Systems Perspectives on Electromobility

2013

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PREFACE

The transportation of goods and people is at the heart of the industrial society. Yet transportation relies heavily upon oil – a scarce fossil fuel that contributes to climate change and local air pollution. The term 'electromobility' refers to an alternative transportation system based on vehicles propelled by electricity. Electromobility is increasingly seen as favourable in that it could circumvent problems related to both oil and biofuels whilst meeting our mobility needs and desires. However, the virtue of electromobility is not uncontested and a range of issues come to the fore. Are electric vehicles energy efficient? Are they safe? How much greenhouse gas is emitted in the production of electricity and advanced vehicle components? Will battery production lead to new resource problems? Will electromobility promote or hinder the diffusion of renewable energy? Will driving patterns shape or be shaped by new types of vehicles? Is electromobility suitable for cars but not freight transport? How is technical knowledge for electromobility produced and by whom? Is the automotive industry up to the challenge? Is there a need for new business models and governmental policy support (or both) to stimulate market demand for electric vehicles?

There is no simple answer to these questions. However, studying electromobility from different systems perspectives can help to resolve these complex issues. Systems Perspectives on Electromobility 2013 is composed of fifteen chapters that address different topics related to the immensely important issue of whether – and to what extent – our transport systems can and should be energised by electricity. The book is far from complete, but we hope it may be a useful starting point for future discussions and debates.

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ASSESSING ELECTROMOBILITY

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Mobility appears to be a distinctive human attribute. Moving ourselves, things and ideas has always been at the heart of human development. During 95% of the two hundred millennia humans have existed, we literally walked the Earth and moved around as hunters and gatherers. Our bodies were designed for long distance walking and running on the savannah and it has been claimed that the most important invention ever was the bag.[1] The one thing that made humans exceptional (apart from our ability to jog) was the ability to communicate, enabling effective cooperation. Lacking physical strength, our early evolutionary advantage was the ability and will to cooperate and share. The bag made it possible to bring home the catch of today and share it with the group.

Similarities in the design of early stone tools found in different geographical areas shows that the long distance transport of goods, the diffusion of ideas and maybe even trade have been around for a long time. The agricultural revolution, the emergence of settled societies and specialisation amplified the volume and importance of trade and transport. As a complement to walking, draught animals were domesticated and placed in front of carriages. Over the centuries, rowing boats and sailing ships opened new pathways for communication and exchange along the waterways of the world. In the 18th century, large sailing ships transported the raw materials and products of the British textile industry, generating capital to be reinvested in the embryonic industrial economy. The invention of the steam engine meant that chemical energy could, for the first time, be transformed into motion beyond the bodies of humans and animals. With coal-fired factories, trains and ships the industrial revolution became a reality. In the 19th century, local and global trade and travel escalated rapidly, changing both power relations between nations and the lives of ordinary people.

1 Berg, L. (2012). Skymningssång i Kalahari. Hur människan bytte tillvaro. (In Swedish). Stockholm, Ordfront förlag.

Electricity systems were developed in the second part of the 19th century, enabling new communication technologies in the form of telegraphs and telephones; providing light to growing cities and powering short-distance vehicles such as trams. The electrified 'horseless carriage', i.e. the electric car, followed shortly after. However, in the 1920s, internal combustion engine vehicles (ICEVs) drove the elegant electric vehicles (EVs) out of the market. People increasingly wanted to travel beyond towns and Henry Ford's assembly line meant that the Model T fell in price every year. The subsequent coevolution of ICEVs and oil extraction and refining changed the way wars are fought, the way cities are built and the way we arrange our daily lives. In 2010, petroleum oil still accounted for more than 90% of the energy used for transport (Chapter 2).[2]

Meanwhile, electric motors continued to develop and conquered steam engines and internal combustion engines in numerous applications. Batteries, first applied in the telegraph systems of the 19th century, entered an era of massive diffusion towards the end of the 20th century as they coevolved with the electronics industry and the ubiquitous deployment of information and communication technology. Despite the failure of the early electric car, transport technologies were slowly becoming more dependent on electricity. Rail transport underwent a shift from steam and horse to electricity, and during the 20th century various electric subsystems were added to ICEVs, ranging from the electric starter in the 1910s to modern computer-based control and entertainment systems (see Figure 2.3).

In the early 21st century, humanity faces a dilemma. While our demand for mobility and transport continues to increase we are challenging nature's capacity to support this growth. The people now walking the Earth are thousand times more numerous than the hunters and gatherers in pre-agrarian times, and to bring home the catch of today the walks across the savannah have been replaced with commuting by car and intercontinental flights. Oil powered ICEVs deplete limited resources, pollute the cities of the world and contribute to climate change at an increasing pace. The overarching question we pose in this book is whether the continued electrification of mobility – electromobility – can resolve this dilemma.

The book covers a wide range of topics that assess electromobility in different ways. One theme addresses the desirability of electric vehicles and propulsion systems; to what extent they are in some sense better than other options; and what is required to make them better. A second theme is related to the likelihood that electric vehicles and propulsion systems will be adopted; if they can compete with other options; and what is required for them to enter markets, develop and diffuse. These themes can be approached from many angles. While some general methodological considerations are found in Chapter 1 in Systems Perspectives on Biorefineries, we here directly jump to the outline of this book and some tentative conclusions that can be drawn from its chapters.

Chapter 2 provides a definition of the term 'electromobility' and describes some general technical configurations that we consider as important variants of electromobility. This chapter also outlines the main drivers and barriers of electromobility. In Chapter 3, we dive into the electric vehicle in order to get to know its

2 Food used for mobility powered by muscles is not included in this figure.

components and some vehicle configurations. From this micro level starting point we then move out in different directions. In Chapter 4, we stay close to the car and discuss safety aspects. In Chapter 5, we investigate the concept of energy efficiency by first addressing the delicate matter of finding a measure for the energy efficiency of vehicles, and then extending the system boundary to include different ways of converting primary energy sources to electricity and fuel. In Chapter 6, this life-cycle perspective is extended further to include different environmental impacts both in the fuel chain and for vehicle and component production.

Component production does not only result in environmental impacts but also relies on the availability of a range of potentially scarce metals, as discussed in Chapter 7. This highlights that electromobility must be adapted to, but will also adapt global materials systems. The success of electromobility will rely on the coevolution of electric propulsion and a number of different systems. Chapter 8 investigates the dependence on future energy supply systems and analyses competition with other options, such as hydrogen from coal plants with carbon capture and storage and biofuels. Chapter 9 explores the link to the electric power systems and examines whether electric vehicles will enable or complicate the introduction of intermittent renewable energy sources such as solar and wind.

Chapters 10-14 address various issues related to market demand, user preferences and cost. What types of electric vehicles fit current driving patterns (Chapter 10)? Will electromobility shape user preferences or vice versa (Chapter 11)? Does the different performance and cost profile of electric vehicles open up for, or even require, new business models (Chapter 12). Alternatively, are substantial governmental subsidies needed to boost market share and production volumes and help in reaching a level of maturity where competitiveness is ensured and growth is self-sustained (Chapter 13)? While Chapters 10-13 address passenger vehicles, Chapter 14 outlines the perspectives of two different types of freight companies and explores the pros and cons of electric city delivery trucks and electric road systems for long distance transport. While Chapters 12 and 13 investigate firm strategies and governmental policies related to market formation, another key issue for firms, as well as governments, is knowledge production. In the final chapter, Chapter 15, we discuss the challenges for the automotive sector in different countries in gaining access to the knowledge and know-how required to build electric vehicles.

One conclusion that can be made is that EVs are not inherently less safe (Chapter 4), more expensive or more complicated than internal combustion engine vehicles (Chapter 3). However, EVs will require the same amount of knowledge and experience that has accumulated around the ICEV (Chapters 2 and 15) and an adapted infrastructure (Chapters 2, 9 and 10).

A second general conclusion is that the environmental benefits of electromobility will depend on the development of renewable electricity (Chapter 6). If electricity is produced from coal, electric propulsion will mainly lead to problem shifting and substantial greenhouse gas emissions. However, electric propulsion allows us to tap into the vast energy resources provided by the sun (Chapter 5, Figure 5.7b) and could thus enable a sustainable global transport system of current proportions or larger. This also implies that the many limits related to biofuel systems can be circumvented (see Systems Perspectives on Bioenergy).

However, battery costs and the a high proportion of short distance trips (Chapters 10-13) and batteries' reliance on potentially scarce metals (Chapter 7) with related environmental impacts (Chapter 6) suggests that plug-in hybrids with smaller batteries combined with the possibility to use, for example, biofuels for infrequent longer trips could be a more viable option (Chapters 8 and 10), in spite of the more complex configuration of the vehicle itself (Chapter 3). An alternative, or complement, could be to use cars in new ways, including car pools that provide a range of different vehicles for different purposes (Chapters 2, 11 and 12). In any case, the electric vehicle is unlikely to be the second vehicle of households due to the high investment cost and low running cost (Chapter 11). The problems of a multipurpose vehicle seem to be even larger in the freight sector, where it seems unlikely that any single electric propulsion system can replace the diesel engine in all applications (Chapter 14). On the other hand, the freight sector might offer ideal niches where different electric propulsion systems can find their first economically viable application, such as quiet electric distribution trucks in cities or electric road systems in freight corridors.

It is also evident that the current transport system based on oil and ICEVs, once incubated in the early 20th century, is entrenched, locked-in and rigid in many dimensions ranging from physical infrastructure to knowledge production and the habits of people (Chapters 2, 11, 12 and 15). Breaking this lock-in and enabling electric propulsion to get a foothold will likely require substantial efforts by established firms and entrepreneurs as well as governments at local, national and supranational levels (Chapters 12, 13 and 15). Inventiveness and policy that support market formation will be required together with measures that stimulate knowledge development and diffusion.

In the end, the future of human mobility will be the outcome of countless decisions taken by humans. The full system consequences of these decisions can never be revealed in advance and we will always to some extent be blind to the impact of our actions. However, we believe that some factors can be exposed and understood and thereby subjected to deliberation. We hope that the knowledge, arguments and ideas provided in this ebook can be useful in the process, stimulate fruitful discussions and provide some guidance.

2
WHY ELECTROMOBILITY AND WHAT IS IT?

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In this chapter we examine the notion of electromobility and aim to provide a working definition of the term that underpins the analyses presented in the rest of this e-book. We also describe electromobility in technological terms by presenting various technological configurations of electric vehicles, charging infrastructure and energy supply. We then proceed to examine why electromobility is currently supported as a favourable means to transform road transport by discussing drivers and barriers of change in the automotive industry. Whilst electromobility represents a significant technical challenge, it also requires complex social changes. By arguing from different perspectives we hope to illustrate that electromobility is best understood by considering a range of systemic perspectives found in this and later chapters of this e-book.

WHAT IS ELECTROMOBILITY?

In this e-book we define electromobility as a road transport system based on vehicles that are propelled by electricity. Some road vehicles are equipped with technologies that make them capable of producing their own electricity (e.g. hybrid electric vehicles). Others utilise energy supplied by a source of electricity *outside* the vehicle – usually the electric grid. This definition works well for battery electric vehicles as well as for vehicles that do not store electrical energy such as trolley busses.

A key feature of our definition is that it focuses on systemic aspects of electromobility. A transport system using electricity from the grid, for instance, can utilise energy from many different sources without major modifications to electric vehicles or energy supply systems. This allows for local variations in energy supply and gradual changes to energy supply systems. Electromobility may thus improve the flexibility and robustness of the transport sector in that electrified vehicles can utilise different types of energy sources. Electricity can be produced from nuclear power, fossil fuels and abundant renewable resources such as solar and wind. This could make electromobility more favourable than other technological alternatives such as vehicles that utilise biofuels, because the production of biofuels is limited by the availability of biomass (see Chapter 5 for a comparison of system efficiencies).[1] Electromobility can also help to reduce CO_2 emissions, especially if electricity is produced using renewable sources (Chapter 6). However, if vehicles utilise electricity produced from coal, the climate impacts of electric propulsion could be negative when compared to gasoline or diesel fuelled vehicles. This exemplifies that systems thinking is key to understanding the benefits and drawbacks of different electric vehicle technologies and systems.

Furthermore, electromobility is a complex phenomenon that will involve technological development, policymaking, innovation, new business models, new driving behaviour and new linkages between industries. The systemic aspects of electromobility thus reach far beyond mere technical aspects and a transition to electric propulsion must be understood as a process of socio-technical transformation.

TECHNOLOGIES FOR ELECTROMOBILITY

Electromobility requires several new technologies. This section provides an overview of the currently most interesting technological alternatives and configurations. It is, however, not an exhaustive list of all possible technologies (see also Chapter 3).

Figure 2.1 shows examples of energy sources and technologies that can transfer energy to electric vehicles. Note that energy sources can be selected irrespective of the technology used for transferring energy to vehicles. The primary means of transferring energy to vehicles is to charge the vehicle while it is parked using a cord or via wireless charging. In order to extend vehicles' driving range it is also possible to use rapid chargers that significantly recharge batteries in about 10 to 30 minutes. Alternatively, battery switching involves exchanging discharged batteries for fully charged ones, usually at a switching station. To reduce (or eliminate) the need for battery capacity it is also possible to supply electric vehicles with energy whilst in motion, either during the whole drive or parts of it. A final way to supply vehicles with electrical energy is to produce hydrogen via electrolysis and store energy in hydrogen tanks rather than batteries.

Three electromobility drivetrain configurations are presented in this chapter: battery electric vehicles (BEVs), continuous power supply electric vehicles (both a conductive and an inductive version) combined with electric road systems (ERS, see also Chapter 14), and fuel cell vehicles (FCVs) (Figure 2.1). Due to limitations in each of these, some hybrid drivetrains are also of interest since the combination of two drivetrains can benefit from their respective strengths and compensate for weaknesses.

1 See Systems Perspectives on Biorefineries 2013 for discussions on various aspects of biofuel use.

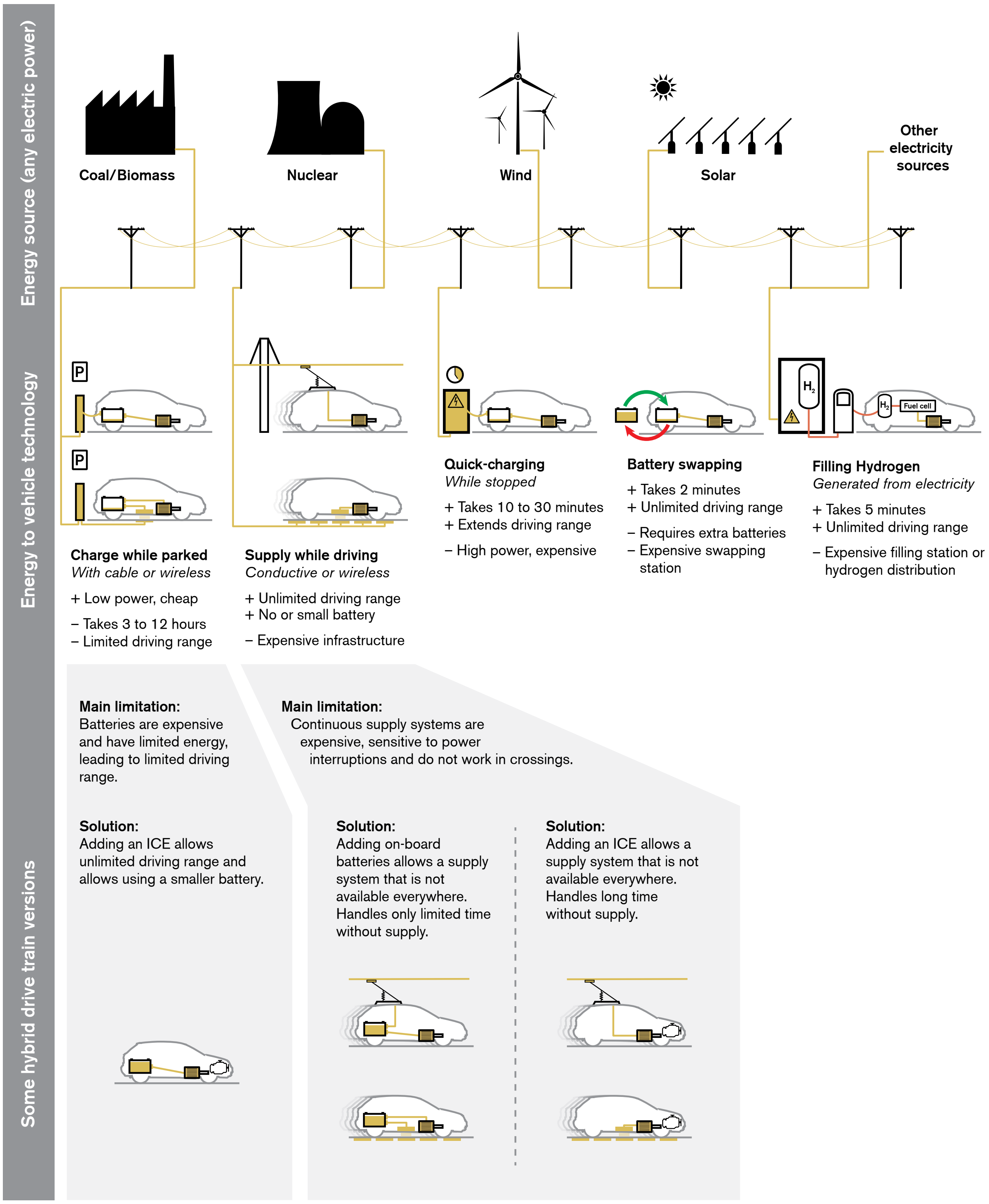

Figure 2.1 Examples of electricity sources, drivetrain configurations and technologies to transfer electrical energy to vehicles.

BEVs run solely on electrical energy from a battery and have a fully electric drivetrain. Batteries can be charged in many different ways as shown in Figure 2.1. A major limitation of BEVs is that the driving range is dependent on battery size, which in turn is constrained by cost and weight.

Plug-in hybrids (PHEV) and range extender vehicles are electric vehicles that combine battery-powered electric machines and combustion engines. This combination can reduce range limitations; allow the use of smaller and cheaper on-board batteries; and reduce the need for a charging infrastructure. The most likely backup power source in such vehicles in the short term is an internal combustion engine. In the long term other types of backup power sources may be used such as fuel cells. Plug-in hybrids come in various configurations with different types of transmission and with different ratios between the size of the combustion engine and the electric machine (see Chapter 3). From an energy-system perspective they all have the same basic functionality of allowing vehicles to run on electricity from the grid, but whenever there is a limit due to battery capacity they can run on alternative fuels until the battery is recharged.

Vehicles with a continuous power supply draw energy from the electricity grid whilst in motion and thus reduce the need to store energy on-board. However the construction of a road infrastructure that integrates conductive power lines or inductive rails requires large investments, and the system would be vulnerable to fluctuations in electricity supply. Hence hybrid configurations that include on-board energy storage devices (batteries or some other secondary power source) may be more attractive. The secondary energy source can be used in road junctions where it is difficult to construct a continuous supply infrastructure; on roads where a continuous supply infrastructure are not economically warranted or not yet installed; and in the event of fluctuations in electricity supply.

Fuel cell vehicles (FCV) are vehicles that carry energy in the form of a fuel such as hydrogen that can be transformed into electricity on-board using fuel cells. FCVs allow for longer driving distances, but require a hydrogen-refuelling infrastructure. Refuelling takes only a few minutes and is much faster than charging batteries, even where fast charging is available. During operation a fuel cell cannot quickly change the power output and FCVs typically also use a small battery to match rapid changes in power demand (a hybrid solution). The battery is also beneficial during acceleration since it can provide peak power, allowing for a smaller fuel cell. It can also store energy during deceleration, which reduces fuel consumption.

These electromobility technologies can be applied in a variety of vehicle types including heavy vehicles (such as buses and long haul trucks), conventional passenger cars, microcars (such as the Renault Twizzy), electric scooters and bicycles, and vehicles that are already electrified such as forklifts, trams, trains and trolley buses.

In sum, there are various technological alternatives associated with electromobility, each with its own set of advantages and disadvantages. Presently it is unclear which, if any, of these alternatives will play a major role in a transformation of the transport sector.

WHY ELECTROMOBILITY NOW?

In this section we switch our attention to the various reasons behind the current interest in electromobility. We note that whilst these reasons offer significant impetus for the electrification of road vehicles, there are various barriers to electromobility, which are for the most part non-technological. We draw on systems approaches to describe the nature of these barriers, which are typically social, economic and to some extent psychological.

Before we address these issues it is important to note that electromobility is not entirely new. BEVs have existed for over a century. Several individuals experimented with electric vehicles in Europe during the latter half of the 19th century and in the US the Electric Carriage and Wagon Company developed the first commercially available electric vehicles in 1897. However, petrol-driven vehicles began to dominate in the US after 1920, mainly because of the development of a more comprehensive road infrastructure. Petrol-driven vehicles could travel faster and further and were seen as superior to electric vehicles that were slow and which had limited range.

Notwithstanding, petrol-driven vehicles can be described as having undergone a process of electrification ever since. During the 20th century electronic components and sub-systems have replaced non-electronic counterparts in fuel injection systems, engine ignition, and engine management (Figure 2.2). One could thus argue that the drivetrain is the last remaining non-electronic element and that its electrification appears to be predestined given the apparent path-dependency of road vehicles.

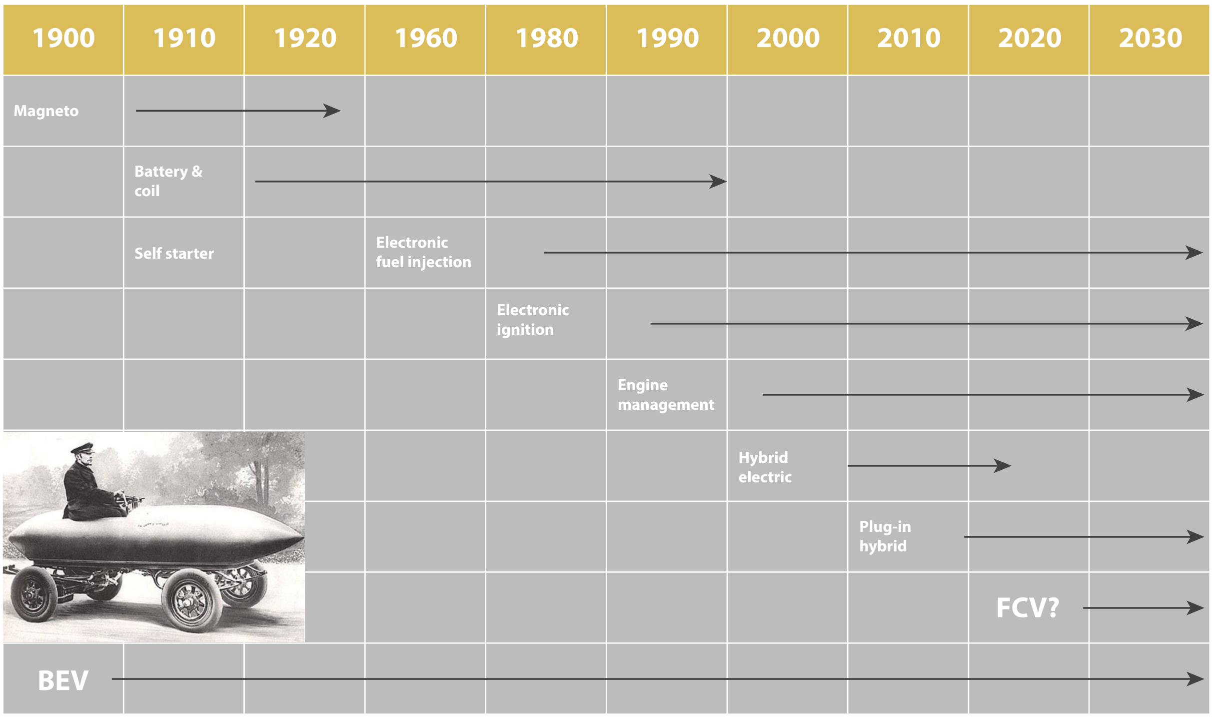

Figure 2.2 the electrification of road vehicles in a historical perspective.[2]

2 Source: Nieuwenhuis, P. (2012) The challenge of decarbonising the car, chapter 2 in: Nilsson, M., Hillman, K., Rickne, A. and Magnusson, T. (eds.) *Paving the Road to Sustainable Transport; Governance and Innovation in Low-carbon Vehicles*, Routledge Studies in Ecological Economics, London: Routledge.

However, substituting the ICE with electrified drivetrains is no simple task. Technologies associated with the internal combustion engine (ICE) are at present hugely significant for road transport and have been developed continuously for around a century. Transforming the road transport system is a major technological challenge in that new technologies must compete with the maturity and efficiency of the ICE. The ICE has evolved alongside infrastructures such as oil extraction, refinement and distribution, and the road infrastructure itself. Furthermore, the ICE has evolved alongside various social systems, such as suburban living and commuting. These systems are all intertwined, and to some extent one could describe them using the notion of lock-in,[3] which means that they mutually reinforce one another and are thus difficult to change. A transition to electromobility thus requires not just technological changes, but broader and more systemic transformations that are in some cases non-technological. For this reason we adopt a systemic approach that serves to highlight the complexities of the road transport system and which can help us examine the range of drivers and barriers related to the electromobility transition.

A large technical system (LTS) is a complex system of technological artefacts that interacts with other technical systems and with actors and institutions.[4] The LTS that encompasses ICE-based road transport represents such complexities. The ICE in road vehicles is itself part of a complex machine that is the automobile, and which is associated with a complex socio-technical system. As noted above, the ICE is supported by other LTS such as that of oil extraction, refinement and distribution. It is also supported by road infrastructures and a range of institutions spanning regulations, standards, policies and subsidy schemes to social norms and ideas related to the automobile itself. This complex set of physical and non-physical entities is what makes the ICE an artefact – it is not just a technological 'object' but also an artefact whose 'meaning' is encompassed in the various social phenomena that support its existence. The interdependencies between these various facets of the ICE mean that the road transport system is to an extent 'locked-in' to a specific path that is resistant to change – at least until recently.

Electromobility is perhaps a reflection of a technological discontinuity in the automotive industry. The latter is currently subject to various pressures and factors that have made paramount the need for technological change. The current and renewed interest in electromobility can be explained in terms of a number of overarching drivers of change in the automotive industry. These drivers of change have elsewhere been described as 'megatrends'[5] and include concerns for energy security; air pollution and climate change legislation; support for industrial competitiveness; recent technology improvements; and growing interest for electromobility in key markets such as China.

In 2010, petroleum accounted for more than 90% of the energy used for transport, implying that more than 60% of all oil used globally was consumed by the transport sector.[6] Oil dependence poses problems in terms of energy security since oil

3 Unruh, G.C., (2000). Understanding carbon lock-in. *Energy Policy,* 28, 817–830.

4 Hughes, T. 1983. Networks of power. Baltimore: Johns Hopkins University Press. W. E. Bijker, T. P. Hughes, & T. J. Pinch (eds.), The social construction of technological systems. Cambridge, MA: MIT Press.

5 Conrady R. 2012. Status quo and future prospects of sustainable mobility. In Trends and Issues in Global Tourism 7, 237-260.

6 IEA 2012, Key World Energy Statistics 2012

is a finite and geopolitically sensitive resource. The energy security problem may result in fuel price shocks or supply interruptions. Oil dependence also contributes to climate change, and the transport sector is presently responsible for 25% of energy-related CO_2 emissions.[7] Notwithstanding, there are strong drivers for an increased demand for oil in the transport sector. Since transportation is strongly correlated with income growth – particularly in emerging economies – the size of the global road vehicle fleet is likely to grow dramatically in the coming decades. Without a major shift in transportation technology or demand, oil use and CO_2 emissions will follow the same trajectory. In other words, oil dependency is increasingly seen as unsustainable in both environmental and economic terms.

Furthermore, the economic crises of 2008 had a huge impact on the automotive industry, and several industry players faced bankruptcy. National governments were forced to intervene and prevent potential job losses using financial support packages. In many cases support was provided on a conditional basis. Large portions of the money had to be spent on green technology. Money was also made available for battery manufacturing, vehicle development and subsidies for purchasing green cars. The automotive industry is of strategic importance to the many regional and national economies. For instance, 12 million people are employed (directly or indirectly) in the European automotive industry. The European automotive industry also spent EUR 28 billion on R&D 2009.[8] Electromobility is considered by many governments to be of strategic importance for the long-term survival of national automotive industries. Finally, the global automotive industry has experienced major structural changes following the emergence of rapidly developing economies. China currently represents the largest vehicle market in the world and its importance will increase in tandem with Chinese economic growth. Many expect that 30% of all cars produced globally will be sold in China in 2025.[9] The Chinese government is a strong advocate of electromobility and this alone represents a driver for the global automotive industry.

From an LTS perspective, problems that accumulate over time can bring about technological change by harnessing the problem-solving capabilities of a range of actors ('system builders' in LTS parlance). These types of macro-level forces have also been described in the literature on technological transitions as 'landscape changes',[10] and typically refer to changes in the socio-technical landscape (e.g. economic pressures, social trends and environmental issues) that can bring about systemic technological transitions. Industries periodically experience transitions to new technologies, and new technologies sometimes serve to create altogether new industries in a manner that destroys existing competences and industrial practices.[11] The current state of the automotive industry is perhaps one of fluidity whereby numerous technologies are being researched, developed, and tested in niche markets. In other words, electromobility presently reflects attempts by an existing industry to bring about a technological transition.

7 IEA. 2012. Energy Technology Perspectives 2012 Pathways to a Clean Energy System.
8 Action plan for the EU automotive industry in 2020. European Commission. 2012.
9 KPMG's Global Automotive Executive Survey 2012.
10 Geels, F. W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study. Research Policy 31 pp. 257-1273
11 Utterback, J., 1994. Mastering the Dynamics of Innovation. Harvard Business School Press, Boston, MA.

A range of recent technological developments supports the electromobility transition. Developments in batteries, electronics and computers have increased the competitiveness of plug-in vehicles compared to those propelled by the ICE. For example, most electric vehicles built in the 90's used lead-acid batteries. The flagship vehicle of the electrification wave in California, General Motors EV1, used a nickel metal hydride battery. The battery pack of EV1 had an energy density of around 20 Wh/kg, whereas most of the lithium-ion battery packs used today have an energy density of 80-120 Wh/kg. In terms of battery technology alone, energy densities have increased fivefold over the last two decades. Moreover, several studies predict that the cost of batteries for plug-in vehicles will decrease.[12] Reductions in the cost of batteries will boost the competitiveness of plug-in vehicles. Some automakers are thus confident that plug-in vehicles will be commercially viable alternative to the ICE in the short term for some vehicle users.

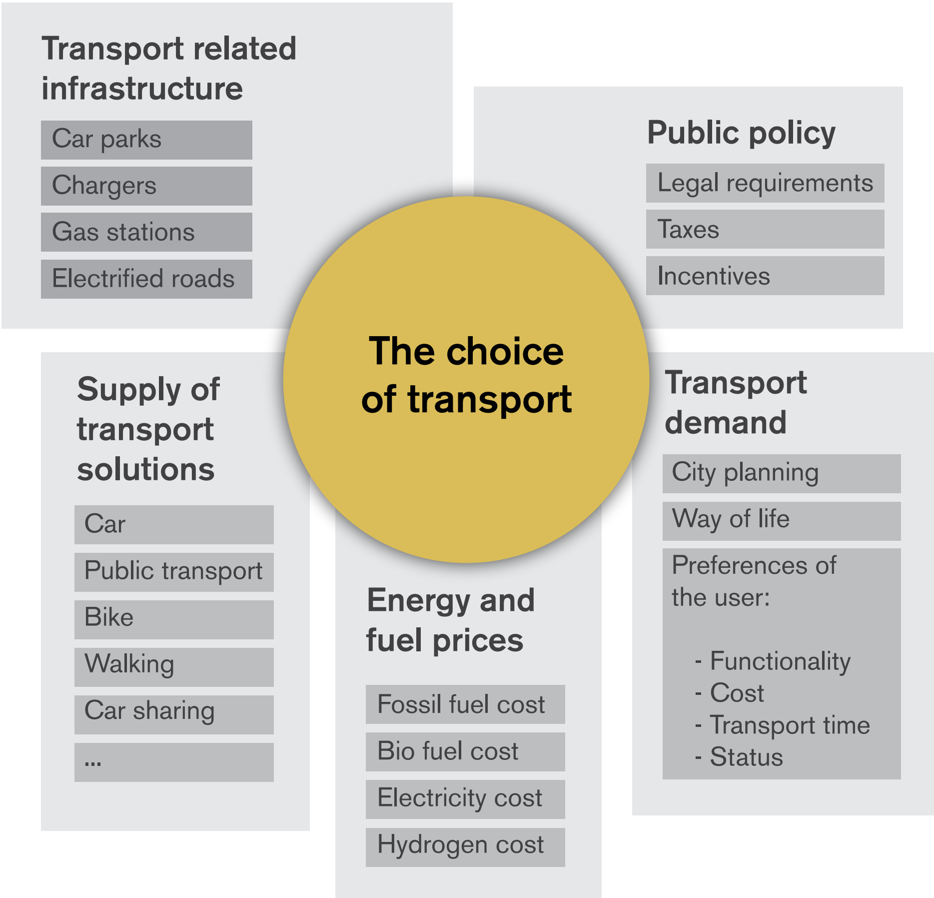

Figure 2.3 Some of the main factors that influence the choice of transport solutions

We know from history that the fluid phase is usually followed by one of selection whereby a dominant design gleans sufficient support from a range of actors and serves to reduce the number of available technological alternatives.[13] However, there are several barriers that must be overcome before electromobility can make

12 The Lithium-Ion Battery Value Chain. Francesco Pavoni. Roland Berger. 12 oct 2012. International Conference on Energy and Automotive Technologies.

13 Utterback, J.M., Abernathy, W.J., 1975. A dynamic model of process and product innovation. Omega 3, 639–656; Utterback, J.M., 1994. Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change. Harvard Business School Press, Boston, MA.

significant inroads vis-à-vis road transport. Vehicles are a central element of road transport systems. However, the technologies utilised for vehicle propulsion are influenced by other factors such as the cost and availability of technological alternatives, fuel costs, the availability of infrastructure, public policies and demand for mobility (see Chapter 8 for an approach that models the impacts of some of these aspects). Figure 2.3 illustrates some of the main factors that influence the utilisation of vehicles and propulsion technologies. A transition to electromobility requires concurrent changes to these other factors, which makes a transition more difficult.

Technological development is often driven by user preferences or by the possibility for companies to gain advantages over competitors. However user preferences are not the main drivers of electromobility. For the most part users are satisfied with the ICE and most electromobility solutions are presently inferior to the ICE in terms of driving range and cost. Furthermore, fossil fuels are not sufficiently expensive to incentivise more expensive electric vehicles for most users. In other words, there are currently few market forces for electromobility in the absence of significant policy measures (see Chapter 11 and 12 on consumer attitudes and new business models for electric vehicles). However electromobility can partly be explained that some companies want to gain advantages over competitors. Some automakers are proactive and are investing heavily in electromobility despite a lack of customer demand at present (see Chapter 15 on knowledge development).

A lack of consumer interest poses a significant obstacle for electromobility. Electromobility solutions are, in the eyes of most users, inferior to combustion engine vehicles and they are more expensive. Electromobility is thus unlikely to be driven by market forces alone, which means that policy has a key role to play. Hence new fuel economy and CO_2 legislation has been implemented in different parts in the world. Electromobility is a means for automakers to comply with legislation that sets performance standards for new vehicles. Especially important are the renewed ZEV mandate legislation in California; the EU goal of 95 g CO_2/km and the Chinese targets for plug-in electric vehicles by 2020.

