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Advancing from efficiency to sustainability in Swedish medium-sized cities: an approach for recommending powertrains and energy carriers for public bus transport systems

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Abstract

European national, regional, and local authorities have started to take action to make public bus transport services more effective and less polluting. Some see the possibility to move beyond a narrow focus on efficiency or carbon dioxide reductions towards an integrated sustainability perspective. This paper uses this perspective to build and test a new assessment approach that should enhance decisions on bus transport powertrains and energy carriers for Swedish medium-sized cities. The study suggests that a superiority of electric powertrains is revealed if a traditional economic analysis is integrated with a strategic sustainability perspective.

Selection and/or peer-review under responsibility of Scientific Committee

Keywords: Electric bus; Life cycle assessment; Greenhouse gas emissions.

1. Introduction

Public transport is vital to support travelers and commuters' to and from suburbs and surroundings for everyone in a more environmental friendly way than using cars. Public bus transport also help people without cars to travel safely. The present European transportation growth is however unsustainable as it is strongly linked to problems such as energy supply and climate change (The European Commission, 2011). There is therefore a need to transform public bus transport systems towards sustainability. This study focuses on recommending powertrains and energy carriers within city buses for small to medium-sized cities with less than 100,000 citizens in Sweden.

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1.1 EU focuses on efficient transport at the expense of sustainability?

The European commission focus on future transport to be energy efficient, have low carbon dioxide emissions, and becoming independent of fossil fuels (The European Commission, 2011). Unfortunately, the focus in the EU directives is sometimes too narrowly set on the use phase, while excluding phases like manufacturing and its' supply chain. This means that the directives in their current form are not enough to ensure a sustainable transport system development. The EU fuel directive (The European Commission, 2009a; 2011), that the bus manufacturers use to calculate their emission levels, is a part of this problem. In line with the EU transport ambitions, European national, regional, and local authorities have started to take action to make public bus transport services more effective. That will ensure a short-term economic return, but inherently unsustainable solutions (like fossil fuelled buses) may be kept for too long at the expense of initially costly renewable energy carrier solutions that are less polluting and more long-term resource effective since fossil fuels is likely to become exceedingly expensive over the decades to come.

1.2 A Framework for Strategic Sustainable Development

It is a complex task to make decisions about how to transform transport systems towards sustainability. A previously presented framework for planning in complex systems (Robèrt, 2000; The European Commission, 2011) has been developed for such tasks. It has been successfully used for strategic sustainability planning both in business (Broman, Holmberg, & Robèrt, 2000; Everard, Monaghan, & Ray, 2000; Nattrass, 1999; Robèrt, 2002) and in municipalities (James & Lahti, 2004; Resort Municipality of Whistler, 2007). This framework uses four basic sustainability principles (SPs) of ecological and social sustainability (Holmberg & Robèrt, 2000; Ny, MacDonald, Broman, Yamamoto, & Robèrt, 2006) as boundary conditions for visioning in planning, followed by analysis, planning, and choice of tools to step-wise get there, as well as optimizing financial outcomes:

In the sustainable society, nature is not subject to systematically increasing . . .
I …concentrations of substances extracted from the Earth's crust,
II …concentrations of substances produced by society,
III …degradation by physical means, and, in that society . . .
IV ...people are not subject to conditions that systematically undermine their capacity to meet their needs.

1.3 From efficiency towards sustainability

The public bus transport system makes a positive contribution to personal mobility, but from a sustainability perspective we also need to consider issues like costs, pollution, and social implications. Aspects of the public bus system's sustainability implications have been described in the literature (Andersson & Norman, 2012; Börjesson, Thufvesson, & Lantz, 2010; Cooney, 2011; Gode et al., 2012; Helms, Pehnt, Lambrecht, & Liebich, 2010). How could we then advance from a narrow focus on efficiency or carbon dioxide emissions towards an integrated sustainability perspective when choosing public bus transport systems in medium-sized cities? And how, if at all, would such a new perspective change the preferred choice of bus transport system?

