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Towards sustainable personal mobility with electric cars and buses

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Sven Borén, Karlskrona, Sweden 2018

Abstract

The aim of this thesis was to explore if, and then how, electric cars and buses can contribute to sustainable personal mobility. Electric vehicles have increasingly been seen as a potential sustainable solution for the transport sector due to their high energy efficiency, close to zero emissions in the use phase, and the possibility to be powered by electricity from renewable resources. However, there are concerns about future scarcity of resources (e.g. lithium and cobalt for batteries), vehicle range, costs, high energy use in the production of batteries, as well as insufficient scientific support for how electric vehicles could be a part of a transition towards sustainability regarding personal mobility.

The challenges for a fast transition towards sustainability are large and many. The transport sector is currently not contributing to such development, mainly due to emissions, use of fossil energy, and use of materials mined and recycled under unacceptable conditions. Furthermore, existing societal goals (e.g. fossil-fuel independent vehicle fleet by 2030 in Sweden, UN Agenda 2030, and the Paris agreement) are insufficient for sustainability and are not complemented by concrete plans or an approach for how to engage stakeholders and achieve coordinated actions for sustainability. The Framework for Strategic Sustainable Development includes a principled definition of sustainability that is necessary and sufficient for sustainability and procedural support for collaborative innovation for a strategic transition to fulfillment of that definition, which is why it has been used as an overarching methodology in this thesis.

The research verified through several studies conditions for how electric vehicles can play a vital role in a strategic transition of personal mobility towards sustainability. Through stakeholder collaboration (e.g. interviews and workshops), a vision for sustainable transport with a focus on electric vehicles and an initial development plan towards that vision were designed. Several life cycle focused studies investigated (through calculations and data collection from literature, life cycle databases, interviews and workshops) about environmental and social impacts and costs for electric cars and buses. The stakeholder collaboration, combined with conceptual modelling, also resulted in models for generic support for multi-stakeholder collaboration and planning for strategic sustainable development of transport systems and communities, and for how to include electric buses in the procurement model of public transport.

The strategic sustainable development perspective of this thesis broadens the analysis beyond the more common focus on climate change issues and should be able to reduce the risk of sub-optimizations in community and transport system development when applied in that context. The generic support for multi-stakeholder collaboration could potentially also promote a more participatory democratic approach to community development, grounded in a scientific foundation.

Keywords: Strategic Sustainable Development, Transport Planning, Electric Vehicles, Testing, Life Cycle Assessment, Mobility

Thesis disposition

This thesis includes an introductory part and the following papers, which have been reformatted from their original publication in order to fit the format of the thesis. The content of the papers, though, is unchanged.

Paper 1:

Robèrt, K.-H., Borén, S., Ny, H., Broman, G., 2017. A strategic approach to sustainable transport system development - Part 1: attempting a generic community planning process model. *Journal of Cleaner Production* 140, pp. 53–61. doi:10.1016/j.jclepro.2016.02.054

Paper 2:

Borén, S., Nurhadi, L., Ny, H., Robèrt, K.-H., Broman, G., Trygg, L., 2017. A strategic approach to sustainable transport system development – part 2: the case of a vision for electric vehicle systems in southeast Sweden. *Journal of Cleaner Production* 140, pp. 62–71. doi:10.1016/j.jclepro.2016.02.055

Paper 3:

Borén, S., Ny, H., 2016. A Strategic Sustainability and Life Cycle Analysis of Electric Vehicles in EU today and by 2050, *Proceedings of the 18th International Conference on Sustainable Urban Transport and Environment (ICSUTE) Conference*, Madrid, Spain, March 24-25, 2016. pp 2288-2296.

Paper 4:

Nurhadi, L., Borén, S., Ny, H., Larsson, T., 2017. Competitiveness and sustainability effects of cars and their business models in Swedish small town regions. *Journal of Cleaner Production* 140, pp. 333–348. doi:10.1016/j.jclepro.2016.04.045

Paper 5:

Borén, S., 2018. Electric buses' sustainability effects, costs, noise, and energy use. *Submitted to Journal.*

Paper 6:

Borén, S., Grauers, A., 2018. Stakeholder collaboration models for public transport procurement of electric bus systems. *Submitted to Journal.*

Other Publications

Borén, S., Nurhadi, L., Ny, H., 2013. How can fossil fuel based public bus transport systems become a sustainable solution for Swedish medium-sized cities? *Poster at the 6th International Conference on Life Cycle Management (LCM)*, Gothenburg, Sweden, August 25-28, 2013.

Nurhadi, L., Borén, S., Ny, H., 2014. A Sensitivity Analysis of Total Cost of Ownership for Electric Public Bus Transport Systems in Swedish Medium-Sized Cities. *Transportation Research Procedia*. pp. 818–827.

Nurhadi, L., Borén, S., Ny, H., 2014. Advancing from Efficiency to Sustainability in Swedish Medium-Sized Cities: An Approach for Recommending Powertrains and Energy Carriers for Public Bus Transport Systems. *Procedia - Social and Behavioral Sciences*. pp. 586–595.

Borén, S., Nurhadi, L., Ny, H., 2016. Preference of Electric Buses in Public Transport: Conclusions from Real Life Testing in Eight Swedish Municipalities. *Proceedings of the 18th International Conference on Sustainable Urban Transport and Environment (ICSUTE)*, Madrid, Spain, March 24-25, 2016. pp. 2297-2306

Ny, H., Borén, S., Nurhadi, L., Schulte, J.P.M., Robèrt, K.-H., Broman, G., 2017. Vägval 2030 (In English: On Track for 2030) (No. diva2: 1089430). Blekinge Tekniska Högskola, Karlskrona.

Acronyms

BEV	Battery Electric Vehicles
EU-28	Member states of the European Union in 2017
EV	Electric Vehicles
FSSD	Framework for Strategic Sustainable Development
ICEV	Internal Combustion Engine Vehicle
HFCEV	Hydrogen Fuel Cell Electric Vehicle
LCA	Life Cycle Assessment
SLCA	Strategic Life Cycle Assessment
SP	Sustainability Principle
TCO	Total Cost of Ownership

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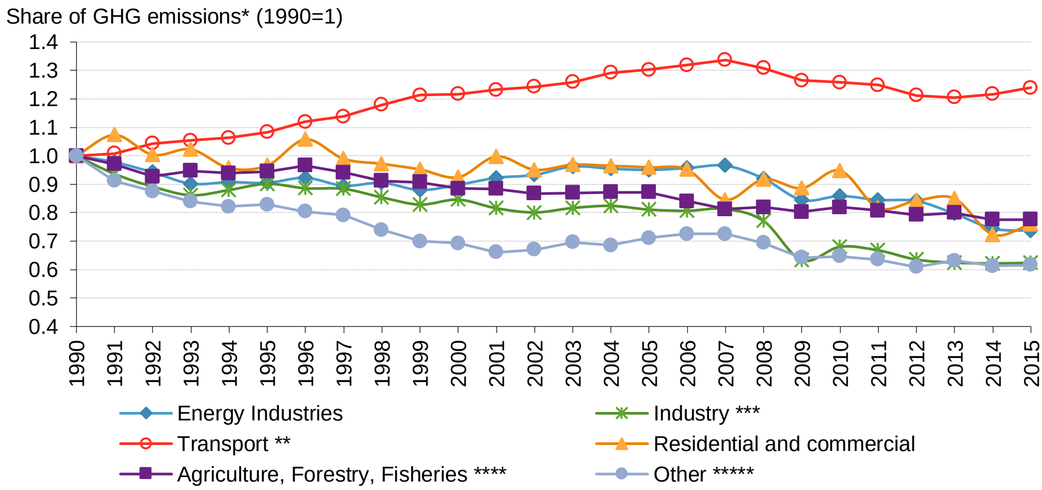
1 Introduction

This section introduces the reader to the subject of the thesis and informs about the embedded strategic sustainability approach and about the aim and scope.

1.1 Sustainability challenges in the transport sector

Global sustainability challenges and the urgency to address these challenges were recognised by several organisations (e.g. United Nations, Club of Rome, World Wildlife Fund, Greenpeace) during the 20th century. Transport is a central element in societal development by making goods and destinations more accessible, but is at the same time a significant contributor to the sustainability challenges. There are large flows within the sector of limited natural resources that will become too expensive in a long-term perspective, and probably some of them already in a short-term perspective (Carlson, 2011; IEA, 2012; Sverdrup et al., 2017). Moreover, transport systems also inhabits large areas (e.g. for roads and parking) and is already today demanding for spatial planning in productive surfaces (e.g. urban sprawl into agriculture land) (Thomson and Newman, 2018). Another major sustainability challenge for the transport sector is the trend of greenhouse gas (GHG) emissions (Figure 1). This trend has been hard to break as the transport volume is steadily increasing. For example, the road-transport in Europe has increased by 23 % between 1995 and 2015 in European memberships states (EU-28) (Eurostat, 2017), and the same applies for Sweden (Myhr, 2018).



* Excluding LULUCF (Land Use, Land – Use Change and Forestry) emissions and international maritime, including international aviation and indirect carbon dioxide emissions
** Excluding international maritime (international traffic departing from the EU), including international aviation
*** Emissions from manufacturing and construction, industrial processes and product use
**** Emissions from fuel combustion and other emissions from agriculture
***** Emissions from other (not elsewhere specified), fugitive emissions from fuels, waste, indirect carbon dioxide emissions and other.

Figure 1: The trend of greenhouse gas emissions from sectors within EU-28. Data source: (Eurostat, 2017).

Governments in Europe have increased restrictions for transport-related emissions since the 1980s, and vehicle manufacturers have since then been making efforts to lower fuel consumption and emissions (e.g. by (tetraethyl)lead-free gasoline, lower sulphur content in diesel, exhaust gas recirculation, catalytic converter, and higher efficiency). Despite that, the transport sector in Sweden emitted in 2016 most air pollutions of all sectors in Sweden (Figure 2), and together with international transport (to and from Sweden) about 40 % of all transport-related emissions. During that year, the sector contributed to 42 % of the GHG emissions when including domestic transport and international fuel bunker (Naturvårdsverket, 2018). Also, 28 % of GHG emissions in EU-28 came from domestic and international transport (to and from EU) in 2015, were 73 % came from road transport (Eurostat, 2017).

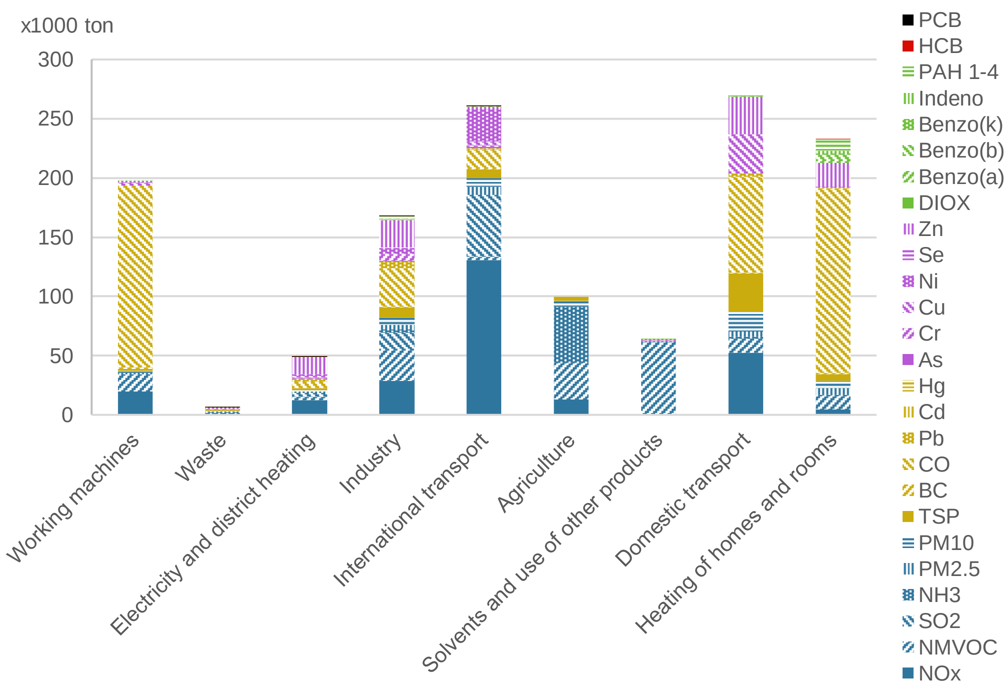


Figure 2: Air pollutions from sectors in Sweden by year 2016. Data source: (SCB, 2017a).

