Feasibility of Battery Switch Stations for Local Emission Free Public Transport

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Abstract

Electric Mobility is one key technology for increased energy efficiency and local zero emissions for vehicles – especially in cities. Urban bus public transportation is in many cities still one main contributor of urban particulate emissions and has not – only in developing countries –significant shares on urban traffic and is therefore a relevant research issue. Different technologies that seem suitable to meet these two targets (energy efficiency and local zero emissions) have been introduced to several field tests. However, little attention has been given to battery electric busses (BEB) in combination with battery switch stations – although both existing hurdles for BEB, range limitation and long charging times, could be solved. Furthermore, power load peaks in the evening hours through the charging process of busses could be prevented.

In this paper we first give an overview of different systems for urban bus transport with respect to characteristics such as emission reductions and technological challenges. In the following, we introduce several battery switch systems and analyze one example battery switch station for BEB and its economic feasibility. The business case is based on empiric data for the Karlsruhe public transportation system and includes a calculation based on the net present value, sensitivity analyses and a possible system extension step. Even though there are various influencing factors, we show that both, a cost-efficient operation of a battery switch station in a current public bus fleet operation and a reduction of local air pollution are possible.

Keywords: electric mobility, urban public road transport, alternative bus technologies, battery switch station, economic analysis

1 Introduction

The human made climate change due to the increasing concentration of greenhouse gases and its following effects [IPCC 2007] have a significant economic impact [Stern 2007]. Both, the energy and the transport sector are among the main contributors. In both sectors the projected emissions will increase worldwide, especially in developing countries [WBCSD 2004], [IEA 2011]. Therefore, the political aim in Europe and especially in Germany is, to reduce carbon emissions and improve energy efficiency with a focus on these two sectors [EC 2011]. In Germany the transformation to a low carbon society is politically framed through ambitious targets [Bundesregierung 2007], with a minimum share of 80 % renewable energies in electricity generation in 2050 [BMWi & BMU 2010] and an increased share of electric vehicles [Bundesregierung 2011]. Not only the reduction of greenhouse gases is intended, but too, the reduction of the import dependency of fossil fuels (i. e. oil) and along with this, the aim for stable mobility costs [Bundesregierung 2011]. Beside the global issues, also the local effects are relevant. Damages from transport in urban areas (in particular the impact of external effects) are three times higher than on interurban roads [Maibach et al. 2008]. Furthermore, transport is emitting about 20 % of greenhouse gases (GHG) in the EU with the strongest increase on the global [WBCSD 2004] and European scale [EU 2010]. Therefore, increased energy efficiency and local zero emissions for vehicles in cities are widely discussed throughout industry, research, and politics [Rothengatter et al. 2011].

Urban public transportation has high shares on total urban transportation all over the world [WBCSD 2004]. In Germany there are significant shares of urban public transportation of between 19 and 26 % of all urban transport [HASPA 2010] (cf. Figure 1). The share of busses is highly dependent on the complete infrastructural situation. With a developed tram, streetcar or city train system, the share of busses tends to be lower. In total, busses have a share of over 50 % of transported passengers in public transport [DeStatis2011b]. Comparing the specific urban CO_2 emissions of busses (67.6 g/pkm) to cars (87.3 g/pkm) [Schreyer et al. 2004], they are in a similar range. All these facts motivate us to concentrate on urban bus transport in this paper.

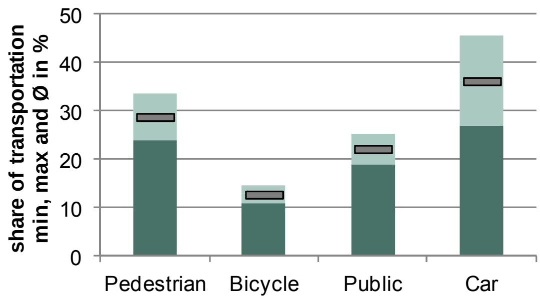

Figure 1: Modal split for urban transportation in German cities, [HASPA2010]

Currently, there is no urgent need for a bus transport business to change the well known and established conventional bus system e. g. because of new regulations or other circumstances. Therefore, an alternative for bus transportation has to be economically attractive in comparison to the existing solution. Different technologies seem suitable for local zero emission (or at least reduced emissions) and economic operation. Some of them have already been introduced to field tests (e. g. hybrid busses) [Faltenbacher et al. 2011].

