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A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities

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Abstract

To reach Swedish national climate change reduction targets, organizations collaborate for a sustainable development to improve energy efficiency, reducing pollution and noise in public bus transport. This follow-up study continues to strengthen the previous study by deepen the economic comparisons of two electric buses with different driving range and different type of chargers. The study aims to emphasize on sensitivity analysis for the total cost of ownership (TCO) to reduce uncertainty by identifying which factors of interest that most likely cause the estimated cost values for the electric bus. The result shows that the percentage change of line distance (km/year), operational years, and investment cost would be the most influential and significant factors on TCO.

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Keywords: Electric bus; Sensitivity analysis; Total cost of ownership; Sustainable development; Climate Change; Emissions

1. Introduction

1.1 Background

The Swedish Government has set targets for greenhouse gas neutrality by 2050 and a fossil fuel independent vehicle fleet by 2030 (International Energy Agency Organization 2013). To reach these targets, regional, local government, and organizations work together to transition towards sustainability, which includes the decision to change public bus transport to become more energy efficient and to emit less pollution and noise (The European Commission 2005; The European Commission 2011).

A previous study (Nurhadi, Borén, and Ny 2014) has built and tested a new assessment approach that could enhance decisions on bus transport powertrains and energy carriers for Swedish medium-sized cities with less than 100,000 citizens. The comparison was made on different energy carriers such as diesel, biodiesel, biogas, hybrid, plug in hybrid, and electricity. The study relied on a framework for strategic sustainable development (Robért 2000; Ny et al. 2006) and tools such as strategic life cycle assessment (Ny et al. 2006), life cycle assessment (International Standardization Organization 2006), and life cycle costing (International 2004; The International Standard Organization 2008). The preliminary result suggested that the priority should be to move from diesel buses to electric buses to shift from the traditional fuel directive approach to a strategic sustainability perspective that included economic, environmental and social issues - both now and in the future. Moreover, that study (Nurhadi, Borén, and Ny 2014) was supported with findings such as:

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- An electric powertrain with new renewable electricity would be the most energy efficient and sustainable choice, although the current European electricity is sourced from fossil fuels.
- The diesel bus was among the poorest solutions for energy efficiency and costs, and the poorest for life-cycle emissions. Since the cost for energy usage was much higher in fossil fuelled buses than in electric buses.
- The hybrid powertrain would in average reduce life-cycle emission by almost 40%, and the plug-in hybrid with around 70% reduction, compared to diesel. Where for plug-in hybrid, its life-cycle energy efficiency is almost 60% better than diesel.
- Compared to diesel, The Total Cost of Ownership (TCO) distributed over 8 years for an electric bus (with 1 extra battery and 1 fast charger) was 20 % lower, and an electric bus (with 1 extra battery and 2 fast chargers) was 17% lower. The cost for the plug-in hybrid was 17% lower and the hybrid that was 7% lower compared to a diesel bus.

Nomenclature

TCO	Total cost of ownership (SEK/km)	B	Battery
PW	Present worth or present value	EC	Energy cost
FW	Future worth or future worth	MC	Maintenance & helping maintenance cost
%	Percentage	EBC	Extra battery cost
SEK	Swedish Kronor	CC	Chargers cost
Km	Kilometer	CT	Carbon tax
kWh	kilowatt-hour	HC	Heating cost
IC	Investment cost	LD	Line distance (km/year)
OY	Operational Year	r	Real Interest rate (%)
MSEK	Million Swedish Kronor	tSEK	Thousand of Swedish Kronor

1.2 The focus of the study

This study aims to follow up on the previous bus study (Nurhadi, Borén, and Ny 2014) and check its validity by continuing to deepen the economic part of the life cycle costing (LCC) comparisons for two electric buses with different driving range and different type of chargers. This new study also adds emphasize on a sensitivity analysis for the total cost of ownership (TCO) in section 2.1. The same assumptions are used as in the previous study. Five city-buses (line 1 and 7 in Karlskrona) with average speed profiles (25 km/h) and average load profiles, with a stop in almost every bus stop that was based on drive cycles of 93 000 km/bus/year. A timeframe of 8 years was used, as this was stipulated by Swedish procurement of public bus authority. In relation to that, 8 years is not the technical lifetime of the bus, which the bus can be used longer time. For TCO, the energy price was assumed to increase annually by about 6%, based on the history of energy price development in the last 10 to 15 years (Svenska Petroleum och biodrivmedelinstitutet; pool 2012) and with a real interest rate of 1%.