ACTOR EXPECTATIONS AND THE ROLE OF PUBLIC POLICY

As noted above, public policy is likely to play a significant role for electrification given that market forces alone are unlikely to drive a transition towards electromobility. The extent to which governments can lead this transition depends in part on the level of support that policy can provide (see Chapter 13 on the effect of some policy instruments). It also depends on the efficacy with which policy 'selects' technologies such as those associated with electromobility.

There is evidence to suggest that the automotive industry supports public policies that seek to bring about a transition in the transport sector. ACEA, the main industry association for European automakers, is in favour of policy-based support for alternative fuels and has highlighted electromobility as a key area of interest. However ACEA is also in favour of technology-neutral policies, that is, policies that focus on performance criteria such as vehicles' CO_2 emission levels and energy efficiency rather than policies that provide support for a particular technology at the expense of others.[14] However, there also is evidence to suggest that policymakers must adopt a more technology-specific approach as regards electromobility. In particular, policies are required to support R&D (particularly for battery technologies) and to ensure the development and deployment of charging infrastructure given that the latter would not be built without policy interventions.[15] Whilst these divergent preferences may reflect differences in policies that seek to stimulate supply (technology push) contrasted with those focused on demand (performance pull); it appears to be the case that technology-specific policies are needed to promote the commercialisation of electric vehicles.

The role of technology-specific policies that promote the commercialisation of EVs is evident in other parts of the world. In California the Air Resources Board (CARB) has since 1990 been developing legislation to mitigate various types of air pollution from road transport. CARB's 'Advanced Clean Cars' program promotes the commercialisation of different alternative vehicle technologies.[16] The program makes two key stipulations regarding 'Low Emission Vehicles' (LEVs) and 'Zero Emission Vehicles' (ZEVs). LEVs refer to vehicles with lower levels of smog-forming pollutants and greenhouse gases, and ZEVs refer to vehicles that have zero emissions during the use-phase. CARB has legislated that a growing proportion of vehicles sold in the state of California has to be LEVs and ZEVs.

Whilst these stipulations appear to be technology-neutral, CARB also specifies the types of vehicle technologies that can meet these performance standards. CARB categorises BEVs and FCVs as 'zero emission' vehicles, and PHEVs, HEVs and PZEVs[17] as 'low emission' vehicles. Existing legislation requires that 62,500 ZEVs and 141,000 PHEVs be sold in California between now and 2017. CARB also argues that the Advanced Clean Cars program will deliver various benefits. In 2025 new cars will release 75% less smog-forming pollutants than the new ICE cars of today; 3-6% lower GHG emissions per year; improvements in fuel economy of 37-50MPG by 2025; and concurrent reductions in the total-cost of ownership of between USD 5,300-9,400 per vehicle (for cars).

However, creating technology-specific policies that promote technological transitions is a challenging task. Road transport is complex in that vehicles are required for different purposes, i.e. different driving patterns and different types of haulage. Creating technology-specific policies to suit these various purposes is challenging because policies must fulfil specific aims and goals within certain technological and economic constraints. A simple way to illustrate this point is to examine European transport policy. Vehicle electrification is generally considered within the auspices of EU institutions as one of many technological alternatives that will assist in achieving transport policy goals, of which two key aspects are environmental sustainability (primarily focused on reducing CO_2 emissions) and economic development (focused on both industrial competitiveness and reducing dependency on foreign oil derivatives). A recent public consultation entitled 'Study on clean transport systems' reveals some of the ways in which actors bring to bear

14 ACEA (2011) ACEA comments on the White Paper on Transport Policy.
15 EC (2010) Study on Clean Transport Systems. European Commission, Directorate-General for Mobility and Transport.
16 CARB (2012) California Air Resources Board: Advanced Clean Cars.
17 PZEVs refers to partial zero emission vehicles, or 'gasoline cars that meet the strictest air quality standards'.

their varying expectations regarding vehicle technologies.[18] Respondents included public, private and third sector organisations and individuals.

The results are as follows. Firstly, respondents regarded electricity to be the most important fuel for the transport sector in the long-term – more important than biofuels, hydrogen, methane, synthetic fuels and LPG. Second, respondents regarded electricity as the most plausible alternative fuel for road and rail applications, but not water or air, where biofuels play a more significant role. Third, respondents felt that different types of electrified road vehicles are useful for different haulage ranges. BEVs, for instance, were expected to be the most operable alternative by 2020 for short-haul passenger and freight purposes, whereas hydrogen fuel cell vehicles were expected to be a viable solution for medium and long-haul trips by 2050. Furthermore, road vehicles linked directly to the grid were more favourable than FCVs for short-haul passenger applications, but less so for medium- and long-haul applications.

These findings of course reflect majority views – the fact is that respondents display divergent sets of expectations regarding both the manner in which electrified vehicles will develop and the role they will adopt in the future transport system. Hence the need for technology-specific policies represents a significant challenge for governments, especially since expectations regarding vehicle technologies tend to change over time following, among other things, technological developments and market trends. Whilst industries tend to prefer policies that are robust and predictable, in practice it provide concrete indications of how policy will develop given the current state of flux in the automotive industry. Notwithstanding policymakers are offering strong support for electromobility and policy appears to assign a major role for technology in bringing about change.

SUMMARY

Several technological alternatives to the ICE have emerged as a result of problems related to the existing road transport system. One option is electromobility, which we define as a road transport system based on vehicles that are propelled by electricity whose energy is supplied by a source of electricity *outside* the vehicle. This chapter discussed electromobility in terms of technological alternatives and examined a range of factors that provide a stimulus for and barriers to change in the road transport system. At present there are various technological paths for us to choose between. It may be the case that these paths remain open, but history suggests that the current fluid phase, which is characterised by the creation, development and trial of technological alternatives will probably be followed by the emergence of a dominant design and the growth of new markets and industries. However, several actors both within and outside the automotive industry depict the future of road transport as one of technological diversity, with applications for different configurations of electrified vehicles for different purposes. Understanding the desirability of these alternatives means that we must look much further than vehicles themselves, and understand how factors such as energy supply, emissions and other socioeconomic and ecological factors influence future alternatives for road transport.

18 EC (2010) Study on Clean Transport Systems. European Commission, Directorate-General for Mobility and Transport.

There are, however, several pressures that make electromobility a desirable option. These include the availability and low cost of electricity relative to other fuels; the potential for electrified vehicles to help resolve environmental problems such as climate change and urban pollution; improvements in electromobility technologies; and the potential growth of a new industry which can deliver economic benefits and new jobs. However, there are also various barriers to electromobility, ranging from user expectations and preferences as regards road vehicles; the 'range anxiety' associated with BEVs; and the costs of key technologies such as battery systems. It is still unclear if electromobility will overcome these barriers and be a large part of our transport future. Consumers are perhaps not the main driver of change in the road transport system whereas policy appears to be an important and influential factor that can help to overcome these barriers. Ecological problems are also transmuted via public policy.

One could argue that electromobility is a technological transition that is supported by a range of forces such as environmental problems, social and economic concerns, technological developments and public policy. However electromobility addresses only some of the problems related to the current road transport system. Global trends towards urbanisation, particularly in rapidly developing countries, are coupled with increased urban traffic congestion and road related deaths. Furthermore, whilst electromobility offers promise in terms of reducing tailpipe emissions and decreasing some countries' dependence on geopolitically sensitive resources such as oil, it does not resolve problems related to other resources such as materials and rare metals that are used in vehicles (see Chapter 7). Technology will hopefully play a part in solving these problems, but many other changes are required to create a sustainable transport system.

3

VEHICLE COMPONENTS AND CONFIGURATIONS

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INTRODUCTION

The main objective of this chapter is to describe components and configurations of electric drive systems used for electric or plug-in hybrid electric vehicles. Components such as the battery and the battery charger are also included. The aim is to describe different alternatives, possibilities and bottlenecks associated with such components and configurations. We also outline some of the key factors that influence automobile design.

One key issue, for instance, relates to cost reduction methods, which are important for commercialisation. Another issue is space requirements. The way in which components are packaged within vehicles is a key design issue that relates to an efficient use of the available space.

SYSTEM COMPONENTS

Batteries are one of the most important components for electromobility and must be combined with a battery charger. In addition to *battery packs* and *chargers*, the following components are essential for vehicle electrification:

- The *electric machine(s)* – used as a traction motor and sometimes as a generator.
- *Propulsion power converters* – such as DC/DC and DC/AC converters, operating both in inverting and rectifying mode.
- *DC/DC converter* – with 12V output for auxiliary equipment (windshield wipers, heating, radio, lights etc). Replaces the alternator in an ordinary car. The DC/DC converter is connected to a 12V battery.
- *Safety equipment* – to break high currents and to monitor the battery, for instance.
- *High voltage cables* – DC cables between battery and power electronics and cables between power electronics and the electric machine (unless those components are placed adjacent to each other). May have a total weight of around 10kg in hybrid vehicles but may be lower for a pure electric vehicle since the battery, motor and converter can be placed closer to one other.
- *Electric cooling compressor* – to keep the batteries from overheating, may also be used to cool the passenger compartment.

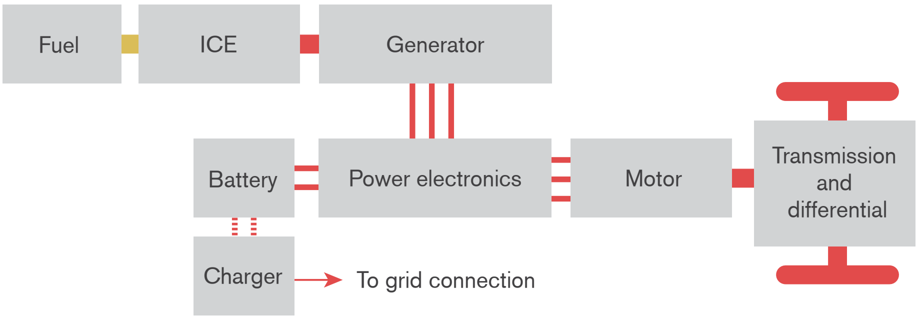
Note that an alternator may still be used to charge the 12V battery in hybrid vehicles. Otherwise, the 12V battery can be charged using a DC/DC converter and a traction battery.

SYSTEM TOPOLOGIES

Hybrid electric vehicles (HEVs) can be classified into four kinds: series hybrids, parallel hybrids, series–parallel hybrids (dual mode), and complex hybrids. These classifications refer to the way in which electric drive systems (battery, power electronic converter, and electric motor) are connected with mechanical drive systems (fuel tank, Internal Combustion Engine (ICE), transmission and differential). A plug-in HEV (PHEV) is a hybrid vehicle whose battery is charged externally. See Figure 3.1 for system overviews. A pure electric vehicle (EV or BEV) has no fuel tank and no ICE.

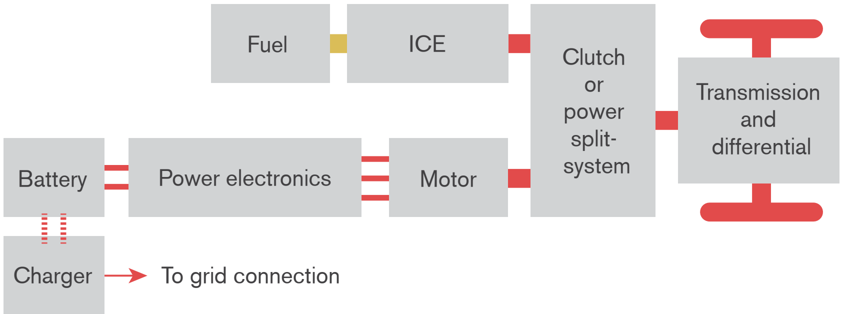
The series hybrid configuration has various benefits. For example, the working point of the ICE can be chosen freely to be that which gives the best efficiency and lowest emissions. The ICE can also be turned off so that the vehicle can be driven in a purely electric mode giving zero emissions (for a limited range). Furthermore, the ICE and generator set can be placed in a separate location to that of the traction motor, alleviating the packaging issue. However, the series hybrid configuration has low system efficiency due the number of energy conversions. Additionally, the electric motor and the battery pack need to be of a high rating, and the generator adds extra weight and cost compared to the parallel configuration, which only requires one electric machine.

The series configuration is particularly advantageous for PHEVs, as the electric motor and the battery pack are already of a high rating. However, the pure series hybrid is rare for the first generation of plug-in vehicles, which are to be rolled out between 2012 and 2014. The mechanical drive train of the series configuration is different to an ordinary drive train (where the ICE is mechanically connected to the transmission system), and most first generation PHEVs are configured to allow conventional mechanical drive train designs, such as parallel or series-parallel configurations.



Series hybrid

A series hybrid drivetrain: the fuel tank and the engine are coupled to an electric generator which can be used to charge the battery. The electric drive (converter and motor) is connected to the battery. Between the generator and the battery there are also power electronic converters.



Parallel hybrid

A parallel hybrid drivetrain: the engine supplies its power mechanically to the wheels similar to a conventional ICE-powered vehicle. It is assisted by an electric motor that is mechanically coupled to the transmission. The powers of the engine and electric motor are coupled together by a mechanical coupling.

Figure 3.1 Hybrid vehicle configurations

In parallel HEVs the operating point of the ICE may also be chosen relatively freely to give the best efficiency. Both the ICE and the electric drive system (battery and electric motor) can be used at the same time to cope with peak loads and to provide extra acceleration. Parallel configurations require fewer electrical components than series configurations – the generator is no longer needed since the traction motor can also be used to generate electricity (charging the battery via regenerative braking). Less power electronics is needed, and the rated values of the electric motor and battery can be lower.

Combinations of the series and parallel configurations are often used to create systems that derive advantages from both configurations, but with higher complexity and cost. In the series–parallel hybrid, the series and parallel systems could either be used independently with a clutch that switches between the two systems or simultaneously (a split system). Figure 3.2 shows a schematic diagram of a dual mode PHEV.

Complex hybrids are similar to series–parallel hybrids but with additional power electronics. Complex hybrids allow for versatile operating modes that cannot be offered by the series–parallel hybrid, such as electric or ICE-assisted four-wheel operation. Similar to series–parallel HEVs, complex hybrids suffer from higher complexity and cost.

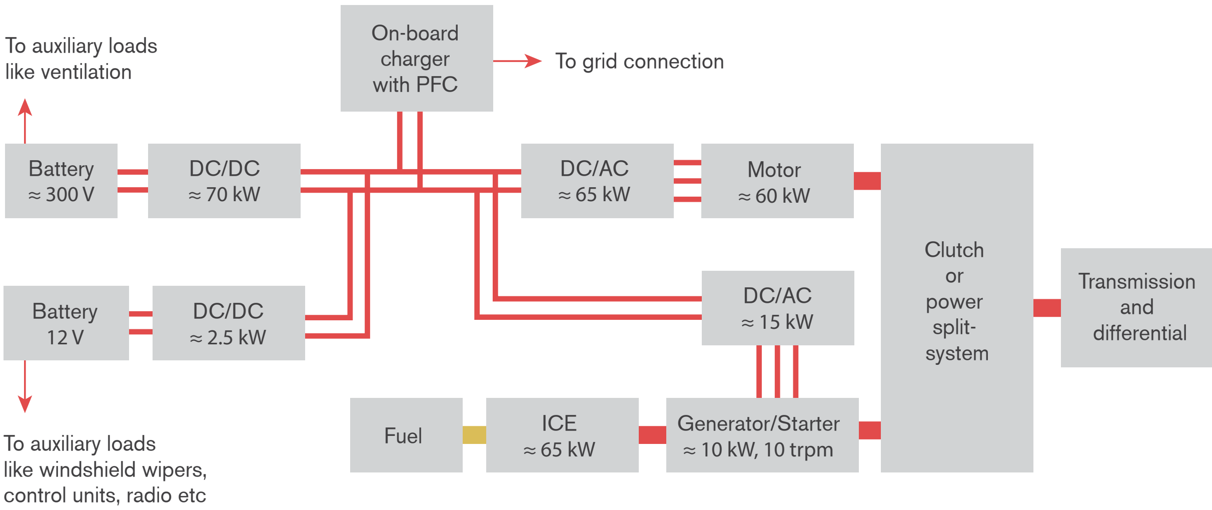


Figure 3.2 Plug-in hybrid vehicle with a parallel configuration with a dual mode. The grid power charges the battery through a power factor corrected (PFC) charger. The inverter and motor control unit drive the electric motor and is one source of mechanical torque, the ICE being the other. The generated torque drives the vehicle through a torque coupler, differential and wheels. The generator can charge the battery/batteries and/or feed electric power to the electric drive system. The generator may also be used as a motor (starter) for the ICE, although a small separate starter is neither big nor expensive. If the generator is to be used as a starter, the DC/AC converter must be bidirectional. Some other auxiliary parts are required, as shown in the figure.

In sum, the size and rated values of vehicle system components and the power value ratio between motor types can be altered in many different ways. Similarly, vehicle weight and differences in drive cycles should be considered. There is no single system configuration that is suitable for all circumstances.

BATTERIES

Electric vehicles require on-board energy storage devices that store energy in a form which is easily converted to electricity in an efficient and cost-effective way. Batteries are presently the most favoured energy storage devices. In particular, lithium-ion batteries are the most attractive option for EVs and PHEVs given their high energy and power densities.[1] Other storage systems such as supercapacitors (also known as ultracapacitors) are more advantageous than batteries in that they can be charged and discharged more rapidly and are sturdily and reliably constructed. The power density of supercapacitors is relatively high (in the order of 5kW/kg), but the energy density is low (usually below 6Wh/kg). Supercapacitors can be used for short power surges but are not sufficient for storing larger

1 Energy density is measured in kWh/kg or kWh/l, and power density in kW/kg or kW/l. Chapter 6 examines geopolitical implications of using lithium-ion for batteries in EVs.

amounts of energy. A lithium-ion battery is better for this purpose due to its considerably higher energy density, which is typically between 50-200Wh/kg. The lower value refers to cells optimised for delivering high power. The power density of lithium-ion batteries varies considerably for different types of cells, with typical values in the range 100-3000W/kg. These values represent individual cells. For a complete battery system these values should be halved. Hence supercapacitors should not be regarded as competitors to batteries – the two types of devices are complementary.

Lithium-ion batteries consist of two electrodes, an anode and a cathode, separated in most cases by a liquid lithium-ion conducting electrolyte soaked into a polymer separator. Lithium-ions are shuttled between the electrodes during charging and discharging. The anode typically consists of lithium intercalated into graphite while for automotive applications the cathode is often based on $LiFePO_4$. The choice of $LiFePO_4$ (usually shortened to LFP) compared to $LiCoO_2$-based materials (which are often used in portable consumer products) is due to stability, superior safety and lower cost – despite the fact that $LiCoO_2$-based materials are slightly better as regards performance.

A single lithium-ion battery cell provides a voltage of about 3V. Several cells are connected in series to obtain the voltage levels necessary for electric vehicles. Strings of cells, connected in parallel, are packed into modules. Modules are assembled into packs to obtain the proper voltage and current specifications. The construction of modules and packs is delicate and aside from the pure electrical properties, several other factors must be considered at the design stage. The cells, modules and packs have to be monitored to avoid damage to the cells. The cells must be actively balanced so that they are in equal states. Cells must be maintained within a certain temperature range. The pack must also protect the battery in case of a collision or a fire, and gases must be vented safely (see Chapter 4).

A battery management system (BMS) is required to monitor and maintain various parameters (voltage, current, temperature) that ensure proper operation of the pack. The BMS also provides signals to actuate relays for balancing cells, and provides cut-off protection in case of severe malfunction. Thermal monitoring is important because lithium-ion batteries have a limited operating temperature range. The pack is sensitive to overheating and should be kept at temperatures between 0-45°C, depending on battery chemistry. Temperatures around 25°C are ideal. This means that efficient control of cooling and heating is required.

Although existing lithium-ion battery technology allows for the construction of battery systems that provide EVs with reasonable performance and range, future battery systems with improved energy densities would provide better ranges. Developing batteries with higher storage capacities is a focal point for research efforts around the world.[2] Battery development is, however, a very slow process. Lithium-ion battery technology is continuously being improved and will likely be the preferred choice for at least the next few years. One promising technology is the

2 R. Marom, S.F. Amalraj, N. Leifer, D. Jacob, and D. Aurbach, (2011)"A review of advanced and practical lithium battery materials", Journal of Materials Chemistry, 2011, Vol. 21, p. 9938

lithium-air battery. Current research efforts aim to develop batteries that can make EVs comparable to petrol-driven vehicles vis-à-vis range. The lithium-air battery uses an air-cathode and an encapsulated lithium metal anode. Despite promising results several barriers must be overcome before lithium-air batteries can be commercialised.[3]

ELECTRIC MOTOR DRIVE SYSTEMS

The most common motors in EVs are the induction motor (IM), the permanent magnet synchronous motor (PMSM), the direct current motor (DCM) and the switched reluctance motor (SRM). It is also possible to use the axial flux motor (AFM), the transverse flux motor (TFM) or synchronous reluctance motors (SyncRM). These have only recently been developed for vehicle applications and currently exist as prototypes or experimental motors.

In the selection and design of electric motors for automotive applications, weight, volume, cost, energy efficiency and reliability are important criteria to consider. Environmental impacts of materials and manufacturing (see Chapter 6), recyclability and noise levels are also important. Table 3.1 summarises some of the advantages and disadvantages of the abovementioned motor types. No single motor performs well in terms of all of these criteria, which is reflected by the range of motors selected for existing vehicles. Each motor type is being continuously developed. For example, a recent trend is to construct the IM rotor with copper instead of aluminium bars, which improves its efficiency. Another trend is to add permanent magnets to the SyncRM in order to improve its efficiency and torque density (yielding a permanent magnet assisted synchronous reluctance machine).

Table 3.1 Comparison of electric motor types. Red indicates less favourable, yellow medium and grey more favourable.

	IM[a]	DCM[b]	SRM[c]	PMSM[d]	SyncRM[e]	AFM & TFM[f]
Weight and volume			Medium	Good	Medium	Good
Energy efficiency	Medium		Medium	Good	Medium	Good
Fault tolerance, Robustness	Good		Good	Medium	Medium	Medium
Cost	Good	Good	Medium		Medium	
Recycling	Good	Good	Good		Good	Medium

[a] Induction motor, [b] DC motor, [c] Switched reluctance motor, [d] Permanent magnet synchronous motor,
[e] Synchronous reluctance motors, [f] Axial flux motor & Transverse flux motor

3 G. Girishkumar, B. McCloskey, AC Luntz, S. Swanson, W. Wilcke (2010) "Lithium-air battery: Promise and challenges" Journal of Physical Chemistry Letters 2010, Vol. 1(14), p. 2193-2203,

When comparing weight, it is most often the active mass that is considered and not, for instance, covers and ventilation systems. Low *weight* and *volume* is achieved with machines with high power and torque density, i.e. machines with high power, or torque, per weight or volume. Electric motors with permanent magnets (PMSM, AFM and TFM) give the highest power and torque density.

Cost is partly related to material requirements and complexity of production. Comparisons between different motor types are difficult and cost comparisons in the literature are often based on material and manufacturing costs in very general terms. The materials used in electrical machines are mainly copper or aluminium for conductors, steel laminations (or in some cases pressed iron powder), and permanent magnets. Material costs depend on the scale of production (purchase volumes) and change over time due to price movements on raw materials markets (see Chapter 7). For example, the price of copper has increased whereas the steel price remained relatively constant during the last decade. For many years, the price of neodymium magnets was 20-30 EUR per kg, but has fluctuated recently, peaking at 150 EUR per kg. This creates incentives to design machines using fewer permanent magnet materials. High material costs also increase the incentive to design for recycling. However, recycling permanent magnets is difficult and not often considered economical. The conventional technique for recycling smaller electric machines (<10 kW) is grinding. Traction motors in hybrid or electric cars are usually of a power rating larger than 10 kW and can therefore not be ground – they have to be disassembled. The recycling process is simplified if the machine steel parts are made of pressed iron powders or made of segments.

Generally, DC motors and induction motors are inexpensive. They use approximately the same amount of material and are manufactured via well-developed techniques. SR motors are inexpensive due to the simple design of stators and rotors. However, manufactured volumes are low and standard power electronic converters cannot always be used, which increases the cost of the drive system. Permanent magnet machines may, as mentioned, be more expensive depending on magnet costs. On the other hand, such motors may be made smaller than an induction motor, for instance, but with the same performance. Hence less copper and steel are required. The AFM and TFM may be particularly expensive due to a complicated design and underdeveloped manufacturing techniques.

In some electric vehicles, two or four motors are used instead of one. This creates the possibility of integrating motors into the wheels, which increases the controllability of the vehicle. However, the inclusion of several motors requires several converters and more transmission devices, resulting in increased costs.

Costs are also related to energy efficiency over the whole speed range (see also Chapter 5). Higher efficiency means less energy-use (fuel or electricity) – but it also means less heat production and therefore reduces the need for cooling. This cuts cost and allows for better packaging. Efficiency decreases with increasing losses. In the electrical machine there are resistive losses in current-carrying conductors; core losses in the steel laminations; and mechanical losses due to ventilation and friction. Larger electrical machines are more efficient than smaller ones because resistive losses decrease with scale. A larger amount of copper, for instance, implies lower current density and resistance. Core losses can be reduced by using better materials (like thinner laminations); using lower frequency; or by adding core material. There is also a possibility to increase efficiency by increasing the motor's maximum speed. This is due to the fact that power output rises in direct proportion to speed while electric losses remain about the same for a given torque. To increase rated speed, higher voltages are required, which in turn require better insulation materials.

Reliability is related to fault tolerance. A fault-tolerant machine is a machine that can continue to operate in a satisfactory manner after a fault event, normally with reduced performance. The most successful design approach involves a multi-phase drive in which each phase may be regarded as a single module. That means that there should be minimal electric, magnetic, and thermal interaction between the phases of the motor drive. Several requirements of fault tolerance are met in a switched reluctance motor (SRM).

POWER ELECTRONIC COMPONENTS

The power electronic components addressed in this section are the power converters and their semiconductor components. The main converter types are DC/AC converters, often called inverters; AC/DC converters, often called rectifiers; and DC/DC converters. The converters should fit the desired voltage, current rating and switching frequency. The latter should be high enough to reduce volume, noise, filter size and EMI and low enough to reduce energy losses. High conversion efficiency is valuable and the converters need to be able to operate in tough environments. A proper cooling arrangement is also required.

The main semiconductor components are the switching components, the transistors. The choice of semiconductor material, or type of transistor, depends partly on power but mostly on voltage levels – IGBTs for higher power levels and voltages above 300-400V and MOSFETs for lower power levels (see below for further descriptions of transistor types).

Research increasingly points towards the use of converters as integrated battery chargers and drive system components[4]. Furthermore, using multi-level converters in conjunction with the battery management systems (BMS) yields certain advantages, such as the possibility for increased efficiency of the complete electric drivetrain for certain drive cycles[5]. New and better semiconductors, such as SiC-components are being developed.[6]

The DC/AC converter is located between the battery and electric motor. The converter is bidirectional, which allows for regeneration (energy is fed from the motor to the battery) during braking. The converter is typically a pulse width modulated (PWM) converter, but can be a multi-level converter. PWM converters switch

4 Haghbin, S., Lundmark, S., Alaküla, M., and Carlson, O. (2013) Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution. IEEE Trans on Industrial Electronics, Vol. 60, No. 2.
5 Josefsson, O. , Thiringer, T., Lundmark, S. and Zelaya, H. (2012) Evaluation and comparison of a two-level and a multilevel inverter for an EV using a modulized battery topology. The 38th Annual Conference of the IEEE Industrial Electronics Society (IECON), Montreal, Canada, 25-27 October 2012.
6 Rabkowski, J., G. Tolstoy, D. Peftitsis and H.P. Nee (2012) Low-Loss High-Performance Base-Drive Unit for SiC BJTs. IEEE Transactions on Power Electronics, Vol. 27, No. 5.

the battery voltage on and off in order to provide a certain voltage to the motor. Multi-level converters consist of many low voltage converters, each connected to a fraction of the battery.

The AC/DC converter is located between the generator (which in turn is connected to the ICE) and the traction battery. These converters are used in series hybrids or in series–parallel hybrids. If the semiconductor components of the AC/DC converter are transistors then the electric machine may operate not only as a generator but also as a motor. It can thus be used as a starter motor for the ICE.

Two types of *DC/DC converters* can be used. A high power DC/DC converter can be used between the high voltage traction battery and the DC/AC converter of the electric machine. Additionally, a small, low power DC/DC converter is used to connect the low voltage battery with the high voltage DC-link or traction battery.

The high power DC/DC converter is optional and can be used to provide a constant DC-link voltage. Without the converter, voltage would vary due to variations of the battery. The DC/DC converter also allows a higher DC-link voltage than the battery voltage. The higher voltage gives higher efficiency in the drive system components (power electronics and electric machines). Disadvantages include higher cost and losses from the DC/DC converter itself.

The low power, DC/DC converter connects the low voltage (12V) battery with the high voltage battery, or with the DC-link if there is a high voltage DC/DC converter. The low voltage is normally 12V for cars and 24V for buses and trucks, but 36V and 48V could also be used as the low voltage level. The 12V battery has one (the negative) terminal connected to earth via the vehicle chassis. Since the 12V battery is connected to the chassis (earth) and the high voltage battery is on a floating potential (with no electrical connections to the chassis), there is a need for galvanic insulation in the low power DC/DC converter in order to disconnect the two systems.

Regarding the converters' *semiconductor components* – the control is made with switching the components on/off using a high frequency PWM-pattern (when the power is higher than some 100 W). With this technique the voltage to a transformer or a machine can be controlled in a fast and precise manner, but not without losses where the switching loss is one important loss component. Semiconductors should give low losses and be able to handle the given power, voltage and current.

IGBT's are most frequently used in high-power applications. The device is widespread and used in applications from 1kW up to several MW. In order to cope with the propulsion power of a passenger car, IGBTs of around 200kW may be needed. *MOS-fets* are typically used in smaller DC/DC-converters, such as the low power DC/DC converter described above, and the main benefit is the ability to handle high frequencies (up to 1MHz). Figure 3.3 shows an IGBT module and a MOS-fet. *Silicon Carbide* (SIC) is a recently developed semiconductor material that allows for high switching frequencies, high-voltage operation and higher temperature capabilities. This can help to simplify the cooling system of the vehicle. Normally, hybrid cars have a high-temperature cooling circuit (of 105°C) and an additional low-temperature cooling circuit for the power electronics and in some cases the motor (of 60 -70°C). SiC makes it possible to exclude the additional low-temperature cooling circuit. This type of component is undergoing rapid development and will likely be commercialised in the near future.

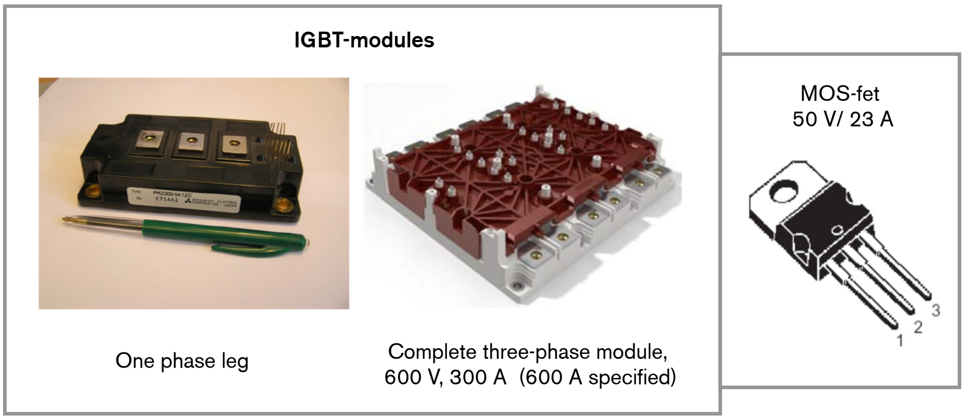


Figure 3.3 Examples of semiconductor components – two IGBT modules and one MOS-fet transistor.

BATTERY CHARGERS

Electric vehicles are usually recharged whilst parked. However it is also possible to charge EVs whilst they are in motion (continuous charging) using 'slide-in' technologies (see Figure 2.1). Different types of chargers are available, including off-board fast chargers, on-board chargers, and 'slide-in' wireless chargers. The latter combine transmission coils in the ground with receiving coils in vehicles. Chargers can also be conductive or inductive. For a conductive charger, power flows through metal-to-metal contacts. In contrast, inductive coupling transfers power magnetically rather than via direct electrical contact.

Off-board chargers can be large and bulky when volume is not a vital constraint. This keeps costs down, and off-board chargers can be placed at charging stations similar to ordinary petrol stations. This arrangement also allows for high-power fast charging. A disadvantage compared to on-board charging is lower availability since the number of charging stations will always be limited. Charging times are typically 15 minutes, but can be more.

On-board chargers are more common at present. On-board charging means that vehicles can be charged wherever electricity is available but with the disadvantage of slower charging and extra weight, cost and space requirements within vehicles. On-board charging typically requires 1 hour of charging per 20km[7]. Increasing the charging speed would require higher power and a larger charger, and thus additional weight, volume and cost.

To alleviate some of the abovementioned disadvantages it is possible to utilise traction drive system components to construct an integrated charger. A battery

7 At 230V and 16A (3.7kW)

charger is basically a voltage transformer with a converter and such a charger can be made by using the electrical motor and the power electronic converter (see above).[8]

Wireless systems allow for inductive charging at dedicated parking spots or whilst driving. Wireless charging could be an important enabler for electromobility and is currently a focal point for R&D efforts. The efficiency is however lower compared to conductive charging and there are several safety concerns.

AUXILIARY LOADS

High voltage auxiliary loads (100-500V) like electric climate control and power steering need relatively high power from high voltage traction batteries. Power consumption must be considered carefully when designing vehicle systems and controllers. Low outdoor temperature, for instance, could result in a high portion of the available vehicle power being used for climate control. In HEVs, the ICE can be used to provide heat due to engine losses, but cold weather will result in shorter driving ranges for hybrids operated in all-electric mode. Furthermore, it is important to consider electromagnetic capability (EMC) when dealing with the auxiliary loads, so that the loads, the drive system or cables do not disturb other loads in the system.

Low voltage auxiliary loads (12V) such as windscreen wipers, control units, radio and electric fuel pumps are operated at lower voltages. Traditionally they require 12V lead-acid batteries. However, power requirements are increasing as more electronic equipment is added to modern vehicles, such as GPS navigation systems (see also Chapter 7 on how the trend to add more electronic devices affects the use of rare materials in vehicles).

CONCLUDING REMARKS

There are many alternative components and configurations of electric drive systems used for electric or plug-in hybrid electric vehicles. There is no single combination or configuration that works well for all vehicle applications, which is reflected in the span of different drive systems and battery solutions in existing vehicles.

Generally, there is a need to improve efficiency and decrease component volume/weight without compromising on costs. Battery materials, for instance, are typically selected by focusing on cost and safety criteria at the expense of performance. Similarly, motor designs that minimise the use of permanent magnets are attractive because of their lower cost, which again reduces vehicle performance. There are several ways to integrate components whilst improving packaging and lowering costs. Integrated battery chargers and the use of SiC in power electronic converters (which allows for the combination of temperature cooling circuits) are two such examples.