1.2 Current solutions for environmentally friendly transport

Existing goals and roadmaps for a more environmentally friendly transport sector see short-term solutions in biofuels and more efficient combustion engines, accompanied by an increased use of public transport and less car travel (Johansson, 2012; Johansson et al., 2013; Sköldberg et al., 2013; Ståhl et al., 2013; The European Commission, 2011). Unfortunately, the availability of biofuels that can be produced in a sustainable way is limited to about half of the global demand of fuels for the transport sector and to one third in Sweden (Grahn and Sprei, 2015). Moreover, the use of biofuels does not significantly lower other emissions than carbon dioxide. Several studies and investigations have suggested an increased use of Electric Vehicles (EVs), mainly because of their high efficiency, very low emissions in the use phase, low noise levels, and the possibility to use electricity based on renewable sources (Johansson et al., 2013; Nurhadi et al., 2014a; UK Department for Transport, 2018). For example, Norway has, mainly due to great policy interventions, the largest share of pure[1] electric cars (5 % of the total fleet and 20 % of the sales in 2017), and aims to reach sales of only zero-emission cars from 2025, coupled up with investments to increase charging possibilities (Figenbaum, 2018). If powered by electricity from renewable sources, an increasing share of EVs in the transport sector could contribute to limiting global warming to 1.5 degrees from pre-industrial levels (United Nations, 2015), and to Swedish national transport-related goals; greenhouse gas neutrality by 2045 and fossil-fuel independent vehicle fleet by 2030 (Regeringskansliet, 2017; 2012). These goals cover some important aspects of sustainability, but are not ambitious enough in relation to the magnitude of the challenges and the urgency for taking action (Ny et al., 2017). Moreover, they do not include other aspects that are needed for sustainable development (e.g. dependency on materials and energy that are to some degree produced from areas of conflicts and poor working conditions, insufficient recycling of heavy metals, and use of land for new infrastructure).

1.3 The need for a strategic sustainability approach

The existing goals and roadmaps mentioned above focus mainly on the transport system in itself and often only on climate issues, or in some cases even only on carbon dioxide emissions. To reach the target of a greenhouse gas neutral Swedish society, and certainly to support the full scope of sustainability, it is important to consider the whole life cycle of the systems in the transport sector and also the interaction between the transport sector and other sectors. There is otherwise a great risk for sub-optimizations and loss of pace in the transition. Development of transport systems is complicated also since there are many different stakeholders involved with different interests and perspectives. Methodological support for development of sustainable transport systems should therefore be based on scientific grounds and allow for differences in values to become clear, so that the values can be weighed against each other and discussed in relation to the scientific grounds. The Framework for Strategic Sustainable Development – FSSD (Broman and Robèrt, 2017) is created to serve such a purpose and has proven useful for analyzing and coordinating the use of various methods, tools and other support for sustainable development, and it has been used in other studies for sustainable transport system development (Alvemo et al., 2010; Borén, 2011; Cars et al., 2008). As further described in section 2.4, the FSSD provides, for example, a principled definition of sustainability, making it possible to inform visions by the full scope of sustainability. It also provides guidelines for how actors can create economically viable strategies that support society’s transition towards fulfillment of that definition. This thesis has therefore embedded the FSSD in the research to guide the investigations.

[1] By ‘pure’ means that the car has only one driveline (a hybrid has two).

1.4 Scope and aim of the research

The EV concept can be applied in many different vehicles, for example, in cars, buses, trucks, trains, ferries, and even airplanes. Electric cars and buses have started to become competitive for mass-market adaptation, and they can make a significant reduction of GHG-emissions possible as cars alone in 2015 emitted 61 % of GHG in the EU-28 (Eurostat, 2017). The thesis work therefore focused on electric cars and buses. Initial studies of the thesis work took place within the GreenCharge project (GreenCharge, 2014), which focused on conditions for a market breakthrough for personal electric road vehicles (i.e. cars and buses) in southeast Sweden. These studies identified the need for further studies on electric buses and for comparisons with other regions. The later part of the thesis work took place within a project about decision support for procurement of electric buses in public transport (Borén and Ny, 2016).

Based on the challenges and possibilities mentioned above, the aim of the research was to investigate if, and then how, EVs can support sustainable personal mobility. The following research questions were developed to guide the studies:

RQ1. What could an approach to sustainable transport planning at large look like?

RQ2. What is the potential role of electric vehicles in, and towards, a sustainable society?

RQ3. What are the main current business models, sustainability effects, and costs of electric cars and buses, and how do these compare to other transport solutions?

RQ4. What are the major barriers and enablers for development of sustainable personal mobility based on electric cars and buses?

RQ5. How could decision support models for procurement of electric bus systems be developed and applied in a Swedish context?

2 Background of the fields

This section gives a more comprehensive background of the fields involved in this thesis.

2.1 Transport sector challenges

We need transport for our everyday life for the flow of services, products, and people. In 2014, the transport sector contributed to the economy with 4,8 % (548 billion €) in Gross Value Added in EU-28, and employed about 4,5 % of the workforce (The European Commission, 2014). The same report also reveals that the demand for passenger transport grew with 20 % and for goods by 25 % between 1995 and 2010, and the latter is expected to grow by 80 % to 2050.

As seen in Figure 3, the transport sector in EU-28 had the greatest share of the energy use in 2015, and road transport is strongly dominant among the transport modes.

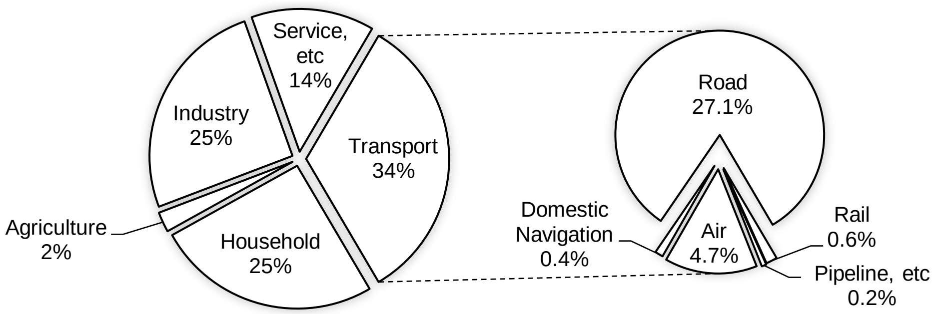
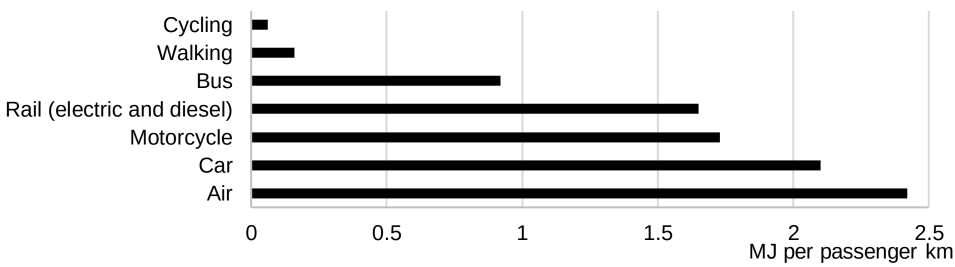


Figure 3: Share of energy use per sector in EU-28 in 2015, excluding international transport. Data source: (Eurostat, 2017).

As seen in Figure 4 and Figure 5, the mode that uses least energy for personal transport is biking, and goods transport it is shipping (boat), while air transport of both goods and people use most energy per passenger and kilometer (km).



Note: Data based on average figures for cars and motorcycles/mopeds weighted according to fleet sizes by the year 2000 in the United Kingdom. Occupancy figures are as follows; air 60 %; rail 28 %; bus 33 %. Car occupancy figures have the weighted average of 1.76 (work 1.2 and non-work 1.85) person per vehicle, and motorcycles 1.11.

Figure 4: Personal transport energy efficiency by modes in the United Kingdom. Data source: (Banister, 2009).

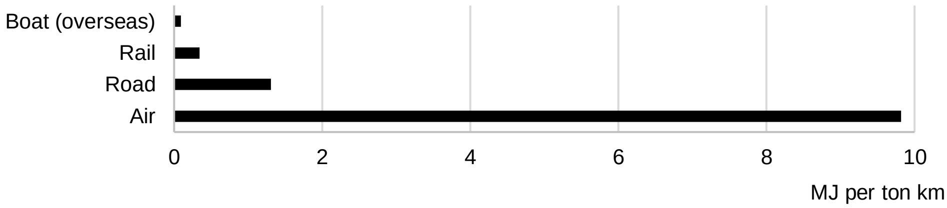


Figure 5: Goods transport energy efficiency by modes used within the Deutsche Bahn Group. Data source: (Deutsche Bahn AG, 2018).

The consumption of fossil oil in 2015 within EU-28 represented 40 % of the total energy use, and 83 % of the energy produced from fossil oil in EU-28 was consumed by the transport sector (Eurostat, 2017). Combustion of fuels based on fossil oil in internal combustion engines generates emissions (e.g. carbon dioxides, hydro carbons, and nitrogen oxides) and noise. As explained in section 1, this makes the transport sector, and especially road transport, a main contributor to such emissions. These emissions cause societal costs because of, for example, climate change effects and negative health effects as well as premature deaths. The indicative economic cost of health impacts from road transports' ambient air pollution including morbidities was for 24 EU member states in 2010 estimated to about 363 720 million USD (Roy et al., 2014). In Sweden, the ASEK-model (Bångman, 2016) assigns costs to emissions of nitrogen oxides (NOx), hydrocarbons/volatile organic compounds (HC/VOC), sulphur dioxide (SO_2), particulate matters (PM), and carbon dioxide equivalents (CO_2e) according to Table 1. As a side note, the ASEK-model recommends that carbon dioxide emissions have a societal cost of 3.5 SEK/kg in sensitivity analyses, and other studies (e.g. Ackerman (2008) and Ny et al. (2017)) recommend even higher costs in order to reach fossil free transport by 2030.

Table 1: Swedish societal costs per air pollutants and GHG emissions in year 2014 according to the ASEK-model (Bångman, 2016). Data source: (SCB, 2017a; 2017b).

Emission	Societal cost (SEK/kg) Regional/Global	Local*	Transport emissions in 2014 (ton)**	Total transport emissions** societal costs (MSEK) in 2014
NO_X	86	11	262 825	25 494
HC/VOC	43	19	163 465	10 135
SO_2	29	94	61 548	7 570
PM 2,5	0	3210	25 900	83 139
CO_2e	1,14	0	26 111 000	29 767
Total				156 105

*Kristianstad as reference

**Including International transport (to and/or from Sweden)

EU transport climate change related goals (e.g. reduction of GHG emissions by 20 % by 2030 when compared to the level of 2008 and 60 % by 2050 when compared to the level of 1990) have acknowledged these problems. Like Swedish transport related goals and roadmaps (e.g. fossil-fuel independent vehicle fleet by 2030, and GHG neutrality by 2045), they include a reduction of fossil fuels, GHG emissions, and air pollution. Still, they are not progressive enough to reach fossil-fuel independency and to limit the global temperature increase to 1.5 degrees from pre-industrial levels, and the transition towards sustainability will be too slow (Ny et al., 2017).

As stated above, it is important to consider the emissions from road transport vehicle in the use phase. However, emissions, as well as other sustainability impacts, occur also in other life cycle phases. This will be further explained in the next section.