The study focuses on 2 main objectives with three questions (Q1-Q3):

1. A sensitivity analysis for the TCO to identify which factors of interest those most likely cause the estimated cost values for the electric bus. This could also help to reduce the uncertainty factors that may impact the TCO, since economic factors such as future investment costs, operating expenses, fuel cost, and others may not be known with great precision.
   Q 1: **Which factor is the most influential and significant when the TCO is determined?**
2. The study uses "what if" analysis and captures this in a spider plot graph to understand the responsiveness of each factor on the outcome of the TCO. Each factor is indicated as percentage deviation in several factors using a specific measure of present worth.
   Q 2: **This involves a whole series of ¨what if¨ questions, such as: What happens to the TCO of an electric bus if the…**
   …future investment cost is overestimated by 10%, 20,%, or 30%?
   …travel line distance is decreased by 10%, 20%, or 30%?
   …number of operational years is increased by 10%, 20%, or 30%?
   …energy cost is increased by 5%, 10%, 20%, or 30%?
   …maintenance cost (or fast charger cost) is reduced by 10%, 20%, or 30%?
   Q 3: **Which of the described factors above are more important for the TCO where the effect of each factor is compared to all others - two by two (pair analysis)?** This would make a stronger decision making to save more on TCO of electric bus if two variables are paired; also identify uncertainty factors that could be avoided in decision making process.

1.3 Limitation

A limitation of this study is that the input of the costs may vary depending on bus manufacturers and the specifications of the electric buses. Moreover, sensitivity analysis does not aim to quantify risk but rather to detect factors that are risk sensitive (Flanagan and Norman 1993). No salvage value or value of asset in the end of the whole investment period for this calculation.

2. Methods

The study begins with the comparison between two different types of electric buses (figure 1). Bus 'A' has a normal charger and bus 'B' a fast charger. The sensitivity analysis (Flanagan and Norman 1993) then calculate the present worth (Leland and Anthony 2012) as the present discounted value for an 8 year period from 2013-2022. Then model input data of three scenarios are used in the calculation of present worth to be captured in a spider plot. In response to that, the base scenario is used to represent the actual conditions of the public bus procurement in Sweden. The other low and high scenarios set the assumed minimum and maximum range that could work as probability of occurrence for variation of each factor. Low Scenario is where the probable choice and increment variation for higher cost-effectiveness of electric bus could occur, and high scenario is where the probable choice and increment variation could occur for lower cost-effectiveness of electric bus. Finally, a tornado graph is used to analyse the relative impact on the TCO as all factors are compared against each other - two by two factors.

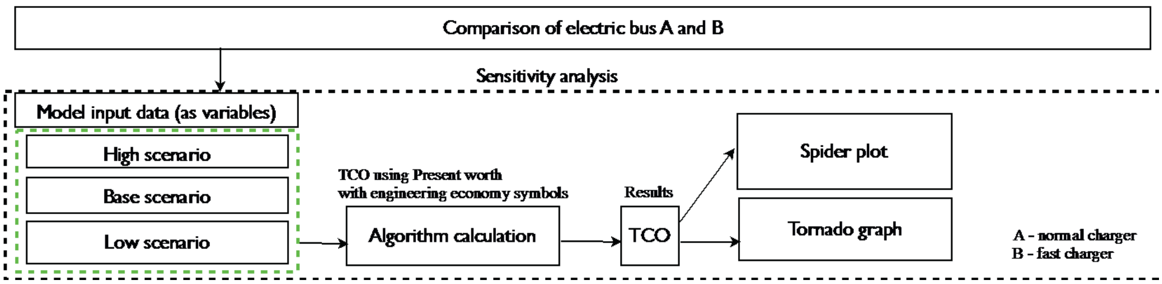

Figure 1. Sketching the sequence of how methods of the study are used

2.1. Total Cost of Ownership (TCO)

Total Cost of Ownership is used to calculate the cost experienced during the entire life cycle. The term of economic assessment has several similar names including the similarity term for TCO and life cycle costing (Mälkki 2010).

$$\mathbf{TCO} = \frac{\sum \mathbf{IC}\,n + \mathbf{B}\,n + \mathbf{EC}\,n + \mathbf{MC}\,n + \mathbf{EBC}\,n + \mathbf{CC}\,n + \mathbf{CT}\,n + \mathbf{HC}\,n}{\sum \mathbf{LD}\,n + \mathbf{OY}\,n} \quad (1)$$

Where, n = average value from year 2013-2020, IC is Investment Cost, B is Battery Cost, EC is Energy Cost, MC is Maintenance & helping Cost, EBC is Extra Battery Cost, CC is Chargers Cost, CT is Carbon Tax (or emission cost), HC is Heating Cost, LD is Line Distance, and OY is Operational Years

2.2. Present worth (PW)

Present worth is widely used in business and economics to compare cash flows at different time periods. It is used here as present discounted value (present worth) in (SEK/km), where the future value of money has been discounted (Leland and Anthony 2012). The present worth is indicated as usually less or equal to future worth (FW) because the money has an interest rate and indicated as time value of money. The time value of money can then in principle be described as 1 dollar today is worth more than 1 dollar tomorrow. Writing the life cycle cost or TCO in the form of a present worth,

$$\text{PW of TCO} = \frac{\sum_{i=1}^{n} \frac{IC + B + EC + MC + EBC + CC + CT + HC}{(1+r)^{i}}}{\sum_{i=1}^{n} \frac{LD + OY}{(1+r)^{i}}} \quad (2)$$

where, PW = present worth from 2013-2020, FW= future worth from 2013-2020, r = real interest rate of 1% where i = year ($1 \leq i \leq 8$) years