2. Methods

The Framework for Strategic Sustainable Development (FSSD), where principles define a sustainable future, is used to move from a shortsighted cost and environmental perspective to a long-term sustainability perspective that allows planning towards a desired future from a current state. As previously suggested by Ny and Gunnarsson in a master thesis (Gunnarsson, 2010), and as described in Fig. 1, Strategic Life Cycle Assessment -

SLCA (Ny, MacDonald, Broman, Yamamoto, & Robèrt, 2006) - is first used to give a quick full scope of sustainability challenges in each bus life cycle stage from raw materials to end of life. After that, Life Cycle Costing - LCC (ISO, 2008), Life Cycle Assessment - LCA (ISO, 2006) and other analyses are iteratively used to ”dig deeper” into prioritized identified challenges. Literature reviews, interviews, and simulations are used as supporting methods. Karlskrona in Southern Sweden with 35,000 inhabitants is used as the case.

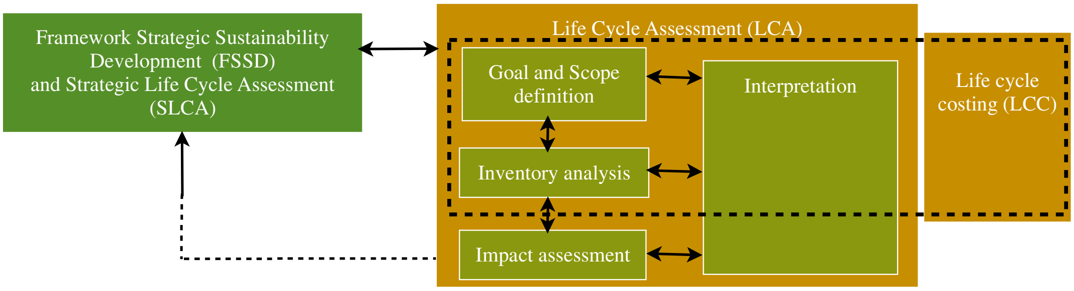

Fig. 1. How a new iterative approach uses SLCA to scope an integrated LCA and LCC analysis

2.1 Strategic life cycle assessment (SLCA)

As a first part in this study, the SLCA is a qualitative method to address social and ecological sustainability aspects. It allows an approach to quickly identify the most important high-level sustainability challenges that can guide necessary decisions and activities and then, if needed, suggest complementary analyses. The SLCA displays the ‘hot-spot’ issues that are particularly important for a sustainable development. The focus is on powertrains and energy carriers that makes a big difference when comparing bus alternatives for city traffic.

2.2 Life Cycle Assessment (LCA) and Life Cycle Costing (LCC)

The second part is to conduct a deepened sustainability study with LCA and economic potential with LCC. This requires assessment from “well to wheel” (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance). The study makes a theoretical comparison of a public bus transport system primarily using several alternative energy carriers (diesel, biodiesel, biogas, and electricity) in different powertrain configurations (internal combustion engines, electric hybrids, and pure electric), as seen in Table 1. Note that wind power is assumed to deliver to the grid at least the yearly required electricity for the electric powertrain configurations. A timeframe of 8 years is used, as this is what is stipulated by procurement of the case. For each type of bus the same driving pattern is used in the calculations: five city-buses (lines 1 and 7) with average speed profiles (25 km/h) and average load profiles, with a stop in almost every bus stop. This is based on drive cycles of 93 000 km/bus/year, and in total 465 000 km/year for five buses.

Table.1. Energy carriers, powertrains. energy usage, energy contents and costs in 2013

Energy carrier	Description	Primary drive	Energy usage	Energy content	Cost (excl VAT)
Diesel	Fossil Diesel with 5% blending of FAME	Combustion	0,45 liter/km	9.96 kWh/ liter	5,90 SEK/km
Biodiesel	Made from Rapeseed methyl Ester (RME)	Combustion	0,50 liter/km	9.3 kWh/ liter	6,30 SEK/km

Biogas	Made from household waste	Combustion	0,57 Nm3/km	9.67 kWh/ Nm3	6,70 SEK/km
Hybrid	Biodiesel (33% energy savings)	Electric/Combustion			4,20 SEK/km
Plug-in hybrid	67% wind electricity - 33% biodiesel	Electric			2,40 SEK/km
Electric bus	Electricity from wind power	Electric	1,4 kWh/km	1 kWh/kWh	1,20 SEK/km

LCA is used to compare negative environmental effects on society of different energy carriers for buses during their lifetime. In line with previous LCA studies on Swedish biofuels (Börjesson et al., 2010) the authors selected the air emission categories Green House Gases (CO_2 eqv), Eutrophication (PO_4 eqv), Acidification (SO_2 eqv), Photochemical oxidants (C_2H_2 eqv), and Particles (PM). These all need to be decreased for a development towards a sustainable future as defined by the SPs.