2.2 Life cycles of vehicles

A vehicle has a life cycle that includes extraction and reuse of materials, production of the vehicle, distribution to the customer via dealers, usage and maintenance, and finally the stage where some components and materials are recycled and others reach End of Life (Figure 6). The life cycles of the fuel and other supporting flows also need to be considered to include all sustainability effects. It is therefore important to include fuels, electricity, equipment, materials, chemicals, and infrastructure, etc., that have to be used to support the vehicle throughout its life cycle. This is usually included in a Life Cycle Assessment - LCA (ISO, 2006) that focuses on environmental impacts throughout the whole life cycle of a product.

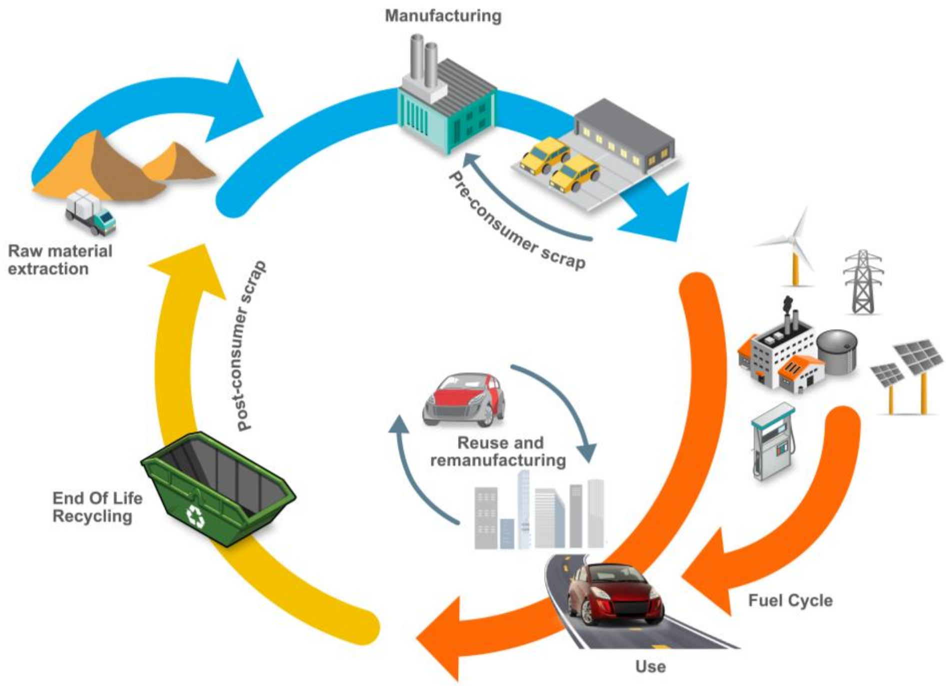


Figure 6: Illustration of a vehicle's life cycle including the fuel life cycle. Source: https://www.worldautosteel.org/life-cycle-thinking/case-studies/battery-electric-vehicle-life-cycle-energy-aluminium-vs-ahss/, with permission from WorldAutoSteel. Accessed (2018-09-22).

The 'Well-to-Wheel' concept that includes 'use' and 'fuel cycle' in Figure 6, has traditionally been in focus regarding costs and environmental impacts, but it has become more common to include the whole life cycle perspective when calculating societal costs and environmental effects. The EU fuel directive is an example that requires this (The European Commission, 2009).

To use a car, one can buy a car, rent a car, go with a taxi, or share a car with others. A bus for public transport is usually owned by a public transport operator to be used in a certain area and for certain routes via a contract with the public transport authority. The value chain for cars and buses follows the life cycle but includes many steps with different businesses as a car manufacturer buys materials and components from suppliers and sub-suppliers that in turn buy materials from the mining industry and/or recycling dealers. A national/regional car retailer then buy batches of cars from the car manufacturer, and then sells these to car customers via local shops. However, it has also become common to order a car online and get it delivered via a local shop or national retailer. For a bus, the public transport operator usually buys vehicles in batches from the manufacturer or via a national/regional retailer. When a car or bus is used up, the owner hands it over to a scrap yard for recycling of some parts, fluids, and most materials (e.g. recyclable plastics and metals). Some of that material goes to landfill, but in 2015, the reuse and recovery will be 95 % by an average weight per vehicle within EU-28 (The European Commission, 2013).

There are several types of vehicles and models available on the market. As stated in section 1.2, electric vehicles can be a possible key solution as it is possible to power them with renewable electricity. The following section will shed some light over EVs and compare them with other vehicles.

2.3 Introduction to electric vehicles

The difference between an EV and an Internal Combustion Engine Vehicle (ICEV) is the driveline from refuelling/charging to the driveshaft. Typically, as shown in Figure 7, an ICEV uses a fuel pump (1) that fills the tank (2) with fuel (e.g. gasoline or diesel) which is pumped into, and combusted in, the engine (3), which in turn power the driveshaft and the gearbox, which then rotates the wheels. EVs, on the other hand, use a charger (5) that charges the battery (6), which powers the electric motor (7), which then rotates the wheels. Regenerative brakes (8) can charge the battery (6) when reducing speed.

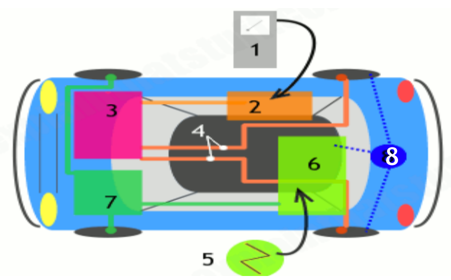


Figure 7: Illustration of drivelines for a vehicle powered by a combustion engine (1-4) and an electric motor (5-7). Adapted from Woodford (2017).

An electric motor has an efficiency of 85-90 %, while a combustion engine has an efficiency of 35-45 % depending on fuel and technology. The electric driveline, though, has losses when charging the battery and also because of battery discharges over time. Still, as seen in Figure 8, an electric car only needs about 25 % of the energy needed by a gasoline powered car to carry one person 100 km.

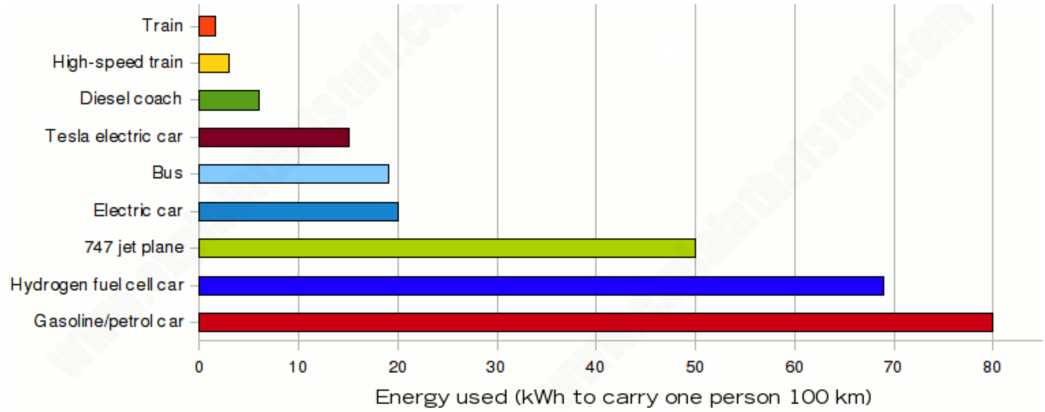


Figure 8: Comparison of different vehicles energy use (kWh to carry one person 100 km). Adapted from Woodford (2017). Data source: (MacKay, 2009).

Currently, batteries in EVs are usually of lithium-ion type, which are also common in electronics (e.g. mobile phones and computers). As the energy density is about 100 times lower for these batteries than for gasoline/diesel, it is common that EVs are about 20 % heavier than ICEVs in comparable size. Due to the demand of achieving longer distances with EVs without increasing the weight too much and to avoid future availability problems regarding cobalt and lithium, battery manufacturers are investigating new compositions (Evarts, 2018) that also can allow an electric car to be recharged in 10 minutes or even less (Morris, 2018). The latter could lead to smaller batteries in EVs, but would also need a denser charging network than current recommendations, i.e. every 50 km (Strömfelt, 2013), with increasing power demand up to 350 kW (Nicholas and Hall, 2018). Another demand is to lower the costs of batteries as it is a major component cost when manufacturing EVs. The price, though, is dropping, and Bloomberg Technology and the electric car manufacturer Tesla claim that the price of electric cars will be comparable to fuel-powered cars in 2025 as the price of lithium-ion batteries is by then expected to be below 100 USD per kWh (Chediak, 2017).

As seen above, EVs have already today some advantages related to efficiency and emissions in the use phase, but there are also challenges in other life cycle phases (e.g. energy use when producing batteries and use of metals that might become scarce or have availability problems due to conflicts). To handle these challenges and opportunities in a strategic way in support of society’s transition towards sustainability, only a life cycle perspective on current situations will not be enough. It requires an approach tailored for planning and acting strategically in complex systems.

2.4 Strategic sustainable development

The framework for strategic sustainable development - FSSD (Broman and Robèrt, 2017) is designed to support planning and actions towards a sustainable future. It is applicable in any area, including the transport area. The FSSD includes a five-level model that helps structuring and clarifying inter-relationships between phenomena of different character (Figure 9).

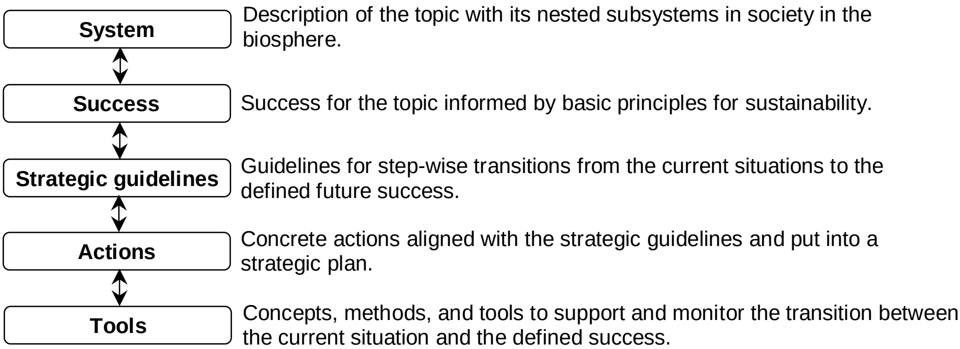


Figure 9: Levels of the FSSD. Source: (Broman and Robèrt, 2017)

The vision of success belongs to the second level and is framed by sustainability principles (SPs), another essential feature of the FSSD. Until recently, the principled definition of sustainability comprised four sustainability principles; three principles for ecological sustainability and one principle for social sustainability. The definition of social sustainability has now been elaborated and comprises five sustainability principles (Missimer et al., 2017a; 2017b). In total, the current version of the principled definition of sustainability of the FSSD comprises eight sustainability principles (Broman and Robèrt, 2017):

In a sustainable society, nature is not subject to systematically increasing ...

1. ... concentrations of substances extracted from the Earth's crust;
2. ... concentrations of substances produced by society;
3. ... degradation by physical means;

and people are not subject to structural obstacles to ...

4. ... health;
5. ... influence;
6. ... competence;
7. ... impartiality;
8. ... meaning-making.

The FSSD also includes a funnel metaphor and an operational planning procedure – ABCD (Broman and Robèrt, 2017), as illustrated in Figure 10.

