. When the power is fed from the catenary traction motors are usually temporarily overloaded, which means that they work with decreased efficiency. Traction drives underloading has a positive impact on energy efficiency but a negative one on the operating parameters (slower acceleration).

g. This point refers to Li-Ion battery predictability. A huge advantage of Li-Ion batteries is that they allow determining with great accuracy the quantity of energy available. One can virtually consume rated current to a state of a complete battery discharge, and the voltage decreases only slightly. That means that Lithium-Ion cells are characterized by very low internal resistance and stable electromotive power. Feeding the trolleybus with Li-Ion traction battery can be compared to supplying power from some idealized catenary but with limited power.

4.3 Comparison of trolleybuses with Li-Ion batteries with other possible solutions

To summarise, table 3 shows the juxtaposition of particular features of all possible vehicles that could be used to extend line 21 to Kościuszko Square Street.

Table 3: Set of most important features of possible solutions for extension of line 21

	Classic trolleybuses fed from overhead traction	Trolleybuses with Li-ion traction battery	Trolleybuses with auxiliary diesel drive	Duobuses
Estimated yearly exhaust emission	None (i.e. zero emissions)	None	Ca. 27 Mg* incl. ca 5 Mg CO_2 exhaust fumes from cold engine	Ca. 33 Mg incl. ca. 6 Mg CO_2 exhaust fumes from cold engine
Noise	Inconsiderable	Inconsiderable	Increased	Increased
Range	Only under the traction network	Under the traction network and ca. 15 km off the grid (assures 100% possibility to serve Skwer Kościuszki street)	Under the traction network and ca. 150* km off the grid (* depends on the fuel tank capacity)	Under the traction network and ca. 150** km off the grid (** depends on the fuel tank capacity)
Technical maintenance	Standard as for the trolleybus	Standard as for the trolleybus	Standard as for the trolleybus + alternative diesel auxiliary drive	Standard for the bodywork + double (bus and trolleybus) for the drives and auxiliary systems
Other	Necessity to build traction network	More expensive vehicle	Necessity to adapt the trolleybus depot/ more expensive vehicle	Necessity of extensive depot adaptation/ only articulated vehicles/ very expensive vehicles

* Mg = mega gram per year (1 tonne = 1,000 kg = 1 Mg (Mega gram))

4.4 Environmental benefits for the city of Gdynia

With the introduction of the two trolleybuses with Li-Ion batteries line 21 was extended by two km, running without wires on a non-electrified section of practically the entire Kosciuszko Square street in both directions. This line is now operated all year round only by full electric hybrid trolleybuses with traction batteries. If PKT had not purchased these trolleybuses, the company could also imagine two alternative solutions: applying duobuses, i.e. trolleybuses with diesel auxiliary drive or building the catenary on this section. However, these alternative solutions would be unreasonable for different reasons. Applying means of transport with auxiliary diesel drives would not be as ecological as purely electric, as well as the current depot is not adapted to maintain trolleybuses with extra auxiliary diesel drives. As for constructing the catenary infrastructure the solution would not be cost effective.

Each route covered by diesel auxiliary drive duobus would result in the emission of at least two kg of CO_2, and other additional toxic components contained in the exhaust fumes emitted in this attractive tourist spot. Given that the content of CO_2 in the exhaust gas is approximately 18% of the total weight emitted during each course, the total mass of exhaust fumes emitted on the relevant section would be above 11 kg. One should also take into account the additional unspecified amount of exhaust gas used to start up cold combustion engines, etc. Considering the above and the timetable of the trolleybus line 21 in the direction of the main train station in Gdynia (10 courses on weekdays and 8 on Saturdays) one can surely say that if line 21 was served by a diesel bus instead of the trolleybus, only in the Kosciuszko Square street the CO_2 emission would add up to about 6 Mg of CO_2 a year, and more than 33 Mg of exhaust gases in general. Thus, the launch of electric public transport in Kosciuszko Square street through the implementation of the CIVITAS DYN@MO project has contributed to exactly these reductions of annual emissions.

4.5 Changes that occurred due to the introduction of Li-Ion traction batteries into service

The most important changes that the introduction of Li-Ion batteries has brought to PKT are:

a. An adjustment was made to the training programme of newly employed drivers. The adjustment was introduced in order to provide relevant information on the new type of trolleybuses and to compare them with others.

b. Additional information was provided to fireman brigades operating in the cities of Gdynia and Sopot in case of a possible intervention. Li-ion batteries are less safe than Ni-Cd in terms of inflammability, explosion and the risk of electric shock.

It is also worth adding that the successful results of implementing the extended line in the DYN@MO measure G2.1 is currently being used and continued in another EU funded project, which PKT became a partner of, namely CIVITAS ELIPTIC “Electrification of public transport in cities”. Within this 33 partner consortium project launched on 1 June 2016 PKT takes forward the great achievements of the CIVITAS DYN@MO project in Gdynia with the next three years by exploring the possibilities of further development of environmentally-friendly electric public transport in the Tricity Metropolitan Area.

As regards the Lithium-Ion battery technology the knowledge and experience gathered within DYN@MO proved to be extremely useful and serves as fundamental source of data, as within the ELIPTIC project PKT further identifies potential routes for extending the existing trolleybus courses with trolley-hybrid buses running partly independent from the traction network on Li-Ion batteries (amongst others an unwired 5 km route has been identified to the big sports stadium in Gdansk ERGO ARENA as well as to Pomorska street in Gdansk where the tramline could for the first time meet with the trolleybus line). Two feasibility studies will be conducted by PKT within ELIPTIC and they will be partly validated on CIVITAS DYNAMO data from the currently running demonstration of extending the unwired trolleybus operation in Skwer Kościuszki street. This EU projects complementarity clearly shows that CIVITAS DYN@MO's aims were justified and its results are easily transferrable and may be successfully continued.

5 Conclusions

Observations of the operation of Li-Ion traction batteries purchased together with the Solaris Trollino 12M trolleybuses provided significant additional experiences to PKT's technical staff working at the trolleybus depot. Li-Ion traction batteries not only definitely meet and even exceeded the operator's expectations but thanks to additional practical experience it turned out that it is possible to further optimise the trolleybuses to be purchased in the future.

The successful operation of the Li-Ion trolleybuses purchased within the CIVITAS DYN@MO project resulted in the further purchase of such vehicles with PKT's own funds in 2016: one more with the same battery capacity and three more with the double battery capacity. The trolleybuses were also ordered from Solaris. The current operation of these Li-Ion battery trolley hybrid buses that allow for successful off-grid extensions is now visibly changing the further path of development of public transport in the city of Gdynia. We hope that PKT's experience may also be useful for other companies and cities exploiting trolleybuses. In conclusion, if PKT had not participated in the CIVITAS DYN@MO project and had not gained valuable experience with Li-Ion batteries, PKT would probably still be ordering less technically optimal trolleybuses, not allowing for regular and scheduled off traction range.

What is more, thanks to the CIVITAS DYN@MO project the technical capabilities of battery hybrid trolleys are constantly being presented to residents and tourists visiting Gdynia. The choice of the extended line extension adds up to this good PR since Kosciuszko Square street is particularly popular, especially in the summer when it is very crowded. The sight of a trolleybus going with lowered pantographs without the overhead catenary catches people's interest and attention, stimulates the discussion, increases awareness of the changing face of electromobility, and breaks down the stereotype of trolleybuses as inflexible means of transport attached to the grid. The CIVITAS DYN@MO project has proven that the further expansion of electric transport based on batteries is viable and useful.