2.3. Spider plot graph

Perry and Hayes (1985) have suggested the spider plot as a particular effective graphical presentation of sensitivity analysis. It is used to analyze many inputs and get the outcome of each single factor (Eschenbach, Ted G 1992), (Peter McNamee 2008). The study uses spider plot to indicate which elements of the TCO are the most sensitive and how they may behave. In engineering economy terms, the algorithm for sensitivity analysis is calculated with PW (of TCO), where the costs for investment, line distance, operational years, and maintenance would vary with real interest rate, is described in equation 3 to 6 below.

(P/F, 1%, 8) below indicates Present Worth of TCO divided by Future Worth of TCO, with real interest rate of 1 % in 8 years operational of the bus. Where **(1 ± p % /100)** indicates 1 ± percentage of Present Worth.

If the investment cost (***IC***) varies by ±10 to 30%, with real interest rate of 1%, then:

$$PW (\pm 10 \text{ to } 30\%) = [\boldsymbol{(1 \pm p\,\% /100)\,(P/F, 1\%, 8)\,(IC)} + (B)(P/F, 1\%, 8) + (EC)(P/F, 1\%, 8) + (MC)(P/F, 1\%, 8) + (EBC)(P/F, 1\%, 8) + (CC)(P/F, 1\%, 8) + (CT)(P/F, 1\%. 8) + (HC)(P/F, 1\%, 8)] / [(LD)(P/F, 1\%, 8) * (OY)(P/F, 1\%, 8)] \quad (3)$$

If the line distance (***LD***) varies by ±10 to 30%, with real interest rate of 1%, then:

$$PW (\pm 10 \text{ to } 30\%) = [(IC)(P/F, 1\%, 8) + (B)(P/F, 1\%, 8) + (EC)(P/F, 1\%, 8) + (MC)(P/F, 1\%, 8) + (EBC)(P/F, 1\%, 8) + (CC)(P/F, 1\%, 8) + (CT)(P/F, 1\%, 8) + (HC)(P/F, 1\%, 8)] / [\boldsymbol{(1 \pm p\,\% /100)\,(P/F, 1\%, 8)\,(LD)} * (OY)(P/F, 1\%, 8)] \quad (4)$$

If the operational year (***OY***) varies by ±10 to 30%, with real interest rate of 1%, then:

$$PW (\pm 10 \text{ to } 30\%) = [(IC)(P/F, 1\%, 8) + (B)(P/F, 1\%, 8) + (EC)(P/F, 1\%, 8) + (MC)(P/F, 1\%, 8) + (EBC)(P/F, 1\%, 8) + (CC)(P/F, 1\%, 8) + (CT)(P/F, 1\%, 8) + (HC)(P/F, 1\%, 8)] / [(LD)(P/F, 1\%, 8) * \boldsymbol{(1 \pm p\,\% /100)\,(P/F, 1\%, 8)\,(OY)]} \quad (5)$$

If, the maintenance cost (***MC***) varies by ±10 to 30%, with real interest rate of 1%, then:

$$PW (\pm 10 \text{ to } 30\%) = [(IC)(P/F, 1\%, 8) + (B)(P/F, 1\%, 8) + (EC)(P/F, 1\%, 8) + \boldsymbol{(1 \pm p\,\% /100)\,(P/F,1\%,8)\,(MC)} + (EBC)(P/F, 1\%, 8) + (CC)(P/F, 1\%, 8) + (CT)(P/F, 1\%, 8) + (HC)(P/F, 1\%, 8)] / [(LD)(P/F, 1\%, 8) * (OY)(P/F, 1\%, 8)] \quad (6)$$

Where, PW is Present Worth, IC is Investment Cost, B is Battery Cost, EC is Energy Cost, MC is Maintenance & helping Cost, EBC is Extra Battery Cost, CC is Chargers Cost, CT is Carbon Tax (or emission cost), HC is Heating Cost, LD is Line Distance, and OY is Operational Years.

2.4 Two-factor tornado graph

The tornado graph is used to show the potential combination of two factors to generate potential highest cost reduction in TCO. It would also possibly show the cost effectiveness while analyzing many uncertain factors that could be avoided from decision making in economic perspective for public bus procurement.

The study uses a two-factor tornado graph concept (Eschenbach, Ted G (1992), (Peter McNamee 2008). The graph considers each pair of input variables and if N is the number of variables, then N*(N-1)/2 pairs will be evaluated. For each pair of two variables, all nine combinations of the low scenario, base scenario, and high scenario input variables are used. Likewise for each pair, the calculation shows the combination of input values that produces the lowest and highest output values and the pairs are sorted by bounds of variation.