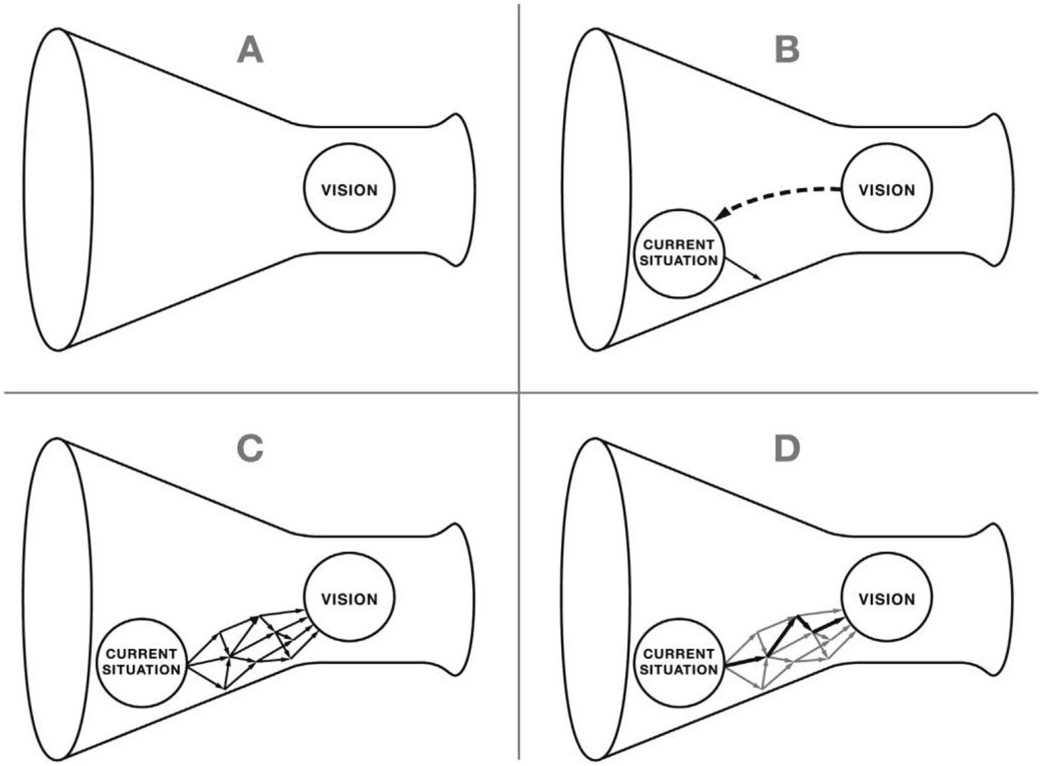


Figure 10: The funnel metaphor and the ABCD-procedure of the FSSD. Reprinted from Broman and Robèrt (2017, page 5), with permission from Elsevier.

As described by Broman and Robèrt (2017), the inclining funnel wall in Figure 10 metaphorically describes the systematic character of the challenge and indicates the self-benefit of strategically working towards a sustainable vision (avoiding hitting the wall of the funnel while moving to the vision in the opening of the funnel). A sustainable vision is developed in 'A'. The current challenges and assets in relation to the vision are captured in 'B'. Possible steps towards the vision are invented in 'C', and these are prioritized into a strategic plan in 'D'.

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3 Research approach

This section positions the research, presents the frameworks that informed the research design, and provides information about the research methods.

3.1 Positioning the research

3.1.1 Theoretical perspectives

According to Crouch and Pearce (2013), theoretical perspectives (also called paradigms or theoretical/conceptual lenses) refer to particular views and assumptions of the researcher, which also influence the choice of research methodology and the interpretation of the findings. These perspectives can change over time and new paradigms can emerge and compete with existing views (Blessing and Chakrabarti, 2009). Mainly three commonly used theoretical perspectives have been considered in this thesis work: ‘positivist’, ‘interpretive’, and ‘design’. In Table 2, these theoretical perspectives are briefly described along the basic beliefs: ‘ontology’ (relates to researcher’s view on reality) and ‘epistemology’ (relates to the researcher’s view on ways to generate, understand and use knowledge). In addition, the basic beliefs ‘methodology’ (relates to the characters and types of research methods) and ‘axiology’ (relates to the researcher’s values and stance in relation to subject studied). All of this can affect the way one investigates reality (Wahyuni, 2012). The different studies of this thesis relate to different degrees to these perspectives. For example, the life cycle analyses and other calculations performed in the thesis rely heavily on quantitative data and lean onto a positivist approach, while the collaborative stakeholder workshops have generated more of qualitative data and have required more of an interpretive approach. Additionally, the research aims at contributing to a transition towards sustainability by finding methods, models and tools for such development, and can therefore also be considered to have a design perspective.

Table 2: Some basic beliefs and theoretical perspectives in science. Adapted from Vaishnavi et al., (2017).

Basic beliefs	Theoretical perspectives Positivist	Interpretive	Design
Ontology	A single reality. Knowable and probabilistic.	Multiple realities and socially constructed.	Socio-technologically enabled. Multiple and contextually situated alternative world-states.
Epistemology	Objective; dispassionate. Detached observer of truth.	Subjective, i.e. values and knowledge emerge from the researcher-participant interaction.	Knowing through making: objectively constrained construction in a context. Iterative circumscription reveals meaning.
Methodology	Observation; quantitative and statistical.	Participation; qualitative. Dialectical and hermeneutical.	Developmental. Measure artefactual impacts on the composite system.
Axiology	Truth: universal and beautiful; prediction	Understanding: situated and description	Control; creation; progress (i.e. improvement); understanding

This is in line with the intentional and solutions oriented character of sustainability research in general (Broman et al., 2017; Kates et al., 2001; Miller, 2013; Miller et al., 2014) and with the experienced need to rapidly transform (redesign) society towards sustainability, the design perspective has indeed played an important role in this thesis work.

An approach in between the positivist and interpretive approaches is often called a pragmatic approach. According to Powell (2001, page 884) "To a pragmatist, a true proposition is one that facilitates fruitful paths of human discovery". A pragmatic (re)design perspective has significantly influenced the framing of the research, the research objectives and the research design and choice of methods in this thesis work.

3.1.2 Research purpose

Investigations can be categorized according to their purpose and the research methods that are to be used. One purpose can dominate a research study, although a particular study may have more than one purpose and could change as the research develops (Robson, 2002). The characteristics of four research purposes: 'exploratory', 'descriptive', 'explanatory' (Robson, 2002) and 'emancipatory' (Letherby, 2006; Tang, 2010) are shown in Table 3. This thesis work has mainly used an exploratory and an explanatory approach. An emancipatory approach has also been used due to the nature of research in strategic sustainable development, which is partly about how to inspire actors to contribute to the society's development towards sustainability.

Table 3: Summary of research purposes. Adapted from Letherby (2006), Robson (2002), and Tang, (2010).

Research purpose	Characteristics
Exploratory	To find out what is happening, particularly in little understood situations; seek new insights; ask questions; assess phenomena in a new light; generate ideas and hypotheses for future research. Usually, but not necessarily, qualitative.
Descriptive	To portray an accurate profile of persons, events or situations. Requires extensive previous knowledge of the situation etc. to be researched or described, so that appropriate aspects on which to gather information can be identified. May be qualitative and/or quantitative.
Explanatory	Seeks an explanation of a situation or problem, usually in causal relationships. To explain patterns relating to the phenomenon being researched, and identify relationships between aspects of the phenomenon. Maybe qualitative and/or quantitative.
Emancipatory	Seeks to empower the subjects of social inquiry. To create opportunities and the will to engage in social action. Usually, but not necessarily, qualitative.

3.1.3 Ways of reasoning

There are three main ways of reasoning that has been used in this thesis work. In 'deductive' research, the classical approach is to select a theory or set of theories, formulate a hypothesis, determine the variables to be measured, and then to test or to falsify or to corroborate. The outcomes, usually quantitative, are used to accept or reject the hypothesis, and the researcher focuses not on the 'why' and 'how' (Blessing and

Chakrabarti, 2009; Gray, 2018). Data-driven research is ‘inductive’, and questions are used for data collection, which can be either qualitative or quantitative. These data are then analysed to see whether any patterns emerge. Generalization, relationships or even theories may then be constructed (Blessing and Chakrabarti, 2009; Gray, 2018). ‘Abductive’ thinking encourages us to imagine what could happen, or what could be the case, or what might happen if there is a change. (Crouch and Pearce, 2013). Further on, “Deductive reasoning is a classic intellectual tool used in natural science research, inductive research is typically used in social science research, and abductive thinking has its distinct usefulness in design research for framing creativity and generating solutions to a problem.” (Kwok, 2017, page 68). In this thesis work, all three ways of reasoning have been used to various extent in the different studies.

3.1.4 Research data

According to Gray (2018), ‘quantitative’ data is collected as numbers, which measures occurrences and delimits phenomena into categories. Quantitative research is often regarded as more valid and reliable because it can generate generalisable and replicable results. ‘Qualitative’ data is usually in the form of text (e.g. interview transcripts and diary entries), and other media (e.g. drawings, photographs, audio and video recordings). The complexity and depth of social interactions is more relevant to be described with qualitative data, but a problem with evaluating qualitative research is that traditional notions of validity and reliability cannot be applied.

The gathering of data for this research has been both qualitative and quantitative. Qualitative data was primarily collected via workshops with stakeholders and experts. The author of this thesis was acting both as an observer and a facilitator who spurred discussions with questions. According to Mackewn (2008), this can be challenging and a paradox in itself. It was important in these workshops to assure that the results were well anchored and agreed upon. For example, one strong voice among workshop participants can convince others to believe in something they are actually sceptical about. It was therefore important in the workshops to make everyone feel invited into the discussions and that they all could have their say before agreeing upon results. It was also important to stand up for results that might not be satisfying for all stakeholders, who on beforehand might have formed their own opinion about (desirable) results of the study. Quantitative data has been used when calculating energy use, environmental impacts, and costs. The validity of the results that were generated from applying these qualitative and quantitative methods is further discussed in section 5.2.

3.2 General research design

The initial research design for this thesis followed the Maxwell Research Design guidelines (Maxwell, 2012), which covers goals, conceptual framework, methods, validity, and guiding questions that inform research questions Figure 11. The guiding questions in Maxwell’s research design methodology have been included in the research plan that framed the thesis and its research questions. As most studies in this thesis have been performed within the GreenCharge project, the goals of that project and the concrete goals of this thesis research have been aligned, for example, to develop a roadmap for fossil free-transport by 2030 in southeast Sweden. Thus, the thesis has had a particular focus on vision design, on sustainability effects of EV-based personal road transport systems, and on finding barriers, enablers and methods/models for development of such systems towards sustainability. Other goals that have affected the research design are: the author's personal desire to contribute to sustainable development of transport systems, society's ambitions for sustainable development in all sectors, and the focus of Blekinge Institute of Technology on applied IT and sustainability (Ahlström, 2014).

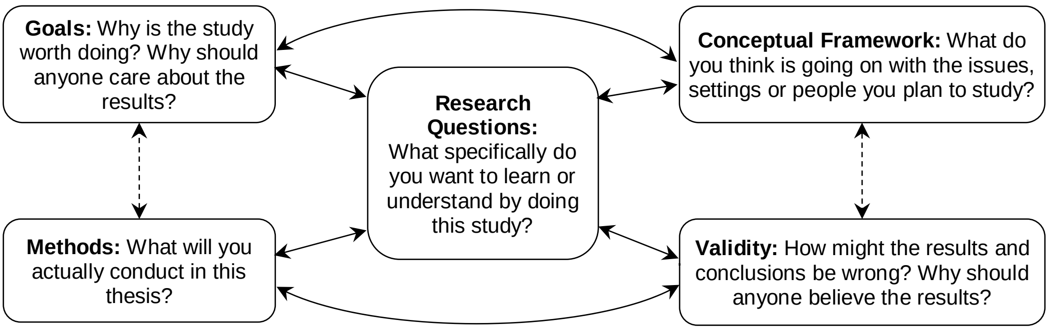

Figure 11: Maxwell's research design methodology. Adapted from Maxwell (2012).

Mapping the conceptual framework (Figure 11) was useful. Studies about what is going on in society regarding energy and vehicles in the context of sustainable transport development provided an important knowledge base. The FSSD is also a conceptual framework that informed the research. This is further described in section 3.3. Methods used in this thesis are described later in this section, and validity is discussed in section 5.2.