8 Haghbin, S., Lundmark, S., Alaküla, M., and Carlson, O. (2013) Grid-Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution. IEEE Trans on Industrial Electronics, Vol. 60, No. 2.

4

ARE ELECTRIC VEHICLES SAFER THAN COMBUSTION ENGINE VEHICLES?

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INTRODUCTION

Replacing conventional vehicles using internal combustion engines with electrified vehicles (EV) is a challenge in many respects. Introduction of new technical solutions, especially those produced for a mass market, may substantially change and possibly increase the risks associated with the products. On the other hand, electric vehicles have other clear advantages concerning safety as they do not carry conventional fuels onboard such as petrol or diesel, both of which are flammable and toxic. Without a combustion engine onboard, the risks of fire and explosion are thus minimized. Therefore, the introduction of electric vehicles promises a transition to a clean, non-polluting, healthy and safe means of transportation (see also Chapter 6 on life cycle environmental impact).

While there is a potential for electric vehicles to be safer than conventional ones we still need to consider what other risks this technological transition will bring as the risks associated with conventional vehicles are well known to most people and thus easily dealt with in daily life. What risks are associated with a large onboard chemical energy storage? Will the hazardous traction voltage of the electrical system pose a danger to the passengers or to rescue personnel in case of an accident? How can eventual risks be diminished in traffic, when vehicles are parked and maintained? All these aspects and more need to be considered when designing the vehicle.

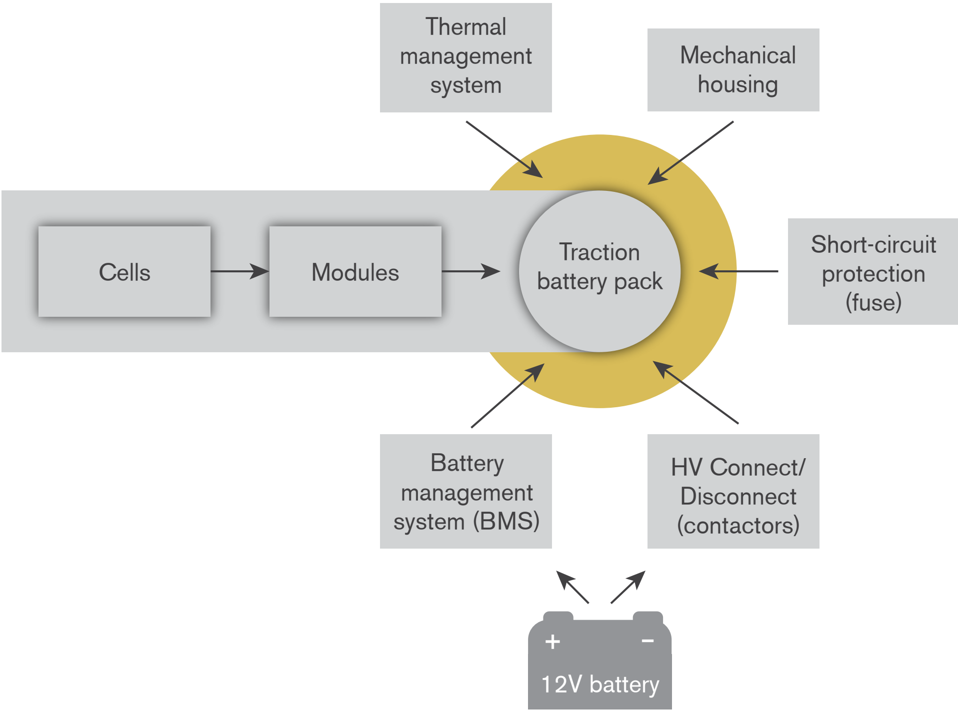
Safety issues for electric vehicles considered here include mainly battery powered vehicles, vehicles which have the battery as the only means to store energy (BEVs) or range extended vehicles where the battery is still the main source of energy but an extended range can be obtained using a combustion engine, for example plug-in hybrid vehicles (PHEVs). Another type of electric vehicle is the fuel cell powered car, using hydrogen gas as fuel. In this case, safety aspects mainly concern the safe handling and storage of hydrogen. While EVs are on the market in rapidly increasing numbers today, the fuel cell car has not reached true commercial introduction yet. Compared to conventional fuels hydrogen has both advantages and disadvantages, but again the risks are different to those we are familiar with and other safety practices are needed. We will, however, not include fuel cell safety issues in this chapter.

Lithium-ion (Li-ion) batteries have high energy and power densities that make it possible to build BEVs and PHEVs with acceptable electric driving range with zero tail pipe emissions. This type of battery has therefore become the preferred choice for manufacturers of these types of vehicles. In this chapter we focus primarily on the lithium-ion battery while other battery types are discussed more briefly. Other technologies for energy storage, e.g. flywheels, compressed air and supercapacitors might be used in future electric vehicles. Presently, they are used to a very limited extent and are therefore not included.

BATTERY SYSTEM DESCRIPTION

The traction battery system in an electric vehicle consists of many parts. Figure 4.1 shows the principle layout for a traction battery system. The basic building block in the battery pack is the battery cells. The cells are connected in series in order to increase the voltage. Cells can also be connected in parallel, in order to increase capacity. Typically a battery pack for an electric vehicle consists of 100-400 cells.

A number of cells form a module, which is typically kept under 60V at present (2013) and is thus not a particular electrical hazard. A battery pack usually consists of several such modules. To monitor and control cells, modules and pack each battery system has a master Battery Management System (BMS), often in combination with one or several slave management systems (e.g. one per module). The BMS has a number of functions essential for safe operation of the battery system: (*i*) Parameters such as cell voltage, current and temperature are monitored in order to ensure that the battery operates within the allowed limits, (*ii*) balancing of cells is performed in order to keep all cells on the same level regarding state of charge (SOC), (*iii*) contactors placed inside the battery pack in order to connect and disconnect the battery to the rest of the vehicle are controlled, (*iv*) the status of the electrical insulation of the traction voltage system is monitored and (*v*) the BMS communicates with the other parts of the vehicle as well as supplies information to the driver. As an independent means of electrical safety the battery often has one or several fuses, for short-circuit protection. Furthermore, the thermal management system of the battery could both heat and cool the cells in order to maintain a temperature within an efficient and safe temperature range. A mechanical housing, the battery box, is used to enclose and protect the battery pack. It has several functions and a suitable tightness-class.



Figur 4.1 The traction battery system overview.

Typically the battery pack uses an external 12V supply from the vehicle's 12V-battery, e.g. a conventional lead-acid battery. The 12V supply is used to power up the BMS and to close the contactors. In principle, the battery could supply its own 12V by an internal DC/DC converter but an external supply is a simple solution that is commonly used.

BATTERY TYPES

Lead-acid batteries (PbA) have been used for more than 150 years and are still produced in large quantities as 12 V and 24 V vehicle batteries. There are several types, e.g. free ventilated or recombination cells (e.g. AGM, GEL). Compared to Nickel-metal-hydride and Li-ion batteries, they have lower power and energy densities and a significantly shorter cycle lifetime. Lead-acid batteries also require a long charging time, typically 10 hours. Since this should be seen as a fully mature technology it has been cost optimized. Due to its high weight and large volume it is not a real option for PHEVs or EVs, even though it was used experimentally in EVs during the 1990s. Presently lead-acid batteries are considered only for micro-hybrid electric vehicles (start and stop techniques). The safety concerns are small and related mainly to the risk of hydrogen gas production during operation. Hydrogen gas can potentially ignite and explode but the buoyancy of hydrogen gas makes it relatively easy to ventilate the battery in order to avoid the formation of an ignitable mixture with air. Since lead acid batteries is a mature technology the battery design is very well developed to avoid these problems.

Nickel-metal-hydride batteries (NiMH) are presently dominating the HEV-market; they are used in the Toyota Prius for instance. NiMH offers significantly improved energy and power densities compared to lead-acid batteries. Further, it offers a high cycle life time and safety concerns are small. They do not, however, have the same energy storage capacity as Li-ion batteries.

Lithium-ion is the dominant battery technology today for PHEVs and EVs due to its high energy and power densities, combined with a long life time. The safety concerns are however larger than for NiMH and lead-acid batteries. This is basically due to the chemistries used for these cells but the large size of the battery systems needed for these types of vehicles also makes the consequences of a malfunction potentially more serious. We will therefore devote most of this chapter to describe safety aspects of Li-ion batteries.

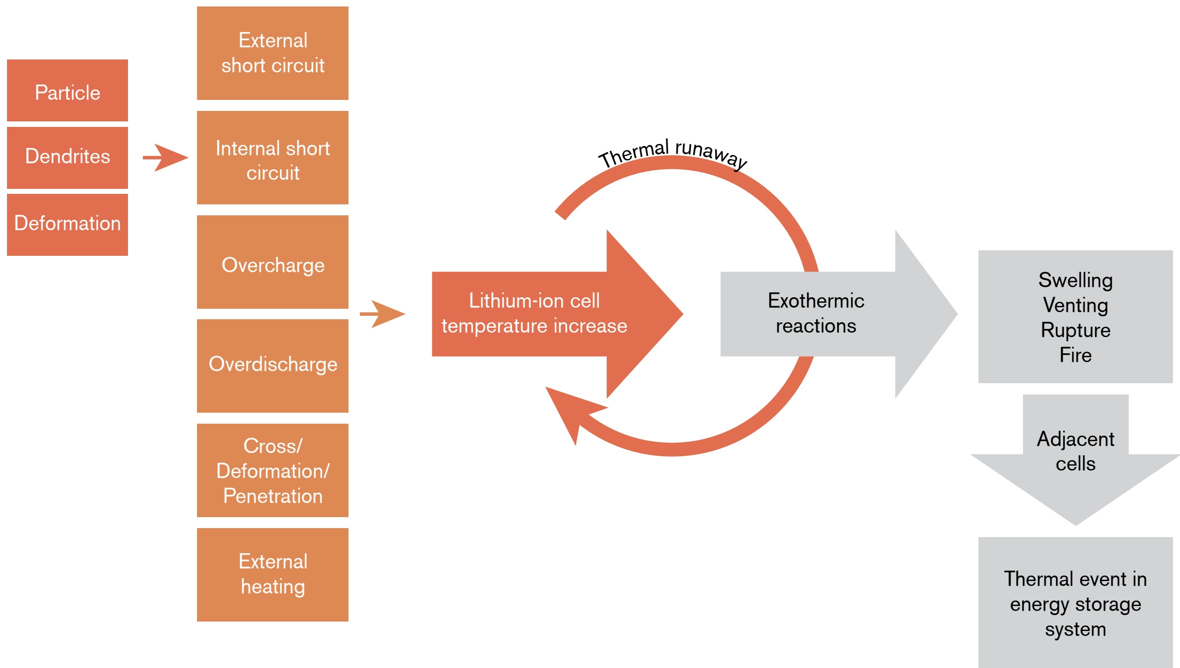
A lithium-ion cell consists essentially of anode, electrolyte, separator and cathode. The lithium ion is shuttled back and forth between the anode and cathode through the electrolyte. Even though a large number of different lithium-ion chemistries are possible there are today (2013) only a few lithium-ion chemistries that are used commercially. The anode and cathode are intercalated lithium compounds. Typically the anode is based on graphite, lithium titanate oxide (LTO) can also be used. The cathode is composed of lithium cobalt oxide (the most common type for small consumer cells), mixed oxides (manganese, nickel, cobalt, and aluminum) or phosphates (mainly iron-phosphate). The electrolyte typically consists of organic solvents, lithium salt and additives. The exact composition differs between the manufacturers and is usually a commercial secret, especially regarding the additives. The separator is a porous polymer where the pores are filled with the electrolyte; its primary function is to avoid direct contact between anode and cathode. In some cases the separator may also have the function of shutting down the ion transport in case of overheating.

The risks involved with the use of lithium-ion batteries are closely related to the chemistries used, the design of cell and system, the handling of the battery when in use and the quality of the production. The choice of cell chemistry is, in turn, determined by the demands regarding energy and power density, cost and safety for the specific application. Small size lithium-ion batteries have been used for more than a decade in consumer products, such as laptop computers and mobile phones. During this time, battery fire incidents have been reported in laptops, iPods, cargo planes and electric vehicles.[1] However, the conditions and requirements for lithium-ion batteries in automotive applications are different and more demanding than those for consumer electronics. Lithium-ion cells for the automotive industry are, for example, characterized by increased quality, safety and life time compared to that of small consumer cells, and generally use more advanced materials with higher degree of purity.

1 Wang, Q., Ping, P., Zhao, X., Chu, G., Sun, J., and Chen, C., "Thermal runaway caused fire and explosion of lithium ion battery", *Journal of Power Sources*, 208 (2012) 210-214.

Lithium-ion batteries have many advantages but the window of stability is relatively small (both regarding temperature and voltage). The cells must therefore be monitored and controlled by the BMS. Overheating may cause a severe malfunction; if the temperature exceeds typically 120-150 °C, exothermal reactions within the cell can start. The exothermal reactions will increase the temperature further, which can trigger additional exothermal reactions. If the overall cell reaction creates a rapid temperature increase, it could result in a so called thermal runaway. A thermal runaway consists usually of one or a combination of the following events: rapid gas release, electrolyte leakage, fire, rapid disassembling/explosion.

The reason for the initial overheating may be an external short-circuit, overcharge, over-discharge, deformation of the battery by external forces, external heating or an internal short-circuit. The latter may be caused by dendrite growth, unwanted particles in the cell etc. If the overheating spreads to adjacent cells a large part of the battery system may be affected. Figure 4.2 shows how a thermal event on the cell level could develop to the system level. In order to obtain a high level of safety such a chain of events must be hindered.



Figur 4.2 Potential chain of events for a thermal event on the cell level developing to system level.

The outcome of these reactions varies with cell design and chemistry, particularly with the electrode and electrolyte composition. The combination of reactive materials and flammable components in the cell pose a risk, the electrolyte is flammable and the oxide materials may release oxygen at elevated temperatures, thus both fuel and oxidant needed for a fire might be present inside the cell.

In order to meet the demand of the automotive industry, improved battery materials have been produced. The selection of the active electrode materials (anode and cathode) strongly affects the thermal runaway and its onset temperature. Lithium iron phosphate (LFP) is for example a more stable cathode material than the cobalt-based lithium oxides that are commonly used in consumer Li-ion batteries. Other electrode materials, for example mixed oxides with cobalt in combination with other metals (e.g. Ni, Mn, Al), have been developed in order to improve safety and other aspects (e.g. life time, cost, energy and power densities).[2]

The electrolyte composition and its additives, e.g. flame retardants, redox shuttles and gas release controllers, are also very important for the overall safety of the battery. The organic solvents involved, e.g. ethylene carbonate (EC) and dimethyl carbonate (DMC) are volatile and flammable. The mechanical packaging, cylindrical, soft or hard prismatic can or pouch-prismatic, also affects the cell behavior during a thermal event. For example, a cylindrical can cell could build up a much higher pressure than a pouch cell.

There are both pros and cons associated with each type of cell packaging. For example, with a cylindrical cell it can be easier to control the venting direction but higher internal cell pressure build up can be potentially more dangerous. Thus, there are a number of safety mechanisms that can be included into a lithium-ion cell construction by its manufacturer depending both on the chemistry and physical design of the battery.

It takes a long time to develop new battery technologies, typically more than 20 years. Potential future battery storage technologies is a very active field of research and one of the most interesting future battery technologies is the *lithium-air battery*, which has a huge potential compared to Li-ion batteries, e.g. the energy density is projected to be more than 10 times that of Li-ion batteries. There are, however, several challenges to be solved for the lithium-air technology, e.g. regarding life time and safety. One safety concern is how to prevent air from reaching the free lithium-metal. Li-air batteries are, however, not likely to be commercialized within at least 20-30 years.[3]

VOLTAGES, CURRENTS AND ELECTRICAL HAZARDS

An electrified vehicle still contains electrical energy in the battery when it is shutdown and parked. The manufacturer has constructed the vehicle in such a way that the hazardous traction voltage is kept inside the battery pack and insulated from the rest of the vehicle. In other words, all parts except the inside of the battery system can be considered as voltage free (provided there are no electrical insulation failures). It is important to understand that also an "empty" battery, meaning fully discharged, 0% SOC, still has a considerable voltage. For an electric vehicle this is still to be considered as a hazardous voltage. The definition of hazardous voltage is that it is potentially dangerous for humans, and it is usually stated as $>$ 60 VDC (although this limit varies in different countries).

Vehicles with internal combustion engines have had a remarkable increase in vehicle safety during the last 10-20 years. Active safety is now starting to be introduced in some cars, e.g. lane departure warnings. The passive safety, e.g.

2 Wang, Y., Jiang, J., Dahn, J., "The reactivity of delithiated Li(Ni1/3Co1/3Mn1/3)O2, Li(Ni0.8Co0.15Al0.05)O2 or LiCoO2 with non-aqueous electrolyte", *Electrochemistry Communications*, 9 (2007) 2534-2540.

3 G. Girishkumar, B. McCloskey, AC Luntz, S. Swanson, W. Wilcke "Lithium- air battery: Promise and challenges" Journal of Physical Chemistry Letters 2010, Vol. 1(14), p. 2193–2203.

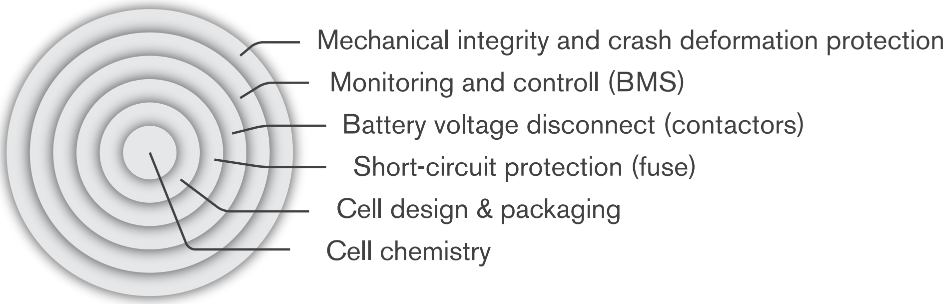
crash protection, has evolved greatly over the years with e.g. the NCAP testing. Computer simulations and crash tests have fostered the development of crash deformation structures significantly and increased crash and collision protection.

Electrified vehicles are likely to have the same level of passive and active safety as conventional vehicles. In order to ensure this, the safety techniques must be adapted for this new technology, e.g. during a crash, crash detection sensors inside the vehicle, also used for activation of airbags, can disconnect the traction voltage from the battery before the crash is complete. This means, that even if the electrical insulation of the traction voltage, containing the hazardous voltage, would be damaged, this voltage will be turned off. Of course, in severe crashes, there is always a risk that this might not be the case.

Presently (2013), car manufacturers crash protect the battery pack so that no short-circuit may occur in its electronics and that no lithium-ion cell can be deformed during pre-defined crash scenarios. In principle, this is done by putting the battery inside a crash protected box. This adds weight, volume and costs. In the future, it is likely that the battery pack instead becomes a part of the crash structure. Battery packs of today can handle some small deformation; this is a matter of design, which today varies depending on cell chemistry, cell design and packaging. In the future, it is likely to have safer lithium-ion cells and battery systems which could to a higher level stand a deformation. In that case the battery can to a larger extent by used in the vehicle's crash structure. The deformation protection design criteria are given by load-cases. This means that for a severe crash, which is outside the design criteria, a deformation which is larger than expected can occur. It is unrealistic and just not possible to design the crash protection for all types of extreme collisions.

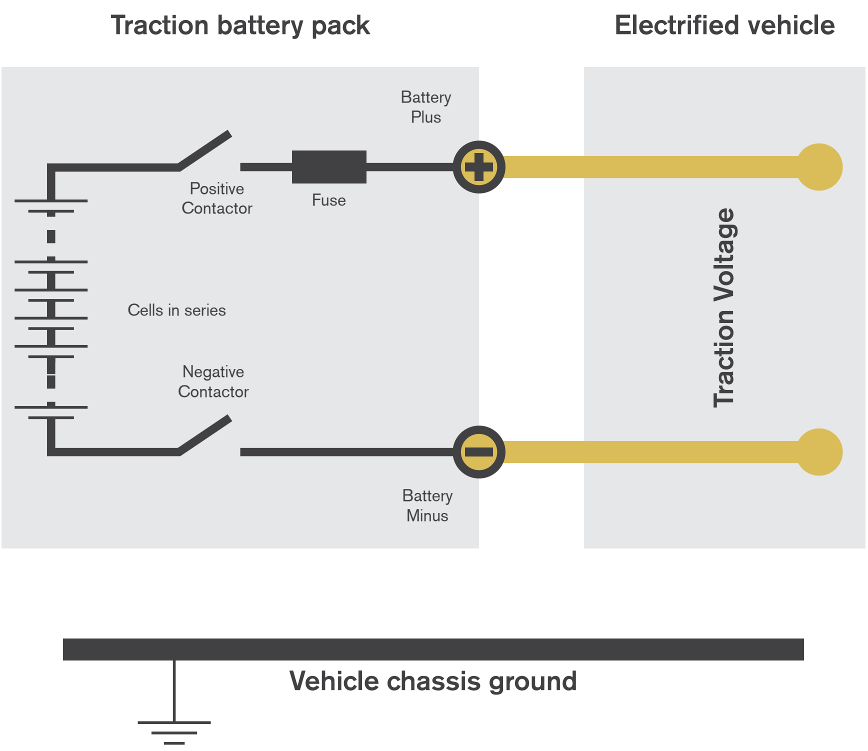
The electrical drive train is made safe by several means. In general the battery cells presently used are in general very safe since judicious choice of Li-ion technology ensures that an unsafe lithium-ion cell would not be chosen. The voltage of each lithium-ion cell is in general monitored and balanced with respect to the other cells. This requires quite advanced electronics and electro-components such as fuses and contactors are used in the battery pack. The electronic parts (electrical components, processors, circuit-boards etc.) of the battery pack are similar to the parts used in conventional vehicles by a large part of the industry. In case of errors in the electronics or sensor failures an unsafe situation could occur. However, the manufacturers work with functional safety (e.g. ISO26262) in order to minimize these risks.

The battery safety is ensured by the manufacturer by adding layer by layer of safety, schematically shown in Figure 4.3. Deformation of the battery cell can result in a thermal event. Therefore the battery is usually placed outside the deformation zone. For a passenger car, this generally results in a battery placement inside or beneath the passenger compartment.



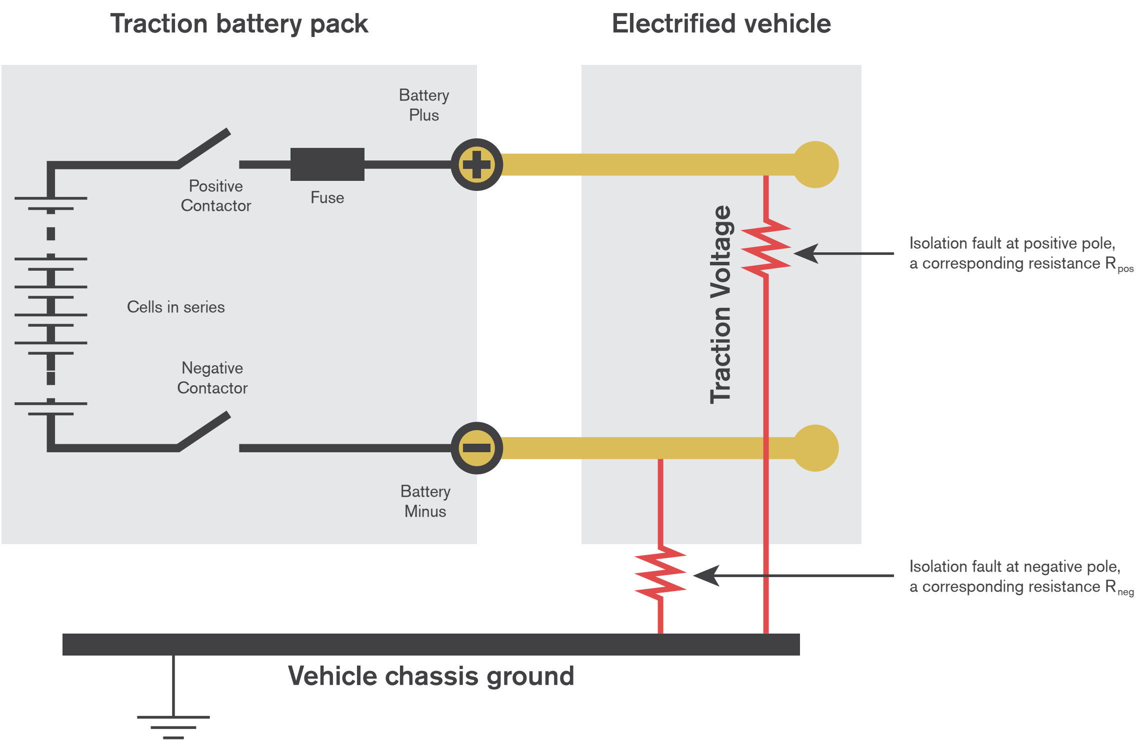
Figur 4.3 An example of battery safety layer by layer.

The components and traction voltage cables carrying a high voltage are usually very well insulated and protected. The risk that a human, e.g. driver, passenger, rescue personnel or firefighter, would be exposed to an electrical shock is in general very low. The traction battery has a so called floating ground, meaning that there is no electrical connection between the traction battery poles and the vehicle chassis ground. The 12V/24V vehicle battery on the other hand (for both conventional ICE vehicles and EVs) uses the vehicle chassis ground as the current return path to the negative 12V/24V pole. The principle of the floating ground and the current path of the traction battery are shown in Figure 4.4.



Figur 4.4 Traction battery pack current path and the floating ground principle. If there are no insulation fault(s), there are no electrical connections between vehicle chassis ground and the battery poles.

Both DC (direct current) and AC (alternating current) voltages are present in EVs (see also Chapter 3). The DC voltage comes from the traction battery and the AC voltage is used by the power electronics and electric motor. Both pose a danger for humans in case of an electric shock caused by either a direct touch of the battery poles, or indirectly by touching the metal chassis. In order for such exposure to occur, two insulation faults are required (one at each pole of the battery) and the victim must touch metallic parts with the different potentials at the same time. Figure 4.5 shows the principle of a double insulation fault.



Figur 4.5 Principle figure that shows a double insulation fault. This means one insulation fault at the plus and one at the minus pole. They are shown as two resistances, Rpos and Rneg, connected to ground. This creates a current path between battery plus and battery minus.

The vehicle chassis ground is usually constructed to electrically act as one pole of the 12/24 V system by having most metal parts connected to each other. In the situation of a double insulation fault there will be a short-circuit through the chassis. Since the current takes the easiest path (i.e., the conducting path with the lowest resistance), the human body will hardly be affected by touching the chassis ground. On the other hand, there could be a potential risk for service personnel repairing a damaged electric vehicle, since they can, during disassembly, have two chassis ground, one with the negative battery potential (minus) and the other with positive battery potential (plus). There are however, protection means for this, e.g. insulation measurements, electrically insulated gloves (typically marked for safe use up to 1000V), and knowledgeable maintenance staff should be able to minimize this risk.

It could be mentioned that hazardous voltages, both DC and AC, inside the components in an EV, sometimes are referred to as “high voltage”. From the automakers perspective, this term conveniently separates the 12/24V system (“low voltage”) and the 300-600 V system (“high voltage”) for the electric drivetrain and the traction battery, However, to name the hazardous traction voltage as “high voltage” is somewhat misleading since there is already a definition and a long time tradition to use the term “high voltage” within the mains (electricity grid), for voltages over 1000 VAC or over 1500 VDC. The term “HV” is actually in automotive industry sometimes interpreted as “hazardous voltage” (instead of “high voltage”).

FIRES, GASES AND EMISSIONS

The energy stored in the battery in an electric vehicle is essentially released once you connect the two poles while the energy in a conventional vehicle requires the fuel to be mixed with air at the right proportion and pressure and then the gas mixture needs to be ignited by a spark or by exposure to high temperatures; the spark could for example be created by the starter engine. The higher voltages and currents used in an electric vehicle may be a risk for fires and lithium-ion batteries pose a special risk as the electrolyte is combustible, with properties similar to gasoline or LPG. Furthermore, the battery might progress into thermal runaway as described previously. One of the safety mechanisms used in these cells to prevent a more severe incident to occur is venting. The gases released in a venting situation are, however, highly toxic and flammable. In particular, a venting cell would release hydrogen fluoride (HF) which is highly toxic. Venting would also release many other fluorinated substances that have a potential of being toxic, but the toxicity of these has not yet been publically investigated.

If a fire starts, many of these substances might be consumed in the fire but the knowledge in this field is still limited and more research is needed regarding evolved gases from battery fires. HF is a gas that evolves in many different types of fires. Recently INERIS in France set two different electric vehicles and two similar conventional ICE vehicles on fire and measured the heat release rate during the fire and also gases evolved including HF. They found that the heat release rate was of the same order of magnitude, independent of vehicle type. High concentrations of HF were emitted in the beginning of the fire for all four vehicles. This might have been caused by the air-conditioning system. Some HF also evolved later in the fire for EVs, but the concentration was less than that of the first spike of HF and distributed over a longer time period.[4]

Anecdotal evidence exists that electric vehicles burn fiercely and that the fire is difficult to extinguish. The INERIS experiment does not confirm this burning behavior but the fire was started by a gas burner in one of the seats in these experiments. Other means of starting the fire might give another result but there are at present a very limited number of investigations, if any, available on this topic.

Extinguishment of a fire is an area where there still are questions to be answered. The advice from manufacturers is often to let the vehicle burn or to use water or sand. Letting the vehicle burn is not a viable option in e.g. a garage, a ferry or in a tunnel. Research for fire-fighters has until now mainly focused on extrication of people from crashed cars and not on extinguishment. In general, water is an excellent extinguishing medium that has a very high extinguishing power per mass. However, when it comes to potential live electric parts the advice is often to avoid using water. Research is therefore needed on how to attack a fire in a battery. Would it be safe to use water both in terms of the risk of electric shock and when it comes to gases evolved? Should other methods be used to respond to a fire? In addition a fire in the battery system might be difficult to reach. It is only just recently that a first extinguishing study was available. This study was conducted by

4 A. Lecocq, M. Bertana, B. Truchot and G. Marlair "Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle" Proceedings of FIVE 2012, Chicago, 27-28 September 2012

DEKRA in Germany where batteries were extinguished using water and different additives.[5] They conclude that more water was needed for the EV fires than for vehicles with conventional internal combustion engines.

The EV users would like to be able to charge their vehicle fast in some situations, similar to filling fuel into a conventional vehicle, or at least have a significantly shorter charging time than that of overnight charging. Systems for fast charging are therefore under development. Fast charging requires high currents and one would therefore intuitively associate this with larger fire risks. The high current would result in a higher risk of overheating or other malfunctions in the charging station or in the vehicle itself and thus careful design is important. These risks are well known and when the number of fast charging stations will grow actions will be taken to minimize associated risks.

INCIDENTS

Despite the manufacturers efforts to produce safe batteries some events have occurred that have reached media attention. One of the major media events in June 2011 was the fire that started in a GM Chevrolet Volt car three weeks after a crash test. The incident was thoroughly investigated by NHTSA and the chain of events was reproduced. The reason was found to be that the cooling media had leaked over the battery and then dried; leaving crystals that finally short-circuited the battery through the metallic belt around it. Changes have since been made to the design, e.g. to avoid leakage of cooling media.

Another event that has drawn some media attention is the fires that occurred after hurricane Sandy hit the Atlantic coast in the New York area in November 2012. At the harbor of Newark, New Jersey, thousands of parked vehicles were flooded. The cars were brand new shipped in from abroad. The water wave that followed Sandy immersed the parked vehicles in 1.5-2.5 meters of seawater during several hours. It has been reported that sixteen Fisker Karma PHEVs and a few Toyota Prius HEV and PHEV burned. Unconfirmed statements from Fisker and Toyota blame the fires on short-circuits in the 12V vehicle electronics. NHTSA and Fisker have started an investigation to find the cause of the fires. To be submersed in 1.5-2.5 meter deep seawater for several hours is a very severe test for an electrical system in general which can only be met with IP68 class or equal water-tightness level. Seawater is a good electrical conductor and can cause short-circuits, for both low voltage (e.g. 12/24V vehicle voltage) systems and for the traction voltage in electrified vehicles.

Apart from these events there are some other events that have not reached media interest. Focus on battery safety has to a large extent been on the cells as such and much progress has been made in this respect. The traction voltage parts of the system are also subject to many protection steps in many cases. It is important, however, to take into account that the cells are part of a large system with a lot of electronics that needs to be functioning in a harsh environment as vehicles are subject to many different situations.

5 Electric car batteries 'at least as safe as combustion cars' (2012)

OUTLOOKS FOR THE FUTURE

Safety issues are of major concern in any introduction of a new product into the market as negative publicity might have a negative impact of general public's perception of a product and the products potential to succeed. Key aspects here are to design safe products and be very open about events that have occurred as ample correct information is the best way to avoid rumors. One threat to a safe introduction could be home-converted vehicles as these, with their limited budget, would have difficulties reaching the same high safety levels as commercially built vehicles.

Lithium-ion batteries for automotive use have shown an increased safety regarding fire and explosion through e.g. improved electrode and electrolyte materials. Therefore, the focus of lithium-ion safety research has moved increasingly towards the safety aspects associated with released gases and smoke, as well as other electrical aspects.

The choice of material for future batteries is a fundamental issue including possible scarcity problems. Further, the choice of different additives to obtain sufficient safety, e.g. flame retardants, or other necessary battery characteristics can result in life-cycle issues which will be untenable. New technologies are necessary which will no doubt pose new risks which will need to be addressed.

The number of EVs on the road is still low so reliable statistical studies of incidents and accidents are not possible yet, anyhow, the numbers are increasing steadily and with that also the possibility to conduct different safety studies as the price per vehicle is lowered and the vehicles are commercially available and not only leased etc. It is therefore likely that we will see an increasing number of studies on different safety aspects that still need to be resolved which will foster the development of safer EVs.

5

HOW ENERGY EFFICIENT IS ELECTRIFIED TRANSPORT?

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WHY ENERGY EFFICIENCY?

This chapter examines the energy efficiency of electromobility. The transport sector accounts for a considerable share of overall energy use in modern societies. More efficient vehicles can help to reduce our use of scarce and costly energy resources such as fossil oil, which is currently the main energy source for transportation.

The total cost of ownership (TCO) is important for many vehicle owners (see Chapter 12 for a discussion on cost versus value and alternatives to vehicle ownership). The TCO can be separated into capital costs (the cost of purchasing vehicles) and operational costs (the cost of using vehicles). Fuel costs typically comprise a significant part of overall operational costs. This is especially true for countries where fuel taxes are high. Increased energy efficiency can thus reduce the TCO.

It is important to note that many other factors influence the attractiveness of different propulsion alternatives. From a climate perspective, CO_2 emissions may be more important than energy efficiency, for instance. Using different renewable energy sources for electromobility brings additional factors into play, such as the area of land required to produce a unit of energy. However, these aspects are related to energy efficiency (see Chapter 6 on environmental issues).

For any given vehicle there may be a conflict between energy efficiency, cost and performance. Efficient components are expensive, and performance demands such as better acceleration typically result in higher energy use. At present, there are several types of alternative fuels and drivetrains to select from. Technologies with higher energy efficiencies will not necessarily deliver in terms of performance and cost. Notwithstanding, there appears to be a need for energy efficient vehicles due to increased global energy demands and related policy developments (See, for instance, the discussion on land use for bioenergy in Chapter 3 in Systems perspectives on Biorefineries.)