The purpose of using **LCC** is to analyze economic lifecycle data that relates to energy carrier manufacturing, operation, and maintenance for buses. Building on energy usage for each energy carriers, this analysis is essential for decision-making when purchasing vehicles, optimizing maintenance, and planning upgrades of public bus infrastructure. The **Scope and Limitation** of the LCA and LCC exclude leakage or energy losses during distribution or transportation of energy carriers, bus manufacturing processes, and end of life. Nor are accidents or other external costs included. The origin of the electricity for the extraction to distribution phases is gathered from literature sources. The electricity in the use phase, though, is always assumed to come from renewable sources (e.g. new local stand-alone wind power plants). The biogas analyzed in the study is locally produced digested biogas-100. Costs and emissions of the substrate before digesting is excluded, as these factors are dependent on digestion quality, land applications, country policy, etc. Biodiesel - Rapeseed Methyl Esther (RME) is locally produced. The system expansion, replacement by-products for RME as rapeseed meal, glycerol, and straw are excluded. The **functional unit** used is travelled bus kilometer. LCA and LCC data are calculated based on 8 years operational period as stipulated by procurement. The Net Present Value method and a real interest rate of 1% (based on historical data for Sweden from the 21st century) are used to calculate the economic potential. Results for each energy carrier are based on best estimates of current energy usage per km, energy content per kWh and costs in SEK per km (Table 1). The **data inventory** is obtained through interviews, literature review, authors' calculation, and bus manufacturer's simulation. Interviews were conducted with bus dealers, bus manufacturer, drivers, and bus service providers in 2012. The interviews brought insights on economic potential of public bus transport and data input and raw data calculation in the inventory list.

2.3 Priority listing of bus types – both for EU fuel directive and form a strategic sustainability perspective

Based on the preliminary results that are available, the authors demonstrate how the desirability of the studied bus systems vary depending on whether the assessment is done with a EU fuel directive or a strategic sustainable development perspective.

3. Results

3.1 Sustainability potential with a life cycle perspective

The SLCA conducted in this study focuses on the life cycles (including raw material extraction, production, transport, use and waste management phases) of energy carriers within city buses (Table 2). As mentioned in section 2, LCA is then used to further analyze sustainability challenges discovered in the SLCA. There is a contribution to social sustainability (SP4) for the biodiesel, biogas and electric alternatives in the first life-cycle phases as they are contributing to local jobs. Meanwhile biodiesel (rapeseed) production may outside of Sweden compete with other more urgent land uses and thereby violate SP4. The electric and hybrid alternatives contribute to SP4 reducing noise level and air quality. Violations for diesel are mainly in SP2 due to emissions, but also in SP3 due to infrastructure and risks of environmental impacts. Batteries within electric and hybrid bus alternatives violate SP1 due to scarce materials such as Lithium. At last, hybrids violate SP2 as powertrains include both combustion engines and electric drives, which increase the production material flows and transport emissions.

Table 2. Strategic Lifecycle Assessment (SLCA) analysis of sustainability principle (SP) impacts for six alternative city bus life cycles