Within the overall research design, the Design Research Methodology - DRM (Blessing and Chakrabarti, 2009) influenced the design of the individual studies and thesis papers. The DRM study phases 'Research Clarification', 'Descriptive 1', 'Prescriptive 1', and 'Descriptive 2' were covered (Figure 12). Papers 1 and 2 helped to refine the goal and focus of the research by literature studies and knowledge that was created in earlier studies (Borén et al., 2016; Nurhadi et al., 2014a; 2014b), which were the foundation of paper 5. Even earlier studies on sustainable transport solutions (Alvemo et al., 2010; Borén, 2011) also formed a knowledge base that was helpful throughout the thesis. A better understanding of the research topics was achieved during the descriptive phase 1, where empirical data was analysed via the methods of Strategic Life Cycle Assessment (SLCA) and Life Cycle Assessment (LCA) methods. During the prescriptive study phase, assumptions, experiences, and syntheses from each study contributed to finding the proposed solutions.

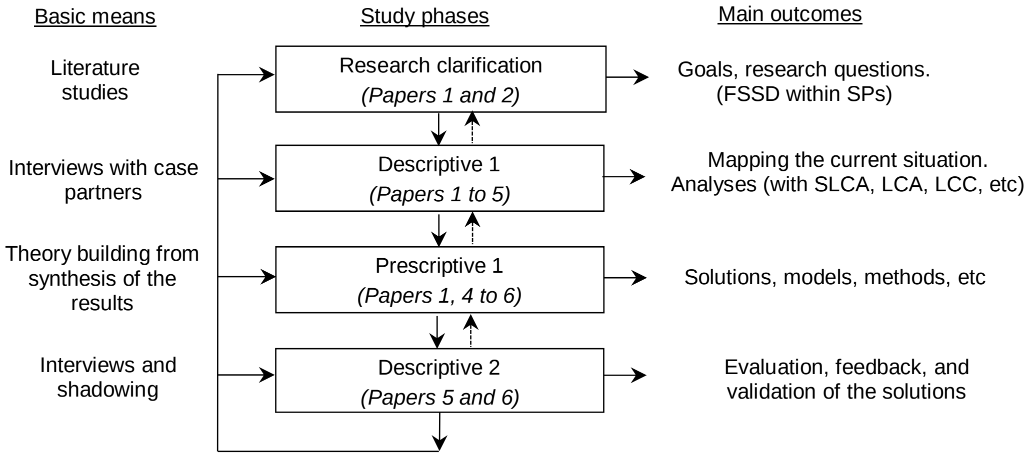

Figure 12: Mapping of thesis papers in DRM. Adapted from Blessing and Chakrabarti (2009).

3.3 Embedding the framework for strategic sustainable development

As explained in section 1.3, this thesis has embedded the FSSD in the research to investigate if, and then how, EVs can facilitate sustainable development of the transport sector. As explained in section 2.4, the SPs, a core element of the FSSD, have been continuously developed since the early 1990’s. Until recently, the set of SPs comprised four principles. Therefore, these four principles were used in papers 1 to 4. The current set of eight sustainability principles have been used primarily in papers 5 and 6.

The ABCD procedure (explained in section 2.4) has informed the structure and the flow of the thesis work and was used in particular in papers 1 and 2 to identify a vision for sustainable transport (A). Moreover, different methods were used to enhance the baseline analysis (B) for comparison of different vehicles in papers 3 to 5. For example, in paper 4, the Business Model Canvas (Osterwalder and Pigneur, 2010), illustrated in Figure 13, was used to identify current business models of car usage (regular purchase, car sharing[2], leasing, and taxi). The Business Model Canvas is primarily used for companies to identify or develop their business model, but can, as in paper 4, also be used to identify different business cases, depending on the usage of each car. This was, however, not needed regarding buses (papers 5 and 6) as there is only one business model available for the use of buses, and the focus in paper 6 was therefore on complementing the existing procurement process.

[2] ’Car sharing’ is called ’car-pooling’ in paper 4, but the correct term is ‘car sharing’.

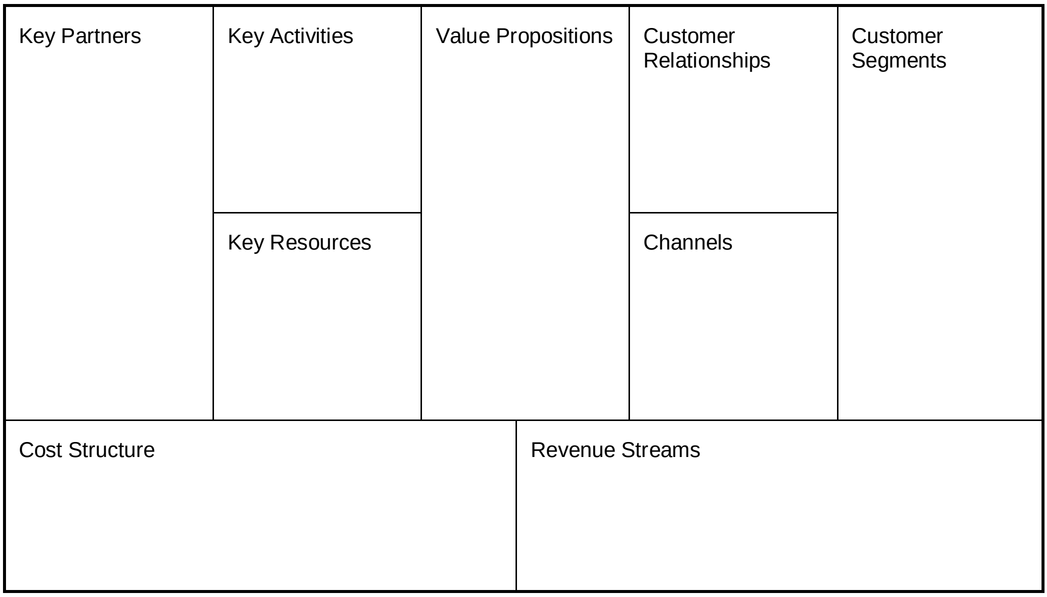

Figure 13: Business Model Canvas template. Adapted from Osterwalder and Pigneur (2010).

In all of the papers 3 to 5, Strategic Life Cycle Assessment - SLCA (Gunnarsson, 2010; Ny et al., 2006) was used. This is an overarching method to assess social and ecological sustainability aspects. It allows for a quick identification of the most important high-level sustainability challenges, which can guide necessary decisions and activities and, if needed, additional analyses. Based on the SLCA results, further studies in papers 3 and 5 were done via LCA (ISO, 2006) to quantify environmental impacts, the use of energy, materials, and land. Total cost of ownership based on Life Cycle Costing - LCC (ISO, 2008) was used in papers 4 and 5 to include costs caused by different vehicles, and externalities (partly covered by emission costs). The integration of the methods mentioned above is explained in Figure 14, and the use of them is further described in papers 3 to 5.

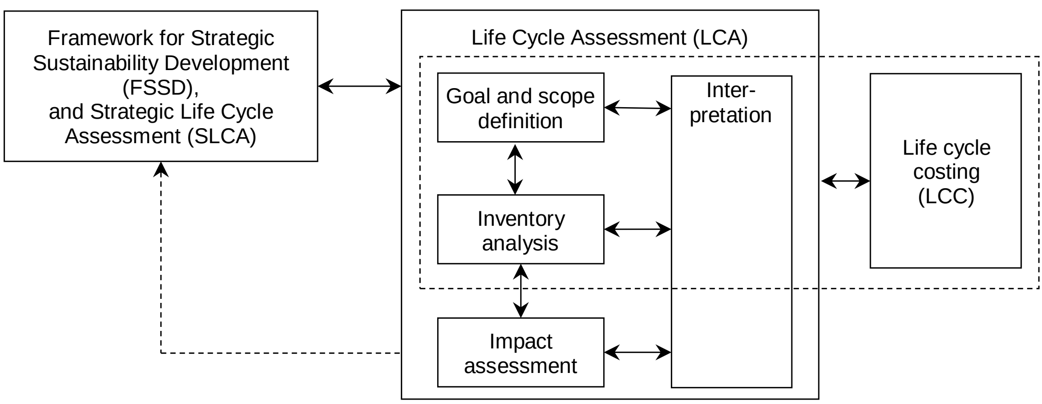

Figure 14: An iterative approach to using SLCA to scope LCA and LCC analyses.

In the B-step, noise was also measured according to the UN standard ECE 51-02 (paper 5) to clarify noise levels from electric and gas-powered buses. As explained below, external and internal project-related workshops were used to brainstorm solutions towards the vision of a sustainable future (papers 1 to 2). The D-step, however, was not included in this thesis.

3.4 Information collection

One common method for obtaining information in this thesis work was literature reviews via databases (e.g. Science Direct, Engineering Village, Web of Science, Elsevier, and Taylor Francis Online) and Internet search engines (e.g. Scopus, Summon, and Google Scholar). Information has also been retrieved from authorities and institutional websites (e.g. the Swedish Environmental Protection Agency, the Swedish Transport Administration, the European Commission, Universities, the Swedish Environmental Institute, and Thomas D. Larson Pennsylvania Transport Institute).

The research has included stakeholder seminars/workshops with experts in Sweden. This has to a high extent informed the results in papers 1, 2, and 6 to develop stakeholder cooperation models, as well as visions for, and paths towards, sustainable transport in paper 2, and to some extent the results in other papers. Results for SLCA and LCA were found in collaboration with colleagues and experts, in combination with logical reasoning, and data from other analysis (e.g. LCA database ‘Ecoinvent’, and literature)

Interviews with experts in mobility-related organisations (e.g. public transport operators and authorities, bus manufacturers, car dealers, and green mobility organisations) regarding operations and manufacturing of cars and buses in Sweden and Europe have been conducted in all studies, especially those described in papers 3 to 6. This was done to gather information about business models, operational costs, and energy use, for calculations and development of decision support.

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4 Summaries of appended papers

This section presents summaries of the appended papers, a short description of the relation of the respective paper to the thesis, and the present author's contribution to each paper.

4.1 Papers 1 and 2

A strategic approach to sustainable transport system development

- Part 1: attempting a generic community planning process model

- Part 2: the case of a vision for electric vehicle systems in Southeast Sweden

Published as:

(1) Robèrt, K.-H., Borén, S., Ny, H., Broman, G., 2017. A strategic approach to sustainable transport system development - Part 1: attempting a generic community planning process model. *Journal of Cleaner Production* 140, pp. 53–61. doi:10.1016/j.jclepro.2016.02.054

(2) Borén, S., Nurhadi, L., Ny, H., Robèrt, K.-H., Broman, G., Trygg, L., 2017. A strategic approach to sustainable transport system development – part 2: the case of a vision for electric vehicle systems in southeast Sweden. *Journal of Cleaner Production* 140, pp. 62–71. doi:10.1016/j.jclepro.2016.02.055

Summary

Paper 1 in this tandem publication presents an iterative multi-stakeholder planning process model (Figure 15) that embeds the FSSD and includes four interdependent planning perspectives ('Resource base', 'Spatial', 'Technical', and 'Governance'). The new process model proved helpful by giving diverse stakeholders with various competences and representing various planning perspectives a common, robust, and easy-to-understand goal and a way of working that was adequate for each of their contexts. In the study presented in paper 2, the process model was applied in cross-sector collaboration among transport stakeholders to develop a sustainable vision for EVs in southeast Sweden. It resulted in a vision of sustainable transport, with a focus on EV systems, within each planning perspective, and an initial development plan towards that vision (Figure 15). Through analyses of strengths, weaknesses and solutions, the seminar participants also identified some major barriers and enablers for EV-system development. Examples of barriers include high prices of EVs and the use of scarce metals in batteries. Examples of enablers include expansion of electricity production based on renewable energy, expansion of charging infrastructures, and extensive recycling of materials. The vision and plan imply a shift to renewable energy and a more optimized use of areas and thus a new type of spatial planning. For example, the vision and plan imply a lower built-in demand for transport, more integrated traffic modes, and more multi-functional use of areas for energy and transport infrastructures. Some inherent benefits of electric vehicles are highlighted in the vision and plan, including near-zero local emissions and flexibility as regards primary energy sources. The vision and plan also imply improved governance for more effective cross-sector collaboration to ensure coordinated development within the transport sector and between the transportation sector and other relevant sectors. After refinement, the authors also suggested that the planning process model could be applicable to strategic sustainable community planning in any societal sector.