Electric drivetrains are more efficient than the ICE because of their high-energy conversion efficiency. The latter is evaluated from 'tank to wheel' (TTW) or from the electricity outlet to the wheel for electric drivetrains. The way in which electricity is produced and distributed from "well to tank" (WTT) can also be important for the overall energy efficiency of the transport system. (See Chapter 6, and Figure 6.1 for definitions of WTT and TTW.)

This chapter examines the energy efficiency of electric cars. The rationale for this limitation is that cars currently dominate both passenger transport and transport energy use. We examine the efficiency of both components within the vehicle and the energy supply system – including upstream energy conversion.

ENERGY EFFICIENCY IN ELECTRIC VEHICLES

We begin by examining the processes and components that determine TTW efficiency. Energy is used for different purposes within vehicles. Most energy is used to propel vehicles (propulsion energy) and is thus supplied to the drivetrain (B_{DL} – see Figure 5.1). A considerable amount of energy is also supplied to auxiliary equipment (B_{Aux}). Some of this equipment is necessary to ensure that the drivetrain functions properly. The cooling system, for instance, requires energy for circulating cooling liquids. Interior heating of the passenger compartment also requires large amounts of energy.

The concept of TTW efficiency was developed for vehicles utilising liquid fuels, in which the process of refuelling vehicles does not involve considerable losses. For electric drivetrains, non-negligible losses occur when charging vehicles. Placing the system boundary at 'the tank' (i.e. the battery) is thus unsuitable. It is important to include energy losses related to charging and restate TTW as *from electric grid to wheel* (GTW). This is broader than considering only energy conversions *from battery to wheel* (BTW).

The ultimate losses in power delivered to the wheels (P_{W+}) are due to air drag resistance and rolling resistance (P_{Res}) (see Figure 5.1). The power needed for acceleration and travelling uphill (P_{St}) is stored as kinetic and potential energy. This stored energy can be utilised when the car is slowing down or travelling downhill. In an ordinary combustion engine car, kinetic and potential energy are converted into heat by braking or by rolling and air resistance losses. Electric vehicles can recover all or part of the energy delivered back from the road to the wheels (P_{W-}). This is because the motor can operate as a generator that is driven by the wheels to deliver energy back to the battery (B_{Rec}). Electric vehicles also avoid idling losses during stops, although some conventional cars are equipped with stop-start or hybrid systems. The amount of energy recovered depends on the recovery efficiency of the car and driving patterns. Driving patterns are determined by road profiles, traffic situations and users' driving styles. It is also convenient to distinguish between gross and net energy efficiency (TTW_{gross} and TTW_{net}). The ultimate necessary net supply of propulsion energy is equal to the resistance losses (P_{Res}), that is, the gross energy supply requirement at the wheels (P_{W+}), minus the option for recovery of energy (P_{W-}).

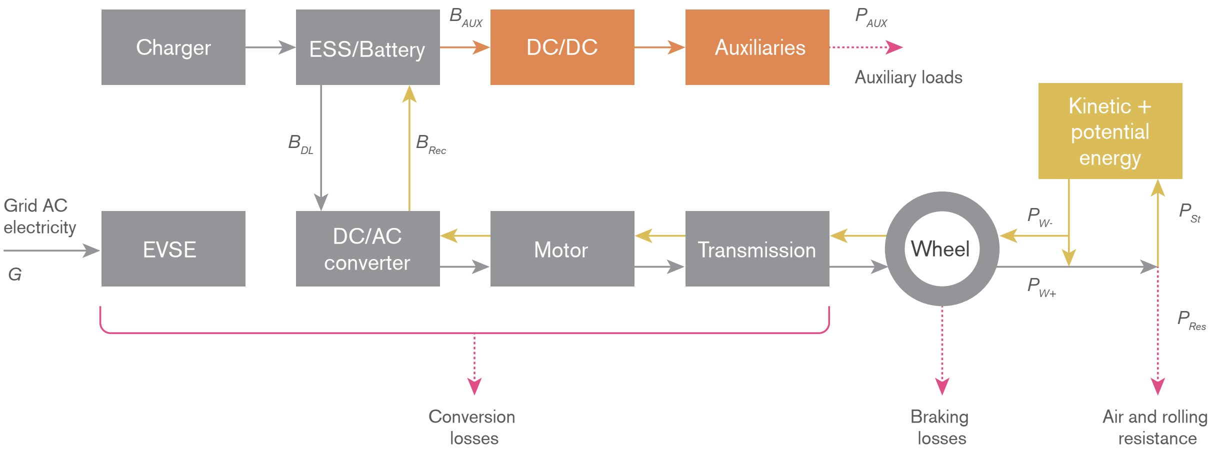


Figure 5.1 The conversion chain in electric vehicles. Energy is transferred from grid electricity (G), via the battery (B_{DL} and B_{Aux}), to energy at the wheels (P_{W+}) and auxiliary equipment (P_{Aux}). Part of stored potential and kinetic energy is recovered through the wheels (P_{W-}) to the battery (B_{Rec}).

ENERGY EFFICIENCY OF THE ELECTRIC COMPONENTS

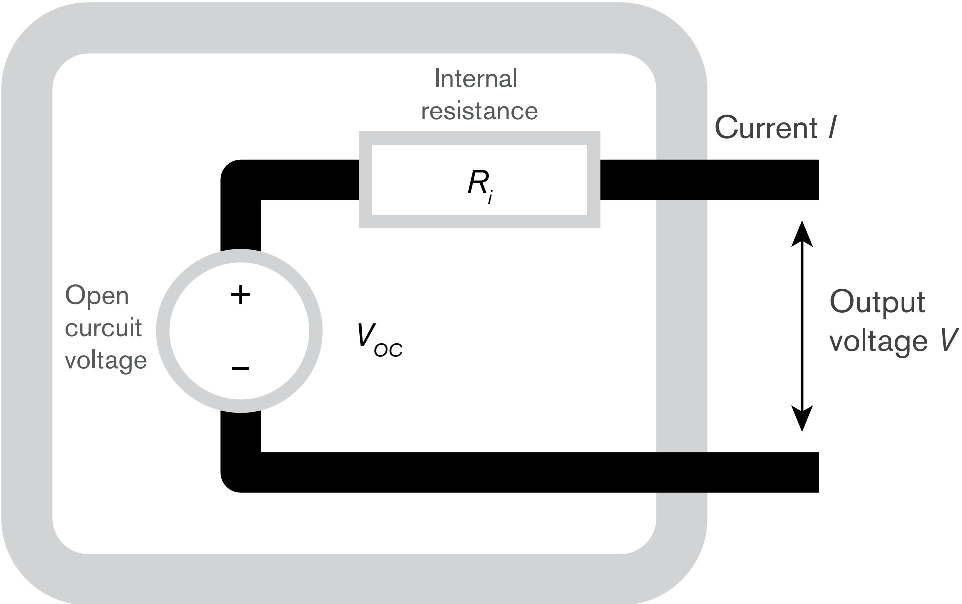
Charging equipment can be placed inside or outside vehicles (see also Chapter 3). Charging from an ordinary low-voltage household outlet commonly makes use of a charger placed in the car, which then converts the outlet AC current into DC. A typical 230 V and 10 A outlet provides about 2 kW of charging power. However, there are several on-board available chargers which can be connected to a three-phase outlet to deliver 10-20 kW. High-power charging (fast charging) can be achieved using an external charger to supply DC current to the car.

Household outlets are not to be used directly but should be complemented with *Electric Vehicle Supply Equipment* (EVSE) with inbuilt safety and control features. Losses in the EVSE are roughly 1-2% of the energy throughput (Table 5.1). The EVSE may also use energy in standby mode. Around 5 W standby power has been measured for commercial equipment. Over a year this can add up to around 40 kWh, which equates to two full charges of an EV.

Although *chargers* can operate with a peak efficiency of 92-95%, most commercially available chargers have much lower peak efficiencies. Lithium-ion batteries are sensitive to overvoltage when charged. Charging empty batteries thus starts at constant current. When a predefined voltage level is reached, the charging is switched to constant voltage with a gradually decrease in current and power. Charger efficiency in this low-power top-up phase may gradually decrease.

The overall efficiency of the Nissan Leaf on-board charger including an EVSE, for instance is 85%. The charger for a GM Volt, also including EVSE, has an efficiency of 89-91%. For the Peugeot Ion the overall efficiency from grid AC to battery DC has been measured to 82%. Commercial fast chargers (50 kW) have an overall efficiency of 89%.[1]

Inductive/resonance charging (see Chapter 2 and 3) incurs energy losses from the contactless transfer of power to the vehicle. Transfer efficiency is 90% under optimal conditions.



Output voltage $V = V_{OC} - R_i I$

Power output $P = V_{OC} I - R_i I^2$

Figure 5.2 A simple model of a battery. Losses increase faster (~ I^2) than the power output (≈ ~ I).

Losses in the *battery* are due to internal resistance, which transforms some of the stored chemical energy into internal heat instead of externally supplied power. A battery can be modelled as a voltage source in series with a resistor (Figure 5.2). With increased charging or output power, a larger share of the energy turns into internal heat losses, lowering the energy efficiency. Increasing the ratio between electrode area and volume can lower the specific resistance and raise the maximum power output. However, for the same energy capacity, this will lead to a more costly battery.

1 Fast charging is restricted to the constant current phase and stops at approximately 80-85% of the battery capacity.

Table 5.1 Conversion efficiency of different components in the electric drivetrain.

Component/ mode	Conversion efficiency	Efficiency characteristics	Possible future development
EVSE	98-99%	Standby losses in EVSE	Standby losses may be considerably lowered
Charger	Peak 85-95% Fast charging around 90%	Charger efficiency decreases for power considerably below rated power	Potential for higher efficiency over a broader power range
Battery	Losses in charging and discharging around 1%/C	Relative losses increase with power both in charging and discharging. Trade-off between losses and cost. (High power batteries have lower losses but at a cost) Different battery chemistries have different characteristics. Losses increase with use and calendar time (ageing).	New electrodes and electrolytes with higher power capabilities can reduce losses
Power electronics, boost converter	96-99%	Lower conversion efficiency for higher voltage steps	
Power electronics, DC/AC converter	Peak 95-99%	Higher voltage and lower switching frequency give higher efficiency.	SiC power electronics (Ch. 3) with very high conversion efficiency > 99%
Electric motor/ generator	Peak 90-96%	Lower conversion efficiency at either low torque or low speed. Higher voltage and motor speed give higher efficiency.	Considerable loss reduction unlikely. Trade-off with cost, size and materials' availability.
Transmission	92-98%	Avoiding gearbox increases efficiency. High motor speed may require reduction gear. Differential necessary if not in wheel motors.	Elimination of transmission by in-wheel motors possible development
Total driveline	Peak eff. ≈ 73-88%. Instant efficiency is the product of driveline component efficiencies, which vary with working point	Depends on the technology as well as the driving pattern. Avoidance of high speeds and frequent and strong accelerations/decelerations will increase efficiency.	The driveline involves many conversions between components, each with high efficiency, which need to be, and can be, even more efficient
Energy recovery in deceleration	Peak efficiency ≈ 100% of forward battery to wheel efficiency	Efficiency roughly same as for forward directed power in the driveline. The power of recovery is limited by motor/power electronics and by the vehicle stability and safety requirements when braking only the driving wheels.	Separate high power recovery system with low losses, such as supercapacitors. In-wheel motors can make recovery more efficient.

BEV-sized batteries have little problem achieving high efficiencies in driving or regeneration. With slow charging and efficient driving during operation and testing, the turnaround battery efficiency in the Nissan Leaf BEV has been measured at up to 97%. Smaller PHEV batteries are more strained, while small HEV batteries suffer from considerable losses at high power. The relationship between power output and energy storage capacity, or the speed at which a battery is emptied, is measured in cycles per hour (C).[2] Existing batteries typically have energy losses of around one percentage of efficiency per C during charging and discharging. Fast charging and low temperature increase the losses considerably. Battery efficiency may also decrease with time because battery ageing leads to a successive increase in the internal resistance and lower capacity.

Existing commercial *power electronics* (converters) are based on silicon-based semiconductors and transistors (see Chapter 3), and have over 95% efficiency through a large part of their operating range (Figure 5.3). Major losses are due to switching and increase with the duration and frequency of switching. While duration is technology dependent, a high switching frequency is desirable for low volume and noise. Power electronics based on silicon carbide (SiC) technology, with considerably faster switching and thus lower losses, are now becoming available. Lower losses and lower temperature sensitivities of SiC components eliminates the need for cooling systems, which provides additional energy savings.

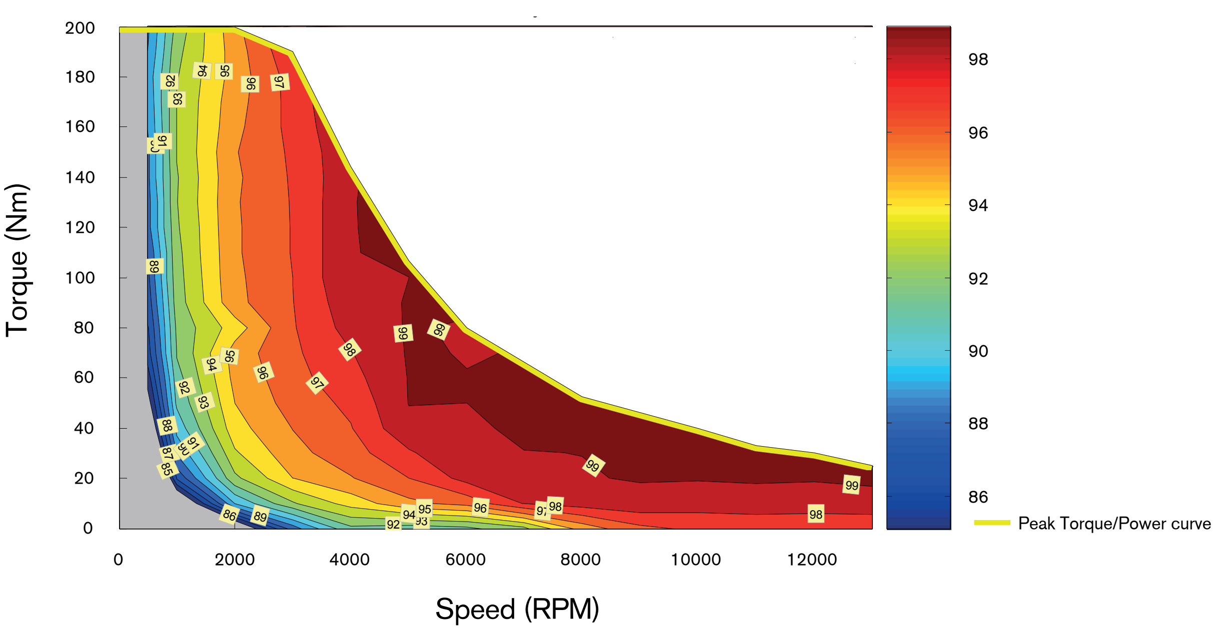


Figure 5.3 2010 Toyota Prius inverter (DC/AC converter) efficiency contours.[3]

If the motor requires a voltage higher than the battery voltage (at high speed, for example), battery power must be raised to a higher voltage before conversion to AC power. This is performed in a DC/DC converter called a 'boost converter'.

2 'C' values refer to an output rate normalized to battery capacity. 1 C is defined as the power at which the battery would be discharged in one hour. Thus 1 C will equal 24 kW and 1.2 kW for a 24 kWh BEV battery and a 1.2 kWh HEV battery, respectively, which can be compared to the average power need for driving of around 10 kW.

3 Efficiences for 650 V_{dc}. T.A. Burress et al, 2011, "Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System." Oak Ridge Nat Lab report ORNL/TM-2010/253.

The energy efficiency of such a converter is between 96-99%, with higher voltage steps resulting in lower efficiency.

The losses in the *motor* (also *generator*) are mainly due to internal resistive losses in the windings, currents induced by magnetisation and mechanical friction. Different types of motors have different efficiencies (Chapter 3, Table 3.1). Permanent magnet synchronous motors (PMSM) are already magnetised and thus incur lower losses.

Electric motors have high efficiencies for particular torque and speed intervals (see Figure 5.4). Efficiency decreases considerably at very low torque and speed, which relates to driving conditions such as vehicle queues. The specific efficiency characteristics versus torque and speed vary with the type and design of the motor and influence the gains or losses achieved with a gearbox. However, due to the high motor efficiency at very different operating points, electric vehicle transmissions are simpler than for ICE vehicles, and may not require a gearbox at all. The transmission losses between the power source and the wheels are therefore normally lower than in conventional cars. A possible (future) option is to mount the electric motors directly to the wheels (in-wheel motors). This can help in reducing transmission losses to a minimum.

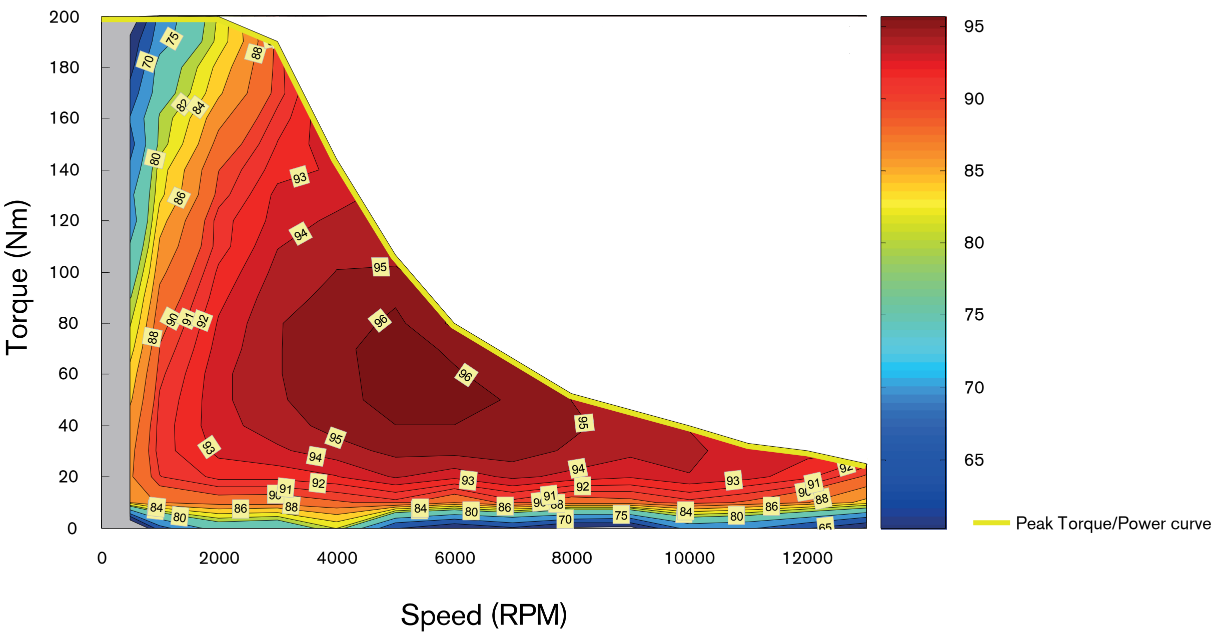


Figure 5.4 2010 Toyota Prius motor efficiency contours.[3]

As mentioned above, recovering kinetic and potential energy is an important feature of electrified vehicles. Recovery by operating the drivetrain ‘backwards’ means that the conversion efficiency is potentially equal to the forward direction. However, fully charged batteries cannot recover any energy. The drivetrain also limits recovery power. The power involved in braking can occasionally be very high since cars can stop much faster than they can accelerate. Recovery occurs through the driving wheels only. Road and weather conditions combined with vehicle control and safety consideration can thus further limit recovery efficiency.

The actual energy recovered in real driving is also strongly dependent on traffic and driving style. Hard braking can restrict energy recovery. Eco-driving techniques that save on propulsion energy in conventional cars will have a similar effect for electric cars, but may produce a smaller benefit when energy recovery is available.

Several kilowatts of *auxiliary power* are required in modern cars. Electric cars require a considerable amount of auxiliary power in addition to that required for the powertrain. The basic electronic functioning does not require that much auxiliary power. Starting a Nissan Leaf, for instance, requires around 0.2 kW, which corresponds to 2–4% of the battery energy used during driving. However, power steering and braking, lighting, wipers, adjustable seats and mirrors, and infotainment require considerable amounts of auxiliary power (see Chapter 7 for consequences in terms of materials requirements of increasing demand for auxiliary components). Battery conditioning is specific for electric vehicles. Because today's lithium-ion batteries are temperature sensitive, auxiliary power for battery temperature conditioning is often necessary. High temperatures, which result from internal heat generation or a warm climate will lower the battery lifetime. Cold ambient temperatures reduce the power and energy capacity of the battery. During driving, the battery must provide this auxiliary energy.

The power requirements for interior heating and cooling require most auxiliary power. Compared to conventional vehicles, electric vehicles generate little or no surplus from the cooling system and interior heating thus requires extra power. The need to supply auxiliary power for interior heating means that cold ambient temperatures can halve electric vehicle ranges.

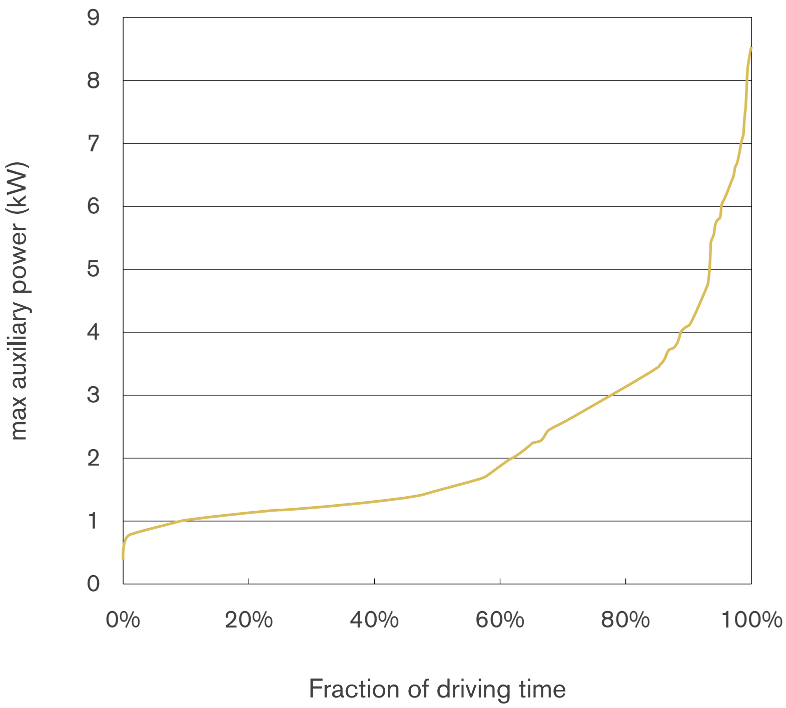


Figure 5.5 Measured auxiliary power use in six Peugeot Ions during real driving. The driving occurred at all seasons of the year in Belgium.[4]

4 Laurent De Vroey, One year behind the wheel of an electric car. Presentation at EEVC-2012, Nov 20-22, 2012 Brussels.

The energy use of auxiliaries has been measured for real driving conditions. For the Peugeot Ion, auxiliaries consumed 37% of the battery energy in average Belgium driving conditions. Auxiliaries required over 2 kW on average, but varied between 0.8 and 8.5 kW (Figure 5.5). Auxiliary power requirements increased considerably in cold temperatures. The average energy consumption (including propulsion) almost doubled for a temperature drop between +25 °C and -10 °C.

It is thus important that car producers consider ways to mitigate auxiliary power requirements by, for instance, insulating the passenger compartment and improving heat recovery. Since air conditioning is supplied via heat pumps in existing vehicles, electric vehicles can use heat pumps for heating and to recover low temperature heat from different sources in the vehicle. Alternatively, heat can be supplied by a fuel burner to alleviate burdens on the battery.

VEHICLE ENERGY USE AND EFFICIENCY

We now return to the efficiency of the full vehicle. Table 5.2 gives some efficiency measures at the vehicle level. The numbers are for a Nissan Leaf electric vehicle driving on two US test drive cycles. The ultimate losses are due to air and rolling resistance, which is the net energy supplied to the road. With this as a basis, the overall propulsion efficiency is around 45-70% for electric vehicles. As an example, the Nissan Leaf on the US UDDS test cycle requires 0.121 kWh/km electric energy from the grid for propulsion, while the air and rolling resistance losses are 0.56 kWh/km. This gives an overall BTW_{net} energy efficiency of 46%. For a conventional vehicle with no energy recovery, the braking energy is often included in the 'needed' energy. This corresponds to the gross energy delivered to the wheel. For a Nissan Leaf on the UDDS this gross energy is 0.117 kWh/km, which gives a BTW_{gross} energy efficiency of 97%.[5]

The table illustrates that any figure for the overall energy conversion efficiency in the vehicle will depend heavily on how it is defined. It is reasonable to compare energy input to the energy delivered to the road – but does this figure also include the energy recovered to the wheels and lost in braking? There are other ambiguities, including how one should handle the energy going to auxiliaries and at which point one should start to account for the input – at the battery or at the grid outlet.

Figure 5.6 illustrates the overall energy efficiency of an electric vehicle. It shows various measurements for Peugeot Ion electric vehicles operating in real driving conditions in Belgium. The energy delivered to the wheels was measured using a dynamometer.[6] Auxiliaries' energy use accounts for a very large share of the net energy delivered to the battery. GTW_{gross} is estimated at only 35-43%. Without any auxiliary energy use the energy delivered from the grid would have been 42% less. The GTW_{gross} efficiency would have been equal to the drivetrain conversion efficiency from the battery to the wheels (= P_{W+}/B_{DL}), estimated at 61-75%.

5 When energy recovery is allowed, this number does not really measure conversion efficiency since it could reach levels above unity if a large share of the battery output energy is recovered.

6 The higher figure is a maximum value achieved in the dynamometer measurement under optimal conditions. The lower figure is an estimated value for year-round real world driving.

Table 5.2 Various energy efficiency measures for Nissan Leaf on the US city test cycle (UDDS) and highway test cycle (HWFET). For comparison the corresponding efficiency for a conventional vehicle is added. Formulas refer to the designation in Figure 5.1.

Efficiency measure	Formula (Fig 5.1)	Energy in	Energy out	En. eff. on UDDS	En. eff. on HWFET
ELECTRIC VEHICLE					
Powertrain efficiency	P_{W+}/B_{DL}	Gross battery output to power-train only	Supplied wheel work (gross energy supplied from wheel to road)	73%	68%
Recovery train efficiency	B_{Rec}/P_{W-}	Energy supplied from road to wheel	Energy recovered to battery	73%	67%
Battery to wheel net, BTW_{net}	$P_{Res}/(B_{DL}+B_{Aux}-B_{Rec})$	Net battery output	Road load (air and rolling resistance = net energy supplied from wheel to road)	46%	63%
Battery to wheel gross, BTW_{gross}	$P_{W+}/(B_{DL}+B_{Aux}-B_{Rec})$	Net battery output	Supplied wheel work	97%	72%
Grid to wheel net, GTW_{net}	P_{Res}/G	AC grid	Road load	38%	52%
Grid to wheel gross, GTW_{gross}	P_{W+}/G	AC grid	Supplied wheel work	79%	59%
CONV. VEHICLE[a]					
Tank to wheel net, TTW_{net}	P_{Res}/F	Fuel energy	Road load	8.5%	21%
Tank to wheel gross, TTW_{gross}	P_{W+}/F	Fuel energy	Supplied wheel work	18%	24%

[a] The conventional vehicle is a 2012 Ford Focus 2.0 litre with 6-speed automatic transmission. Its fuel consumption on the European drive cycle NEDC is 6.1 litres/100 km.

The efficiency of the charging process is relatively low – only 82%. This could be justified by the fact that these losses imply greater use of grid electricity. In contrast, conversion losses in the drivetrain reduce range and performance and are thus more critical to engineering efforts.

We can compare the conversion efficiency figures discussed here with the corresponding figures for conventional cars. Table 5.2 compares the efficiency of a Nissan Leaf with a similarly sized vehicle – a Ford Focus with a 2 litre gasoline engine. The TTW_{gross} and TTW_{net} values are 4.5 and 2.5 times smaller for US city and highway cycles, respectively. For cases with a cold climate the differences will decrease – especially for urban driving where electric vehicles produce less surplus energy for interior heating.

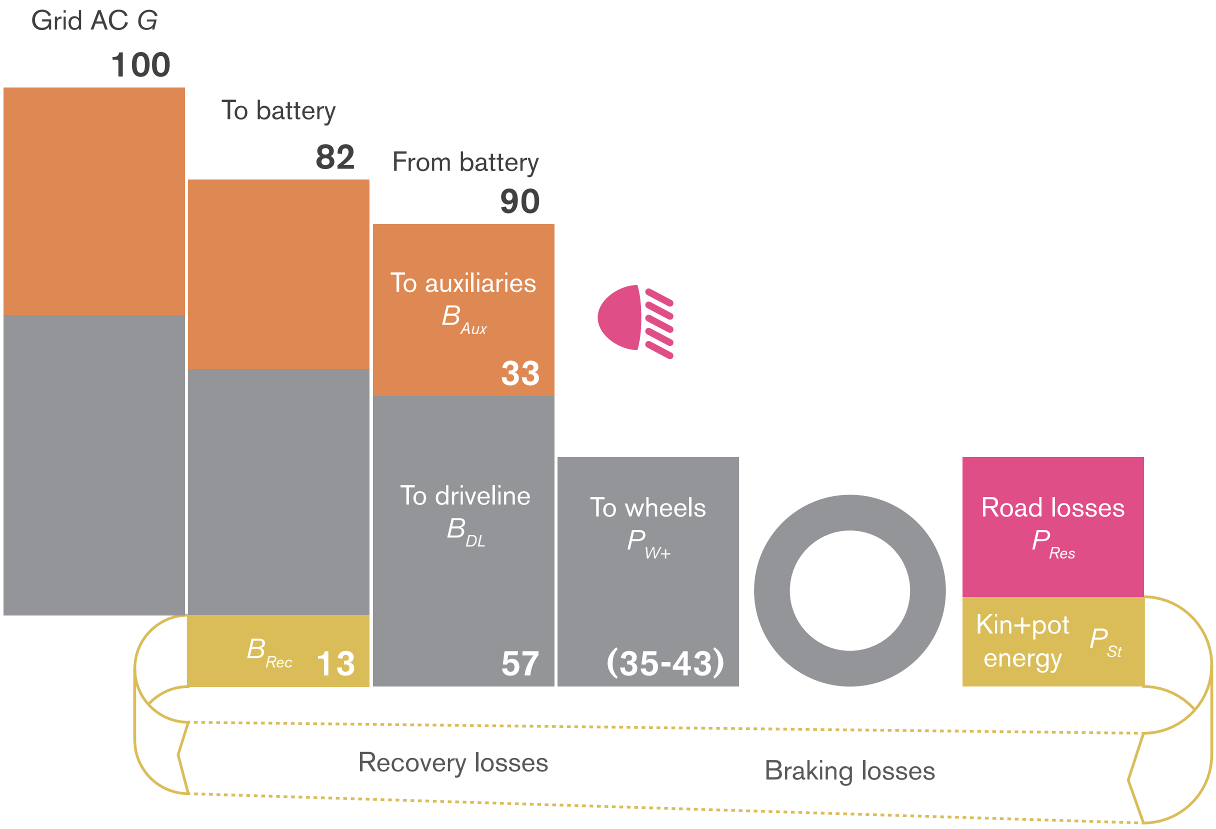


Figure 5.6 Energy fluxes for a Peugeot Ion electric vehicle during real driving conditions in Belgium. Figures in parenthesis are estimates based on dynamometer measurement. The figures are given in percentages of the energy delivered from the grid = 100. Orange denotes the share required by auxiliaries.[7]

The current push for lower fuel consumption, driven mainly by the European Union legislation on CO_2 emissions, has decreased the energy use gap between ordinary cars and electric vehicles. New vehicles have bodies with lower air resistance and are equipped with low rolling resistance tires, which decreases fuel consumption. Combustion engines have become more sophisticated and have lower specific fuel use because of techniques such as direct injection, stratified charging, downsizing, turbocharging, and by lowering auxiliary power requirements. Drivetrains have been gradually or wholly hybridised by introducing start-stop systems, for instance. Moreover, over 50% of newly sold cars in the EU are equipped with the more efficient diesel engines.

Battery weight affects energy efficiency. Many commercially available electric cars have ranges in the order of 150 km under 'light conditions' (low acceleration, speed and auxiliary power requirements). Ranges are typically halved by more severe driving conditions. These cars have a battery pack that weighs around 300 kg, which thus corresponds to 2-4 kg of battery for every km of range.[8] Further extension of the range will increase the battery weight, implying higher specific energy use. Technological developments leading to higher specific capacity will not only lower energy storage costs but also increase the energy efficiency of the vehicle for a given range. The construction of an extensive charging infrastructure

7 Laurent De Vroey, One year behind the wheel of an electric car. Presentation at EEVC-2012, Nov 20-22, 2012, Brussels.
8 This corresponds to, for instance, a specific energy use for these conditions of around 14 kWh/100 km for 'light conditions'; a battery capacity utilisation of 90%; and a specific battery pack capacity of 80 Wh/kg.

may assist in increasing energy efficiency by allowing for smaller batteries and lower weight.

Finally, in Table 5.3, the energy characteristics for electric and conventional vehicles in different situations are compared qualitatively. The electric vehicle is not superior in all situations, concerning refuelling, for instance. However, the superior average efficiency of the propulsion driveline makes electric vehicles a more efficient option in general terms, as shown in Table 5.2.

Table 5.3 Comparison of the electric drivetrain with a conventional drivetrain.

Situation	Electric driveline	Conventional driveline
Supplying energy to the vehicle	Charging involves losses	Negligible losses
Vehicle stops	No energy use	Energy wasting due to idling
City traffic with many stops and acceleration	Energy recovery possible in deceleration/downhill driving	Much energy lost in braking. No energy recovery
Low speed/low power need	High conversion efficiency	Engine works with low conversion efficiency
High speed/high power need	Conversion efficiency goes down somewhat with power	Engine works in more efficient mode
Cold climate	Extra energy for cabin heating needed, possibly also for battery conditioning, possibly also when parked	Heat for cabin heating available for free from engine waste heat
Warm climate	ACC energy efficiently delivered from battery	ACC energy from fuel via less efficient engine
Requirement for long range, large auxiliary or comfort energy use	The extra weight due to larger battery will increase the power and energy need for propulsion	Negligible influence

SYSTEMS ENERGY USE AND EFFICIENCY

We have so far discussed the energy efficiency of electric vehicles. Electric vehicles will be part of a larger energy and electricity system and the way in which electricity is produced and delivered to the vehicle will play an important role in the total efficiency of that larger system (see also Chapters 8 and 9). The efficiency of the entire fuel chain (the WTW efficiency) can be calculated by combining information on how the fuel or electricity for vehicles is produced with the previously discussed numbers on vehicle efficiency.

Table 5.4 and Figure 5.7 show some examples of supply chain efficiencies and the corresponding total fuel chain energy use. We can conclude that the supply chain is very important for the total efficiency. The chains O-CV and O-EV in Table 5.4 illustrate the case for using crude oil for either conventional or electric vehicle fuels. Despite the higher vehicle efficiency for the EV, the difference in WTW efficiency between the electric and the conventional car almost disappears because the crude oil WTT process is much more efficient for conventional vehicles, as illustrated in Figure 5.7. There are substantial losses in the production of electrical or mechanical energy from fuels and any chains using fuels will contain one such conversion. With electric cars this conversion step is just moved to the system for electricity production.