Sustainability Principle	Life cycle phase	Biogas	Biodiesel	Diesel	Electric	Hybrid	Plug-in Hybrid
SP1	Raw material	slightly negative	slightly negative	slightly negative	negative	slightly negative	negative
	Production	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Transport	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Use phase	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Waste	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
SP2	Raw material	slightly negative	slightly negative	negative	slightly negative	slightly negative	slightly negative
	Production	slightly negative	slightly negative	negative	slightly negative	slightly negative	slightly negative
	Transport	slightly negative	slightly negative	slightly negative	slightly negative	negative	negative
	Use phase	neutral	slightly negative	negative	neutral	neutral	neutral
	Waste	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
SP3	Raw material	neutral	neutral	slightly negative	neutral	neutral	neutral
	Production	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Transport	slightly negative	slightly negative	negative	slightly negative	slightly negative	slightly negative
	Use phase	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Waste	slightly negative	slightly negative	slightly negative	neutral	slightly negative	slightly negative
SP4	Raw material	slightly positive	neutral	slightly negative	neutral	slightly positive	slightly positive
	Production	slightly positive	slightly positive	neutral	slightly positive	slightly positive	slightly positive
	Transport	neutral	slightly negative	slightly negative	slightly negative	slightly negative	slightly negative
	Use phase	neutral	neutral	neutral	slightly positive	neutral	slightly positive
	Waste	neutral	neutral	neutral	neutral	neutral	neutral

Indicators: negative, slightly negative, neutral, slightly positive

Electric powertrains are the most efficient and biodiesel the least efficient during the whole life cycle. Biogas uses most energy of all energy carriers during the use phase, but is the second best after the 15 times smaller electric energy carrier in the extraction to distribution (E-D) phase (Fig. 2).

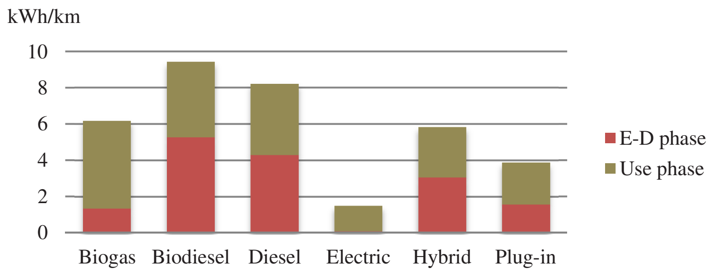

Fig. 2. Life Cycle energy use per energy carrier

The emissions to air depend upon the type of energy carrier and powertrain (Börjesson et al., 2010; Gode et al., 2012) Emissions from hybrids (including Plug-in) are calculated based on energy savings. Within all these results, biofuels are considered carbon dioxide neutral in the use phase according to the Swedish annual Greenhouse Gas reporting to the UN (Swedish Environmental Protection Agency, 2012). The electric alternative emits the least per km and biodiesel together with diesel emits the most (Fig. 3), but the hybrids would emit much less if they would run on biogas.

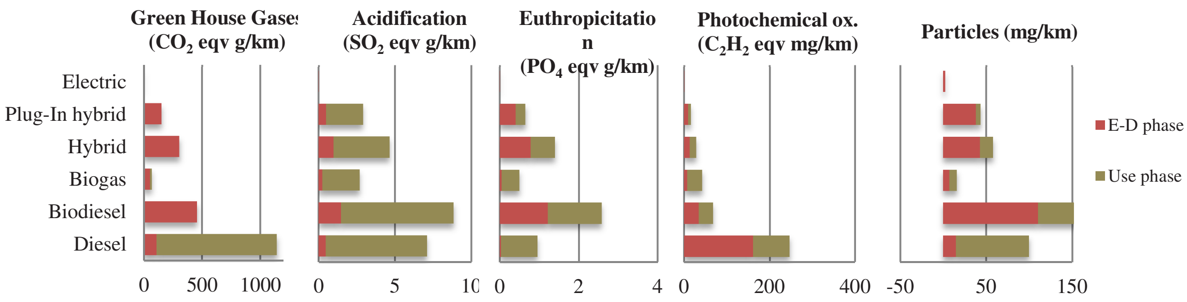

Fig. 3. Life-cycle emissions per energy carrier for Extraction to Distribution (E-D) and Use phases

If the EU fuel directive (The European Commission, 2009a) calculation model is used instead of the UN GHG approach, the biodiesel carbon dioxide emissions would be halved and the biogas carbon dioxide emissions reduced by about 20 % compared to diesel in the use phase. When calculating GHG-emissions in the use phase, biodiesel will emit 60 % less than the diesel alternative, and biogas about 75 % less. Biodiesel would then emit a few percent more GHG (life cycle) than diesel.