In this paper we give an overview of different systems for urban bus transport with respect to characteristics like emission reduction, technological challenges and coupling with the energy system. One of these promising alternatives is the battery switch station in combination with battery electric busses (BEB). We focus on this system and introduce it as well as several concepts. In the next section of the paper analyzes a battery switch station for BEBs for its economic feasibility. The business case is based on empiric data for the Karlsruhe public transportation system. We include a location finding for the battery switch station, system extension steps for the integration of further bus lines, dynamic economics calculation (net present value) and sensitivity analyses. We conclude with a summery and an outlook.

2 Overview of alternatives for urban bus transport

In the recent decades road transportation was dominated by combustion engine vehicles with gasoline or diesel fuel [Davis et al. 2011]. Based on the mentioned environmental and political aspects alternative technologies and fuels for road transportation and busses have been becoming of more interest with a strong focus on electrification of the power train in the recent years [Michaelis et al. 1996] (cf. Figure 2). Beside several hybridization stages to enhance energy efficiency the complete electrical power train is also of interest due to a reduction of constructional (technological) complexity. The other approach is to change the fuel (from fossil to renewable resources) keeping the principle of the combustion engine. Beside these possibilities, which are also applicable for individual transportation (cars), the trolley-bus, a combination of bus and city train with an electric engine, is possible, too.

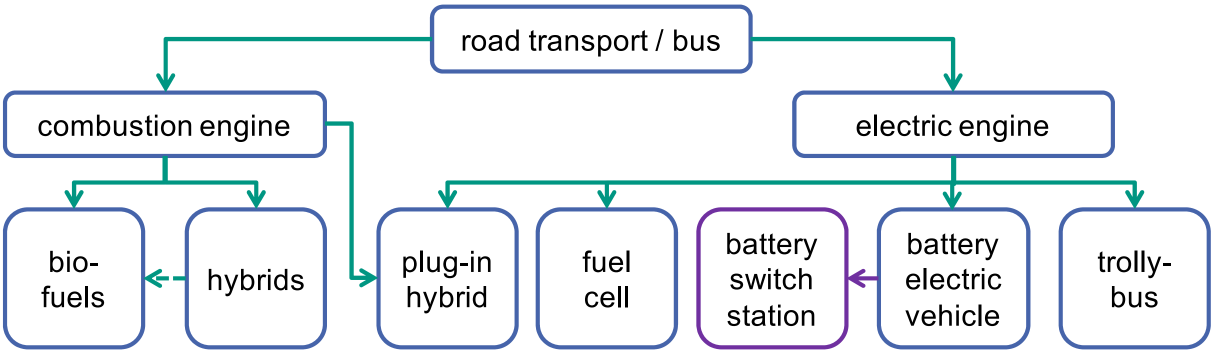

Figure 2: Overview of alternative technologies for road transport (i. e. busses)

All these different technologies seem suitable to reduce local emission and economical operation for urban bus transport [Aigle et al. 2008]. Most of them have been introduced to field tests (e. g. hybrid busses) or operate in special applications like an airport transfer [Aigle et al. 2008], [Faltenbacher et al. 2011]. The conventional internal combustion engine (ICE) has further technical improvements (e. g. optimized heat use), can be used with alternative fuels or can be supplemented with hybrid system components. However, the reduction of emissions is limited and local zero emission is not achievable. Only electric systems can offer this option in shifting emissions to the electricity power plants, which are usually outside of urban areas, more efficient and have a flue gas treatment. In using electricity coming from renewable energies the overall emissions can be reduced to nearly zero. Compared to ICE, the electric power train is more efficient and the well to wheel CO_2 balance can be reduced strongly [Gerbracht et al. 2009].

Battery electric busses (BEB) are not common yet, only few models are available (e. g. EURABUS 600, Contract e.COBUS 2500, Rampini ALE' Elettrico or BYD eBus-12). The range limitation, that is also significant for electric cars, is increased by auxiliary units like the air conditioning (heating and cooling), that need additional electricity. The second important problem, the dependency on the long-lasting charging process (often for several hours), could be avoided with battery switch stations, which reduce the "charging process" down to minutes. However, the system has high investments for the switch station and additional battery packs that need to be turned over through high numbers of battery switches. Two further alternatives for electric busses need expensive infrastructure: trolleybusses (overhead contact line or induction systems) and fuel cell electric busses. An overview of relevant advantages and disadvantages is given in Table 1.