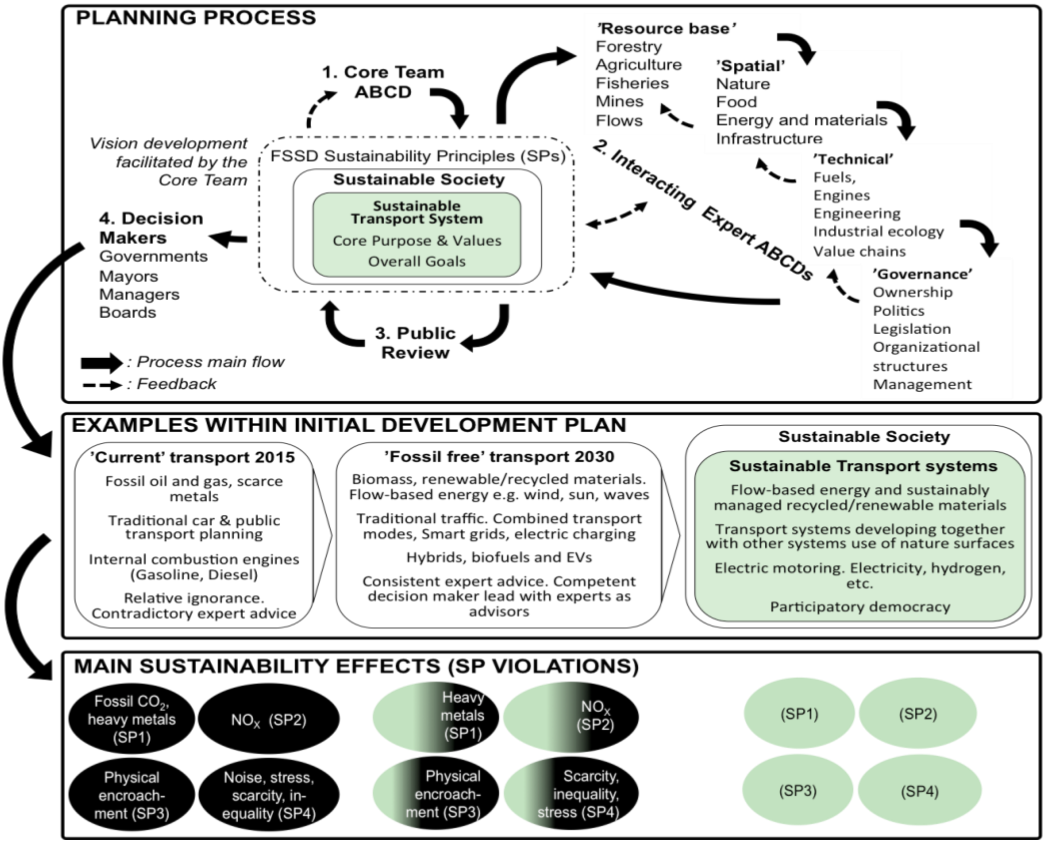

Figure 15: How the iterative process applied on road transport (top) can result in transport system development (centre), gradually phasing out the main sustainability effects (bottom).

Relation to the thesis

The work presented in this tandem publication included development and testing of a process model for enhancement of transport planning towards sustainability and resulted in a vision and preliminary roadmap for how electric vehicles and transport systems at large can be developed to fit into a sustainable society. This is strongly related to the FSSD and specifically its ABCD procedure, especially the A and the C-step (Section 2.4), which were used as guidance for the research. The results answer the first, second, and partly the fourth thesis research questions.

Author's contribution

The author of this thesis led the planning and writing process of both papers, took part in the creation of results, co-managed seminars, compiled results, and finalised the papers after feedback from co-authors and the journal's review.

4.2 Paper 3

A strategic sustainability and life cycle analysis of electric vehicles in EU today and by 2050

Published as:

Borén, S., Ny, H., 2016. A Strategic Sustainability and Life Cycle Analysis of Electric Vehicles in EU today and by 2050, *Proceedings of the 18th International Conference on Sustainable Urban Transport and Environment (ICSUTE) Conference*, Madrid, Spain, March 24-25, 2016. Pp 229-237.

Summary

In this study, sustainability effects of internal combustion engine vehicles (ICEVs) and EVs were compared, in the EU context today and by 2050. SLCA results revealed the major SP effects of today's ICEVs, battery electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (HFCEVs) (Table 4). These were related to the current use of fossil fuels and scarce materials for batteries and fuel cells, and also during most life cycle phases for all vehicles when fossil fuels are used in mining, production and transport. Still, the studied current BEVs and HFCEVs had less severe violations than fossil-fuel cars.

Table 4: Strategic life cycle assessment identifying the major SP effects of today's ICEVs, BEVs, and HFCEVs. Adapted from paper 3.

Life cycle phase	SP effects by ICEV powered by fossil fuels	SP effects by BEV powered by wind-generated electricity	SP effects by HFCEV powered by hydrogen produced from renewable fuels and wind-generated electricity	Sustainability Principle
Extraction	Negative	Negative	Negative	SP1
Production	Negative	Negative	Slightly	
Distribution	Slightly	Slightly	Slightly	
Use	Negative	Slightly	Slightly	
Waste	Slightly	Slightly	Slightly	
Extraction	Negative	Negative	Negative	SP2
Production	Negative	Negative	Negative	
Distribution	Slightly	Slightly	Slightly	
Use	Negative	Slightly	Slightly	
Waste	Slightly	Slightly	Slightly	
Extraction	Negative	Negative	Negative	SP3
Production	Slightly	Neutral	Neutral	
Distribution	Slightly	Slightly	Slightly	
Use	Slightly	Slightly	Slightly	
Waste	Slightly	Slightly	Slightly	
Extraction	Negative	Negative	Negative	SP4
Production	Slightly	Slightly	Slightly	
Distribution	Slightly	Slightly	Slightly	
Use	Negative	Slightly	Slightly	
Waste	Slightly	Slightly	Slightly	

Legend: Negative Slightly Neutral

An LCA, including uncertainty considerations, then quantified environmental impacts within these sustainability violations. The LCA showed, among other things, that BEVs charged with electricity from the EU-27 electricity grid have less life cycle climate change impact and overall less life cycle environmental impact than ICEVs powered by gasoline. On the other hand, they have 50 % higher climate change impact and overall higher life cycle environmental impact than BEVs charged with electricity generated from wind turbines.

Further results showed that possibilities for a sustainable development of EVs depend on the development of some main sustainability implications:

- The use of scarce metals in batteries and fuel cells can be reduced due to increased recycling of batteries, but platinum has to be replaced in fuel cells;
- Emissions and leakages from mining and of materials can be reduced if recycling is developed for all substances violating the SPs, and when mining and transport are powered by fossil-free energy
- The share of fossil fuels in the energy mix for production and distribution of motoring systems and energy carriers can be reduced if the EU 2050 energy goals will be fulfilled, but hydrogen still needs to be produced from renewable sources.

Relation to the thesis

Results in this paper contribute to the identification of current EV systems' sustainability effects, and to the identification of barriers and enablers for EV system development, by comparing cars with different powertrains. The comparison was then discussed in relation to a future scenario directed by EU 2050 energy goals. The results fit into the B-step and partly into the C-step of the ABCD procedure (Section 2.4). With regards to EVs in general and their life cycle environmental impacts, the results answer the fourth thesis research question, and partly the third thesis research question.

Author's contribution

The author of this thesis led the planning and writing process, co-created the results with colleagues, finalised the paper after feedback from co-authors and the conference's review, and presented the paper at the conference.

4.3 Paper 4

Competitiveness and Sustainability Effects of Cars and their Business Models in Swedish small town regions.

Published as:

Nurhadi, L., Borén, S., Ny, H., Larsson, T., 2017. Competitiveness and sustainability effects of cars and their business models in Swedish small town regions. Journal of Cleaner Production 140, 333–348. doi:10.1016/j.jclepro.2016.04.045

Summary

This fourth paper aimed to develop and test an approach to comparing sustainability effects (mainly through carbon dioxide emissions) and Total Cost of Ownership of various business models (regular purchase, car sharing, car leasing, and taxi), applied to private cars with different energy carriers (biogas, ethanol, gasoline, plug-in hybrid, and electric).

Besides the scientific peer-review, the results were reviewed by a motoring organization, Miljöfordon Syd, as well as by two car-sharing companies, Sunfleet and Move About. The study found that when driving 15 000 km/year during nine years, electric vehicles have a lower Total Cost of Ownership than cars powered by gasoline and approximately the same Total Cost of Ownership as cars powered by biogas and ethanol (Figure 16).

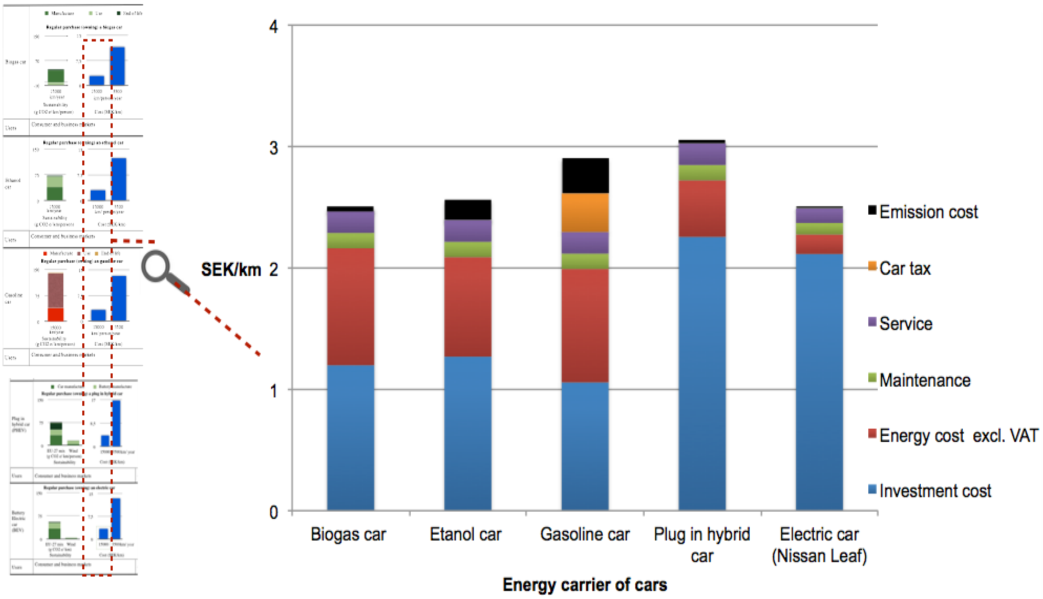

Figure 16. Total Cost of Ownership of Regular Purchase of cars (15000 km/year during nine years) powered by different energy carriers.

From a climate change perspective (Figure 17), car sharing was found to be preferable for short to medium distances due to a reduction of carbon dioxide emissions by 20-40 % when compared to regularly purchased cars. Leased cars have the same amount of carbon dioxide emissions as the regularly purchased cars if both are driven the same distance per year. Taking a closer look at the cost effectiveness of various uses of electric vehicles, it was found that people who travel by car less than 2000 km per year should consider using a taxi, while car sharing is most cost-effective for those who travel between 2000 and 8500 km. If travelling between 8500 and 13500 km per year, car leasing is the most cost-effective, and regular purchase is the best option for those who travel more than 13.500 km per year.