2.5 Comparison of two different electric buses

The electric buses have two alternatives, which involves different driving range (battery capacity) with different type of chargers. The electric bus A refers to an electric bus provided with a normal charger for 2.5 to 4 hours, while the electric bus B refers to an electric bus provided with a fast charger (10 minutes charging time). The comparison can be seen in table 1 where the data is gathered from bus manufacturers in Sweden.

Table 1. Comparison of two different types of electric buses with different driving range and chargers

Characteristic	Specification of electric bus A	Cost (2014)	Specification of electric bus B	Cost (2014)
Bus*	Custom made 100% electric, 12 m long	3.3 MSEK	Custom made 100% electric, 12 m long	3.42 MSEK
Battery capacity*	242kWh or 311 kWh		80 kWh	
Battery type*	Lithium iron phosphate	0.45 MSEK	Lithium iron phosphate (2 extra battery)	0.4 MSEK
Charger*	Normal charger (2.5-4 hours full charge)	0.09 MSEK	Fast charger (10 minutes to fully charge)	2.8 MSEK
Charger lifetime (technical)*	10 years		10-30 years	
Charging rate*	100kW/h		200-300kW/h	
Bus energy usage*	0.9kWh/ km		1.14kWh/ km	
Driving range*	200-300 km		60 -70 km	

* Data from bus manufacturer in Sweden

2.6 Scenario description

The sensitivity analysis is used to test the most influential factor for the change of TCO of electric buses. Three scenarios below are included to give the variation to the probable range in the analysis.

1. **Low scenario** where the purpose is to assume the minimum values and get the lower bounds that could work as probability of occurrence. In the low scenario set to the line distance to 65 000 km, 6 years of operational years, and real interest rate of 0.5%, also where investment cost is 2.8 MSEK and energy cost per year is 0.78 MSEK.
2. **Base scenario** as the baseline of the model data input to generate the calculation of the algorithm to be plotted in the spider plot. This is based on the actual data from a bus manufacturer and bus operator in Sweden. Electric bus A and B has the similar numbers for maintenance cost of 1.53 MSEK per year, line distance 93000 km per year, 8 operational years, and real interest rate of 1%, and carbon tax. The investment cost and energy cost of electric bus B is higher than for electric bus A, as an electric bus that can use fast chargers is slightly more expensive than an electric bus for a normal charger.
3. **High scenario** consists of an investment cost of 4.17 MSEK, energy cost of 1.02 MSEK per year, line distance of 121 000 km per year, 10 operational years, and real interest rate of 2%. These are assumed to be the same between electric bus A and B, and with the purpose to generate the upper bounds of possible values as the maximum values. The battery and charger costs are set with different numbers between electric bus A and B to get the reasonable maximum values since current normal charger cost of 0.25 MSEK per bus and per charger is much lower cost than current fast charger of 1.2 MSEK per bus and per charger.

2.7 Model Input data

This study uses input variables that are expected to vary over the probable range as shown in table 2 and 3. The measure of present worth (PW) (section 2.2) is calculated using three parameters: high scenario, base scenario, and low scenario. The input variables are considered to bring impact to the change of electric buses Total Cost of Ownership (TCO) in section 2.1.

Table 2. Model input data for **electric bus A** (with 1 extra battery and 2 normal chargers)

Input variables in present worth (2013-2020)	High scenario	Base scenario	Low scenario
% Change of investment cost including battery (MSEK)*a	4.17	3.7	2.8
Energy cost per year (MSEK)*a	1.02	0.72	0.86
Maintenance cost & helping maintenance per year (MSEK)*a	1.65	1.53	1.20
Extra battery cost (MSEK)*a	0.58	0.44	0.30
2 Normal chargers cost (tSEK)*a	25	15.3	7.5
Carbon tax per year (tSEK)*a	29.2	14.6	7.3
Line distance per year (km)*a	65 000	93 000	121 000
Operational year (years)*a	10	8	6
Real interest rate*b	2%	1%	0.5%

*a Input variables for high scenario and low scenario are assumed, while base scenario is expected values from bus manufacturer in Sweden.
*b Input variables for high scenario and low scenario are assumed, while for average real interest rate for base scenario is known from Swedish banks.

Table 3. Model input data for **electric bus B** (with 1 extra battery and 2 fast chargers)

Input variables in present worth (2013-2020)	High scenario	Base scenario	Low scenario
% Change of investment cost including battery (MSEK)*a	4.17	3.82	2.8
Energy cost per year (MSEK)*a	1.02	0.9	0.78
Maintenance cost & helping maintenance per year (MSEK)*a	1.65	1.53	1.20
Extra battery cost (MSEK)*a	0.48	0.39	0.30
2 Fast chargers cost (MSEK)*a	1.2	0.98	0.75
Carbon tax / year (tSEK)*a	29.2	14.6	7.3
Line distance / year (km)*a	65 000	93 000	121 000
Operational year (years)*a	10	8	6
Real interest rate*b	2%	1%	0.5%

*a Input variables for high scenario and low scenario are assumed, while base scenario is expected values from bus manufacturer in Sweden.
*b Input variables for high scenario and low scenario are assumed, while for average real interest rate for base scenario is known from Swedish banks.