In general busses have a high road performance, with 50,000 to 100,000 km/a and 10 to 12 a lifetime [Frank et al. 2008]. Together with low average speed and high number of starts and stops, these use characteristics are optimal for electric busses. But the high daily road performance requires a large and costly battery, which reduces the efficiency due to higher weight. The charging is often only possible after end of business in the evening. However, little attention has been given to battery electric busses (BEB) in combination with battery switch stations, yet. This is especially remarkable, as both, range limitations and long charging times can be solved. Furthermore, power load peaks in the evening hours can be prevented, through constant charging all over the day.

Table 1: Comparison of energy efficient systems for local public road transport

Alternatives	Advantages		Disadvantages
ICE with biofuels	reduction of emissions or more efficiency	easy to convert from conventional bus	limit of reductions: biomass life cycle is not (local) emissions free
hybrid systems		recuperation	limit of reductions: conventional ICE
battery electric busses (BEB)	high efficiency, zero local emissions, possible green electricity	similar to electric cars	range limitation, infrastructure dependency, high weight and costs, ancillary units, charging peak-loads
battery switch stations		small battery size	expensive battery switch infrastructure
overhead contact line (trolleybus)		no distance restrictions	non-autonomous, fixed routes and lines, overhead electric wires disturb townscape
induction and magnetic resonance systems		innovative technology	less efficiency, far from applicability
fuel cell electric busses	zero local emissions (fuel: H2)	fast refilling	expensive infrastructure, fuel and fuel cell

3 Battery switch stations

Battery switch stations (or battery swap stations) as complement for charging infrastructure enable a fast and automated switching of the vehicle battery. The time needed is comparable to a refueling of conventional vehicles at a petrol station; even the frequency of 'refueling' could be higher due to the shorter range. This switch process needs furthermore a unique battery, special vehicles with the technical opportunity to switch the battery and a special infrastructure with corresponding switching machines. One popular example is the Better Place battery switch station system with a car of Renault (Fluence Z. E.).

In a battery switch station the vehicle can drive in on a defined place and the depleted battery will be replaced by a fully charged battery. The process is done by an automated robot or by skilled workers. It has to be secured for the high voltage and needs special tools to carry the heavy battery packs (up to several hundred kilos), to place it and to mount the batteries safe at the vehicle. The process should last only one to several minutes, wherefore an automated process is more likely. Further parameters to classify the battery switch station are the battery integration side at the vehicle (e. g. from top or bottom) or the number of battery packs (one or more). The battery switch system can be integrated in a private fleet or operated for public:

- *Private service*: The operation of the battery switch station and the use of it are in one hand. E. g. a company operates a battery switch station for their own or internal electric car park and the battery swapping is only accessible for own vehicles.
- *Public service*: The battery switch station is operated independently from the vehicles and everyone can use the open switching service – similar to a petrol station. The battery swapping would cost a fee that is due to the service in general higher than the energy price for the recharged battery.

The battery station needs enough charging spaces for the batteries and recharges the batteries either all day with relative constant power load, or in off-peak hours for reduced energy price. The off-peak charging may result in a higher battery provision factor (χ_{Bat})[1] and hence a higher battery investment. Though there are no general problems for battery switch stations especially in technical

[1] The battery provision factor (χ_{Bat}) gives the factor of batteries by vehicle. $\chi_{Bat} = 2$ means e. g. 12 batteries for six busses.

terms, there are three challenges from an economic and institutional point of view [De Luchi et al. 1989]:

1. *Standardization*: battery packs, connections and compartments should be standardized or limited to only few (better one) configurations. This is especially important for public service battery switch stations and reduces the price for battery packs and vehicle production. This standardization requires cooperation between vehicle and battery manufacturers and seems not likely nowadays [Järvinen et al. 2012].
2. *Battery pack quality*: the quality and age of each battery pack will be different. Especially for public service battery stations, this fact has to be taken into account and should result at least in an adjustment of the switching fee. Furthermore, this could result in an acceptance problem, wherefore the battery packs should be completely owned by the battery switch stations operator. In case of a real market for battery switching there would be several operators, which require cooperation for battery “roaming”.
3. *Investment*: the investments for the battery switch station and additional batteries seem to be very high. Therefore, the “non energy costs” are probable higher than those of petrol stations. The total swapping fee is dependent on many influences, like battery costs, size of the station and especially from the competition with fast-charging for electric vehicles or total-cost of ownership (TCO) compared to alternative vehicles. The acceptance is furthermore an unquantifiable factor.