3.2 Current Economic potential

Table 3. The difference in life cycle cost between combinations of energy carriers and bus powertrains for the year 2013

Indicator	Biogas	Biodiesel	Diesel	Electric	Hybrid	Plug in hybrid
Bus investment cost (MSEK)*[a]	3.0-3.1	2.3-2.4	2.3-2.4	3,5-5.0	3.05	3.05
Energy usage per km (kWh/km)	5.50	4.65	4.90	1.40	3.10	4.00
Energy price excl. VAT (SEK/kWh)*[a]	1.22	1.35	1.20	0.86	-	-
Energy cost (SEK/km) *[a]	6.70	6.30	5.90	1.20	4.30	2.40
Energy usage kWh/ yr	623 100	585 900	548 700	111 600	399 900	223 200
Fuel station cost (MSEK)*[a]	25	2.5	7.5	5	-	-
Facility cost (MSEK)*[a]	55	2.5	-	30 (Wind)	-	-
Maintenance cost (SEK/yr)	69 000	49 300	49 300	180 000	140 000	170 000
Helping maintenance (SEK/yr)	127 700	123 300	111 000	200 000	150 000	190 000
Production fuel/electr.(SEK/kWh)*[a]	0.30-0.70	0.68-0.74	0.59	0.05-0.10	-	-
Upgrading to gas (SEK/kWh)	0.15-0.20	-	-	-	-	-
Additive cost (SEK/kWh)*[b]	-	0.072	0.05-0.1	-	-	-
Distribution (SEK/kWh)*[b]	0.10-1.10	0.005-0.01	0.005-0.01	0.1-0.2	-	-
Selling cost (SEK/kWh)*[b]	0.8-2.40	0.025-0.03	0.025-0.04	0.02-0.01	-	-

*[a] Data from bus manufacturers, bus operators (maintenance cost), energy suppliers, biofuels supplier, and facility station in Sweden
*[b] Recalculated from reference (Börjesson et al., 2010)

MSEK=Million of Swedish Kronor; SEK=Swedish Kronor; l/km=litres/kilometre; Nm3/km=Normal cubic meter / kilometre; l/yr=litres/year; kWh/km=Kilowatt-hour/kilometre; kWh/yr=Kilowatt-hour/year; SEK/l = Swedish Kronor/litres; SEK/kWh=Swedish Kronor/kilowatt-hour
Average energy price exclude VAT (Eon Sweden, 2013; Svensk Energi, 2013; Svenska Petroleum och biodrivmedelinstitutet, 2013).

When calculating Total Cost of Ownership by the Net Present Value method and a real interest rate of 1%, the results shown in fig. 4 reveals that there is already today an economic advantage to chose electric propulsion (from wind power) in city buses instead of fossil fuels. The highest initial investment cost in year 2013 is for an electric bus (3,7 MSEK), and the lowest for a diesel and biodiesel bus (2.3-2.4 MSEK) (Table 3 and Fig. 4). This could from a traditional economic calculation seem to suggest that it is beneficial to select the diesel bus as a short term investment. Still, the energy use is relatively high for fossil fuelled buses (0.4-0.5 liter/km or 4 kWh/km) and relatively low for electric buses (1.4 kWh/km). Moreover, the diesel bus generates the most external environmental costs such as air, land and sea pollution. When using the LCC approach, other costs are also included (e.g. maintenance, helping maintenance, energy consumption, overhead cost, depreciation value and battery costs for buses with electric propulsion). In this calculation, the energy price increases annually by about 6%, based on the history of energy price development in the last 10 years. Investment costs are assumed to be constant overtime. Several uncertain factors also indicate that fossil fuelled buses are probably not desirable from a life cycle cost perspective in the long run. This can for example be seen from the total energy demand in Sweden that is expected to increase from almost 380 Million ton oil equivalents (Mtoe) in 2012 to 437 Mtoe in 2030 (The European Commission, 2009b). This is also related to the geopolitical situation, new technologies, depleting reserves of fossil fuels, volatility in the price of crude oil, inflation rates volatility, taxation and increasing concerns about environmental pollution and greenhouse gas emissions.