3. Results

3.1 The TCO comparison between 2 different types of electric buses with different number of extra battery and type of chargers compared to hybrid bus

In figure 2 below, the electric bus (with 1 extra battery and 1 normal charger) has the lowest TCO, 15% lower compared to other electric buses and 25% lower compared to hybrid buses. This could be appropriate for driving in the city area where there might be a fully charged electric bus as a back-up, if electric bus A has been driving for 200-300km in a day. The reason is that the normal charger uses 2.5-4 hours to be fully charged. A hybrid bus has the highest TCO (11.23 SEK/km) among the electric buses, where energy cost of fossil fuel generates high TCO compared to electric alternatives, even though the investment cost is lower. The second highest TCO is electric bus B (with 2 extra battery and 2 fast chargers) that is generated from the current high cost of fast chargers. During the lifetime of the 8 years, electric bus B needs 2 batteries, while electric bus A only needs 1 battery. This is mainly because the battery capacity is more in bus A, and it does not necessary charge as many times as the battery in bus B.

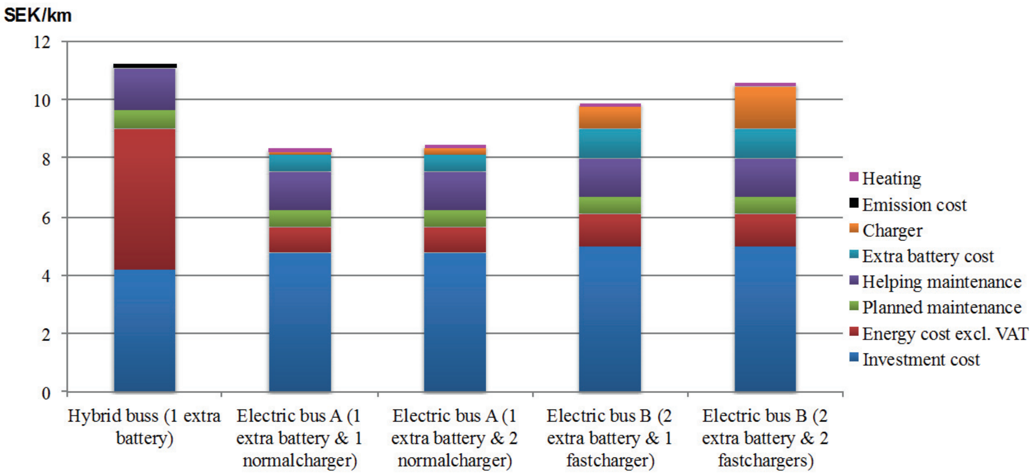

Figure 2. How cost varies depending with electric buses configuration compared to hybrid

3.2 Answer to Q 1: The spider plot of electric bus A

The spider plot show how the result of estimated TCO varies depending on percentage change of individual parameter (-30%,-20%,-10%,0,+10%,+20%,+30%). The present worth (PW) of different factors of electric bus A would also change depending on the changes (%) of each input variable. The steepest line in the spider plot represents the most influential and significant factors, which have significant impact on the change of TCO. The PW of TCO of electric bus A with 1 extra battery and 2 normal chargers is 8.44 SEK per km. The spider plot (figure 3) shows the most influential and significant factors, which are line distance per year and operational year. Where these two variables have the greatest impact on the change of TCO. In relation to that, the PW of TCO would be significantly lower if the electric bus drive would be more than 100 000 km per year and operate for more than 9 years. Similarly, the investment cost also plays a significant role of lowering the TCO if it is reduced by more than 5%. Where maintenance cost also give a slight impact to the change of TCO. On the other hand, the cost of normal charger and extra battery does not impact the result of TCO significantly since it gives a low contribution to the change of TCO. A carbon tax does not give any significant impact to the change of TCO for the electric bus. However, it would give significant impact on TCO for fossil fuel buses, given by their carbon dioxide emissions (Nurhadi, Borén, and Ny 2014).