These three challenges are less relevant in a private service. Therefore, already today, battery switching is common for industrial used vehicles like forklift trucks or autonomous container transporter [VDI 2011]. For cars, there is one enterprise (Better Place) active to build up an electric car infrastructure including battery swapping system in several regions and countries [Andersen et al. 2009]. Beside Better Place there are other concepts both for cars and busses:

- URECA - Unlimited Range Electric Car Systems
  Development of an automated battery swap station with modular battery packs, battery control and monitoring system [URECA 2012].
- Kitto Batteriewechselsystem
  A mechanical battery switch station was build only as prototype in Saarland, Germany [BWmobil 2010].
- EnergieTransport Container
  A concept as part for a battery switch station. A transportable container is used as charging place with many slots [Weber 2009].
- Mercedes battery switch station
  The station built in 1972 battery switch station and operated for several years. Also the Deutsche Post was involved with cars [Daimler 2008].
- Grid Surver
  The research project Grid Surver planned to build a battery switch station for cars [Next Energy 2011].
- Lithium Force
  For the Olympic Games 2008 in Beijing a battery switch station for busses was built and is in normal operation [Shine 2009].
- Wallner Energietechnik
  A battery switch station concept for busses with top loaded batteries [Wallner et al. 2010].

This list is not exhaustive. Further projects are known in China, but no concrete data and information are available [Li et al. 2011]. In the following two systems for busses are highlighted. First, there is one system in operation in Beijing since the Summer Olympics 2008 by Lithium Force. The second system is a concept designed for a full automated use by Wallner Energietechnik.

Lithium Force e-Bus System for Beijing

The battery switching station by Lithium Force is in operation in Beijing since the Summer Olympics 2008. The switching station located at the bus depot is used for 50 solo electric busses in full operation. The not fully automated swapping station needs several workers and land use of more than 1,000 m² [Shine 2010]. The robot takes four battery packs out of the bus and places them into the charging slot at the opposite side of the robot [Wallentowitz et al. 2011]. The busses have a range of about 130 to 150 km, depending on the use of air conditioning [Shine 2009] and a battery capacity of 142 kWh. The batteries are located underneath the bus and are switchable from the side. The battery factor per bus is $\chi_{Bat} = 1.6$. The investment for the battery switch station incl. spare batteries and other components is estimated at approx. RMB 50M (about 6 M€). The system is developed and deployed by Evida Power Inc [Shine 2010].

Change it Battery Change System

The concept of a battery switch station system for busses is called ‘change it’ and is developed by the Bavarian consulting Wallner Energietechnik [Wallner 2010]. The battery is located on the roof of the bus and will be switched at the bus station from top [Wallner et al. 2010]. With this concept the required area for the battery switch depot is much smaller compared to the Lithium Force system or the Better Place system. The system seems to be modular.

The experiences in Beijing show, that a battery switching station is technical possible and operable in normal daily operation of urban public bus transport. And also further possibilities and potentials of this technology and alternative for public bus transport are shown. Not clear is the question, if also an economical operation is possible. Therefore we analyze one business case as example for a regular urban bus service.

4 Business case analysis

A battery switch station for bus transport reduces complexity when it is integrated as private service (only accessible for the own busses). In this case, two of the general problems (cf. chapter 3), the standardization and the quality of the switched battery packs, are not relevant within this business case calculation. Only the above mentioned third problem, the profitability of the battery switch system (in particular the investments) compared to the common diesel busses, has to be evaluated.

A battery electric bus is more economical in inner-city routes with high numbers of starts and stops and high miles travelled to maximize the benefits of the low variable costs compared to a conventional bus. In addition a small battery reduces weight and fixed costs, but is only applicable with a battery switch station with frequent battery switches and by omitting long single trips away from the switching stations.

Therefore we analyze in the following a battery switch station for battery electric bus (BEB) for its economic feasibility. The business case is based on empiric data for the Karlsruhe public transportation system and does not intend to replace the complete bus fleet but analyses if some bus lines might be economically replaced. Therefore, we implemented a location analysis for the battery switch station and a possible first system extension step for the integration of further bus lines. The investment appraisal is based on the net present value, the yearly EBIT and a sensitivity analyses.