Table 5.4 Well to Tank (WTT) efficiencies for crude oil and solar energy transport fuel chains.

		Efficiency				
WTT energy supply chain		**Solar energy conversion**[a]	**Conversion to fuel**[b]	**Distribution to fuelling point**	**WTT' (=conv. + distr.)**	**Solar energy to tank**
O-CV	*Crude oil*–Refinery–*Gasoline* (–CV)		0.8-0.9	0.99	0.79-0.89	
O-EV	*Crude oil*–Refinery–*Fuel oil*–Power plant–*Electricity* (–EV)		0.30-0.45	0.90-0.95	0.27-0.43	
Sc-CV	*Solar energy*–Farming–*Corn*–Biorefinery–*Ethanol* (–CV)	0.003	0.25	0.99	0.25	0.00075
Sc-EV	*Solar energy*–Farming–*Willow*–Power plant–*Electricity* (–EV)	0.005	0.30-0.40	0.90-0.95	0.27-0.38	0.0014-0.0019
Se-EV	*Solar energy*–Solar cell–*Electricity* (–EV)	0.05-0.10	1	0.90-0.95	0.90-0.95	0.045-0.095

[a]Starting from solar energy flux onto utilised surface area. Solar to corn production efficiency: average US values. Solar to willow: Swedish values. Solar energy to electricity: assumed at 0.10-0.20 for the solar cell panels, with a ground cover ratio (panel to ground area) of 0.5.

[b]US data for corn to ethanol: 1 MJ of ethanol requires 2.14 MJ of corn and 0.72 MJ of fossil fuels, of which half is assumed to be substituted by ethanol and half directly with biomass. Source: Geyer et al, 2013. Spatially explicit life cycle assessment of sun-to-wheels transportation pathways in the US. Env Sci & Techn 47, 1170-1176. The indirect energy required for the energy investment in the technical artefacts used for energy conversion, e.g. oil refinery plants or solar cells, is not included. Adding this number would, however, not change the result substantially since in most systems it would amount to less than 10% of the energy turnover. See e.g. Kushnir, D., Sandén, B.A., 2011. Multi-level energy analysis of emerging technologies: A case study in new materials for lithium ion batteries. Journal of Cleaner Production 19, 1405-1416.

When starting from a renewable crop (see chains Sc-CV and Sc-EV) the difference once again increases. The production of liquid fuels such as ethanol from energy crops is typically less energy efficient than direct production of gasoline from crude oil. This is true even when disregarding the solar energy input, due to large energy inputs in biomass growth with intensive crop production and large conversion losses and energy inputs in the production of the high-quality liquid fuel. Any liquid fuel production from solid fossil coal will suffer similar conversion losses. Directly converting solar energy into electricity (chain Se-EV) avoids all of these losses and results in an efficient WTT process for EVs.

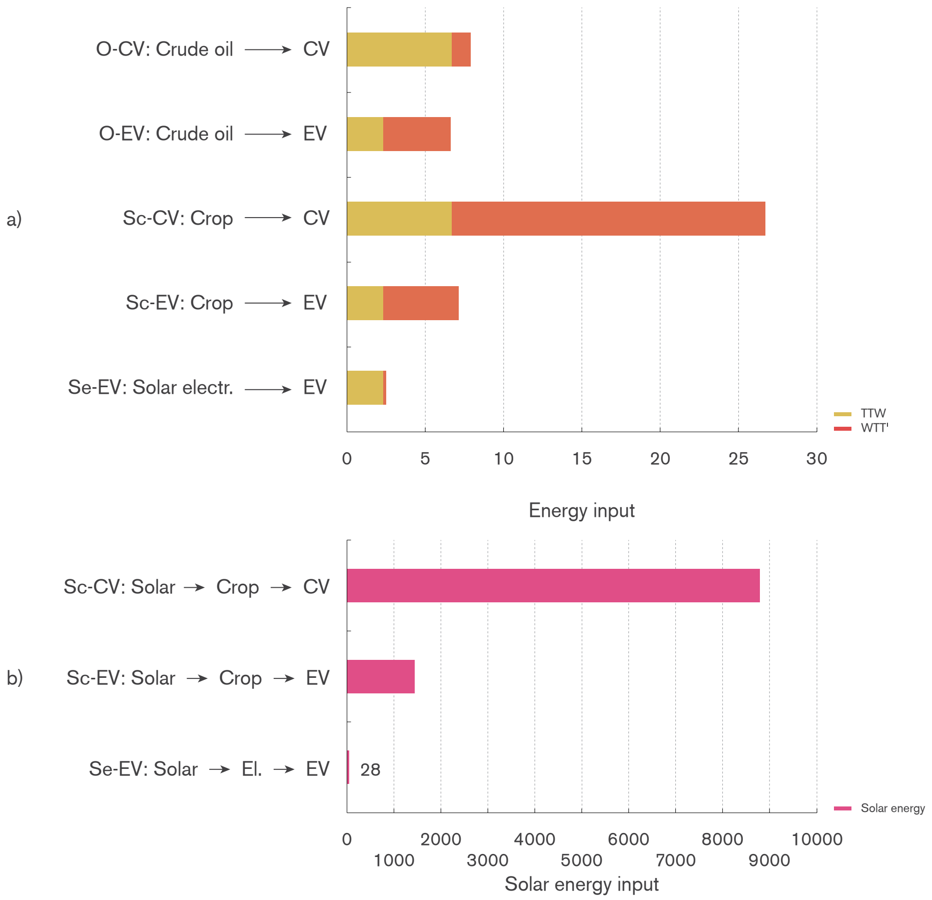


Figure 5.7 Well to wheel (WTW) energy input requirements along the different vehicle energy chains normalised to 1 at the wheels. Figure a) includes the energy input required to compensate for losses in the vehicle, TTW (from Table 5.2), and the fuel/electricity chain (excluding conversion from solar energy), WTT' (from Table 5.4). TTW is here defined as GTW_{net} and TTW_{net} for the EV and CV drivetrains, respectively. The mean value of the two drive cycles is used. Taking the efficiency of solar energy conversion into account (Table 5.4) as in Figure b), the losses in the bioenergy systems exceed those of direct solar energy conversion by two orders of magnitude. This indicates that electromobility opens up a pathway to radically more energy efficient transport systems based on renewable energy compared to those dependent on liquid biofuels, independently of the efficiency of the electric drive train *per se*.

The utilised solar energy (taken as the influx of the solar energy on the area utilised for energy capture) for the renewable energy chains is very large – see Figure 5.7b. This is especially the case for the two chains that utilise biological crop production, which has very low efficiency in terms of solar energy capture. The solar energy input is a factor 50-300 times larger for bio-production paths compared to the chain utilising solar cells. Although this energy is 'free', the solar energy input is directly proportional to the land area needed for the capture and land area may be limited. Furthermore land for growing crops must be fertile, whereas the solar cells have no such requirements and can be placed on marginal land or buildings.

Comparing the energy efficiency of different energy chains is a complex issue (discussed further in Chapter 6). When energy is coproduced, for instance, the allocation of the energy inputs will be arbitrary to some extent. When renewable resources such as wind and solar energy are utilised, various factors influence the ultimate renewable energy input. A factor omitted here (but which is further discussed in Chapter 6) is the energy cost for production (and recycling) of the vehicle itself, which is non-negligible and must be considered in an overall assessment.

SUMMARY

We can conclude that the energy efficiencies of the various components within the electric cars are generally very high. However, the many components in electric cars incur their own losses, lowering the total chain conversion efficiency. Non-propulsion energy use may also be considerable in comparison, especially for compartment heating and cooling. Notwithstanding, electric cars are more energy efficient than cars with internal combustion engines.

Besides the conversion efficiency within the vehicle, the efficiency of the energy supply (WTT efficiency) is a very important factor for the efficiency of the total energy chain (WTW) of the electric vehicle. Furthermore, electric vehicles are potentially important components in energy systems of the future. For such systems it is important to consider the energy and cost efficiency of the energy system as a whole. With limited fossil fuel resources, bio-productive land areas and greenhouse gas sinks, the single energy chain must be balanced against its influence on the total system. It is thus important to examine the role of electric vehicles in future energy systems in terms of energy efficiency alongside environmental, economic and other societal parameters.

6

LESS OR DIFFERENT ENVIRONMENTAL IMPACT?

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INTRODUCTION

Electric and hybrid drivetrains are currently regarded as a promising technology for vehicle propulsion. They can reduce greenhouse and other exhaust gas emissions from road transport. Electric drivetrains are more efficient than conventional internal combustion engines fuelled by petrol or diesel (Chapter 5), and fully electrified vehicles does not give any tailpipe emissions. In addition, electric drivetrains can also assist in decoupling the transport sector from its heavy reliance on fossil fuels. On the other hand, electric vehicles will require that more electricity is produced and this can be done from several different energy sources with diverse environmental impacts. Furthermore, electric drivetrains require new advanced components (Chapter 3) that result in additional, or at least different, environmental impacts compared to conventional vehicles.

The trade-off between the benefits when operating of the vehicle and possible negative impacts from the production and from energy supply can be analysed using life cycle assessment (LCA). However, LCA studies come in many shapes and diverging arguments on the utility of technology are based on them. Some advocate the technology (using for example the well-to-wheels approach to guide government promotion policies on different types of drivetrains and alternative fuel options)[1] and others claim that the prospective for electric cars to reduce the environmental impacts of mobility is "substantially overrated"[2] or that there will be "significant increases in human toxicity".[3]

This chapter provides an overview of the life cycle impacts of electric vehicles, with general conclusions and examples of results. We review existing research and sort studies found in literature into categories by asking what we can learn from different LCA approaches. More specifically, which answers do we get from well-to-wheels (WTW) studies in comparison to complete LCA studies, and what difference does it make if a study includes a narrow or broad set of environmental impacts. We conclude by summarising these learnings and discuss implications for a set of stakeholders identified in the area of vehicle electrification, such as policy makers and various branches of industry.

LIFE CYCLE ASSESSMENT OF ROAD VEHICLES

LCA is a systemic tool for evaluating the environmental impacts of goods and services. It includes technically surveying all stages of a product's life cycle – from material acquisition and manufacturing to use and disposal. Data is gathered for inflows in terms of raw materials and energy, and outflows of products, emissions and waste at each stage. By linking the processes from cradle to grave, a system model is constructed to describe how flows are connected and influence one another. The overall result is an inventory of inflows to the system in terms of natural resources and outflows in terms of emissions to the surrounding natural system. The inventory is then analysed to evaluate various categories of potential environmental impacts, such as global warming, human toxicity and acidification.

LCA can be applied to vehicles in different ways. The WTW study is one type of LCA, which focuses on the life cycle of the energy carrier used to propel the vehicle, such as liquid fuel or electricity, rather than the life cycle of the vehicle itself (Figure 6.1). However, the vehicle operation is considered in the step where the energy carrier is used to propel the vehicle, called 'tank-to-wheels' (TTW).[4] The stage before this, entitled 'well-to-tank' (WTT), focuses on the delivery of energy to the vehicle. It involves all processes from harnessing a primary energy flow or stock to different forms of energy conversion, distribution and storage. The environmental burden of the WTT phase varies depending on how the energy carrier is produced. For example, the difference is large between electricity produced from hydropower and coal fired plants. A WTW analysis is performed by connecting the WTT and TTW phases, as illustrated in Figure 6.1. In the case of liquid fuels, the TTW phase includes both exhaust and evaporative emissions. For pure electric vehicles charged from the grid, the TTW phase involves no emissions at all.

1 Ou, X. et al. (2010). Alternative fuel buses currently in use in China: Life-cycle fossil energy use, GHG emissions and policy recommendations. *Energy Policy,* 38, pp. 406-418.

2 Frischknecht, R. and Flury, K. (2011). Life cycle assessment of electric mobility: answers and challenges – Zurich, April 6, 2011. *The International Journal of Life Cycle Assessment,* 16, pp. 691-695.

3 Hawkins, T. R. et al. (2013). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology,* 17, pp. 53-64.

4 In Chapter 5, the term grid-to-wheels (GTW) is used to examine electric vehicles' energy efficiency. GTW accounts for charging losses that affect energy efficiency but do not influence the environmental impacts of the operation phase.

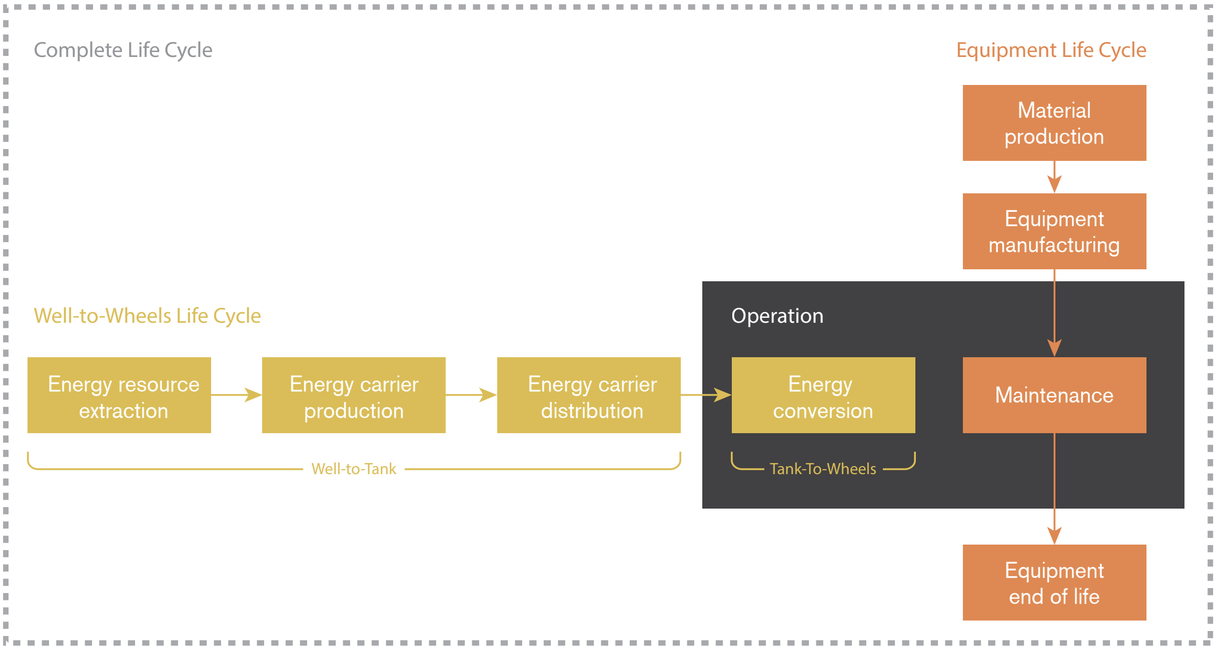

Figure 6.1 Simplified view of the well-to-wheels and equipment flows.

The vertical flow in Figure 6.1 represents the life cycle of the vehicle itself, which is sometimes referred to as the 'the vehicle cycle'.[5] In this text we use the term 'equipment life cycle', which is more general in that it is also applicable to both individual components and the drivetrain. This way of dividing the complete life cycle into two main flows is common in vehicle LCA and for studies where all processes are included, i.e. both the WTW and equipment life cycles, the term 'complete LCA' is used hereinafter.

The first phase in the equipment life cycle consists of raw material extraction and material processing. It is followed by manufacturing where parts are fabricated and assembled into a vehicle. The subsequent activity is the vehicle operation where the energy carrier and equipment cycles overlap. However, some aspects of the operation are solely connected to the equipment life cycle, namely service and reparation, shown in Figure 6.1 as maintenance. The final phase (end-of-life) includes dismantling the vehicle, recovering and recycling parts, and shredding and disposing of residues.

Table 6.1 is a compilation of 65 scientific articles, conference papers, government agency reports and reports published by other organisations that have conducted life cycle assessments of electric and hybrid vehicles. They are divided into three groups: WTW studies, complete LCAs and battery LCA studies. The table provides an overview of the research field and what the different groups of studies covers in terms of vehicle types and impact assessment. The term 'functional unit' refers to the entity used to assess the life cycle data (e.g. 1 km of driving). Note that the assumed vehicle lifetime (in km) differs widely between studies that perform complete LCA, and that the majority of studies focus on light passenger vehicles and greenhouse gas (GHG) emissions.

5 See for example Messagie, M. et al. (2010). *Life cycle assessment of conventional and alternative small passenger vehicles in Belgium*. 2010 IEEE Vehicle Power and Propulsion Conference, VPPC 2010. 1-3 Sept. 2010, Lille: IEEE.

Table 6.1 An overview of the scope of publications on LCA of electric and hybrid vehicles from 1998 to early 2013. The main share consists of scientific articles (43 titles) and conference papers (11 titles) and the remaining titles are different types of reports and books.

Articles / Category	WTW study	Complete LCA	LCA of Batteries[a]	TOTAL
FUNCTIONAL UNITS	1 km of driving	1 km of driving 1 vehicle life (95,000-560,000 km)	1 km of driving 1 kg battery 1 kWh battery	
TECHNOLOGY				
Light duty or passenger vehicles	18	30	5	53
Other vehicle types[b]	3	2	8	13
Externally chargeable	18	27	13	58
LEVEL OF IMPACT ASSESSMENT				
Global Warming (GHG)	19	32	4	55
Energy	9	14	8	31
Broader assessments[c]	8	17	9	34
TOTAL	20	32	13	65

[a] Equipment life cycle or complete LCA of batteries.
[b] In the case of battery studies, this means that no vehicle type has been specified
[c] Studies including several impact categories and emissions besides GHGs and energy.

WHAT CAN WE LEARN FROM WELL-TO-WHEELS STUDIES?

Drivetrain electrification can potentially reduce GHG emissions by increasing the TTW efficiency and by making it possible to abandon energy produced from fossil fuels in the WTT phase. For externally chargeable vehicles such as battery electric and plug-in hybrid electric vehicles (BEVs and PHEVs), GHG emissions depend on the entire WTW life cycle. Consequently, it is common to adopt the WTW perspective when the purpose of a study is to assess the efficiency of different drivetrain options; to assess the climate impacts of different energy carriers; and to examine how electricity production influence vehicles' environmental performance (see Chapter 8 and 9 for wider system implications via links to other sectors).

In a large WTW study commissioned by the European Union, externally chargeable electric vehicles in the compact class were compared with conventional vehicles. The study focused on GHG emissions, based on the standard European driving cycle (NEDC).[6] Three categories of vehicles were defined: PHEVs, BEVs and so-called 'extended range electric vehicles' (E-REVs). The data used in the study was based on prototypes and development vehicles with batteries and electric motors in a range of different sizes[7] to provide a worst-maximum case and a best-minimum case for each category. All use of liquid fuel was limited to petrol. The PHEV category has limited electric performance and an electric driving range of 20-40 km, with start-up in either pure electric or blended hybrid mode. The

6 Edwards, R. et al. (2011). *Well-to-Wheels Analysis of Future Automotive and Powertrains in the European Context – Well-to-Wheels Appendix 2 Version 3C, WTW GHG-Emissions of Externally Chargeable Electric Vehicles*. EUR – Scientific and Technical Research series – ISSN 1831-9424. July 2011, Luxembourg. (ISBN 978-92-79-21395-3, reported by Joint Research Centre of the European Commission, EUCAR and CONCAWE).
7 See Chapter 3 for a discussion on different EV components and configurations.

E-REV category refers to vehicles driven by the electric motor but they have an internal combustion engine that is used to generate electricity for the battery and thus extend the driving range of the vehicle. The BEV category includes vehicles propelled entirely by externally-produced electricity. The study excludes auxiliary energy use by applications such as air conditioning and lighting (see Chapter 5). These vehicles are compared to a 'reference' case based on conventional petrol driven vehicles.[8]

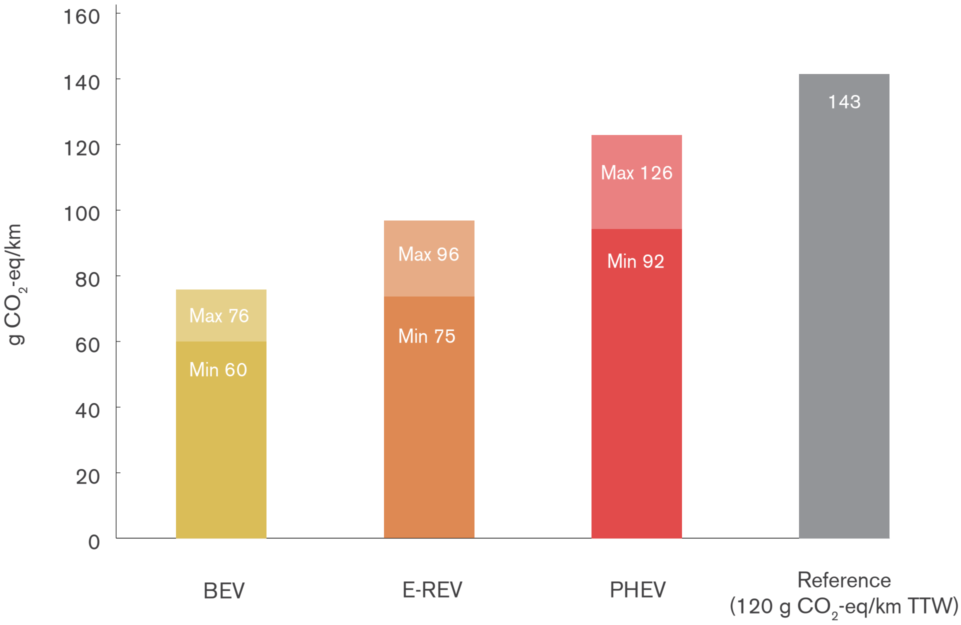

Figure 6.2 WTW GHG emissions based on an average EU electricity mix (467 g CO_2-eq/kWh). The reference vehicle corresponds to a former EU fleet target for tailpipe emissions of new sold cars. Source: Edwards et al. (2011), Position of the European Parliament (2008).

Figure 6.2 shows the results of the WTW analysis based on the average EU electricity mix (467 g CO_2-eq/kWh for 2008). As can be seen, all electrified vehicles have lower emissions than the reference case. The data also demonstrates a reduction in GHG emissions with an increasing degree of electrification, although the different vehicle categories overlap with regard to minimum and maximum values. However, Figure 6.2 does not show that overlaps are larger for higher electricity GHG intensities. At intensities greater than 900 g CO_2-eq/kWh (which corresponds to oil-fired electricity) even the BEV category starts to emit more than the reference vehicle.[6]

Figure 6.3 shows how different electricity production gives altered WTW GHG emissions for a small, family-sized BEV. It is clear that carbon intensive fossil electricity production results in strikingly higher emissions than nuclear or renewable electricity, also when the impacts of power plant construction are considered.[9] Equally noteworthy is that electric vehicles that run on oil- and coal-fired electricity have life cycle emissions similar to the tailpipe emissions of modern diesel and petrol cars.

8 Conventional petrol-driven vehicles with tailpipe emissions of 120 g CO_2-eq/km. Tailpipe emissions refer to the TTW phase and correspond to 143 g CO_2-eq/km for the full WTW.

9 Electricity production is treated as a 'background system' to the foreground technology that is studied. See Figure 10.2 in Systems Perspectives on Biorefineries 2013 for another example of the importance of background systems.

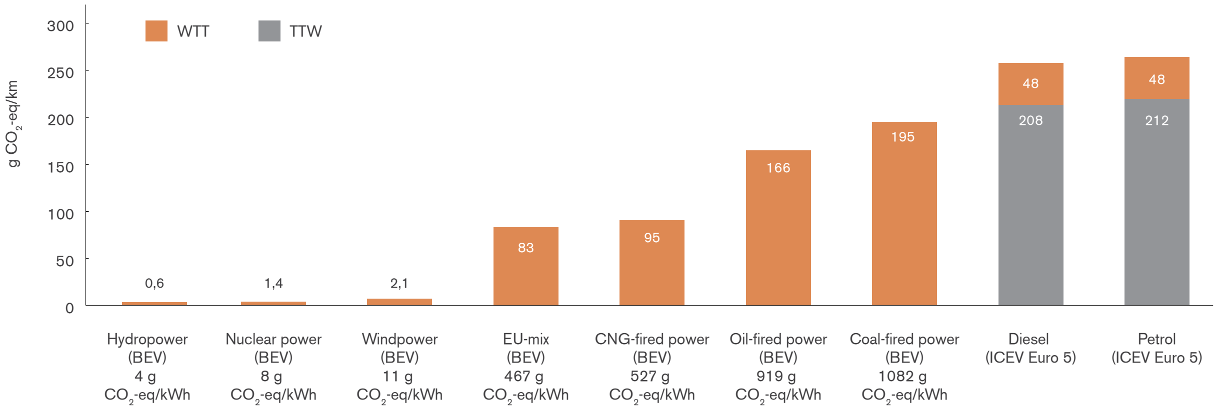

Figure 6.3 WTW GHG emissions for the small family car segment with different types of energy production (with the construction of the power plants included). Reference vehicles correspond to the average Euro 5 vehicles for petrol and diesel in the same segment in Belgium at the time of the study. Source: Messagie et al. (2010)

A vehicle classified as 'small family-sized' is roughly of the same size as one classified as a 'compact car', i.e. they belong to the same size class or segment. However, the conventional petrol- and diesel-fuelled reference vehicles in Figure 6.3 correspond to average values of the Belgium vehicle fleet, whereas the reference in Figure 6.2 correspond to a fleet target value for new sales in EU[10]. Nevertheless, passenger cars come in many different sizes and vehicle weight is a key factor for environmental performance.[2] This is important to have in mind when one is analysing results of various studies. Table 6.2 shows typical vehicle segments and corresponding representative vehicles. BEVs are usually classed as city or compact cars and PHEVs are usually classed as family vehicles, whereas and HEVs (Hybrid Electric Vehicles) can be found in all segments.

Table 6.2 Typical conventional light passenger vehicles divided into groups of established segments with similar vehicle size.

Segments grouped according to size	Examples	Electric categories
City cars / Mini vehicles	Fiat Punto, Citroen C1, Peugeot 106, Smart	HEVs, BEVs
Compact cars / Small family cars	Volvo C30, Ford Focus, VW Golf, Nissan Leaf	HEVs, BEVs, PHEVs
Executive compact cars / Family cars	Volvo S40/V40/V60, Toyota Prius	HEVs, PHEVs
Executive cars / Large family cars	Volvo V70/S80, Ford Mondeo,	HEVs, PHEVs
Small monovolumes / Small multi-purpose vehicles	Ford Focus C-Max, Opel Zafira,	HEVs, PHEVs
Monovolumes / Multi-purpose vehicles	Ford Galaxy/S-Max, Peugeot 807	HEVs
Luxury cars	Lexus LS, Mercedes S-Klasse,	HEVs
Sport Utility Vehicles	Lexus RX, Mercedes M-Klasse	HEVs

WTW studies can also be used to assess the impacts of different modes of operation and vehicle control strategies. Typically this could be the impact of different driving styles and traffic situations. Figure 6.4 shows an example of such a

10 This former target of 120 g CO_2-eq/km has been rephrased into a mandatory fleet value for the type approval per manufacturer of 130 g CO_2-eq/km by 2015.

WTW study, which examines the GHG emissions of a conventional petrol vehicle compared to a HEV and a PHEV operating in different traffic conditions.[11] The study is limited to large family cars and with similar specifications. The results for three driving modes are shown. City driving refers to slow driving with many starts and stops in highly congested city traffic. Suburban driving refers to a scenario with less congestion, allowing higher speeds. Highway driving refers to a scenario with high speeds and no stops. The results show that the hybridised drivetrains are beneficial in congested traffic as there are many stops, which allows for regenerative breaking to recover energy. At a standstill, conventional vehicle engines are kept idling whereas in hybridised vehicles they are automatically turned off (see Chapter 5 and Figure 5.1).

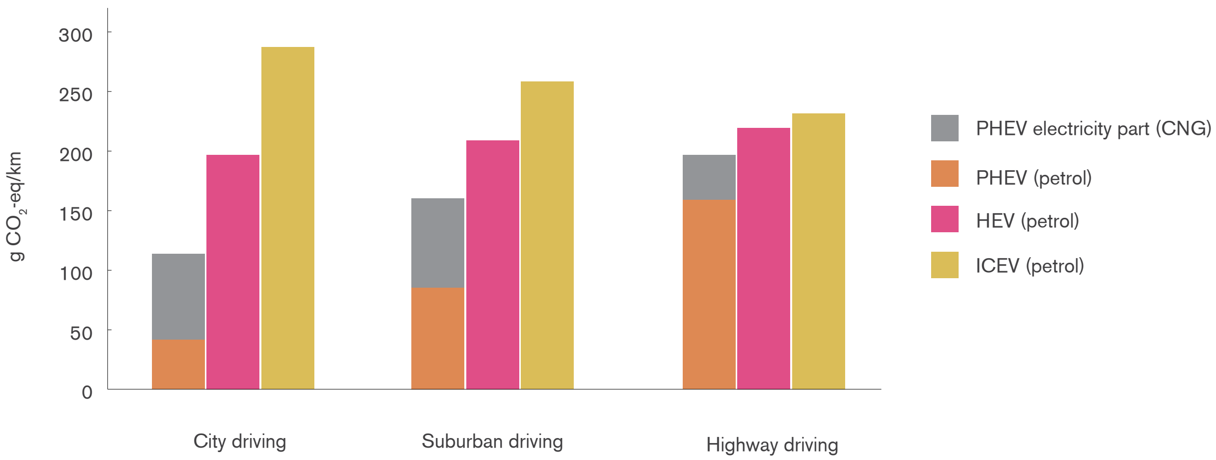

Figure 6.4 WTW GHG emissions for three types of large family petrol vehicles in three traffic situations. The data for the PHEV is based on charging with electricity produced from natural gas. Source: Raykin et al. (2012)

Reflecting a bit on the use of the WTW studies, it should be pointed out that when data is presented for an all-electric vehicle charged with low carbon electricity, it might give the impression that electric vehicles have no environmental burden at all. This is not true. In other cases, WTW studies are used to compare the climate impacts of vehicles in very diverse segments (see Table 6.2). In both these cases it can be argued that a complete LCA would add valuable insights.

WHAT CAN WE LEARN BY INCLUDING THE EQUIPMENT LIFE CYCLE?

Including both the WTW chain and the equipment life cycle as part of a complete LCA can provide a more comprehensive mapping of vehicles' environmental impacts. Vehicles of different sizes but with similar fuel consumption can be compared with more relevance because drivetrain sizing and composition are included in the assessment. Figure 6.5 shows the overall lifetime GHG emissions per kilometre for some well-known brands and models in four different segments. The data is based on NEDC-certified fuel consumption rates and an average EU electricity mix. The general trend is, as expected, that larger vehicles have higher emissions and that emissions decrease as the vehicles get smaller. Notable is that the HEVs have low emissions in each segment and that the small family-sized BEV has the lowest lifetime GHG emissions, also when compared to the smaller city

11 Raykin, L. et al. (2012). Implications of Driving Patterns on Well-to-Wheel Performance of Plug-in Hybrid Electric Vehicles. *Environmental science & technology*, 46, pp. 6363-6370.

segment. However, in this case vehicles in different segments are stipulated to have the same lifetime in terms of driven kilometres, which can be disputed.

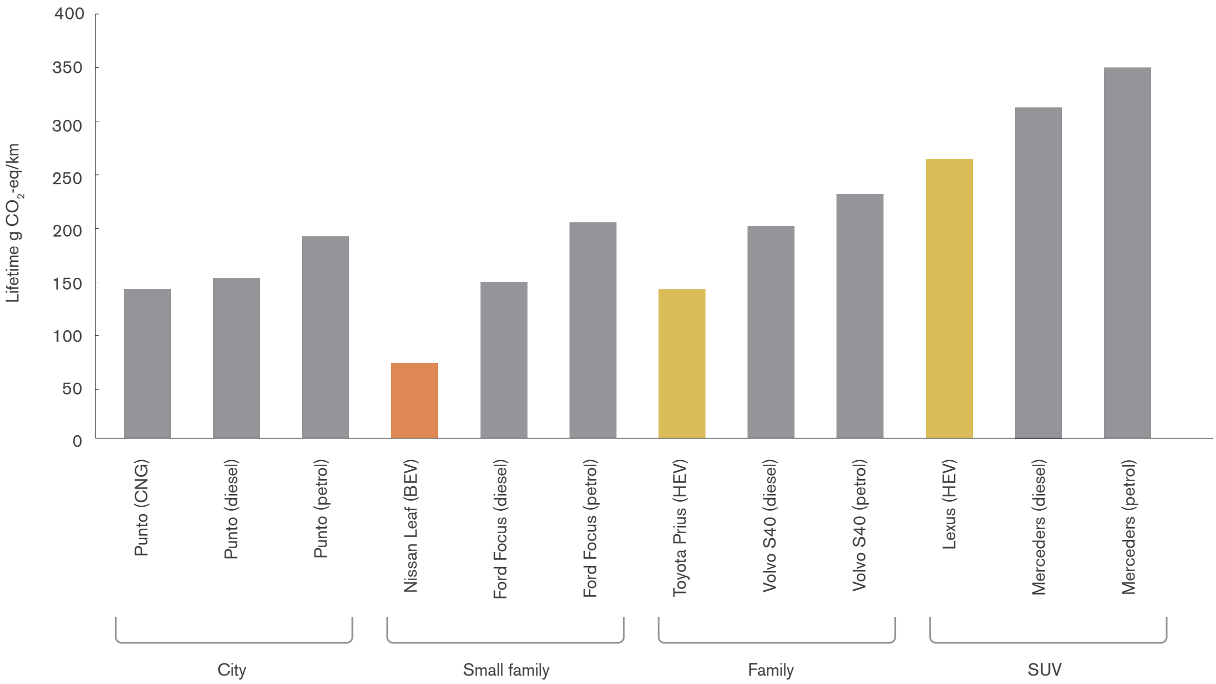

Figure 6.5 Life cycle CO_2-emissions for passenger cars divided into typical segments showing the general trend in CO_2-emissions for the full life cycle. An average vehicle lifetime of 230500 km corresponding to 13.7 years has been used, based on statistical data from the Belgian vehicle registration database. Fuel consumption is based on NEDC data. The Nissan Leaf BEV has been assumed to run on the EU electricity mix. Source: Messagie (2012).

A general rule of thumb may be established by comparing the complete life cycle results with the earlier WTW results. It is that vehicle operation is the dominating stage with regard to energy use, both for conventional vehicles and those with electrified drivetrains. However, many studies point out that the relative importance of the manufacturing stages increases with electrification. This is due to the reduction of emissions (in absolute numbers) from the WTW cycle as well as the introduction of new components. A study made in the UK which includes the full life cycle of light passenger vehicles, provides some typical results. It indicates that the GHG emissions are coming in approximately equal shares from the WTW life cycle of the energy carrier and equipment life cycle of the vehicle, see Figure 6.6. In this case it is a BEV driven in urban conditions, and charged with a projected average grid mix in the UK. However, the WTW share of the total GHG emissions becomes dominating as soon as more fossil intense electricity is considered or the driving scenario is set to highway or suburban. Another observation is that vehicles of different types, segments and brands have different life lenghts both in terms of total driving distance and years of operation (see Table 6.1). For this reason it is important to review and question the assumptions made for the total amount of kilometers driven whenever complete life cycle results are presented per kilometer.