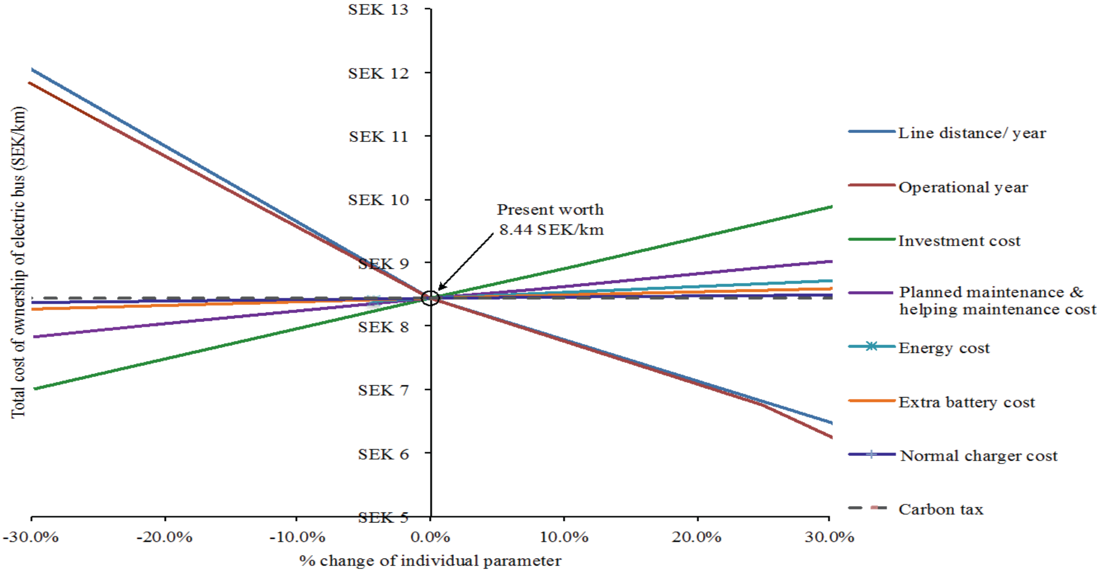

Figure 3. How TCO of electric bus A (with 1 extra battery & 2 normal chargers) varies with changes (%) in different parameters.

3.3 Answer to Q 1: The Spider plot of electric bus B

The present worth (PW) of different factors of electric bus B would also change base on those percentage changes of its individual parameter. The PW of TCO of electric bus B with 2 extra battery and 2 fast chargers is 10.56 SEK per km. The results (figure 4) shows almost similar findings for bus B as for bus A above (figure 3). The steepest line in the spider plot represents the most influential and significant factors, which have impact on the change of TCO. In relation to that, the most influential and significant factor is line distance per year, the second most influential factor is operational year, then the third most influential factor of the investment cost and maintenance cost. Similarly to the fast charger cost brings quite substantial impact to the change of TCO since it contributes quite high values especially if it includes two of fast chargers. The summary of the most influential factor is captured in figure 5 below.

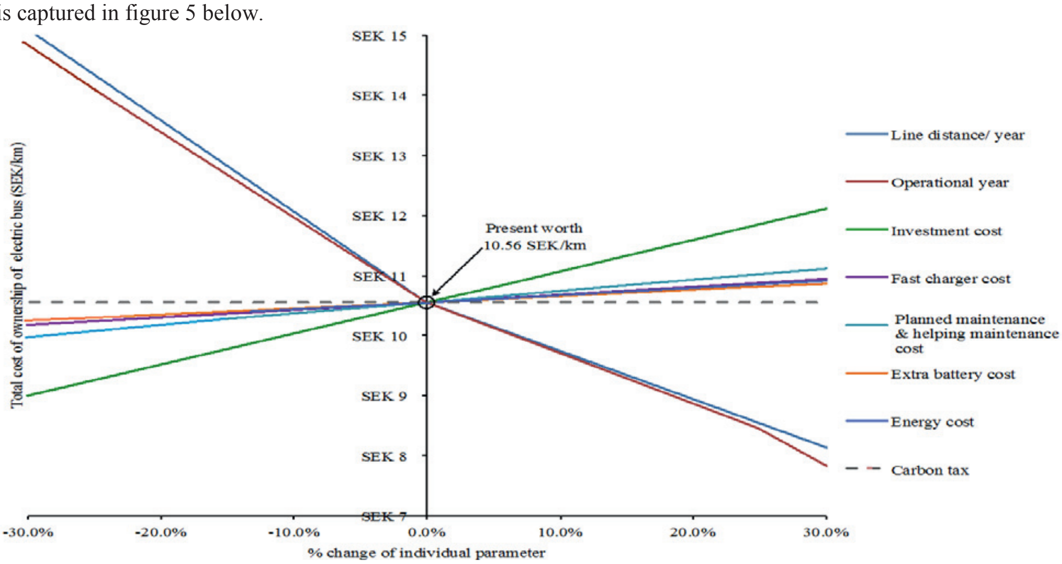

Figure 4. How TCO of electric bus B (with 2 extra battery & 2 fast chargers) varies with changes (%) in different parameters.

From figure 3 and 4, a summary of the most influential factors are captured as a result from the spider plot that ranked from the most to the least influential factor in electric A and B, as shown in table 4 below.