In a first step for the business case it is analyzed, which location for the battery switch station is possible and advantageous. In addition the size of the capacity of the system has to be defined. Due to the general shortage of free space it is assumed, that the battery switch station is designed similar to the concept of 'Change it' (cf. chapter 3), where nearly no additional space is needed and the bus modification is limited to the top of the bus. This might reduce costs and an automatic operation is possible. Therefore, no additional space and workers have to be regarded. In Karlsruhe the bus transport is additional to the tram system (cf. Figure 3). The two bus depots are located away from the bus lines and are therefore not appropriate for a battery switch stations (cf. red dots in Figure 3). The busses are separated in a western and an eastern part of the city, wherefore no single battery switch station for all busses is realizable (cf. Figure 3). In the eastern part of the city there is one bus station, as junction of several bus lines and central located (cf. blue square in Figure 3). The bus station has enough space for some small extensions for the battery switch stations and the busses have

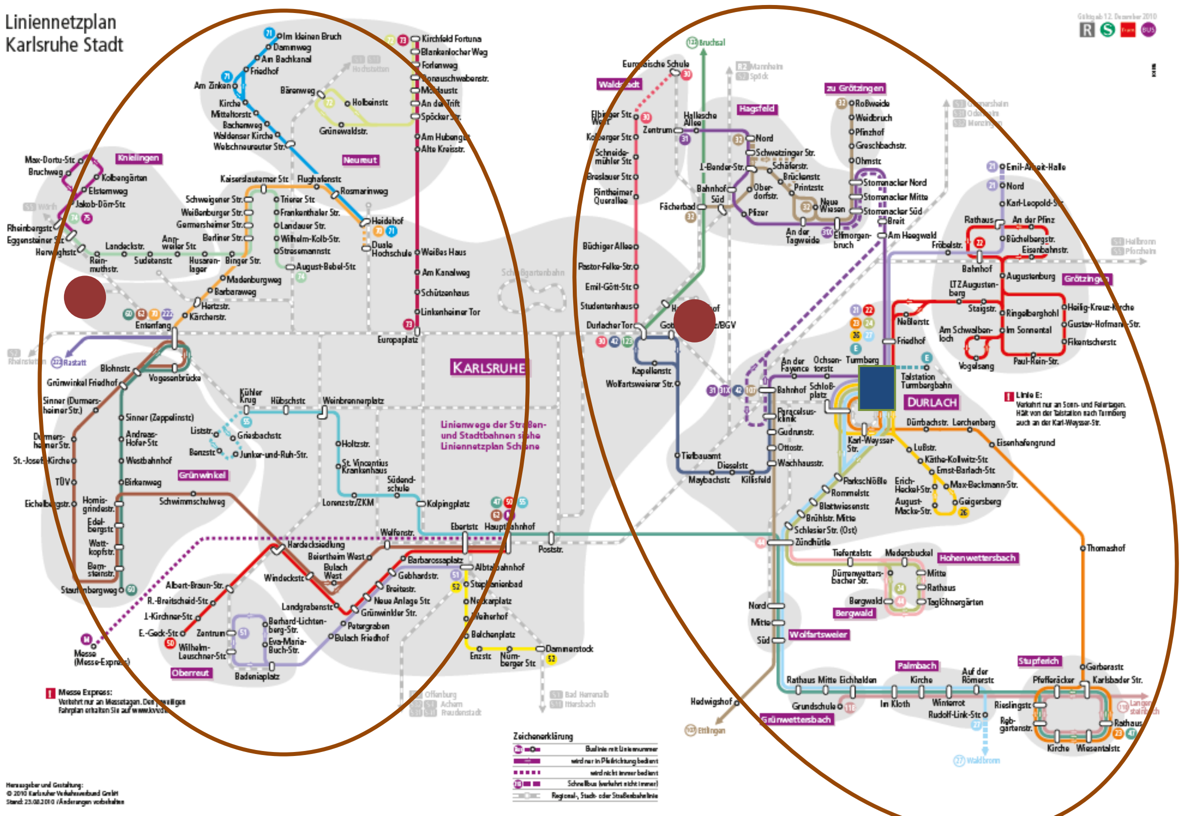

Figure 3: Karlsruhe bus line system with two main regions, two bus depots (red dots) and the identified switch station bus stop (blue square) [KVV 10]