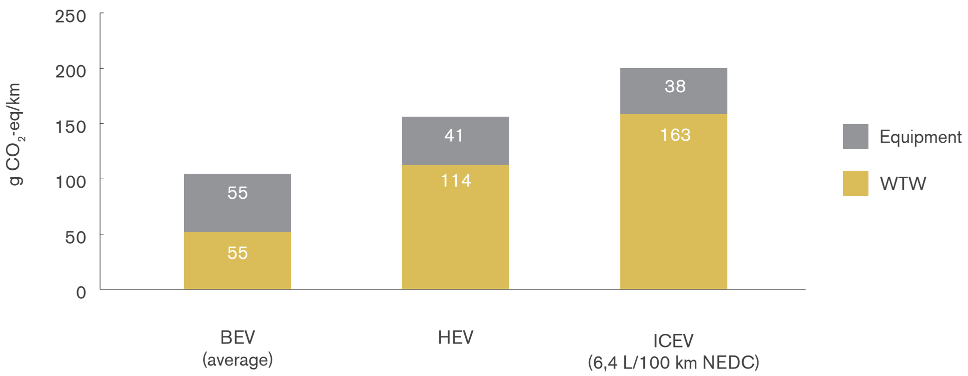

Figure 6.6 GHG emissions from the WTW cycle and the equipment cycle in a UK urban driving scenario with low speed and load (15 years lifetime and 12000 km/year). Electricity is based on a projected UK, mix corresponding to 450 g CO_2-eq/kWh. Source: Ma et al. (2012).

It can also be pointed out that electric drivetrains can be realized in many different configurations and that the components in general are immature for automotive application (see Chapter 3). This implies that there is both a large span from the best to worst case, and that various assumptions made during the course of the LCA may play an important role. It is also very important to remember that there is a large improvement potential for the future.

Summing up, by adding the equipment and WTW life cycles a more complete assessment is achieved. This is useful when vehicles with similar WTW performance, but different degree of equipment complexity, are analysed and compared. It also gives better understanding of where focus should be put for further improvements. The WTW phase often plays a dominating role for the emission of GHG. As long as it does, keys to improvement of environmental performance will be to minimise the demand for fossil fuels in the WTT phase and to increase efficiency in the TTW phase. Nevertheless, the addition of the equipment life cycle perspective provides information about the roles of the different components and the effects of changes in the drivetrain.

WHAT CAN WE LEARN FROM A BROADER IMPACT ASSESSMENT?

So far this chapter has reflected only upon environmental aspects connected to the use of energy and emissions of GHG. However, there are also other resources and emissions which are relevant to include if the aim is to establish a more comprehensive description of the environmental performance of electrified vehicles. For a life cycle assessment to be regarded as extensive and complete, it should cover the impacts on three important areas of protection: natural environment, natural resources and human health (see also the discussion on horizontal system delineation in Chapter 1 in Systems perspectives on Biorefineries).[12]

LCA results may also be presented in different formats. For example, the inventory format (detailed resource use and emission categories) is useful when the target audience is well informed about the substances emitted from the product chain.

12 ISO (2006). Environmental management - *Life cycle assessment - Principles and framework (ISO 14040:2006)*. 2006-10-05 2006, Geneva, Switzerland: International Organization for Standardization.

This is the case of the automotive industry, which is familiar with the regulated tailpipe emissions – carbon monoxide (CO), unburned hydrocarbons (HC/VOC), nitrogen oxides (NO_X) and particulate matter (PM). However, there are also numerous other substance flows including resources and non-regulated emissions. Furthermore, these flows may interact in complex manners. This is why life cycle impact assessment (LCIA) is often conducted. LCIA aggregates emissions contributing to the same type of environmental effect into one indicator and likewise for resource use. Aggregation can be done all the way to one single number, a one-dimensional measure of the environmental impact. However, whatever weighting method is used to achieve this, it will include a large number of contested value judgements. Therefore, so called 'mid-point' indicators are often used. These aggregate the inventory results into a limited number of impact categories.

A typical such midpoint indicator is the already frequently shown global warming potential (GWP) reporting all GHGs as CO_2-equivalents. Another is the photo-oxidant creation potential (POCP) which describes the local air pollutants that build up smog under the influence of sunlight and harm both human health and growing crops. The eutrophication potential (EP) covers the effect of macronutrients in soil and water (including NO_x). The acidification potential (AP) indicates the potential environmental impact of acidifying substances such as NO_x and sulphur oxides (SO_x). The results may also be further aggregated into so called end-point indicators, describing effects on e.g. human health and biodiversity.

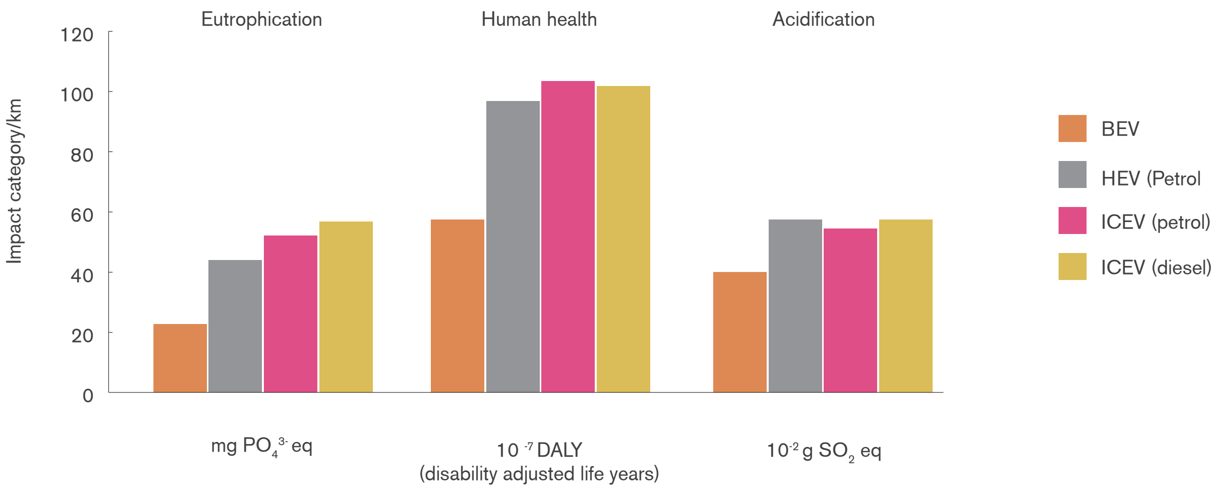

Figure 6.7 Results for the eutrophication (left), human health (middle) and acidification (right) impact categories in an LCA of small family vehicles in Belgium. The BEV is equipped with a lithium ion battery charged with the Belgian electricity mix. The HEV has a NiMH battery and a Euro 4 emission standard engine. The conventional references for petrol and diesel are both of Euro 5 standards. Sources: Messagie et al. (2010) for eutrophication and human health and Boureima et al. (2012) for acidification. Eutrophication and acidification characterization factors according to CML (2002). Human health characterization factors according to Jolliet et al. (2003).

Figure 6.7 shows examples of LCA results presented as LCIA indicators. They are based on the same data as those presented in Figure 6.3, but this time for the Belgian electricity mix. A BEV and a HEV in the small family-size segment are compared with conventional references. LCIA results are shown for eutrophication, acidification and an endpoint impact indicator summarizing the overall damage potential for human health. As can be seen, the trend is that the impact decreases with increased electrification and this applies to all impact categories, just as in the case of GHG emissions. The explanation for this covariance is that all the shown types of impacts are caused by airborne pollutants which mainly are coupled to combustion, either in the vehicle or at a power plant. Consequently, the results for externally chargeable vehicles are strongly dependent on the electricity production and the overall efficiency of the WTW life cycle.

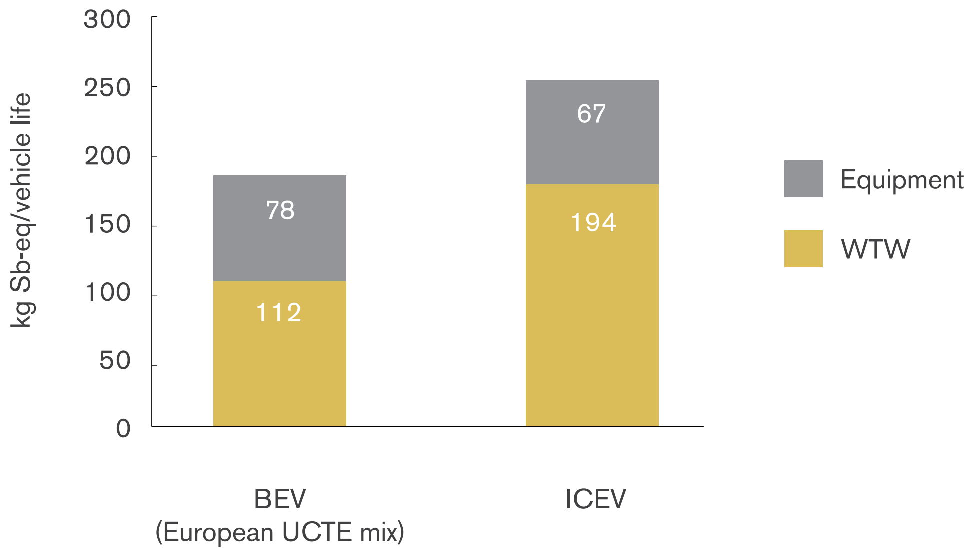

Figure 6.8 Results for the abiotic resource depletion impact category for two different version of a vehicle in the compact class divided into the WTW and equipment life cycles. The BEV is charged with a part of the European electricity mix referred to as UCTE (596 g CO_2-eq/kWh and 4.4 g Sb-eq/kWh). Source: Notter et al. (2010).

All indicators discussed so far relate to emissions of pollutants. However, LCA aspires to also include resource use. The use of abiotic resources may be aggregated into an indicator for abiotic resource depletion potential (ADP). It covers non-living resources such as metals and oil. An example is shown for an ICEV and a BEV in the compact class in Figure 6.8. It displays abiotic resource depletion in terms of antimony equivalents (kg Sb-eq). Although the use of metal resources in the vehicle cycle is higher for the BEV, this is still outweighed by the larger use of the fossil energy reserve by the ICEV, according to the study. However, worth mentioning is that the ADP used in the example is based on estimates of the global reserves of each mineral combined with their extraction rates. By now these are 10-15 years old. As a consequence, high scores are given for fossil energy depletion in comparison to copper, nickel, lithium and rare earth metals relevant for electric and hybrid vehicles. Other resource use indicators provide much higher values on copper and nickel, but still relatively high values on fossil fuels and do often not cover lithium and rare earth metals.[13] (See Chapter 7 for a more in depth analysis of electric vehicles and metal resource constraints)

13 See for example Goedkoop, M. J. et al. (2012). *ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.* Report I: Characterisation. First (revised) ed. July 2012.

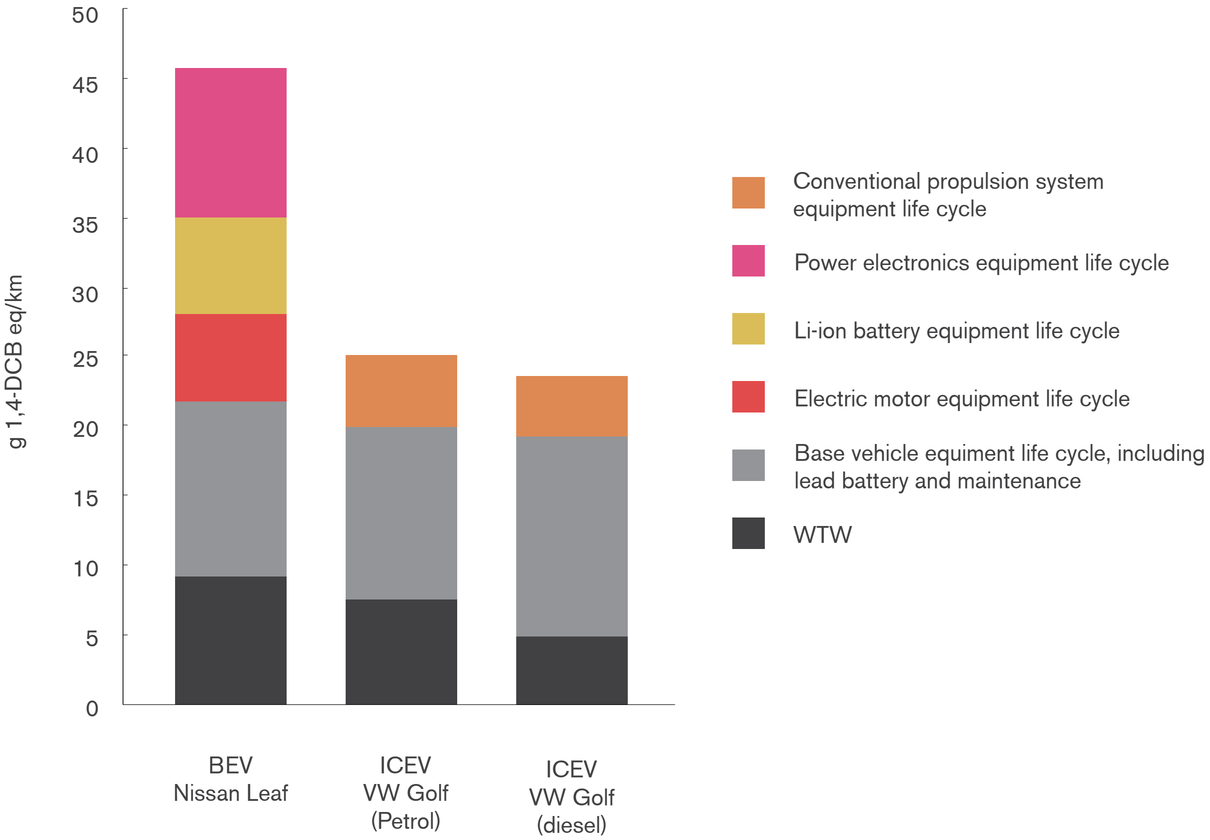

Figure 6.9 Results for the human toxicity potential comparing compact class vehicles for different drivetrain options. A vehicle life distance of 209470 km has been assumed and the BEV is charged with the Belgian electricity mix. All use of petrol and diesel are of Euro 5 standard. Sources: Messagie (2013) (manuscript). Characterization factors according to Goedkoop et al. (2012).

Local emissions of toxic substances from the manufacturing stages are an environmental aspect which has been brought up in some studies as a possible disadvantage of electric drivetrains, especially in connection to battery production. Figure 6.9 presents the human toxicity potential (HTP) in units of 1,4-dichlorobenzene, a well-known pesticide. It indicates significantly higher impact with respect to toxicity from BEVs than conventional vehicles. A very important part of the explanation to the HTP results in Figure 6.9 is mining processes, both in the production of electricity and components. The big difference revealed for WTW phase has its cause in leakage from the mining spoils of coal and lignite for electricity production. And the larger equipment life cycle emissions of the BEV refer to disposal of sulphides in mine tailings. It is coupled to increased use of copper and nickel, both in the battery and the electric motor, and copper and gold in the power electronics. Improved waste handling in the mining industry and a less coal dependent energy mix could therefore dramatically change these results.

Furthermore, toxicity is a complicated impact category. It accounts for many different substances and their inherent toxicity, along with the potential that humans and/or ecosystems are exposed to the substances in a manner that cause adverse effects. This impact category is generally coupled to a high degree of uncertainty due to its dependence on various background conditions and the need for very large data sets in the assessment.

To this point only studies modelling the whole vehicle, or at least the drivetrain, with a similar level of detail have been described. A different, but also quite common approach is to set the focus on a single component such as the battery, either in the context of a full vehicle LCA or more specifically in a component LCA study. The reason is that there is a consensus among all studies that the traction battery is a key component in terms of weight, performance and durability.[14]

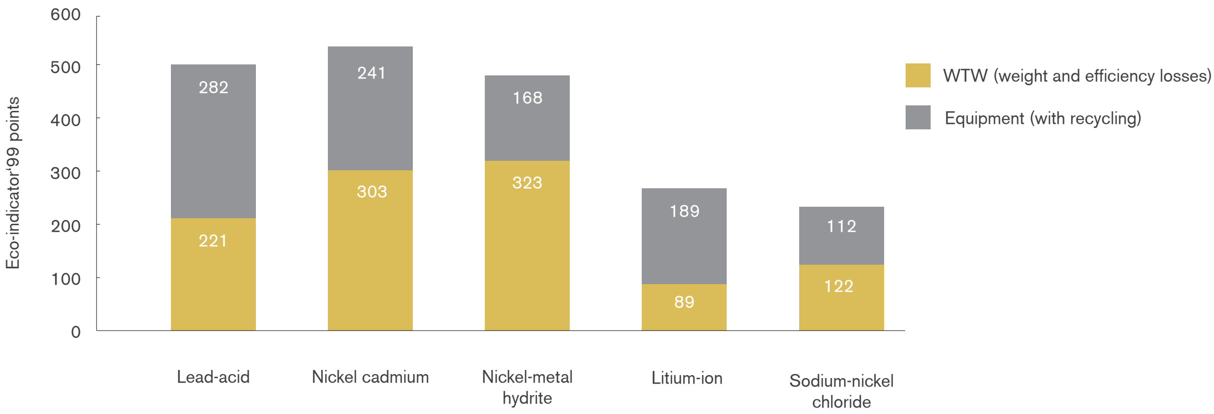

Figure 6.10 Eco-indicator'99 net results (credited for recycling) for the environmental score of different battery types – all dimensioned to provide 60 km range at an 80% depth of discharge for an 888 kg electric car (excluding the weight of the battery) and a vehicle life distance of 180 000 km with 3000 charge-discharge cycles. The WTW phase corresponds to the amount of electricity needed to cover for internal losses and to carry the weight of the battery itself, based on a European mix. Source: Van den Bossche et al. (2006)

Figure 6.10 shows the scores of different battery types for a fully electric compact car according to a panel-based weighting system named Eco-indicator'99.[15] It is possible, as mentioned above, to aggregate LCA results to one single score in order to analyse the trade-off between benefits in several impact categories and drawbacks in others. Different impact categories are then weighted based on societal values and summed up. It shows that the high energy density and low system losses of the lithium-ion and sodium-nickel chloride technologies are rewarded with low scores. Recycling is important for the results for all battery types – high collection rates and that almost all material can be recovered with virgin material quality has been assumed in the study. For the newer technologies this means that an entire new recycling industry must come into place on a large scale if these results are to be realized (see Chapter 7 for a critical discussion on this assumption).

Another thing to bear in mind when reading results from traction battery LCAs is that battery technology is progressing very rapidly. A consequence is that data for environmental performance very quickly get outdated. Evidence of this is that in studies conducted around 2005 it was common to assume one or even two battery replacements over an average vehicle life time, while today it is often argued

14 See for example Frischknecht and Flury (2011). Life cycle assessment of electric mobility: answers and challenges – Zurich, April 6, 2011. *The International Journal of Life Cycle Assessment,* 16, pp. 691-695.

15 LCA impact assessment can be performed to achieve a single scale for all categories – to provide support for the interpretation of the results. Eco-indicator'99 is such a method where the weighting principle is based on the average damage a certain environmental load causes in Europe.

that the battery will last as long as the vehicle.[16] At the same time critical steps in the manufacturing have also been improved. Finally, technology development also change which battery types that are considered relevant and therefore included in the study in the first place.

Summing up, impact assessment beyond GHG can be conducted to very different degrees, from a couple of selected additional emissions in inventory format to more than ten different aggregated impact categories or even further to a weighted result. However, with regard to emissions of airborne pollutants in general, it turns out that the values for GHG is a good overall indicator for all related impact categories. On the other hand, impact categories related to resource extraction, such as abiotic resource depletion and toxicity, provide new information and indicate that further in depth analysis is needed.

REFLECTIONS AND CRITICISMS

Traditionally, LCA is a tool for analysing the environmental burden of a reasonably well defined and mature product or service, for all stages of its life cycle. However, key traits of emerging technologies, such as electric propulsion of road vehicles, are that they have not yet reached the level of maturity and scale that they show potential for. The examples given in this chapter show that most assessments focus on the performance of today's electric vehicle technology used in today´s electricity production system. Still, both vehicle technology and electricity production may be expected to have changed considerably before the vehicle volumes are comparable to those of ICEVs. Furthermore, improvements in the production, both due to progress in manufacturing technology and benefits of scale, may decrease the future environmental load significantly in different equipment life cycle stages.

As an alternative, LCA can be regarded as a tool for strategic assessments of a technology. It is then less relevant to examine the environmental performance in the current state of development, in contrast to some future state where the technology has reached its full potential.[17] This time aspect is relevant not only for the actual vehicles and components, but even more so for the electricity production mix. As shown, all impact categories are dependent on the WTW electricity and in most cases this is the dominating factor. Most studies today are designed to answer a set of specific questions based on the current electricity production and technology level. The numerical results provided are then particular for the given context and study format. Consequently, there is a risk to be misled if too much focus is set on detailed results and less on the very varying input. Instead is important that LCA studies identify and also broadcast the one crucial message on which all studies show consensus – for externally chargeable electric vehicles to reach their full potential to help mitigate global warming, the electricity production must be made clean and free from emissions of fossil carbon (see also Chapter 2, 5 and 8).

16 See for example Zackrisson, M. et al. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues. *Journal of Cleaner Production,* 18, pp. 1517-1527.
17 See Hillman, K. M. and Sanden, B. A. (2008). Time and scale in Life Cycle Assessment: the case of fuel choice in the transport sector. *International Journal of Alternative Propulsion,* 2, pp. 1-12.

Nevertheless, given the different results presented in this chapter it should also be pointed out that some impact categories are more well-established than others and generate more robust results. Those relating to the vehicle tailpipe emissions, such as global warming, are very robust. In all such categories electric drivetrains show clear benefits to conventional ones. In the case of human toxicity there are many uncertainties related to data availability and aggregation procedure. At the same time, there is reason to heed the signal from LCA studies, however uncertain, and try and minimise use of mineral resources and leakage of toxic substances from mine tailing. The risk of problem shifting from emissions related impact to impact related to dependence on certain metals is further discussed in Chapter 7. The direct risks related to handling vehicles (such as risk for explosion) is not normally part of LCAs, but could in principle be weighed against the more indirect toxic effects that are included. The direct risks related to handling are discussed in Chapter 4.

Another observation, which is also reflected in this chapter, is that almost all scientifically published LCA studies concern cars for individual transportation. Other vehicle types such as heavy duty trucks and buses remain to be more fully explored (see Chapter 14 on the perspective of freight transport companies). It should also be pointed out that the vehicle end-of-life generally is not so well mapped. Effective recycling of materials with high quality is currently difficult to achieve. At the same time, a high degree of recycling is necessary, again, for these vehicles to reach the environmental performance they show potential for.

As a final reflection, the holistic perspective of LCA is a key to its usability as a learning tool. For example, it can help identify dependencies and relationships which are not obvious at first, such as the dependency on electricity production system and the need for efficient recycling.

CONCLUDING REMARKS

This chapter has presented different setups for LCA studies on electric and hybrid vehicles. It has discussed how the answers provided depend on both the technical and methodological scope. WTW studies demonstrate that greenhouse gas emissions from vehicles in general are reduced with increased electrification of the drivetrain, but the main conclusion is that this improvement is heavily dependent on the fossil content of the electricity mix. As a consequence, assuming that BEVs and PHEVs will constitute a large share of all vehicles only in the long term, power companies and policy makers must acknowledge that electrifying vehicles with external charging capability make their task of enforcing fossil free electricity production, on a global scale, even more urgent and important.

In addition, WTW studies also show that the driving behaviour and traffic situation is important. Electrified drivetrains are most beneficial in city traffic with a lot of driving at slow speed. This is a perfect match with the built-in reduction of local tailpipe emissions and limited range. Moreover, complete LCA studies point out an increased importance of the equipment life cycle, indicating that it is most beneficial to make use of electric drivetrains in vehicles that are intensively used (see Chapters 10 and 11 for the economic version of the same argument). This conclusion may be of importance to policy design as well as strategies in the automotive sector, e.g. which market sectors that should be targeted with incentives and investments, and how the size of electric and combustion drivetrains should be balanced in PHEV designs.

Studies providing more extensive impact assessment mainly confirm the important role of the electricity production. However, with regard to toxicity issues, environmental agencies and policy makers as well as the automotive and power industries should be aware that aspects related to mining possibly can become an environmental area of attention in the future. Efforts made to improve these practices are beneficial also for hybrid and electric vehicles.

Moreover, policy makers, the automotive industry and the recycling industry should learn that establishing a proper recycling system for lithium batteries and other components is yet another key to success. It is, in fact, a necessary condition for technology diffusion beyond minor niche markets. It can also be noted that the current LCIA of resources accentuates fossil energy and does not reveal depletion of minerals such as lithium or rare earth metals which may become critical for electric and hybrid vehicles in the future (Chapter 7).

Finally, it may be concluded that the answer to the main question of this chapter is that electrified passenger cars already today generally gives less environmental impact than their conventional counterparts. These results are robust and supported by a large number of publications. In this context, LCA may then be regarded as a learning tool giving the possibility to identify important improvement areas in striving for increased sustainability of electrified vehicles.

7

WILL METAL SCARCITY LIMIT THE USE OF ELECTRIC VEHICLES?

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INTRODUCTION

The possibility that material scarcity might restrain technologies is an old and complex issue. Arguments have traditionally been from one of two perspectives: one beginning with the fact that the planet is finite, and the other pointing out that both the technologies that supply materials and those that demand them evolve, and thus the economic availability of resources and the capacity of innovation to substitute materials are the most important factors determining scarcity.[1] The real price of most material commodities has dropped in an almost unbroken trend for a century, indicating that most materials are more economically available than ever before[2]. There is therefore a burden of proof on those who would claim that innovation cannot continue this trend. Yet, some materials such as gold and platinum are so rare that it would be unthinkable to use them instead of iron as construction material in buildings and bridges. More sophisticated analysis is required to say anything useful about the possibilities for using a given material for a given application.

Discussions on material scarcity have come back to the forefront of industrial politics and research through issues such as China's current dominance of the rare earth elements (REE) supply. Electric vehicles are one of several applications that make use of a range of the materials discussed.[3] Cars in general contain a

1 For an excellent overview of the arguments, see Tilton, J. E. (2003). On Borrowed Time? Assessing the Threat of Mineral Depletion. Washington, D.C, RFF Press.
2 See Tilton (2003) and Slade, M. E. (1982). "Trends in natural-resource commodity prices: An analysis of the time domain." Journal of Environmental Economics and Management 9(2): 122-137.
3 See for example European Commission (2010) "Critical raw materials for the EU", US DoE (2010) "Critical materials strategy" and Federal Ministry of Economics and Technology (2010) "The German Government's Raw Materials Strategy".

large variety of materials, and a general trend towards lightweight materials and electronic components is enlarging the roster of metals used. Electric vehicle drivetrains contain a number of additional components using large quantities of metal, such as batteries and electric machines. To achieve a transition to broad usage of electric vehicles, large stocks of some of these metals will need to be supplied at rates far exceeding current extraction, why the speed and timing of such a transition is critical. Recycling will be required for many materials in order to maintain a large societal stock of metals, but achieving this may be a challenge. Finally, the concerns regarding many of the materials, are not a result of either physical rarity or economic scarcity, but arise instead from the reliance of some actors upon a very concentrated supply chain. In order to discuss the possibilities and implications of material scarcity for electric vehicles it is important to achieve better understanding of the factors that may cause concern for a number of materials, as well as the possibility for substituting other materials in their place.

ASSESSING RESOURCE CONSTRAINTS ON TECHNOLOGY DIFFUSION

As implied in the introduction, there is a difference between *scarcity* and *rarity*. A metal that is rare doesn't have to be scarce if the demand for the metal is low. The concept of scarcity implies that there is a demand that somehow exceeds supply. In this chapter we are not primarily interested in rarity, not even in scarcity in general, but in the *availability* of a material for a specific application. To be even more precise, we are interested in the relationship between the availability of a given material for a specific application and the *requirement* of that application for that particular material. If the envisioned *requirement* exceeds the envisioned availability, we may talk about *resource constraints* on technology diffusion.[4] The resource constraint may be global or applicable only to a set of actors with restricted access to the required resource.[5] A *critical* material, in this context, is typically defined as a material which availability is constrained, not only for something (a technology or a set of technologies) that is considered important, but also for someone (a company, a country or society as a whole).[6]

In the previous two paragraphs, we briefly addressed the questions 'How much?' and 'For whom?'. A third equally important question is 'When?'. It is not only the *total available stock* of a material that needs to match the total requirement for the material in a prospective technical system (such as a global fleet of electric vehicles); the *annual availability* and the requirement in different phases of development also need to match. The timing of demand and supply is essential.[7] It should be noted that conclusions drawn in studies with a time frame of the next ten years are of limited value for discussions on longer term constraints, and vice versa. Short term (<10 years), medium term (say 10-40 years) and long term (>40 years) constraints may be qualitatively different.

4 See Andersson, B. A. and I. Råde (2001). "Metal resource constraints for electric-vehicle batteries." Transportation Research Part D: Transport and Environment 6(5): 297-324 and Andersson, B. A. and I. Råde (2002). Material constraints on technology evolution: the case of scarce metals and emerging energy technologies. A handbook of Industrial Ecology. R. U. Ayres and L. W. Ayres. Cheltenham, UK, Edward Elgar Publishing ltd.

5 Similarly, one may analyse limited access to key techniques due to patenting or trade secrets or limited access to key markets.

6 In addition, the concept of critical materials normally also implicate limited substitution opportunities at the level of materials, products and functions.

7 See Andersson and Råde (2001) and in particular Kushnir, D. and B. A. Sandén (2012). "The time dimension and lithium resource constraints for electric vehicles." Resources Policy 37:93-103.

To measure the severity of a constraint we need to put numbers on material requirement and availability, in terms of total stocks as well as annual flows. Estimates of materials requirement have to be made from one or many demand scenarios. Any demand scenario is a product of two factors, the *specific materials requirement*, i.e. the materials demand per functional unit, i.e. per unit of the technology in question, and the *number of units* demanded.

To put a number on the specific materials requirement we need to carefully define which technology we are assessing, i.e. define a functional unit and define how generally the results apply. Indistinctness about technology definition is a common reason for misinterpretation. Examples of this may include when an assessment of 'lead acid battery electric vehicles' in the 1990s was used to make claims about 'battery electric vehicles', which by definition includes vehicles with all kinds of battery chemistries,[8] or when an assessment of 'family sized battery electric cars' are used to make claims also about 'electric vehicles in general', which should include a variety of vehicle sizes and transport modes (see also Chapter 2 and 6). Examples from other technology areas include attempts to defame or raise concerns about 'wind power' (in general) because of the use or rare earth elements in some designs and about 'solar cells' because some designs use indium and tellurium.

In any scenario, assumptions need to be made about how technical development and changing performance characteristics (e.g. speed, range, comfort and safety) for the defined functional unit (e.g. a car) will affect specific materials requirements. Observe that such assumptions should not be viewed as forecasts, in particular if longer time frames are applied. Instead, they form parts of an *explorative scenario* (what-if scenario) that should inform us about something interesting or relevant to upcoming decisions.

The explorative character of the demand scenario is even more evident when it comes to assumptions about the scale of the system, i.e. the number of units (e.g. vehicles) demanded. One can make use of various assumptions about population growth and per capita consumption of a technology. *Extreme scenarios* are often informative. An alternative is to let this parameter be the dependent variable of the study, e.g. by posing a question such as: How many battery electric cars per year can be produced before materials availability constrains production rates?[9]

On the supply side, we need to distinguish between *primary* and *secondary* resources, where the former is virgin resources still in the ground (or sea) and the latter is already processed and used material that is stored in artefacts in use or in waste deposits.

There are many different measures of primary resources. On one hand you have the total number of atoms in the Earth's crust and sea, and on the other, you have the *reserves*, i.e. the amount of discovered resources that are economically recoverable at current prices. For almost all elements the former exceeds the latter by a factor of 1 million to 100 million. Neither of these measures represent a proper

8 Today, not many would consider the lead acid battery EV to be a good proxy for EVs, while this was not uncommon in the 1990s. See e.g. Lave, L.B. et al., (1995). Environmental implications of electric cars. *Science* 268, 993-995.
9 See Andersson and Råde (2001).

estimate of the resources that could become available within a relevant time frame (a couple of decades to a century).

While some elements like silicon, iron and aluminium are abundantly available in ordinary rock, most metals are *rare* and could only conceivably be extracted from the tiny fraction that is concentrated in certain rare minerals (Figure 7.1). One of the few attempts to estimate the size of this fraction suggests that for rare metals only 1-10 ppm of the amount in the crust is available in ores (the major part being diluted in ordinary rock). This conclusion suggests that for some highly exploited metals like copper, actual physical limits on resources may not be that far away despite much more material remaining in the crust.[10] While crustal abundance is not a measure of metal availability in absolute terms, Figure 7.1 indicates that there is some correlation between crustal abundance and annual extraction. Iron is almost one billion times more abundant than ruthenium and, as consequence, can be extracted in volumes exceeding 100 kg per capita per year compared to a few milligrams of ruthenium.

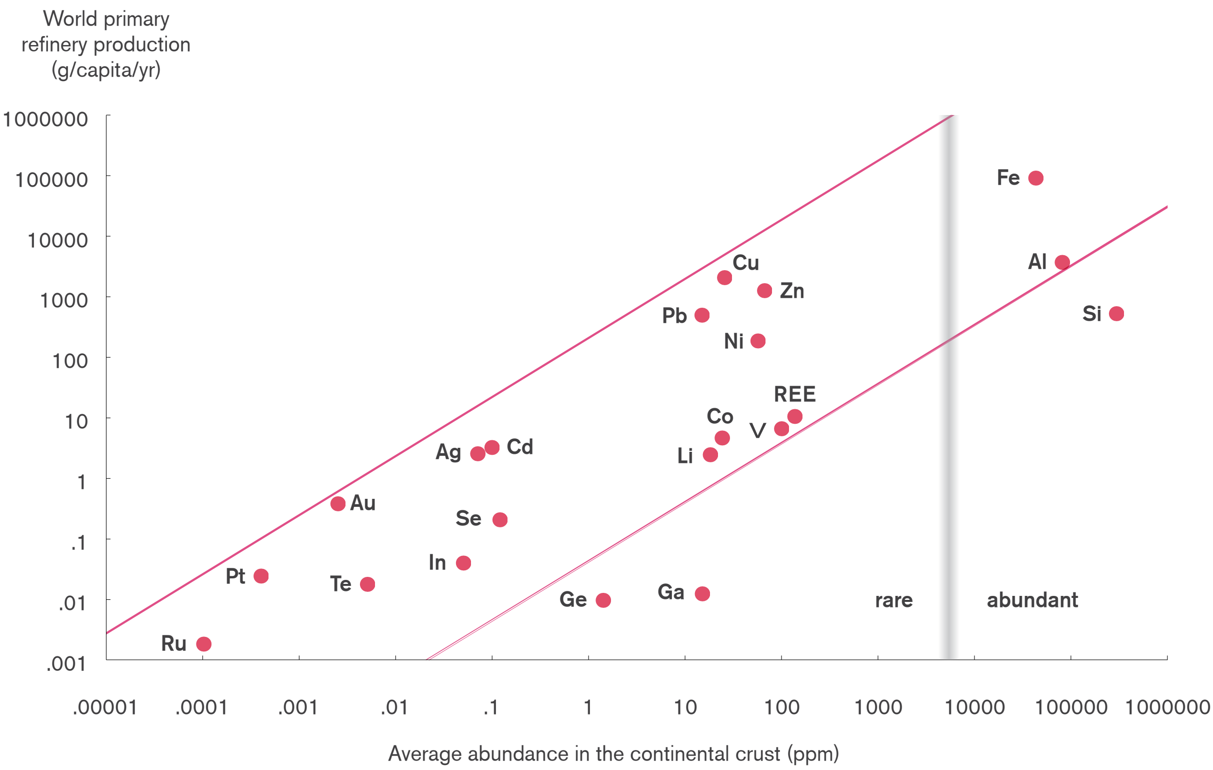


Figure 7.1 A comparison of annual extraction, measured as world primary production per capita, and geological rarity, measured as average abundance in the continental crust. Most of the metals can be capped within a band spanning three orders of magnitude. Towards the upper end of the band with relatively high extraction rates one finds the 'industrially mature' metals like gold, silver, lead and copper. A distinction can be made between abundant elements, such as iron, aluminium and silicon that are building blocks of minerals in common rock, and rare metals that are found in extractable concentrations only in certain minerals in specific locations. Source: Andersson, B. A. and I. Råde (2002). Material constraints on technology evolution: the case of scarce metals and emerging energy technologies. A handbook of Industrial Ecology. R. U. Ayres and L. W. Ayres. Cheltenham, UK, Edward Elgar Publishing ltd. Original data from Wedepohl, K. H. (1995). "The Composition of the continental crust." Geochimica et Cosmochimica Acta 59(7): 1217-1232; and US Geological Survey (2000), Mineral commodity summaries.