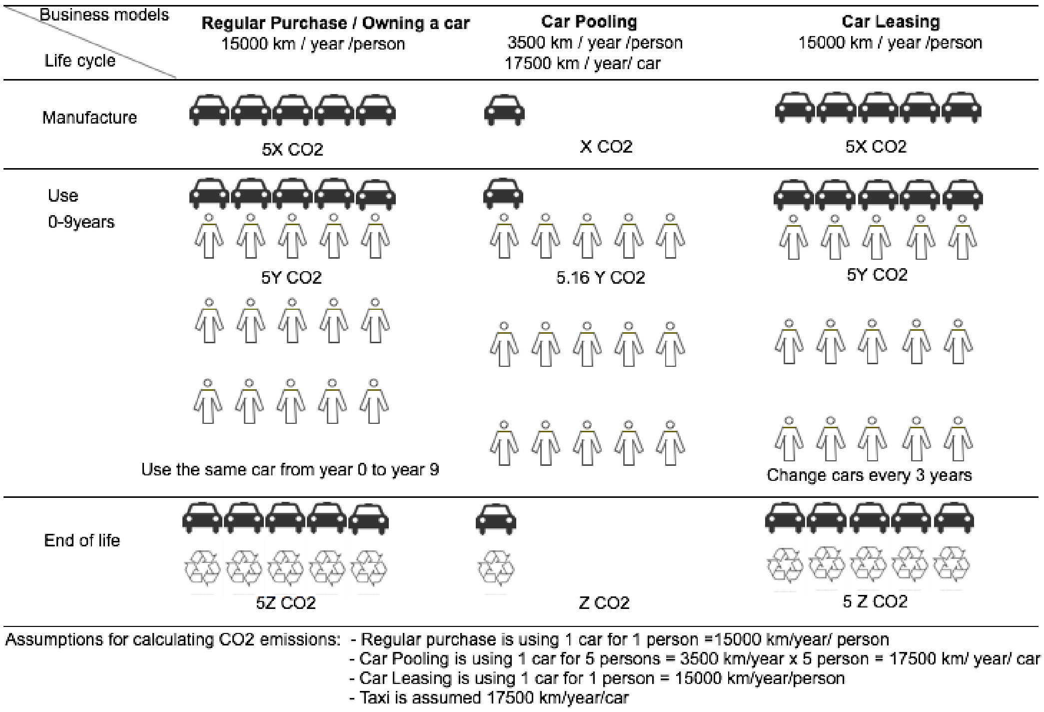

Figure 17. Car sharing (called pooling in this paper) using less cars and causing less CO_2 emissions than Regular Purchasing and Car Leasing.

Relation to the thesis

The study contributed to this thesis by clarifying sustainability effects, Total Cost of Ownership, and different car business models for the Swedish market for cars powered by biogas, electricity, ethanol, and petrol. The study also showed how competitive electric cars can be, and how they could be used to contribute most to sustainability. The results fit into the B-step and partly into C-step of the ABCD procedure (Section 2.4). The paper primarily answers the third thesis research question and also gave valuable insights related to the fourth thesis research question.

Author's contribution

The author of this thesis took part in the planning, writing and finalising of the text and illustrations, as well as created results and illustrations for the SLCA, and supported the Total Cost of Ownership Analysis.

4.4 Paper 5

Electric buses' sustainability effects, costs, noise, and energy use.

Submitted as:

Boren, S., 2018. Electric buses' sustainability effects, costs, noise, and energy use. *Submitted to Journal.*

Summary

This study aimed at investigating sustainability effects, energy use and costs of electric buses during at least one year when used in public transport. The aim was also to measure exterior noise during acceleration. It was found that when compared to other buses, electric buses have significantly lower sustainability impacts than other options during the use phase when the fuel for heating the interior and the electricity for propulsion stems from renewable sources. It was also found that further development towards sustainability of electric bus systems has to include renewably sourced energy throughout the whole life cycle, along with extensive recycling of material (e.g. heavy metals) and also account for social sustainability (e.g. fair and healthy working conditions). After further investigations and calculations, it was found that energy use and emissions throughout the whole life cycle were significantly lower for electric buses than for buses powered by fuels (Figure 18).

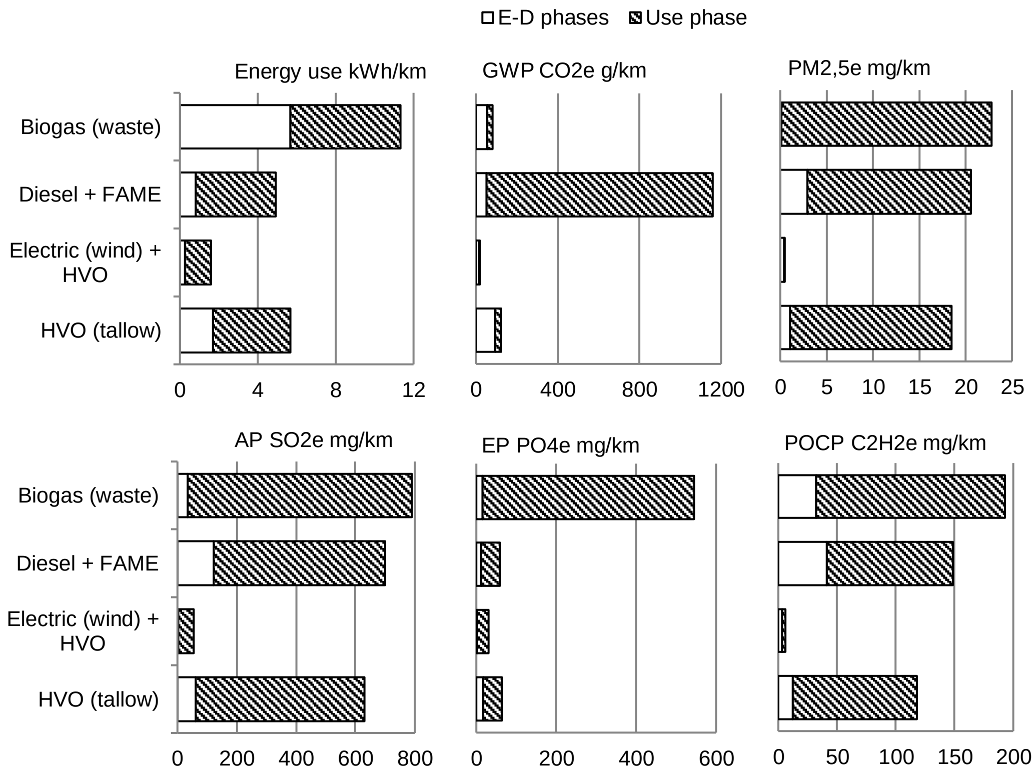

Figure 18. Energy use, contributions to Global Warming Potential (GWP), Acidification (AP), Eutrophication (EP), Photochemical Oxidant Creation Potential (POCP), and Particulate Matters (PM) during the use phase and extraction to distribution (E-D) phases of buses on route no. 1 in Karlskrona when powered by Biogas, Diesel, Electricity, or HVO.

It was found that on a yearly basis in the city of Gothenburg and Ängelholm, electric buses use about 1 kWh electricity per km for propulsion and about 0.3 kWh HVO per km for heating the interior of the bus. During January and February, the energy use by the interior heater was the same as for the propulsion. Regarding noise, an electric bus generated about 5 dBA less exterior noise during acceleration than a diesel bus, and about 7 dBA less than a biogas bus. This leads to a reduction of the societal cost for noise by 750 kSEK per year for electric powered buses, and an increase by 820 kSEK per year for biogas powered buses, when compared to diesel-powered buses along the main route in Karlskrona (route 1). The societal costs for emissions from diesel buses during their use phase were 12 SEK/100 km, which is more than six times higher than for buses powered by biogas, more than 9 times higher than for buses powered by HVO, and 100 times higher than for buses that would be powered by electricity from wind power. For TCO Figure 19, it was found that it is currently 14 % more expensive to run a diesel bus than an opportunity charged 12-meter electric bus, on route 1 in Karlskrona. This assumes a contract period of 10 years (starting in 2018), a continuation of rising fuel and electricity prices, and also slightly decreased battery prices and maintenance costs for electric buses.

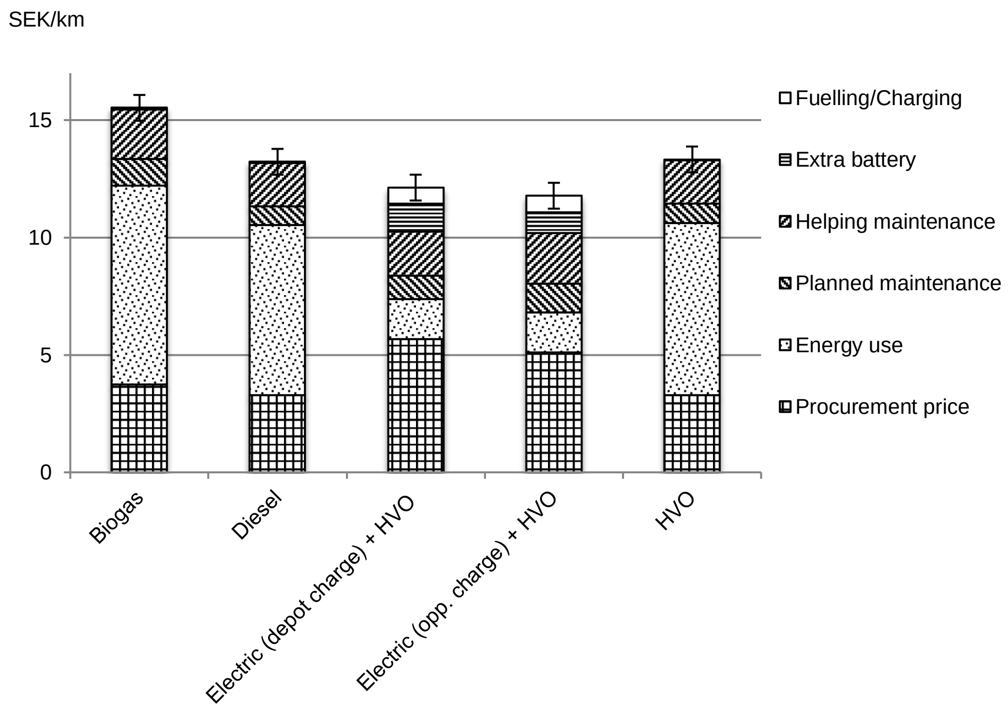

Figure 19. Total Cost of Ownership categories for different categories of energy carriers for 12-meter buses when operating at route #1 in Karlskrona during 10 years.

Relation to the thesis

This paper contributed primarily to the second and third thesis research questions as it clarified sustainability effects, life cycle environmental effects, societal costs, and Total Cost of Ownership. The paper also contributed to the fourth thesis research question through the clarification of general barriers and enablers for electric buses when used in public transport in Sweden. The proposed models for calculating societal costs and the updated model for total cost of ownership for buses also contributed to the fourth research question about clarification of enablers. The results fit into the B-step and partly into the C-step of the ABCD procedure (Section 2.4).

Author's contribution

The author of this thesis led the planning and writing process as well as the planning, realization and compilation of the results, finalised the paper after feedback from supervisors and partners within the study, and submitted the paper for journal publication.

4.5 Paper 6

Stakeholder collaboration model for procurement of public electric bus transport systems.

Submitted as:

Borén, S., Grauers, A, 2018. Stakeholder collaboration model for procurement of public electric bus transport systems. *Submitted to Journal*.

Summary

This study aimed to investigate how to include electric bus systems in current procurement processes for public bus transport in Sweden. Through stakeholder collaboration, the authors found two models that enhance planning for procurement of public transport with electric buses. They include stakeholders/roles and their leaderships/responsibilities, which partners to establish contracts with, and also suitable stakeholder collaboration steps. The first model (Figure 20) fits electric bus systems with opportunity charged buses and/or stakeholders with a low level of experience of electric bus systems. The second model fits electric bus systems with depot charged buses and/or stakeholders with a high level of experience of electric bus systems. Both models first steps about bus ecosystem and charging infrastructure design should be used during “stakeholder consultation” in the current procurement process when public transport authorities gather stakeholders and discuss the upcoming procurement of public transport. Construction of charging infrastructure in the first model should then be started after the decision to do procurement or not, and the charging infrastructure should also be operational before commissioning the bus traffic.