more than 5 min stop time, which is sufficient for battery swapping. Other locations or bus stations integrate less bus lines or have other disadvantages, e. g. fewer bus lines or shorter stop times. Therefore a first business case includes one battery switch station at the bus station "Turmberg" for several bus lines. Two bus lines (23 and 24) have 20 min frequency in daytime and could use one platform together, each with 10 min stop time. In addition in nighttime the line NL6 and part of line 21 could increase the average utilization. This would mean 742 battery switches per week with a maximum of six switches per hour. Therefore a battery switch station with one switching robot and six charging slots in the battery switch station to charge the batteries is sufficient. The average station utilization is then 74 % of possible switches, which is higher at working days and lower at the weekend.

In the next step, all further essential assumptions have to be defined (cf. Table 2). In order to cover all integrated lines with electric busses, six busses with 12 battery packs (χ_{Bat} = 2) are necessary. The reported prices for the battery switch stations vary between 0.37 and 0.79 million Euros [Kudling 2011], [Shukla et al. 2011]. The battery switch station seems to be simpler[2] compared to the switch stations of Better Place, therefore the lower price is assumed. Further assumptions can be explored in Table 2. In case of a failure in the switching system or at one of the battery electric busses the scheduled bus service has to be guaranteed as well. The provision of conventional backup busses is not integrated in the calculation, because they are not additional.

Table 2: Assumptions and input data for the business case

Parameter	**Value**	**Explanation and Source**
battery switch station	400,000 €	prices for Better Place battery switch station vary between [Kudling 2011] and [Shukla et al. 2011] additional space is neglected
battery capacities	12x 65 kWh	χ_{Bat} = 2; two battery packs for each bus
battery costs	600 €/kWh	[Yuan et al. 2011]; [Kalhammer et al. 2007] projected battery costs for 25 kWh pack at 20k batteries per year: 280 €/kWh; current prices are unsecure
battery life time	10 a	both calendar and cycle life time considered; cycle numbers with max. 40 % depth of discharge
electric bus surcharge	6x 21,000 €	bus without battery; see battery capacities and costs
electrical connection	30,000 €	expert assumption; prices are not determined but calculated at cost
amortization period	10 a	all system components have a longer operation life
inflation rate	2 %/a	in DE 1,6 %/a for the last ten years [Destatis 2011]
credit capital rate	4,5 %/a	Assumption
insurance	2.3 %/a	based on the investment; according insurance tables
employees	--	no extra employees necessary
maintenance and service	7.5 %/a	high value according to new technologies
electricity (2010)	12.3 ct/kWh and +0.3 %/a	[BNetzA 2011] for industrial consumers; linear extrapolation of historical data from 2006 to 2010
diesel (2010)	1.23 €/l and +5.5 %/a	[BMWi 2012]; linear extrapolation of historical data from 2001 to 2011
charging efficiency	85 %	average efficiency [Gerbracht et al. 2010]
additional bus weight	< 600 kg	assuming 120 Wh/kWh for the battery
reference exchange rate	1,36 $/€	[Bundesbank 2012] average from 2010 and 2011
consumption diesel bus	0.45 l/km	[Hördegen et al. 2000]
consumption electric bus	1.5 kWh/km	incl. auxiliary consumers; praxis tests are with 1.15 kWh/km below [OVB 2011]

The additional investment is being accounted with the lower variable costs, mainly based on fuel prices. The net present value is calculated with 10 years operation for the busses and the battery

[2] The charging slots are limited and the batteries switching on the top do not require a system below ground.

switch station. The 10 years correspond with the lower usual bus lifetime (cf. chapter 2). The investments of over 1 M€ are being amortized over this period. The needed capital is borrowed with a common capital rate of 4.5 %. The yearly electricity demand is 687 MWh/a; based on the distances of the bus lines and the assumed consumption of the electric bus. For this volume of needed electrical power, an average industry electricity price can be assumed. In contrast to the household electricity price with high increasing rates of about 3 %/a in Germany in the resent years, the industrial consumer price is nearly constant with only 0.3 %/a price increase.

Based on these assumptions the capital value is at 99 k€. In addition, the EBIT is calculated. It is rising each year, which is mainly due to the diverging electricity and diesel prices (cf. Figure 4); and already in the second year after the investment (2011) the EBIT is positive. These results show that an economic operation of the battery switch station system compared to the common diesel busses is possible.