10 Skinner, B.J. (1987). Supplies of geochemically scarce metals, in: McLaren, D.J., Skinner, B.J. (Eds.), Resources and world development. John Wiley and Sons, Chichester, pp. 305-325.

The reserves in most cases under-estimate available resources. New discoveries, improved extraction technology, and changed prices will affect what is economically recoverable. On the other hand, environmental and social concerns may limit the full utilisation of resources even if they are considered to be economically recoverable. Furthermore, losses will inevitably occur in the mining and refining of ore. Nevertheless, since reserve data is readily available for most metals, it can be used in initial preliminary surveys that probe for possible resource constraints. When such probing indicates potential mismatches with the scale or rate of a possible application, further investigations can be made. To estimate the availability of a metal for a specific technology the extraction cost from different sources can be compared to willingness to pay for the metal in the application in question. One may also need to assess the likelihood of new major discoveries.

The relationship between the size of primary and secondary resources differ greatly between metals. For some, that we here term 'industrially mature' metals, such as lead, copper and silver, the total historical extraction, and hence the potential secondary resources in the societal stock, are in parity with or even exceed the virgin reserves. Others, that we term 'industrially immature' metals, such as rare earth elements and lithium, have reserves that exceed cumulative extraction by two orders of magnitude.[11] Observe also the relation between extraction and crustal abundance in Figure 7.1, where lithium and REE have relatively low extraction rates compared to crustal abundance while the opposite is true for lead, copper, silver and gold.

The availability of the industrially mature metals to electric vehicles is likely to be constrained by *competition* with already established end-uses. The willingness to pay for a metal will determine how well a certain technology, e.g. electric vehicle batteries, can compete with other applications for the metal, and thus determine the future availability of the metal to this particular application. It might also be the case that the demand from the new application will not take off until we enter a period of increasing general scarcity, which will further increase the fierceness of competition.

In contrast, industrially immature metals could have low current extraction rates compared to the potential annual demand from a growing technology, e.g. electric vehicles. The challenge may then be to scale up extraction rates at pace with the growing technology. Hence, an assessment of the potential for *increased mining rates* is essential. A ramp up of mining and recovery may be constrained by physical limitations at mines, environmental considerations, monopolistic behaviour of producers, lack of investment due to tight capital markets or distrust and limited foresight, accidents and sabotage etc. Some of these factors may in themselves be temporary but still have long lasting consequences from price fluctuations and lack of trust. Most of them increase in likelihood and effect if metal supply is *concentrated* to a small number of producers and geographical locations.

Finally, recycling of used resources will have a profound effect on total resource availability as well as annual availability in the longer term. Efficient recycling systems need to grow at pace with the electric vehicle industry or primary supplies

11 Andersson and Råde (2002)

of many materials may be rapidly degraded. Given the low recycling rates of many metals at present, such a development cannot be taken for granted (Figure 7.2). Instead, the economic and institutional prerequisites need to be assessed for future supply of secondary as well as primary materials.

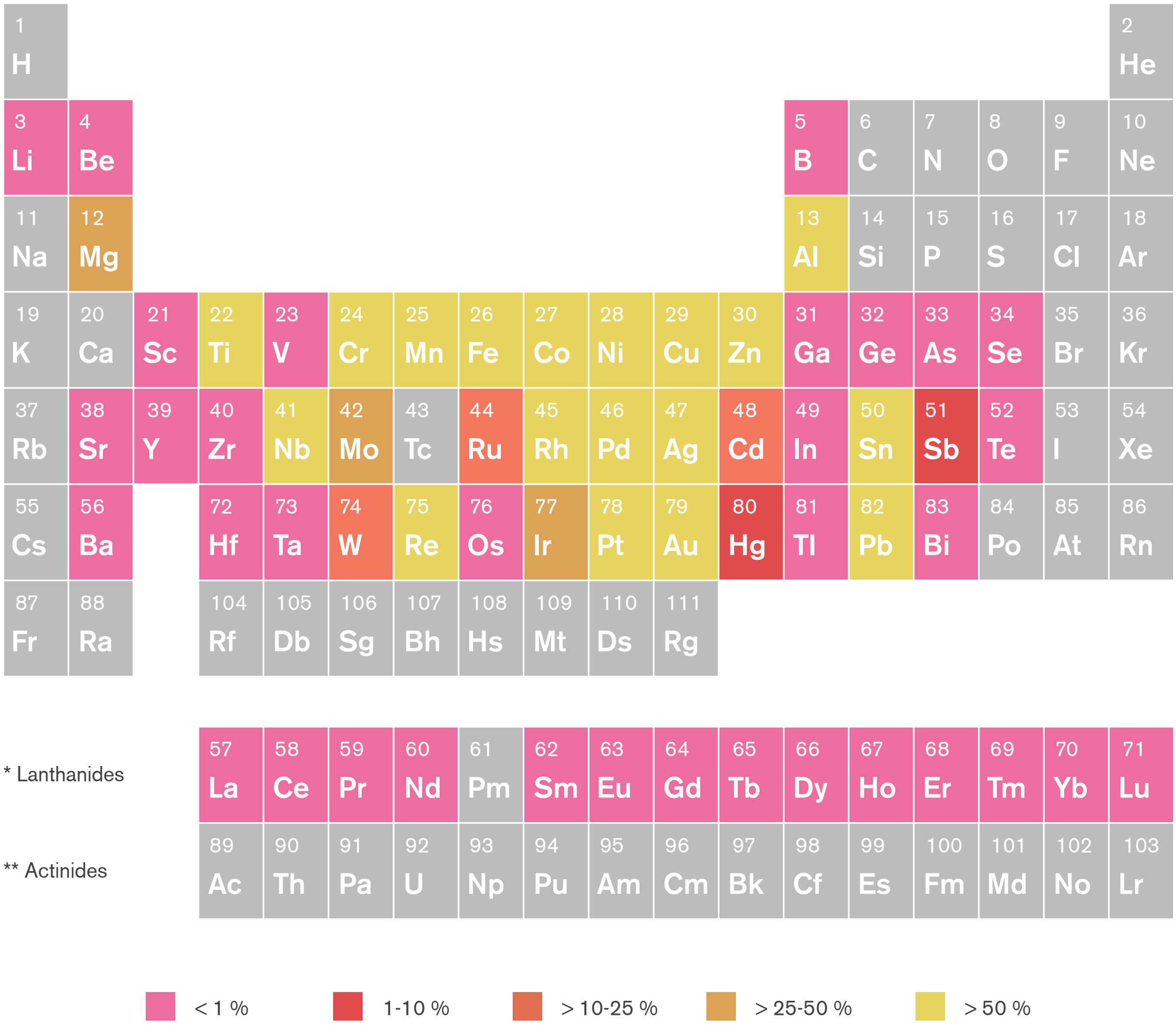


Figure 7.2 Current recycling rates are very low for many metals. Note that even at fairly high recycling rates, the accumulated material losses are substantial after a few cycles. Source: UNEP International Resource Panel (2011) Recycling rates of metals. A status report.

POTENTIAL MATERIAL CONSTRAINTS TO ELECTRIC VEHICLES

Material composition in cars has changed over time. As requirements have shifted and car designs and available materials have evolved, the diversity of materials has increased and new materials have been introduced. Over the years, cars have seen a fundamental shift in composition from wood to steel and further towards higher strength steels, aluminium, magnesium, plastics, composites and other materials, see Figure 7.3.

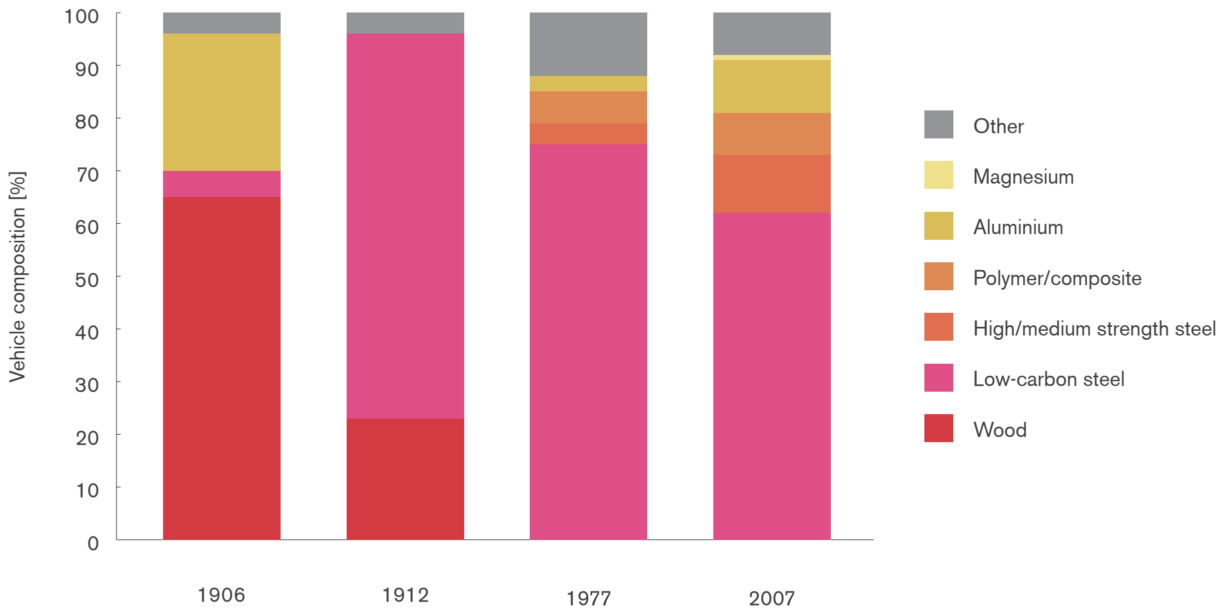


Figure 7.3 Historical shift in car composition by mass. Source: Lutsey, N. (2010) Review of technical literature and trends related to automobile mass-reduction technology, UCD-ITS-RR-10-10, Institute of Transportation Studies, University of California, Davis.

As a consequence of the push for increased energy efficiency of cars, mass-reduction designs with strong and light materials are most likely part of future car trends (Figure 7.4). Increasing the use of magnesium and high strength steels, which might contain niobium[12], means increasing dependence of metals for which concerns of their availability to the EU and US have been raised.[13]

Current material trends for cars in general point at increasing material diversity as well as increasing dependence on rare metals. This chapter focuses on metals for *electric* vehicles, but it may be relevant to ask if there are enough metals for a high global car intensity in general. Regulatory as well as customer driven requirements push the use of rare metals in cars. For example, control of tail-pipe emissions with catalytic converters typically requires platinum group metals (PGM) and REE. Safety and driver assistance features, powertrain control and 'infotainment' typically require the use of automotive electronics containing e.g. gold, silver, PGM, gallium, tantalum and REE.[14]

There are, nevertheless, a number of materials that are particular to electric vehicles. Electric vehicles rely on additional components including batteries, electric machines, high-voltage power electronics such as converters and alternators, battery chargers, and high voltage cables (see Chapter 3). The current designs of these components make use of a number of metals that may warrant further investigation. The rare earth elements neodymium, dysprosium and terbium are used in permanent magnets in electric machines and alternators. Batteries may contain lithium, cobalt, nickel, REE and manganese. Silver is used in electronic control systems and copper in high voltage cables.

12 SSAB (2012) Advanced High Strength Steels For The Automotive Industry, SSAB, Borlänge, Sweden.
13 See for example European Commission (2010) "Critical raw materials for the EU", US DoE (2010) "Critical materials strategy" and Federal Ministry of Economics and Technology (2010) "The German Government's Raw Materials Strategy".
14 Cullbrand, K. and Magnusson, O. (2012) The use of potentially critical materials in passenger cars, Master of Science Thesis, Chalmers University of Technology, Gothenburg, Sweden.

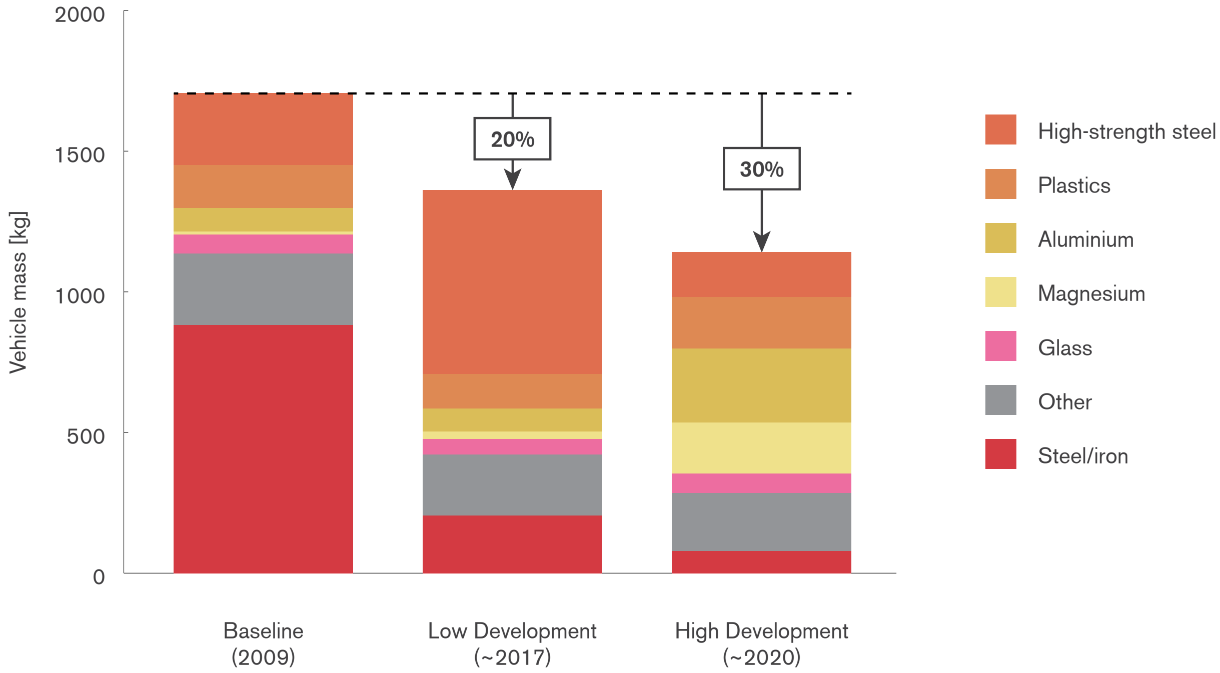
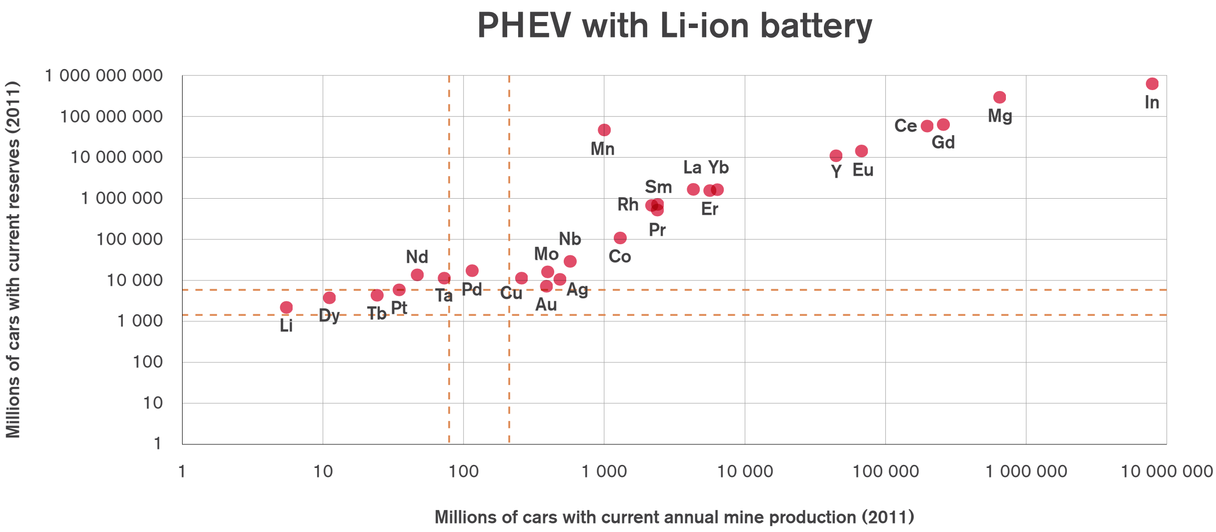


Figure 7.4. The mass by material of the Lotus baseline and mass-reduced car designs. Low and High Development illustrate concepts available for model years 2017 and 2020 commercial deployment. Source: Lotus Engineering, Inc. (2010). An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Vehicle Program as referred to in Lutsey, N. (2010) Review of technical literature and trends related to automobile mass-reduction technology, UCD-ITS-RR-10-10, Institute of Transportation Studies, University of California, Davis.

The materials requirement depends on the type of drivetrain. Plug-in hybrid electric vehicles (PHEVs) demand smaller batteries and electric machines than battery electric vehicles (BEVs), but contain combustion engines and catalytic converters which BEVs do not. A PHEV with Li-ion battery thus typically require less lithium, copper and the rare earth elements neodymium, dysprosium and terbium, but more alloyed aluminium (combustion engine) and PGM (catalytic converter) than a BEV with Li-ion battery. Both PHEVs and BEVs typically require more lithium, copper and the rare earth elements neodymium, dysprosium and terbium, but less aluminium alloys and platinum group metals than Internal Combustion Engine (ICE) vehicles.

The observed requirements of rare metals do not necessarily lead to the conclusion that resource availability will constrain diffusion of electric vehicles. To probe if some of these metals deserve closer attention we make use of two simple indicators. First, we compare the specific materials requirement of one car to the reserves of a set of selected metals. Second, we compare the specific materials requirement to annual resource extraction. The resulting indicators give us (a) the maximum number of cars that the current reserves would allow, and (b) the maximum annual growth rate of the car fleet that the current annual resource extraction would allow, if, hypothetically, each metal would be used only for passenger cars and if there were no material losses (of primary and secondary resources) to maintain the car fleet that has been built up. Figure 7.5 illustrates these indicator values plotted in a log-log diagram for two commercially available cars: one PHEV and one diesel ICE car of comparative size.



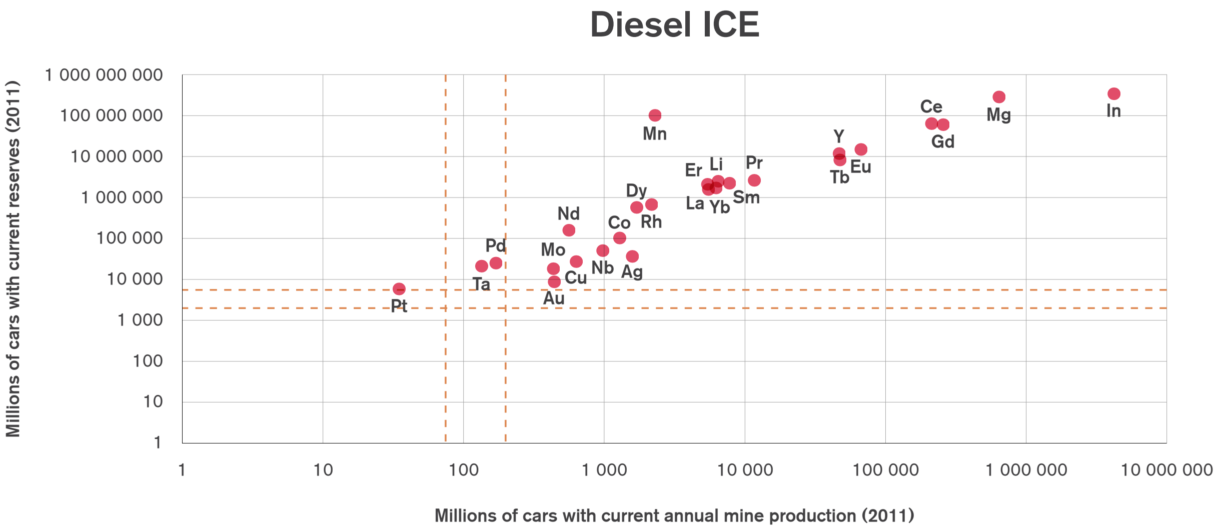


Figure 7.5 Comparison of metal requirements for a PHEV with Li-ion battery and a diesel ICE (both in the executive compact family car segment, see Table 6.2). The diagrams show, for each car, the maximum number of cars that the current reserves would allow (y-axis) and the maximum annual growth rate of the vehicle fleet that the current annual resource extraction would allow (x-axis), if, hypothetically, each metal would be used only for passenger cars and if there were no material losses. Note that reserves data can differ between sources, e.g. REE (a factor of 2) and indium (a factor of 10), and for the purpose of this analysis, low reserve estimates were chosen. Data source for material requirements: Cullbrand, K. and Magnusson, O. (2012), The use of potentially critical materials in passenger cars, Master of Science Thesis, Chalmers University of Technology, Gothenburg, Sweden. Data source for reserves and resource extraction: primarily U.S. Geological Survey (2012), Mineral commodity summaries 2012; complemented by Technology Metals Research (2012), Total code-compliant mineral resources Nov 2012; Alonso et al (2012), Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies, Environ. Sci. Technol., 2012, 46 (6), pp 3406–3414; Johnson Mathey (2011) Platinum, Interim review; and European Commission (2010) Critical raw materials for the EU.

How should this figure be interpreted? The positions of the metals along the y-axis reveal that the included metals are spread over a large range indicating resource constraints at levels from 2 billion PHEVs. *If* we assume a scenario where the PHEV model is introduced to a level corresponding to 0.2 (near future) or 0.5 (western Europe at present) cars/capita globally, and a global population of about ten billion, this results in a fleet of 2-5 billion PHEVs, indicated by the horizontal red lines. From this first rough order of magnitude estimate, it appears that current reserves seem to be sufficient for most of the included metals, even at very high car penetration rates, with the possible exception of lithium, dysprosium and terbium.

The positions of the metals along the x-axis indicate potential constraints on the annual growth of the car fleet due to limited resource extraction. While the resource extraction of several metals allows for production of several hundred million cars per year, again lithium appears at the bottom end with 5 million cars per year. The current production of electric vehicles is not near this number (PHEV and BEV around 70 000 - 100 000 units in 2012, out of some 60 million passenger cars in total), so there does not seem to be any immediate risk of constraints. But *what if* we want to expand the car production significantly over time? If a scenario of a 0.2 to 0.5 PHEVs per capita car fleet is to be reached within say 40 years, due to a ramp-up phase of maybe 15 years, about 80 or 200 million cars need to be produced annually over a period of 25 years. These numbers are represented by the two vertical red lines. In such a scenario, it is clear that the current resource extraction of some metals would have to be increased significantly, in particular lithium but also dysprosium, terbium, platinum, neodymium, tantalum and palladium. Note that the scenario also assumes that there are no material losses so that the built-up material stock in cars is maintained.

With this rough analysis we could not identify any metals as undisputable showstoppers for large-scale introduction of PHEVs. However, the extraction rate required for some materials may produce bottlenecks and thus merit further investigation. Before we continue with such a more in-depth analysis of lithium in the next section, the results presented in Figure 7.5 warrant a couple of additional remarks.

It cannot be ruled out that the seemingly unproblematic metals (those with neither resource nor rate constraints) do not constitute a risk for certain designs of electric vehicles. For example, the industrially mature metals copper, gold and silver are used in a large number of other applications. Although our analysis shows that it is less likely that electric vehicles drive the scarcity of these materials, they might still present other issues. If the competition for these materials is already fierce and increases over time, substantial price increases and even physical constraints on availability could materialise.

The comparison between the PHEV car and the diesel ICE car shows that platinum presents a similar constraint for the two vehicles (Figure 7.5). Lithium, dysprosium, terbium and neodymium are used in the ICE car, but at significantly lower levels. Praseodymium, silver, samarium and copper are also used at lower levels. Tantalum and palladium are among those remaining at approximately the same levels. In a scenario with a global expansion of diesel ICE with the specific material requirements of our design, the current extraction rate of platinum could be a constraint. The main use of platinum in cars is in catalytic converters, why platinum car demand correlates tightly with local requirements on tail-pipe emissions. If global requirements on tail-pipe emissions would reach European levels or beyond and our car design's specific platinum requirement is representative, platinum could pose a risk even at current car production levels (around 60 million cars annually).

IS LITHIUM AVAILABILITY A CONSTRAINT TO ELECTROMOBILITY?

The availability of lithium resources for a large global transition to electric vehicles with lithium-ion batteries has been studied through explorative scenarios by e.g. Kushnir and Sandén (2012).[15] The primary result is that there are many interesting and somewhat overlooked aspects affecting the prospective availability of lithium: primarily limits to the rate at which extraction can be ramped up and the gloomy conditions for recycling. The study also illustrates a variety of factors that can affect resource availability in general, from physical factors, such as material requirements of technologies and geographic concentration of resources, to market concentration, political stability and industrial politics.

The implications of a rapid global transition to EVs is explored through a scenario in which global population will stabilise at 9.3 billion towards the end of the century, global car density will reach between 0.2 and 0.5 cars/capita and EV market penetration will develop along a logistic curve to reach 95% by 2050, with 50% of all vehicles having some sort of battery by 2035. Two size assumptions for batteries bound the study, representing PHEVs and BEVs, both using lithium-ion batteries, at 9kWh capacity and 36kWh capacity respectively. Three different recycling levels (100, 80 and 0%) are assumed. The resulting cumulative lithium demand over the remainder of the century ranges from 4 to 150 Mt, see Figure 7.6.

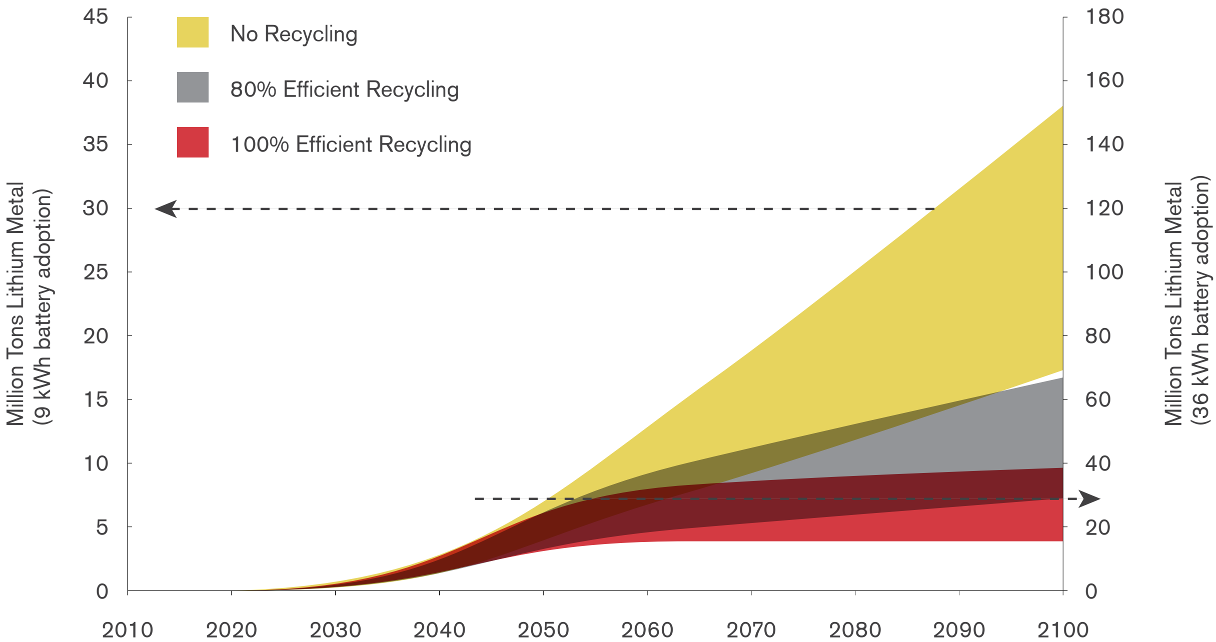


Figure 7.6 Cumulative lithium demand in the scenarios with and without recycling. The figure shows the cumulative virgin lithium demand in million tons (Mt), for growth scenarios of PHEV (left scale) and BEV (right scale). The dashed lines indicate the 30 Mt lithium reserves. The bottom end of each band corresponds to 0.2 cars per capita and the upper end to 0.5 cars per capita. Source: Kushnir and Sandén (2012).

Global terrestrial lithium reserves consist of brine and mineral deposits, which make up 85% and 15% respectively of the estimated reserves (including some marginal resources) of about 30 Mt in terms of recoverable metal. A comparison of these reserves to the cumulative lithium demand in the explorative scenarios

15 Kushnir, D. and B. A. Sandén (2012). "The time dimension and lithium resource constraints for electric vehicles." Resources Policy 37:93-103.

clearly demonstrates that the size of the battery (PHEV or BEV) matter and that efficient recycling is essential, see Figure 7.6.

Ocean resources greatly exceed any conceivable societal need and are theoretically extractable at low energy use, but have not been proven in practice. Established processes for extracting substantial lithium levels from the ocean would require vast surfaces in high insolation areas. The problems and uncertainties surrounding ocean extraction are so large that it should not be assumed for planning of the build-up phase.

The extraction rate may represent a more salient limit to a transition to EVs. Current annual lithium extraction is around 25 kton per year, a rate that will have to increase considerably to meet the demand explored in the scenarios, see Figure 7.7. Two different problems related to annual lithium availability can be pointed out. Firstly, since extraction from minerals is predicted to be constrained at about 100 kt per year (grey area in Figure 7.7)[16] the ability and willingness to expand extraction from a small number of brine sources (concentrated to a few locations and companies in Chile, Bolivia, Argentina and China) will determine the possible timeframe and form of an electric vehicle transition based on lithium batteries. This means that the build-up of a BEV fleet presents a huge challenge, while a PHEV fleet is within reach. Secondly, maintaining the lithium stock in the long run requires a very high recycling rate and a recycling industry of magnificent scale.

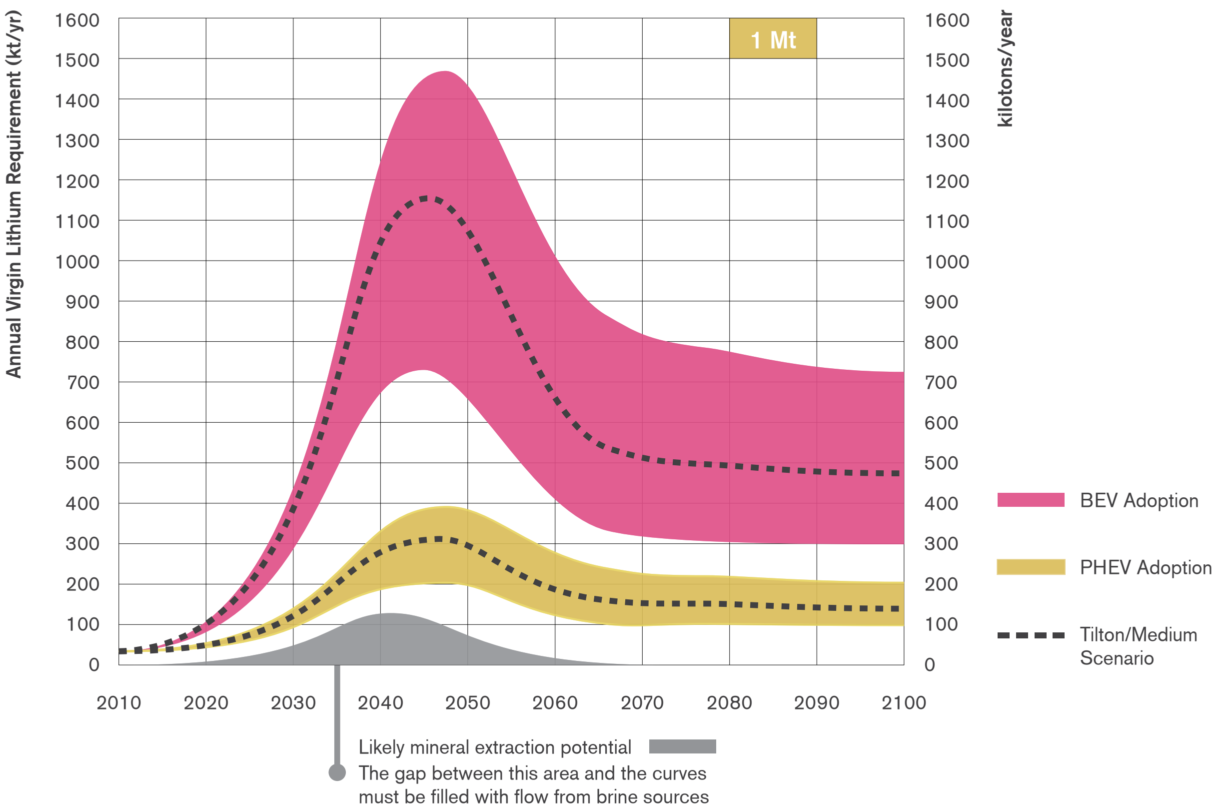


Figure 7.7 Implied annual lithium extraction rates. The demand curves assume 80% recycling. The bottom end of each band corresponds to the 0.2 cars per capita scenario and the upper end to the 0.5 cars per capita scenario. The estimated limited extraction rate from minerals (in grey) indicates the role of lithium from brines and ocean. Source: Kushnir and Sandén (2012).

16 See Kushnir and Sandén (2012) for details.

Despite the importance of recycling, its economics are currently not good and may even degrade as battery material evolves towards less expensive and valuable compositions (such as the removal of cobalt). Due to the assumed exponential growth of initial EV diffusion and the possibility to expand lithium production up to a certain level, it could take a long time until any real shortage of lithium occurs. If this will be case, the market price alone is unlikely to provide incentives for a timely development of the recycling capability and capacity that will be required to maintain a large societal lithium stock, and hence, it will be necessary to design policies to encourage recycling.