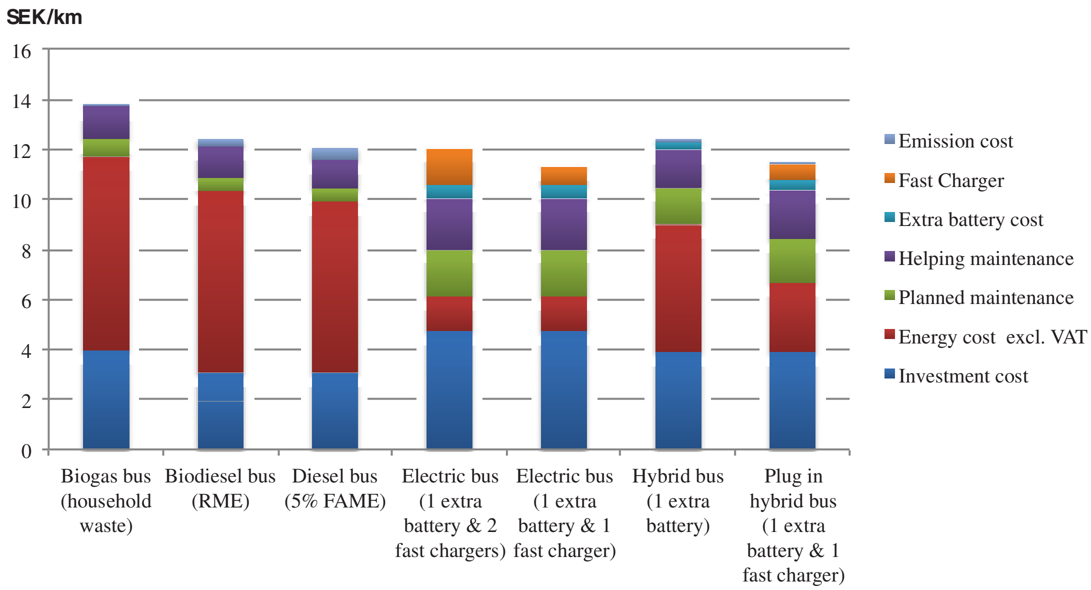

Fig. 4. Total Cost of Ownership (SEK/km) 2013-2020

3.3 Priority listing of bus types – both for EU fuel directive and form a strategic sustainability perspective

The EU fuel directive would favor the buses with the lowest current life cycle costs. On the other hand, the Strategic Sustainable Development perspective prioritizes the buses from the most to the least sustainable (Fig. 5). The diesel bus then moves from being the most to the least prioritized.

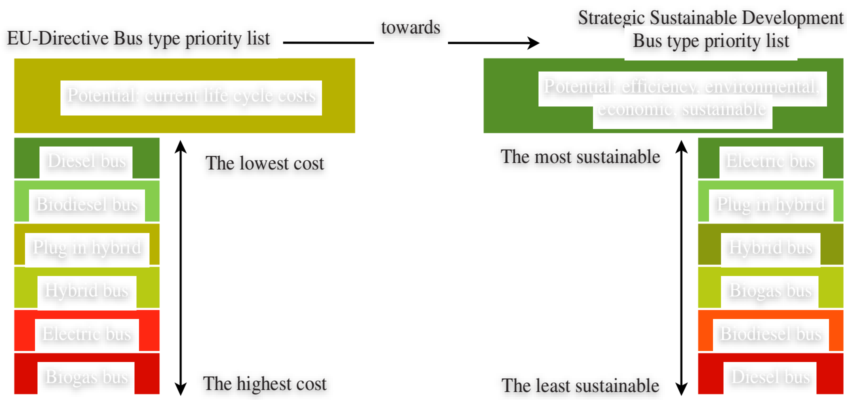

Fig. 5. Bus priority lists based on result of current life cycle costs vs. sustainability

4. Concluding discussion

This study is the first part of the longer study on buses outside of major cities and the results are therefore preliminary. However, the results suggest that the priority shifts from diesel buses to electric buses when we move from a traditional EU fuel directive calculation approach to a strategic sustainability perspective that includes economic, environmental and social issues - both now and in the future. More specifically, the authors have found indications that:

- Even though current European electricity to a large degree is generated from fossil fuels, an electric powertrain powered by new renewable electricity would be the most energy efficient and sustainable.
- Compared to diesel, the Total Cost of Ownership distributed over 8 years for Electric buses (with 1 extra battery and 1 fast charger) are more than 6 % lower, and the electric buses (with 1 extra battery and 2 fast chargers) are slightly cheaper. Future battery and fast charger uncertainties generates high costs in this study, but electric busses would be even more competitive if the cost could be spread out over nine years instead of the eight years that were stipulated by the procurement period of this case. The hybrid is 3% more expensive and Plug-in is 5% cheaper than the diesel bus.
- The fossil diesel, within a traditional combustion engine powertrain, is a poorer solution than an electric powertrain powered by green electricity in terms of energy efficiency, life-cycle emissions and costs, as well as resource management for future generations. It can compete in the use phase with biofuel buses regarding energy efficiency, and with biodiesel regarding the emission categories acidification and eutrophication.
- The hybrid powertrain would in average reduce life-cycle emission with almost 40%, and the plug-in hybrid with around 70%, compared to diesel. Plug-in Life-cycle energy efficiency is almost 60% better than Diesel.

This paper relies heavily on the FSSD and related tools like SLCA. This could be seen as a potential shortcoming, but these tools have earlier been successfully applied at senior management levels in several companies (Broman et al., 2000; Everard et al., 2000; Nattrass, 1999; Robèrt, 2002). The main difference between the authors' sustainability and life cycle approaches and the traditional focus on energy efficiency or carbon dioxide reductions in the use phase, can be related to the strategic shift from reducing currently known impacts to covering the remaining gap to full socio-ecological sustainability. In line with this, the authors suggest that the EU fuel directive, to become a tool for sustainable development of bus transport, needs to be integrated with more progressive initiatives, as well as include both vision and a robust definition of sustainability.

Even if the authors favor the idea of electric bus powertrains, that concept still needs to develop to be the 'silver bullet' for bus transport regarding sustainable development. Careful recycling using a regenerative approach might in the short run solve the issue of scarce materials like Lithium in batteries, but it would be more strategic to use materials that are easier to manage in a sustainable way (like Sodium or Graphene). Another challenge is the marginal effect of electricity, which can lead to more usage of fossil fuels in other parts of Europe as a response to the extra demand of electricity caused by for example charging of electric vehicles (Trygg & Karlsson, 2005). One solution to deal with this is to use charging facilities powered by stand-alone solar/wind-power units delivering surplus to the upcoming smart electricity grid.

Two comparable studies searched for a practical way to use an LCA approach to compare biogas and electric buses. An LCA on car systems (Hawkins, Singh, Majeau-Bettez, & Strømman, 2012) showed comparable result for electric powertrains regarding life cycle emissions and environmental impacts including batteries. Another study in Borlänge, Sweden (Andersson & Norman, 2012) concludes that an electric bus is a less expensive alternative in spite of high initial costs.

The electric bus has been put forward as a potential contributor to sustainable growth in the transportation sector. If this claim can be concretized, the time may soon come for a commercial scale up around Sweden. This study aims to support this development with a new suggested assessment approach that can integrate efficiency, carbon emissions and other socio-ecological sustainability issues with the economic potential for public bus transport systems. Unfortunately there are uncertainties in the timing and strength of many important influencing factors. The fossil fuel price is not only depending on the demand of different supply and demand conditions, but also including the geopolitical situation, import diversification, network costs, severe weather conditions, and taxation (The European Commission, 2013). Renewable electricity, on the other hand, is likely to decrease in price but depending on the technologies selected this development may be delayed by resource constraints as electric generators contain many rare metals. Meanwhile, the electric power sources and powertrains are currently in early stages of the learning curve and costs are likely to decrease substantially as these solutions are scaled up. On top of this there are uncertainties of governmental and legislative support for transport system transformation towards sustainability. The authors therefore see a need for further refinement of the suggested approach and its initial results, through simulation scenarios, and testing in practice.

Nomenclature

EU	European Union
GHG	Green House Gases
FSSD	Framework for Strategic Sustainable Development
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NM^3	Normal Cubic meter
SLCA	Strategic Life Cycle Assessment
SPs	Sustainability Principles

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