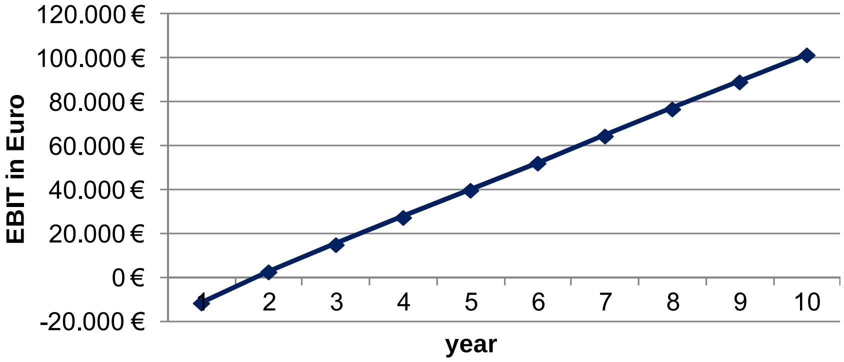

Figure 4: EBIT of each operation year

The yearly costs have four main parts (cf. Figure 5). The annuities[3] of the battery switch station[4] and batteries have each a part of about one third. The annuity for the bus surcharges are with 9 % less relevant. The costs for insurance, maintenance and service have a share of one quarter.

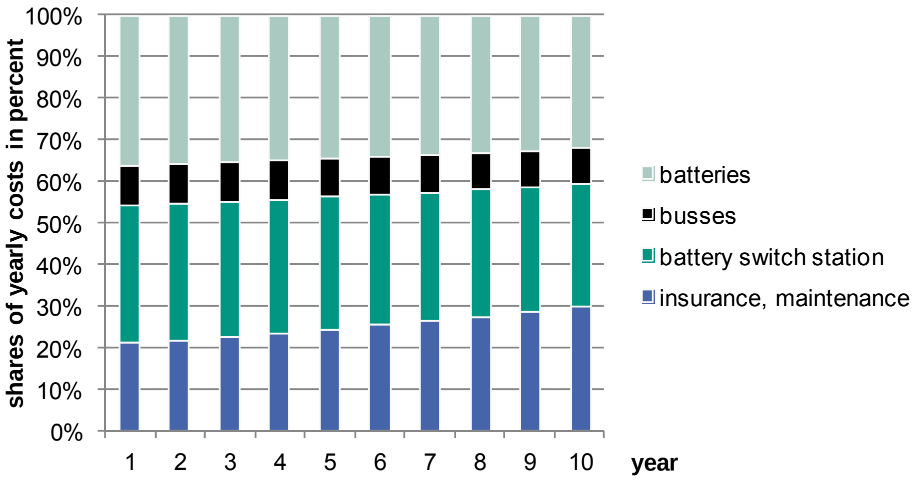

Figure 5: Shares of yearly costs for the battery switch station system

In order to clarify the relevance of the input values and the risk of the investment, a sensitive analysis has been realized (cf. Figure 6). The input parameters have been reduced to 50 % or increased to

[3] The annuity includes the yearly redemption and the capital rate.
[4] Included is the annuity for the electrical connection.

150 % from the value listed in Table 2. The results for the capital values are given in Figure 6. The investments of the battery switch station and the battery have the most relevant influence. Already smaller investment increases show a negative capital value. A further electricity price increase is less important. The same can be said for insurance and maintenance costs (both not displayed in Figure 6). But if the diesel price increase is getting reduced below approx. 4 %/a, the battery switching station system will not become economically anymore.