Table 4. Summary of the most influential factors that cause the change of TCO

Rank.	Influential factors in Electric bus A	Influential factors in Electric bus B	The factors
1	Line distance / year (km)	Line distance / year (km)	The most influential
2	Operational year	Operational year	↑
3	Investment cost including battery	Investment cost including battery	
4	Maintenance cost & helping maintenance per year	Maintenance cost & helping maintenance per year	
5	Energy cost per year	Fast chargers cost	
6	Extra battery cost	Energy cost	
7	Normal chargers cost	Extra battery cost	
8	Carbon tax / year	Carbon tax/ year	Insignificant factor

*3.4 Answer to **Q 2**: a whole series of ¨what if ¨ questions* that generate answers such as: The result is shown in figure 3 and 4, with the following table 5 that answers the question: *what happens to TCO of electric bus A or B if…*

Table 5. What happens to TCO of electric bus A or B if…change

The most influential factor	% Change	TCO of Electric bus A	TCO Electric bus B
Future Investment	+(10-30%)	5 – 14%	5 – 13%
Travel line distance	-(10-30%)	13 – 30%	12 – 30%
Operational year	+(10-30%)	8 – 34%	7 – 33%
Energy cost	+(10-30%)	2 – 4%	0 – 3%
Maintenance and helping maintenance	-(10-30%)	2 – 5%	2 – 5%

The PW of TCO is 8.44 SEK per km for bus A, and 10.56 SEK per km for bus B. From table 5 shows more detail below:

…***the future investment cost is overestimated by 10% to 30%?*** TCO for bus A will increase from 5.2 to 14%, while TCO for bus B will increase by 4.8 to 13%.

…***travel line distance is decreased by 10 to 30%?*** TCO for bus A will increase from 13 to 30%, and TCO for bus B will increase from 12.3 to 30%. The result reveals that it would be profitable to drive longer distance as it lowers the TCO, especially if the distance is more than at least 75 000 km. but even when 100,000 km per year is passed.

…***number of operational year is increased by 10 to 30%?*** TCO for bus A will be reduced by 8 to 34%, and TCO for bus B will be reduced from 7 to 33%. This reveals that the most profitable to drive more than 8 years operational life, since the 6 years would give much higher TCO. It is not cost effective to drive less than 8 years. The most desirable is 10 years of operational life that bring much lower TCO.

…***energy cost is increased by 10 to 30%?*** TCO for bus A and B will increase from 1.8 to 4%, and TCO for bus B will increase from 0.4 to 3%, if **electricity** cost increase by 10 to 30%. Energy cost, normal charger cost, and carbon tax are quite substantial but it is not significant enough to affect the change of TCO.

…***maintenance cost and helping maintenance cost (or fast charger for electric bus B) is reduced by 10 to 30%?*** TCO for bus A and B, and fast charger cost for electric bus B, will be reduced from 2.2 to 5%. If the maintenance cost of electric bus is not lower than maintenance cost for diesel bus, then it will impact much on the increase of TCO of electric bus. Fast charger cost also influences a lot to TCO since the cost of fast charger is still high cost today.

*3.5 Answer to **Q 3**: What are the important factors when making a pair analyses for TCO of electric bus A?*

The result has N = 8 input variables, so there are N*(N-1)/2 = 8*(8-1)/2 = 28 pairs to evaluate as shown in the figure 5 below. This also shows what would happen to TCO of electric bus A if the two variables are paired and what are the minimum and maximum values. This would make stronger decision making to save more on TCO of electric bus if two variables are paired. The two-factor analysis shows that a line distance of 121 000 km per year and 10 operational years could generate the lowest PW of TCO. On contrary, the highest cost is caused by low line distance 65,000km per year and 6 operational years.