PT model phase	"Stakeholder consultation"		"Procurement"		
Stakeholder/Role	**Bus ecosystem**	**Charging infra. design**	**Charging infra. construction**	**Bus traffic procurement**	**Operation and maintenance**
Electricity dealers				I	I
Electricity grid owners	V	I	I	I	R_2
Charging manufacturers	V	I	I		R_2
Charging operators	I	R/I	R_2/I	R_3	R_2
City planners/ municipality	I	I	I/R_2	I	V
Public transport authority	R	I/R	R_1	R_1	I
Bus traffic operators	I	I	I	R_2	R_1
Bus manufacturers	I	I	V	I	R_2

R: Responsible | I: Involved | V: Volunteer | ↑: Contract

Figure 20. A stakeholder collaboration model tailored for **opportunity charging** and stakeholders with a **low level of experience** regarding procurement of electric bus systems. The model includes stakeholders/roles and their leaderships/responsibilities (in sequence 1-3), which partners to establish contracts with, and also steps that fit into different parts of the existing procurement process model (PT model phase).

Relation to the thesis

This paper contributes with two models for how to include electric buses in the procurement process and thereby contributes to answer the fourth thesis research question. It also informs answers to the third research question. The results fit into the C-step of the ABCD procedure (Section 2.4).

Author's contribution

The author of this thesis led the planning and writing process as well as the study planning, realization of the investigations and the compilation of the results, and together with the co-author finalised the paper after feedback from supervisors and partners within the study. The author of this thesis presented a preliminary version at the 'On Sustainability' conference in Cairns in 2018, and thereafter submitted the paper for Journal publication.

5 Main results and discussion

This section summarizes the main synthesized results, discusses validity, and compares the results with those of other related studies.

5.1 Main results

The thesis proposes what sustainable transport planning at large could look like and describes the potential role of electric vehicles in a sustainable society. Furthermore, current business models, likely sustainability effects, and costs of electric cars and buses are compared with those of the vehicles dominating the current transport systems. Also, major barriers and enablers for development of a road transport system based on electric cars and buses are clarified. Finally, the thesis proposes decision support models for strategic sustainable development of personal mobility in terms of a process model for strategic sustainable transport planning, and stakeholder collaboration models for procurement of public electric bus transport systems. Each of these main results are further discussed below.

5.1.1 An approach to sustainable transport planning at large

A methodological support for sustainable transport system development was elaborated. It comprises an iterative multi-stakeholder planning process model embedding the FSSD and includes four independent planning perspectives (further described in paper 1). Because of the integration of the FSSD, the methodological support is capable of guiding planning for transport system development and other community development from a strategic sustainability perspective. The initial testing through a real case indicates that the support works as intended.

5.1.2 Potential role of electric vehicles in, and towards, a sustainable society

As part of the work on developing a generic process model for strategic sustainable transport planning, a vision of a sustainable transport system in southeast Sweden was developed, and an initial development plan towards that vison was designed. The focus was on EVs for personal road transport. The vision includes: sustainably managed and sourced energy and materials; optimized use of areas; a small share of hybrids and bio-fueled vehicles that complement the otherwise electrified vehicle fleet; and governance for effective cross-sector collaboration (further described in paper 2). The broad array of involved stakeholders in southeast Sweden has generally acknowledged the vision and the initial development plan as being relevant and anchored in the region.

5.1.3 Business models, sustainability effects and costs

The studies show that the business model of ‘taxi’ is suitable from a cost perspective when driving less than 2000 km/year, ‘car sharing’ between 2000 and 8500 km/year, ‘car leasing’ between 8500 and 13500 km/year, and ‘regular purchase’ over 13500 km/year. Variations in the general business model for buses were found, where in general public transport operators own buses on 10-year contracts with public transport authorities.

Major sustainability effects of electric cars and buses were found, mainly related to extensive use of fossil fuels, insufficient recycling of materials, resources extracted through open pit mining for some materials, child labor and dangerous working conditions during extraction and recycling of some materials, and conflicts over resources (e.g. oil and metals). Regarding GHG emissions, a car powered by electricity from renewable sources has a reduction of 90 % when compared to a gasoline-powered car during the use phase. An electric bus has less than one percentage of GHG emissions over the whole life cycle when compared to a diesel-powered bus. Moreover, an electric bus was found to have much less contribution to acidification, eutrophication, photochemical oxidant creation potential, and particulate matter than buses powered by biogas, diesel, and HVO.

After nine years of ownership (15 000 km/year), an electric car was found to be at least 10 % cheaper than a gasoline-powered car. An electric bus was found to be about 14 % cheaper than a diesel-powered bus when operating at the main bus route in Karlskrona (route 1) for 10 years (67 000 km/year). Societal costs regarding GHG emissions and air pollutions were identified for electric buses to be 100 times lower than for a diesel-powered bus along the same route. It was also found that societal costs regarding noise can be reduced by 750 kSEK/year when an electric bus instead of a diesel-powered bus operates that same route in Karlskrona.

5.1.4 Barriers and enablers for development of sustainable personal mobility

The main barriers for personal mobility based on electric cars and buses were found to be the high prices of EVs and the use of scarce metals in batteries. The main enablers were found to be related to expansion of electricity production based on renewable energy, expansion of charging infrastructures, and extensive recycling of materials.

5.1.5 Decision support models for procurement of electric bus systems

Two models for how to include electric buses and supporting infrastructure in the current procurement process were developed. The first model was designed for a system that includes chargers at certain locations along a route, and/or stakeholders with a low level of experience of electric bus systems. The second model was designed for a system that includes buses charged at the depot and/or stakeholders with a high level of experience of electric bus systems.

Approaches to decision support models for comparing sustainability performance and costs were developed for buses and cars. These approaches embedded the framework for strategic sustainable development and analyzed sustainability effects through strategic life cycle assessments and life cycle assessments, and then total cost of ownership and societal costs.

5.2 Validity considerations and comparisons with other studies

Anyone using the results of this thesis should be aware of the following:

- The technology development is fast regarding charging, energy storage in batteries and fuel cells, and business models (e.g. ride-hailing and autonomous taxi). For further studies based on this thesis, an update of the results answering thesis research questions three to five might be required.

- The LCC results may change depending on shifts in the financial market, but the study results are anyhow expected to be useful for strategic purposes due to the inherent advantages of electric vehicles (e.g. lower noise, higher energy efficiency and the possibilities to reach fossil-fuel independency). In addition, the data from various vehicles are not consistently comparable regarding prices, and there could be possible weaknesses in the current cost calculations related to the assumptions that have been made. However, the author of this thesis believes that the prices are representative enough for this LCC study and that they give a reasonable indication of the most likely TCO and carbon dioxide emissions per km. Similar numbers are consistently identified from several reliable key resources. Moreover, in line with assumptions in this thesis (papers 3-5), a recent investigation in Sweden by Söderholm (2018) found that the maintenance costs are lower for electric cars, and similar for plug-in cars, when compared to cars powered by combustion engines. This could affect the answers to thesis research question three regarding cost calculations.
- The SLCAs and LCAs (papers 3-5) were based on results from different sources, which might be updated after respective study has been published. This could affect answers to thesis research questions three and four.
- Barriers and enablers regarding fast charging of electric cars that were identified in this thesis were verified by a recently published in-depth literature review by Nicholas and Hall (2018). That study also found, for example, that the price of fast charging, and the location of fast charging stations (tailored to regional needs and to match slow charging possibilities), have to be considered to get more electric cars on the road. This strengthens the answers to thesis research question four.
- The stakeholder collaboration models developed in papers 1 and 6 should be tested and anchored further. The model developed in paper 1 is currently tested and further developed by researchers at BTH in the INTERCONNECT project (Borén and Ny, 2018) with a focus on improving public transport in the south Baltic region, and in PhD studies by Lisa Wälitalo (Ahlström, 2015) focusing on process support for strategic sustainable development in municipalities and regions. Generally, it should be noted that the proposed new methodological support has so far been tested mainly in the context of the GreenCharge project, the focus being on personal road transport and EV systems in southeast Sweden. This implies a limitation from a validity point of view. However, since the support embeds the well-validated FSSD, it is likely more generally applicable, but, of course, this cannot be claimed with full confidence until the support has been tested more comprehensively. The model developed in paper 6 should also be tested and further developed with stakeholders that are about to procure public bus transport. This relates to the answer to thesis research question one and five.

- Testing of electric buses in paper 5 could have involved more vehicles in order to achieve more data regarding energy use, costs, and noise. Nevertheless, the results had good validity for the purpose of the study and could be strengthened when combined with results from earlier studies. This relates to thesis research questions three and four.

There is currently a focus on climate change effects caused by road transport in the research community, often quantified by carbon dioxide emissions during the vehicle's use phase. Some studies include a life cycle perspective, usually by using a Well-to-Wheel approach as explained in section 2.2 (Edwards et al., 2014; Reis, 2010) where environmental impacts typically exclude the disposal and production of vehicles. The FSSD, on the other hand, includes a science-based all-encompassing principled definition of sustainability, where SPs 1-3 focus on environmental aspects and SP 4 focuses on social aspects. A few of the most comprehensive LCA studies, (e.g. Bartolozzi et al., (2013), Girardi et al. (2015), Messagie et al. (2014), Offer et al. (2010)), cover most of the aspects related to SPs 1-3, but still lack analysis of social sustainability aspects. Nevertheless, the results from these LCA studies have been helpful for verification of the LCA results of this thesis work (papers 3 and 4). Differences in results are mainly related to prerequisites and assumptions for each LCA. Moreover, several roadmaps have been published lately that include the development of electric vehicles, which primarily estimate the vehicles' environmental effects in terms of carbon dioxide emissions (H. Johansson, 2012; T. B. Johansson et al., 2013; Sköldberg et al., 2013; Ståhl et al., 2013; The European Commission, 2011). By using FSSD-informed methods and tools, such as SLCA, this thesis goes beyond other studies to include a full systems perspective and strategic planning towards a future where no SPs are violated.

6 Contributions and future work

This section points out some key contributions, and points to further work.

This thesis work started in 2013 when it was assumed that electric vehicles could contribute to a sustainable development of personal mobility, but a scientific investigation was required. It was also unclear whether such development could comply with a science-based and rigorous perception of sustainability that includes the whole society. The Framework for Strategic Sustainable Development, that includes a principled definition of sustainability, was identified as suitable to address this.

6.1 Contributions to research and society

This thesis has contributed to the research community and to society with knowledge and stakeholder collaboration models for strategic sustainable development of personal mobility with a focus on electric cars and buses. The author of this thesis also believes that stakeholders involved in the studies were influenced by the findings in the GreenCharge project and the electric bus project, and they have initiated work in line with recommendations from these projects (e.g. strategies for upcoming procurement of public transport, integrated transport planning on regional and municipal levels, and investments in electric vehicles and charging systems in municipal organizations). Also, it is likely that some stakeholders involved in the projects mentioned above increased their knowledge through discussions and workshops about strategic sustainable development of personal mobility. The strategic sustainable development perspective of this thesis broadens the analysis beyond the more common focus on climate change issues and reduces the risk of sub-optimizations in community and transport system development. The generic support for multi-stakeholder collaboration could potentially also promote a more participatory democratic approach to community development, grounded in a scientific foundation.

6.2 Further work

Future research could explore specific decision support systems for sustainable transport development based on the generic planning process model presented in this thesis. It is also proposed that future studies should include more modes of transportation, on land and at sea, as their integration with road transport of people likely would facilitate higher total system efficiency. As mentioned in section 5.2, the development of batteries, charging, and business models is fast. For further studies based on this thesis, it is therefore recommended to regularly check for updates in these areas.

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