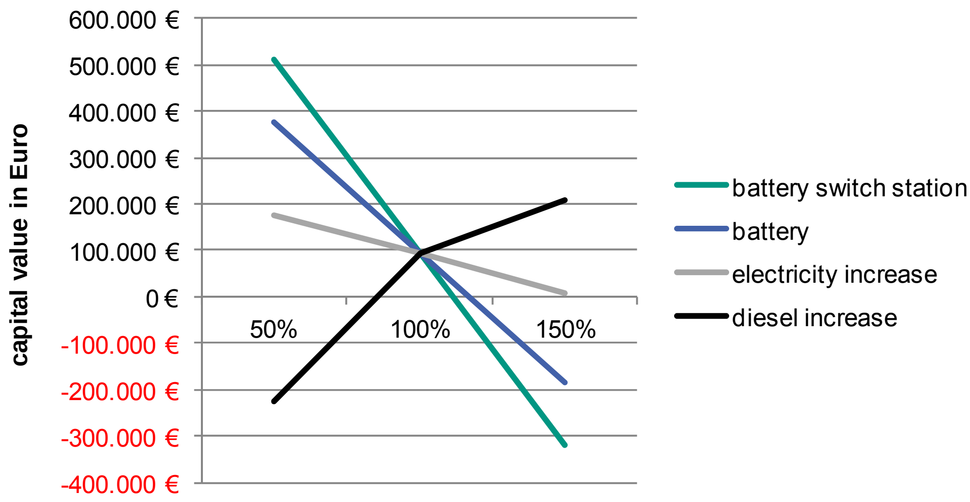

Figure 6: Sensitive analyses

These results show that the profitability of this battery switching station system is not as certain as it seems to be on the first view. To analyze the implications of a delayed investment of four years (i. e. 2015) is assumed. Through the increasing difference between diesel and electricity price, the capital value rises to 356 T€ in this case. In addition the battery prices are estimated to decrease [Jochem et al. 2011], which is not regarded in this case. Therefore it may be rational to wait some time before investing in the battery switch station.

One possible extension step is to set up a similar second battery switch station at the same bus station 'Turmberg'. With this addition also the bus lines 21, 26 and 31 could be integrated completely. With 476 battery switches per week, the average utilization is significant lower. Therefore, an extension is expected to be less attractive from an economic point of view as the first battery switching station.

Not included in these calculations are ancillary services for the grid like vehicle to grid (V2G), reactive power compensation or balancing power. These services may be positive for the economy but are coupled with other estimations and framework conditions. Therefore, theses additional services are from our perspective not of interest in this stage of research.

5 Summary & Conclusions

Reducing CO_2 emissions and fossil fuel consumption are the main challenges for most means of transport in the coming years. In urban areas the reduction of local pollutants and noise is of similar importance. There are several technologies, which promise to solve these issues. The electrification of urban busses seems to be one of the more attractive solutions. However, the technical feasibility and the corresponding profitability of this technology are ambiguous, so far. Especially the long charging times and the limited range of the battery electric busses make their introduction unattractive. The recent development of battery switch stations, however, is a possible solution for the limited range and charging times – if the system is still profitable.

In order to analyze the profitability, we present a first analysis on a hypothetic implementation of BEBs in combination with a battery switch station in the public bus service system of Karlsruhe. The switch station is introduced as an exclusive station for the considered BEBs only. This leads to a significant simplification and reduction of cost of this private service system as the general problem of standardization with respect to their batteries could be handled on their own. Furthermore, the fact, that the batteries and the BEBs belongs to the same company, the second main criticism of switching stations, that possibly a new battery is changed for an old one can be prevented, too.

Our analysis was focused on the bus lines at the bus station 'Turmberg'. Including four bus lines leads to 742 battery switches per week with a maximum of six switches per hour. The conventional system shows lower investments and higher variable costs as the system with the BEBs and battery switching stations. In using the annuity method we observe four main categories: The annuities of the battery switch station and the batteries have a part of 66 %; the annuity of the busses only 9 %. Further costs include the insurance, maintenance and service (about 25 %). The investment has a positive capital value of approx. 100 T€ and a positive EBIT already in the second year.

The sensitivity analysis identified the main influences on the profitability of the considered system. It turns out that the price of the batteries and the battery switch station itself, as well as the diesel price are the most relevant factors. Due to the forecasted increasing diesel price and decreasing battery costs, the profitability might increase significantly in the following years.

The conclusion is twofold: Public transport service providers should analyze different technologies when investing in a new fleet and bus manufacturers should be aware of the possibility of a profitable BEB in their utilization in public transport and consider an introduction of BEB in their offered fleet. In combination with battery switch stations also the range limitation could be prevented. For research, we argue for further and deeper technical and economic analysis on the technology and costs of battery switching stations and their interactions with BEB and electrical power systems. This includes the analysis of the possibilities of demand response or the possibilities to offer grid services to the local electricity grid (e. g. on the reserve energy market).

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This work was supported by the student work of Carsten Dickhut.