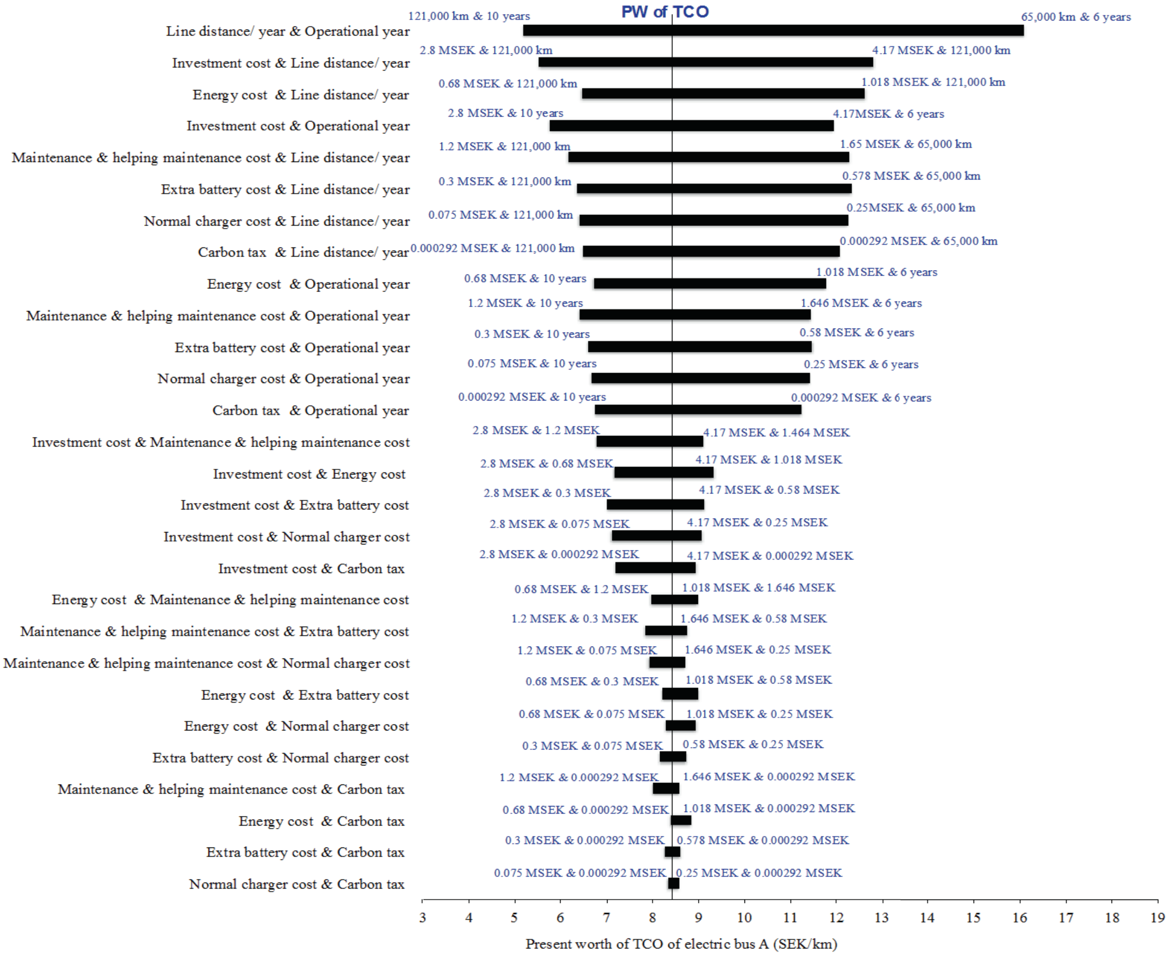

Figure 5. A tornado graph that shows how minimum and maximum value of TCO of electric bus A depends on pair analyses

4. Concluding discussion

The present worth (PW) of Total Cost of Ownership (TCO) for electric bus A (with 1 extra battery and 2 normal chargers) is 8.44 SEK per km, and 10.56 SEK per km for electric bus B (with 1 extra battery and 2 fast chargers). The result suggests that the electric bus A would be more preferable in term of cost effectiveness since the normal chargers are cheaper and allows a longer battery life. This might be a good solution for a city or suburb where a fully charged electric bus can be available as a back-up after a bus has been driving for 200-300km. Electric bus B could be an intermediate solution for a city that run on tight schedule since it charges within 10 minutes. This study aims to make previous study more credible by showing the ¨what if" analysis of the most influential individual parameters to be considered in the TCO for an electric bus. This is supported with findings such as:

- The TCO of electric bus A will get 13 to 30% more expensive while the TCO of electric bus B will increase 12 to 30%, if the travel of line distance (which is the most influential factor in the change of TCO), is decreased by 10 to 30%.
- The TCO of electric bus A will decrease by 8 to 34% while the TCO of electric bus B will decrease by 7 to 33%, if the total number of operational years (which is considered as the second most influential factor in the change of TCO), is increased by 10 to 30%,

The previous study of that recommended the electric powertrain, is strengthened by this study, where the result could be used to avoid many economic uncertainty factors from the decision-making process for public bus procurement. A potential shortcoming of this study is the lack of real life testing of the assumptions and scenarios. Also the numbers presented depend on the reliability of the sources might not in great precision that may affect the result, however it gives a good indicator to show the most likely TCO and its influential factors.

The validity of the approach of this paper is however strengthened by another study (Ong et al. 2012) that used a similar approach to identify life cycle costs of palm biodiesel production. They also made a sensitivity analysis. In their case, they could examine how uncertainty in international prices could alter project outcomes. Another study of marine renewable energy (MacGillivray et al. 2013) was done with a similar purpose. It displayed that even small changes of input assumptions can have a dramatic effect on the overall investment required for a sector to reach uniformity with benchmark technologies in marine renewable energy.

The paper also considered the implications of cost reduction to these uncertainties for marine energy innovation management. The electric buses have been expected as a potential solution to sustainable growth in the transportation sector. If this can be concretized, this aims to support the development for public bus transport systems with the economic analysis to potentially foresee uncertainty factors and bring cost effectiveness. A next expected step is real-life testing of electric buses around South of Sweden as an attempt to validate the assumptions and approaches used in this and the previous bus comparison study.

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