In conclusion, it is not enough to look at lithium resource stocks and conclude that there is enough. If recycling does occur, then resource exhaustion does not appear to be a credible threat. Yet recycling is nowhere near economic and will likely require policy support to realise. The time dimension is more important than the resource stock in the case of lithium; issues surrounding the required rate of lithium flows, and particularly their dependency on a concentration of producers and countries, will occur well before any limits to resource quantity. Maintaining the present vision of personal mobility through changing the technology of the car may thus be unrealistic unless the time scale for such a transition is extended.

A worldwide push for lithium batteries risks building up a large, capital intensive stock of cars and associated production systems that are vulnerable to resources more concentrated to a few producers and countries than that of the oil supply system existing today; more than two thirds of the terrestrial resources considered here are concentrated in a small area shared by the three countries Chile, Bolivia and Argentina and possibly to be exported via a single Chilean port. There is currently no battery technology able to compete with lithium for large vehicle batteries, and no concrete indication that this will change in the foreseeable future (Chapter 3). If there are no readily scalable alternative to lithium supplies or alternative vehicle energy technologies, this would be a considerable risk to critical societal infrastructure. This is a strong case for maintaining diversity at all levels of the system. Possible policy responses could be to maintain a portfolio of known lithium resources that are already assessed at the mine feasibility stage in order to minimise the time of any prospective disruption as well as bringing other vehicle and battery technologies to competitive readiness.

CONCLUDING REMARKS

The purpose of this chapter is to discuss the risk that metal scarcity might constrain a large-scale diffusion of electric vehicles. We have tried to show the multi-faceted nature of the materials scarcity issue. It is not enough to answer the question of “how much” of certain materials electric vehicles require in relation to available geological resources. It is also necessary to answer “to whom” are the resources available, as well as “when” can they be supplied.

Cars in general are complex products relying on a large number of metals. Current trends towards lightweight materials, electronic components and tail-pipe emissions control will enlarge this dependence. Electric vehicles are likely to increase it even further with components such as batteries, electric machines, high-voltage power electronics such as converters and alternators, battery chargers, and high voltage cables. Notable examples of such metals are lithium, terbium, dysprosium, neodymium, praseodymium, silver, samarium and copper.

A rough analysis of material requirements for PHEVs did not identify any of these as undisputable showstoppers for large-scale technology diffusion. However, given that lithium batteries are used, lithium is singled out as potentially problematic and clearly warrants some consideration for policy makers. The in-depth investigation of lithium availability clearly demonstrates that a transition to electric vehicles based on lithium batteries is not unproblematic mainly due to concerns about limits to annual extraction and geographical concentration of reserves. Dysprosium, neodymium, platinum and tantalum might also pose a problem concerning the current extraction rate. We also noted that some industrially mature metals such as copper, gold, silver and molybdenum, might present a risk, in the sense that fierce competition from other end uses could lead to substantially higher prices and even physical constraints on availability in the long term.

Another striking result is the role of recycling. Recycling of rare metals in cars is so far neither well developed nor well understood. An example is lithium battery recycling. In all ambitious EV scenarios, extensive recycling will be needed, but currently no lithium is recycled back into battery grade lithium. The dispersive use of many rare metals in cars presents a huge challenge for making recycling happen, in particular on pure commercial grounds.

Finally, we want to return to a fundamental, but sometimes overlooked feature of technology assessments. A constraint to the diffusion of a specific technology does not necessarily imply a constraint to a broader phenomenon. A constraint to some forms of electric vehicles does not imply a constraint to a transition to electromobility in general. Different battery types present different risks and some are less constrained than others. Different car designs offer different opportunities. In terms of material resource efficiency, hybrid electric vehicles might be advantageous in requiring less battery material than pure battery electric vehicles (there could also be other reasons for a smaller battery, see Chapter 10). In addition, smaller vehicles such as electric bicycles, other means to distribute energy such as electric roads (Chapter 2 and 14), and more efficient transport modes are examples of a plethora of substitution opportunities and alternative routes to electromobility. Resource availability will play a role in determining future technological trajectories, but will unlikely be a showstopper for electromobility in general, and even less so, if potential materials constraints are continuously monitored and taken into consideration.

8

FUTURE ENERGY SUPPLY AND THE COMPETITIVENESS OF ELECTRIC VEHICLES

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INTRODUCTION

The future market for electric vehicles (battery electric vehicles and plug-in hybrid vehicles) will likely depend on technological developments (improvements to batteries and charging systems, for instance, see e.g. Chapter 3 and 15); regulatory and institutional settings; public acceptance and customer demands (Chapter 10-14). Academic scholars have examined these factors quite comprehensively. However, it is not sufficient that battery technology improves to a certain level; that charging becomes more efficient; or that regulatory frameworks support electric cars. Electric cars must also compete with other alternative vehicle technologies such as cars fuelled by biofuels or hydrogen fuel cell vehicles. Vehicles are also embedded in larger energy and transport systems. This holds true for all technologies, but may be of greater importance for electromobility, as electric cars are connected to and dependent on the electricity system. The cost and environmental impacts of electric vehicles are influenced by electricity costs and technologies used for producing electricity (see Chapter 5 and 6 on some environmental and energy resource implications of different types of electricity production). In this chapter we examine how the development of the energy sector can influence the competitiveness of electric cars in a carbon-constrained future.[1]

1 This chapter is largely based on Hedenus et al (2010) *Cost-effective energy carriers for transport - the role of the energy supply system in a carbon-constrained world. International Journal of Hydrogen Energy 35 (10) pp. 4638-4651*, and Grahn et al (2009) *Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO_2 Targets: Connections between transportation and other energy sectors, Environmental Science and Technology (ES&T) 43(9) pp. 3365-3371.*

The cost of producing electricity and transportation fuels will, in the long run, depend on the performance of conversion technologies and availability of resources. Scarce oil resources will increase the price of gasoline, whereas limited areas of productive land will drive up prices of biofuels. The development of technologies such as solar, wind and nuclear energy will be a key determinant of future electricity costs. There is also a potential link between electric cars and intermittent energy sources such as wind and solar, as batteries may temporarily store electric energy to be used in the grid during peak demand (Chapter 9).

This chapter focuses primarily on light duty vehicles for personal transport. We investigate if, and in which ways, the stationary energy system may influence the use of car technologies and fuel options, in a carbon-constrained future. We present data on competing vehicle technologies and explain which overall system effects influence cost-competitiveness. This is illustrated with results from the global long-term energy systems model GET. We conclude by discussing some policy implications of these potential system effects.

FUTURE COSTS OF ELECTRIC CARS AND ITS COMPETITORS

There are several alternative vehicle propulsion technologies and energy carriers that can achieve near-zero emission of greenhouse gases. These may or may not include an electric drivetrain (Chapter 2). In Hybrid Electric Vehicles (HEV), an electric motor is coupled to the internal combustion engine drivetrain (Chapter 3). The battery cannot be charged from the grid but enables the internal combustion engine to run more efficiently and excess energy is stored in the battery. When the engine needs extra power, such as during acceleration, stored electricity supports propulsion. This yields an overall efficiency about 30% higher than that of the conventional internal combustion engine (ICE) vehicle (see e.g. Chapter 6, Figure 6.4). HEVs are presently available on the market where the Toyota Prius is the market leader. At present, hybrid engines can be fuelled with either gasoline or diesel. In the future they may also be compatible with biofuels or gaseous fuels such as methane or hydrogen.

The Plug-In Hybrid Electric Vehicles (PHEVs) are similar to HEVs but with larger batteries that can be charged from the electric grid. PHEVs have a similar driving range to ICE vehicles, since the combustion engine is used when the battery is discharged. Again, fuel used in the internal combustion engine could, in principle, be liquid or gaseous. Today there are few commercially available PHEVs, but markets are expected to grow in years to come.

Battery Electric Vehicles (BEVs) use only a grid charged battery as power source, and are typically around three times more efficient than internal combustion engines (see Chapter 5 for an in depth discussion on efficiency). BEVs also eliminate most local pollutants. From a climate perspective, the electricity supplied to BEVs must be produced from low-emitting power sources such as renewables, nuclear energy or fossil energy using Carbon Capture and Storage (CCS) technology (see Chapter 6). BEVs typically have shorter driving ranges (100-200 km) compared to around 500 km for conventional vehicles. For this reason, BEVs are not directly comparable to other vehicles. There are a few BEVs available today, but batteries (which comprise a large part of vehicle costs) are expensive. To make BEVs commercially competitive, the battery production costs, capacity, and lifetime must be improved. BEVs are best suited to urban commuting due to their limited range (Chapter 10). Unless the overall transport system changes dramatically, BEVs cannot reasonably be expected to out-compete conventional vehicles (see Chapter 11 and 12 for alternative appraisals of customer value).

Fuel cells in vehicles generate electricity to drive an electric motor using hydrogen fuel and oxygen from the air. Fuel cell vehicles (FCVs) are expected to be around 50% more efficient than conventional gasoline vehicles. There are a few FCVs available today, but there is no mass-production. Fuel cells are expensive and improvements to production cost and lifetime are required. Additionally, hydrogen is challenging and costly to distribute and store, and there is a lack of an infrastructure to supply hydrogen to vehicles. FCVs could also be equipped with a reformer so that biofuel or fossil fuel could be converted to hydrogen on board, but this implies both a loss of efficiency and increased cost.

Since this chapter focuses on the climate impacts of transportation, we consider energy carriers such as electricity, hydrogen and biofuels that can lower the CO_2-emissions compared to current fuel use. Fossil fuels considered are gasoline, diesel and natural gas whereas coal-based fuels are assumed to give raise to too large amounts of CO_2-emissions to be considered part of a carbon-constrained future. In principle, the vehicle technologies described here may be combined with all types of fuels, as presented in Table 8.1.

Table 8.1 Examples of combined propulsion technologies and energy carriers for road vehicles that could be consistent with stringent climate targets.

Vehicle technology	Electricity	Hydrogen	Biofuels	Fossil fuels
Battery electric vehicles (BEVs)	X			
Plug-in hybrid electric vehicles (PHEVs)	X	X	X	X
Internal combustion engine vehicles (ICEVs)		X	X	X
Hybrid electric vehicles (HEVs)		X	X	X
Fuel cell vehicles (FCVs)		X	X	X

Hydro and nuclear power are two well-established electricity production technologies with low greenhouse gas emissions. Other alternatives include renewable energy technologies, such as wind power and solar cells (PV), which are currently experiencing rapid growth. Both wind and solar are intermittent energy sources – they generate electricity when the wind is blowing and the sun is shining. The use of wind power and solar PV is thus limited unless temporary storage, enhanced transmission between regions or advanced demand-side management is introduced. Analyses indicate that around 20 % of the electricity supply can be produced from wind power alone in the EU without major systemic changes.[2] There appears to be three possible routes that can achieve significant global reductions of greenhouse gas emissions from electricity production. These are:

2 Gregor Giebel. A Variance Analysis of the Capacity Displaced by Wind Energy in Europe Wind Energy (2007) 10:69–79.

renewable electricity systems with energy storage; fossil fuels with carbon capture and storage; and advanced nuclear technologies with a high level of safety and safeguards against nuclear weapon proliferation.

Hydrogen is currently produced commercially from natural gas (via steam reforming) and from electricity (via electrolysis). Hydrogen can be considered a low-emission fuel if the electricity used for electrolysis is produced with low carbon emissions. However, hydrogen produced via electrolysis is more costly than the electricity used to produce it. Other options for producing hydrogen with low emissions include thermo-chemical cycles fuelled by thermal solar or nuclear energy, steam-reforming of methane (natural gas or biogas) or gasification of solid energy sources (coal or biomass) where low or negative emissions can be achieved if carbon capture and storage technologies are applied to the conversion process. Hydrogen production options are less mature (with the exception of electrolysis) than renewable electricity production. Additionally, hydrogen requires a new distribution infrastructure, which is not the case for electricity.

The technological maturity of biofuel production varies for different kinds of fuels. Ethanol production from wheat and sugarcane and FAME production are commercially viable technologies. In contrast, second generation biofuels such as methanol, ethanol or DME produced from cellulosic materials are presently at research or demonstration phases (see Systems Perspectives on Biorefineries 2013, Chapters 2 and 12).

Internal combustion engines that use fossil fuels (gasoline and diesel) are presently the most competitive technology for road transport. This holds true even if there is a CO_2 price of around 100 EUR/ton CO_2, which is the case in many European countries. This is essentially due to the scale and maturity of the industrial system delivering the technology. This may change when the competing technologies benefit from economies of scale and learning. We therefore attempt to make a cost assessment of the various propulsion and energy carrier combinations from a future perspective (year 2030) (see discussion on time perspectives in Systems Perspectives on Biorefineries 2013, Chapter 1).

As a reference, we assume that a gasoline car with an 80 kW mechanical output has a specific price of 11,000 EUR (2010). Incremental costs for more advanced vehicle technologies are estimated for 2030, including an uncertainty range for key components.[3] Vehicle costs depend heavily on component costs. The cost of batteries, fuel cells, and hydrogen storage tanks are the most uncertain. As can be seen in Figure 8.1, the uncertainty of the HEV cost (which is already a relatively mature technology) is low compared to the cost of, e.g., FCVs. Based on our estimates, FCVs and BEVs are likely to be more expensive than alternatives in 2030.

Here we assume that BEVs have a range of 150 km, whereas all other types of cars have a range of 500 km. If we instead assume that the range is more than

3 Battery costs are assumed to vary between 100-330 EUR/kWh compared to current cost around 700 EUR/kWh. Fuel cell stacks presently cost around 520 EUR/kW, and for the future scenario it is assumed that fuel cells are mass-produced in a cost range from 30-200 EUR/kW. Hydrogen and natural gas storage costs are varied over the ranges from 4-13 EUR/kWh and from 3-4 EUR/kWh respectively.

150 km, BEVs would be considerably more expensive as battery costs comprise a substantial part of total costs.

Fuel costs depend largely on how fuel is produced, and for this reason we consider the same types of vehicles in two different scenarios where we either assume that CCS will be large scale available (a CCS scenario) or not where in the latter scenario renewables, first and foremost solar energy, will dominate (a renewable scenario). Comparisons should mainly be made within each scenario. However the costs related to the HEV cars (on the right hand side in Figure 8.1) can be compared to both scenarios since these costs are not directly affected by the stationary energy system. Note that the fuel cost category includes costs of liquid or gaseous fuels alongside the cost of electricity and carbon dioxide emissions (at a price of 300 EUR/ton CO_2). Distribution and handling costs are also included, taking energy losses in different steps into account. The capital costs for producing fuels and electricity are varied by ±50%.

When the total costs are compared in Figure 8.1, hybrid biofuel vehicles are the lowest cost alternative (per km). They are followed by PHEVs run on biofuels, which are the most competitive alternative both in the solar and coal CCS scenarios. Note that the uncertainties are large, and in many cases cost ranges overlap for different vehicles technologies.

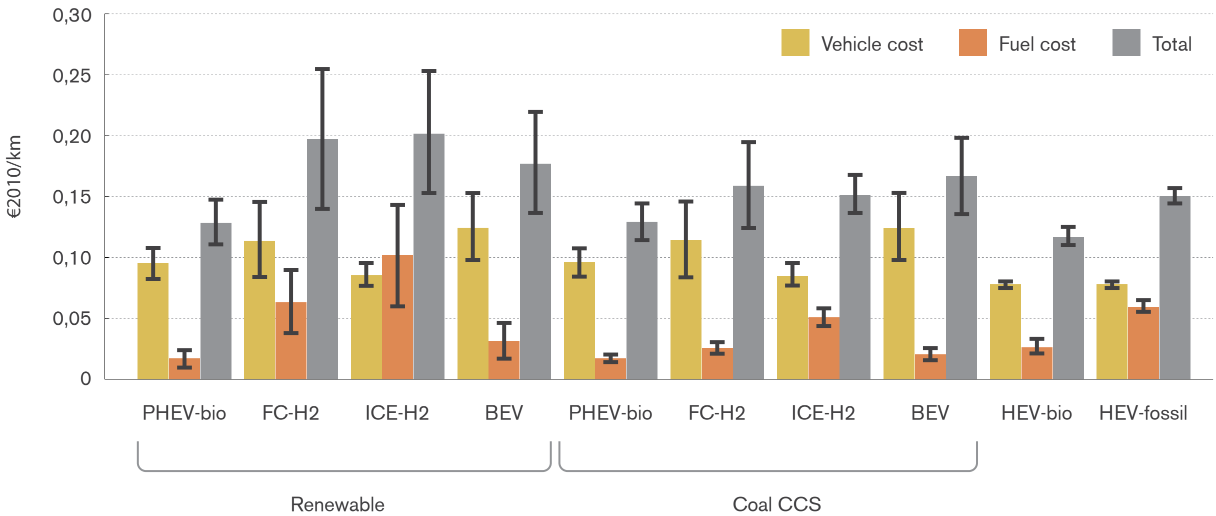

Figure 8.1 Costs per km for different propulsion and energy carrier combinations with uncertainty bars. Two different supply production scenarios are showed: one assuming that CCS will be large scale available and one without CCS where instead renewables dominate. A carbon dioxide cost of 300 EUR/ton CO_2 is applied to all fossil-based options. Vehicle costs are based on a theoretical standard car with an 80 kW engine and a driving range of 500 km. BEVs are assumed to have a driving range of 150 km.

IMPACT OF RESOURCE SCARCITY AND THE FUTURE EVOLUTION OF THE ENERGY SUPPLY SYSTEM

The costs in Figure 8.1 are basically estimates of production costs for vehicles and fuels. However, consumer prices are not only related to production costs. One critical issue is how the scarcity of different energy sources will affect the price of electricity and fuels.

If the demand for a product increases at a higher rate than production, there emerges a scarcity of that good and the price increases. For example, the high prices of apartments in city centres are related to a high demand and limited supply. It does not cost more to build an apartment in the centre compared to in the country side. But as demand for apartments in the centre grows, prices increase, and since there is not adequate space for more apartments supply cannot increase. A permanently higher price of apartments in attractive areas compared to less attractive areas is the result.

If there is a limited supply capacity for crude oil, for instance, the price of oil may increase rapidly if demand increases. A temporary scarcity rent may thus emerge. However, as new investments are made, supply increases and the price drops. However, if there is a physical scarcity of oil because of natural resource depletion, prices will continue to increase unless substitutes are available. To evaluate the relative competitiveness between different vehicle types it is thus important to evaluate scarcities that may emerge in the future. To this end one must assess geological resources; developments in extraction technologies; and demand projections. Oil is mainly used for transport and coal is mainly used for producing electricity and heat for industrial processes. Since the geological resources of oil are smaller than those of coal, it is likely that the oil price will rise at a faster pace than the coal price. This could favour a transition to electric cars because gasoline prices will increase faster than electricity prices – assuming that coal continues to be the primary fuel for electricity production.

However, resources such as biomass may also be subject to scarcity effects. Productive land and water is needed to produce biomass. Land is a limited resource that is subject to competition between food and fibre production. There is approximately 1.5 Gha of arable land and 3.5 Gha of pastoral land in the world. With rather optimistic assumptions we could dedicate 0.5 Gha to bioenergy production, which could produce around 100 EJs of raw biomass and perhaps an additional 100 EJ of bioenergy could be produced from residues in agriculture and forestry (see also Chapter 4 on bioenergy resources in Systems perspectives on Biorefineries). Energy demand for global road transport by 2050 is expected to be around 100 EJ of fuel, which is approximately the amount of fuel that can be produced from 200 EJ of raw biomass. However, other sectors may also demand biomass for industrial process heat, feedstock for chemicals, or electricity production. If demand is higher than the potential supply, a scarcity problem emerges and the price of land increases. This means that the price of both food and bioenergy will increase.[4] It is thus not sufficient only to assess production cost of biomass today. It must be assessed from a long-term perspective that includes scarcities.

Hydrogen and electricity are energy carriers that must be produced from other energy sources. The relative price between electricity and hydrogen will influence the competitiveness of electric cars or hydrogen fuel cell cars in the future. Furthermore, the efficiency of the drive train is roughly 50% higher in an electric car than in a hydrogen fuel cell car. If hydrogen is produced from electricity with electrolysis, the price of hydrogen will be higher than electricity. Given the lower

4 D. J. Johansson and C. Azar. A scenario based analysis of land competition between food and bioenergy production in the US. Climatic Change (2007) 82: 267–291.

efficiency of hydrogen cars, there must be a considerable difference between fuel cell and battery costs in order for fuel cell vehicles to become cost-effective in a scenario where hydrogen is produced with electrolysis. However, it should be noted that hydrogen can be produced at times when intermittent electricity is abundant and therefore electricity price is low. Hydrogen produced with electrolysis at low electricity prices can thus be cheaper than electricity produced when supply is scarce (i.e. when electricity prices are high).

Hydrogen can also be produced directly from high temperature heat with a thermo-chemical cycle. Hydrogen can thus be produced from concentrating solar collectors or nuclear energy at about the same cost and efficiency as electricity.

Coal with CCS can be used to produce both hydrogen and electricity with low carbon emissions. If hydrogen is produced from coal with gasification, a rather pure CO_2 stream is produced and can be captured and stored. If integrated gasified combined cycle (IGCC) with CCS becomes the preferred technology to produce coal-based electricity in the future, the price of producing hydrogen can be expected to be around half that of electricity. This would make hydrogen cars more competitive than PHEVs and BEVs.

From this we can conclude that the future electricity system will have an important impact on the competitiveness of future vehicle types. For this reason it is important not only to explore different future scenarios that assess different costs for batteries, biomass, etc. as is often done, but also overall developments of energy systems.

MODELLING RESULTS

In order to explore the potential effects of changing production costs and scarcity rents; we include them in an energy system model. The GET (Global Energy Transition) model is a linearly programmed cost-minimising model that describes the global energy system in a 100-year perspective. The model generates the fuel and technology mix scenario that meets energy demands at lowest global energy system cost. The model includes demand scenarios for different end-use sectors; estimates of primary energy resources; and the costs and efficiencies of energy conversion and vehicle technologies.

Primary energy sources in GET include fossil fuels (crude oil, natural gas, and coal); non-renewable non-fossil sources (nuclear); and renewable sources (hydroelectric, wind, solar, and biomass). These energy sources can be converted to transportation fuels or used for heat generation, electricity, or both (cogeneration). The use of nuclear energy has been limited to the present level, as the model represents a future influenced by political concerns for nuclear proliferation and safety.

Capture and storage of CO_2 from combustion of fossil fuels is an energy technology that can facilitate the production of low-CO_2 electricity, industrial process heat and hydrogen. Its potential to mitigate climate change is substantial given that it can be applied to several different types of energy conversion. Furthermore, if biomass is equipped with CCS, electricity or hydrogen can be produced with net negative CO_2 emissions (see also Chapter 7 in Systems Perspectives on Biorefineries 2013).

In the road transportation sectors, cars, trucks, and buses are represented. The GET model includes five fuel options: petroleum, natural gas, synthetic fuels (produced from coal, natural gas or biomass) electricity and hydrogen. The model also includes five vehicle powertrain technologies: internal combustion engine vehicles, hybrid-electric vehicles, plug-in hybrid electric vehicles, battery-electric vehicles and fuel cell vehicles.

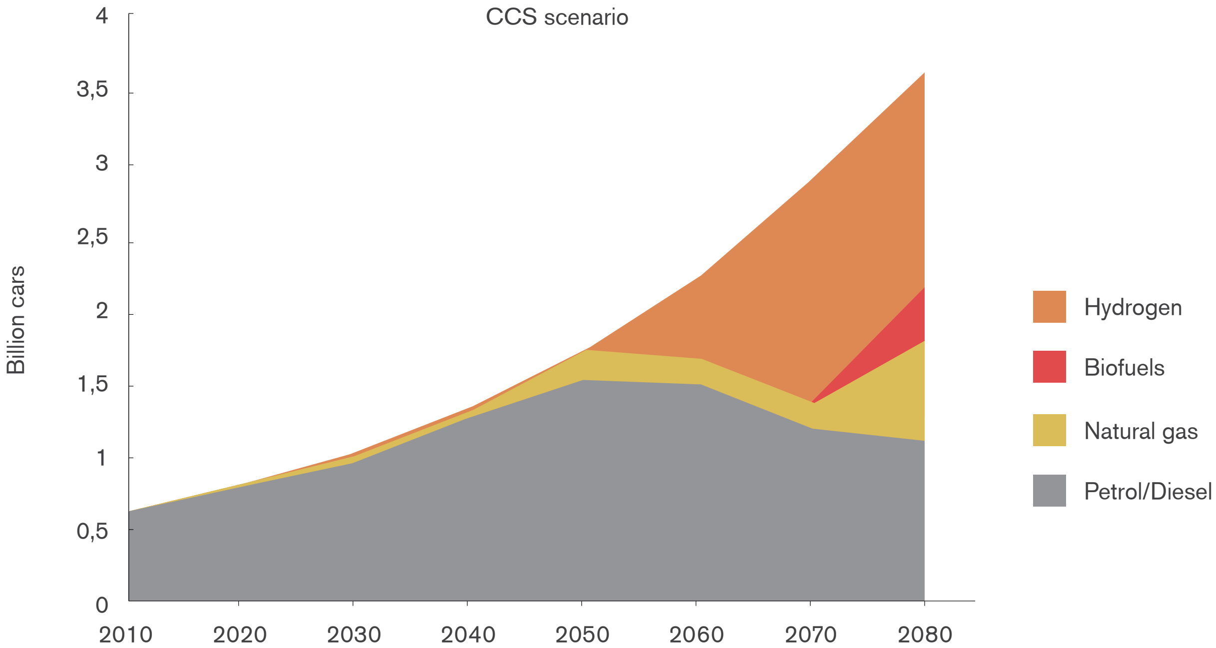

Figure 8.2 Cost-effective fuel choices for the global car fleet in a scenario where atmospheric CO_2 concentration are stabilised at 400 ppm. CCS technology is assumed to be available on a large scale.

This modelling framework is useful for studying how the development of different aspects of the energy sector can affect cost-effective choices of transportation fuels and propulsion technologies that can meet stringent climate targets. To illustrate this, we run the model twice, both towards a CO_2 concentration stabilization target of 400 ppm. In one run CCS technology is assumed to be available on a large scale and in the other it is not. CCS technology is currently under development, and there are presently no full-scale facilities in the world. CCS has also been subject to public resistance in Germany and there are uncertainties regarding legislative frameworks. Even though CCS has the potential to be an important mitigation technology, there remain technical and social barriers to its widespread deployment. Results in terms of lowest cost fuel choices for the world's car fleet are presented for the two model runs in Figure 8.2 and 8.3.

Figures 8.2 and 8.3 show that an energy system based on CCS vs. renewables has an important effect on the cost-effective choice of transportation technologies. Note that fossil fuels remain in the global car fleet until 2080 in both scenarios. This is because the cost of reducing emissions in other sectors, such as electricity production and residential heat, is typically lower than reducing emissions in the transportation sectors. Here it is assumed that the climate target is reached at lowest possible cost, which also implies that more expensive investments are delayed. This is related to the assumption that GDP will increase over the coming century and that society (according to standard economic theory) prefers to burden more wealthy future generations. Interestingly, fossil fuels are more prominent in the CCS scenario compared to the renewable scenario. The reason is that the cost of reducing emissions in the energy and industrial sector is lower when CCS is available. In this scenario less mitigation efforts are required within the transportation sector, which explains the larger use of fossil fuels.

Although biofuels have gleaned a relatively high level of public support, they are used to a limited extent in our transport scenarios. Biofuels are rarely used in internal combustion engines in our scenarios, but emerge in plug-in hybrids in the model run where CCS is not available on a large scale. However, electricity is used for around 65 % of the distance travelled by plug-in hybrids. Around 10 EJ biofuel is thus used for cars in 2070 in our renewable scenario, which could be compared to around 170 EJ crude oil produced, and around 30 EJ used in global car fleet, annually today. The limited use of biofuel in the transport sector is related to the fact that there are alternative uses for biomass (residential and industrial process heat) where the same amount of biomass can reduce CO_2 emissions at a lower cost.

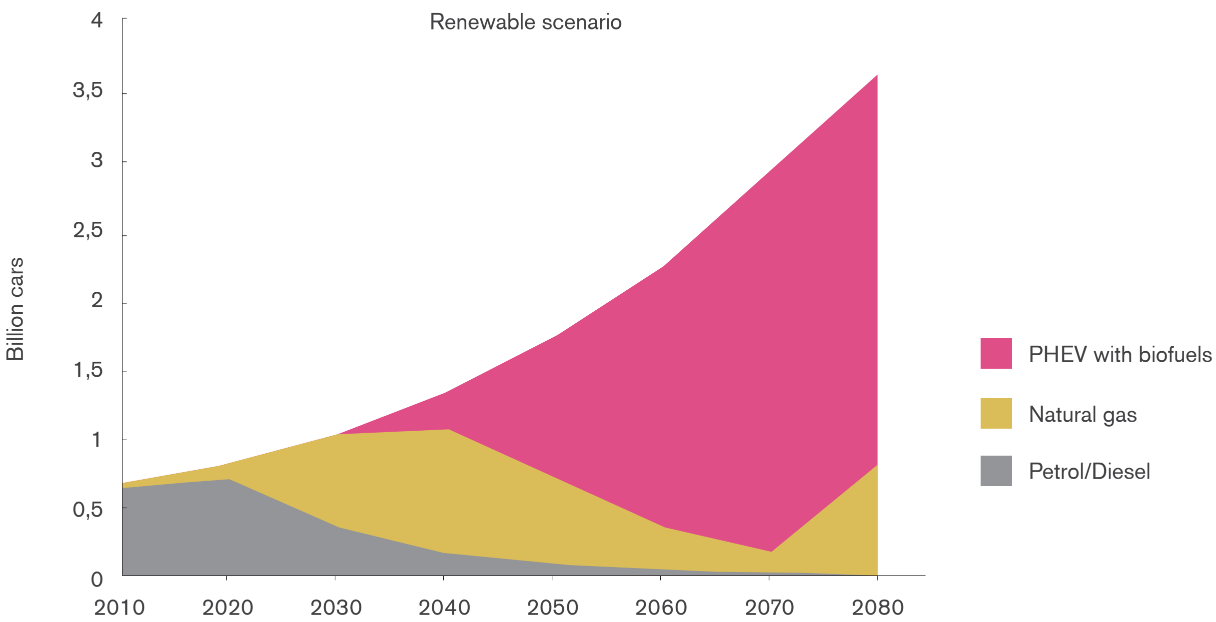

Figure 8.3 Cost-effective fuel choices for the global car fleet in a scenario where atmospheric CO_2 concentration are stabilised at 400 ppm. CCS technology is assumed *not* to be available on a large scale.

In the renewable scenario the cost of producing hydrogen and electricity from solar energy is roughly the same. Here PHEVs are expected to be more cost-effective than hydrogen cars. However, when CCS is applied, hydrogen can be produced at almost half the cost of electricity. This is because CCS can be applied to plants that produce hydrogen from fossil fuels with steam reforming or gasification. In the renewable scenario we assume that 80 % of electricity could be supplied by wind and solar energy using a combination of low cost storage technologies, demand side management, and extended grid expansion. For this reason, hydrogen is not utilised as an electricity storage option in the renewable scenario. However, if we are less optimistic about the potential of introducing large-scale renewables without using hydrogen as an energy storage option, we expect that electricity prices are around 50% higher than hydrogen prices. Notwithstanding, PHEVs are projected to be the long-term dominant vehicle technology in this scenario.

IMPLICATIONS FOR POLICYMAKERS

In the modelling exercise above we assume that the climate target is met in the most cost-effective way from a global perspective. In reality, this is not the most likely development for several reasons. It seems very unlikely that developing countries, having lower levels of GDP, will adopt similar emissions restrictions as OECD. However, our global results would probably hold in qualitative terms for smaller regions such as the European Union. Yet it is unlikely even in this case that internal EU targets will be met in a cost-effective manner. Current policy incentives for emissions reduction are generally much stronger in the road transportation sector compared to the stationary energy sector. Some sectors such as agriculture and shipping are still unregulated as regards to greenhouse gas emissions. There are several reasons for this. First, there is a long tradition of environmental regulation in the transport sector. Second, agricultural lobbyists have an interest in promoting biofuels and governments strive to become less dependent on imported fuels for energy security reasons. Third, road transport is not exposed to international competition in the same way as some industries. For these reasons policymakers tend to impose weaker regulations on globally competitive industries in order to protect jobs and to avoid carbon leakage (where industries relocate to other countries and continue to pollute). In conclusion, we can expect that the emission reductions in the transportation sector will be larger than what could be expected from a pure cost-efficiency perspective.

The way this affects the relative competitiveness of different vehicle technologies depends on which policy instruments are introduced. A biofuel mandate would promote further use of biofuels. Energy taxation, where the energy carrier is taxed based on its energy content (common in Europe today) would promote electricity and hydrogen as they have higher drivetrain efficiencies (see Chapter 5).

CONCLUSIONS

Many factors affect the competition between BEVs, PHEVs, FCVs and ICEVs and the relative roles of electricity, hydrogen, biofuels and fossil fuels. In this chapter we examined the influence of factors such as vehicle cost and efficiency, discussed the importance of policy design and briefly mentioned institutional and behavioural aspects. We focused mainly on how developments in the electricity supply sector affect the cost-efficiency of fuel and propulsion technologies in the transportation sector. Out of many possible model runs, we displayed a renewable scenario and a CCS scenario. There are two main mechanisms that we would like to highlight. First, the relative cost of producing electricity and hydrogen (which is mainly determined by technological factors) is a major component in the development of the transportation sector. Second, technologies available to mitigate climate change in other sectors affect the urgency with which one need to reduce the use of fossil fuels in the transportation sector. Uncertainties remain regarding how technologies will perform in the future and related to their application in different industrial contexts. However, our main conclusion is that connections between the energy sector and the transportation sector are important to understand for the long-term development of electromobility and use of biofuels for transport.

9

ELECTRIC VEHICLES AND INTERMITTENT ELECTRICITY PRODUCTION

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INTRODUCTION

A critical component in the ongoing development of electricity utility infrastructure is the increasing inclusion of environmentally-friendly and renewable sources of generation, as well as increasing the adoption of technology which can utilize this energy.[1] Modernization of the electrical grid is very likely to see a drastic increase in the amount of electrical energy being produced from renewable sources such as wind and solar. While the reduced environmental impact and low marginal production costs of renewable energy compose a set of readily apparent benefits which motivates the inclusion of renewable energy generation technologies in the modernization of the electrical grid, the use of these technologies is not without its own obstacles.

Owing to the nature of the renewable energy sources (primarily wind and solar), it is impossible to predict the energy production of such a source with complete

1 See Chapters 5, 6 and 8 for discussions on the importance of renewable energy sources for the efficiency and environmental impact of electromobility.

certainty. Even though probabilistic variations creating forecast inaccuracy lead to difficulties in operational planning of reserves, perhaps the greater challenge of renewable energy resources is their intermittent nature, i.e. there is no method available for controlling the timing or the rate of energy production coming from the original source. Incorporating small amounts of renewable generation requires little modification to the power system, but as the share of energy derived from renewable sources increases it will become important to supplement renewable generation with technologies for energy storage and flexible consumption which can make use of renewable electrical energy in an effective manner. Electrified vehicles have the potential to meet this supplemental need, given the flexibility in the charging of vehicles over time as well as their inherent ability to store electrical energy.

Not only is the nature of the physical components (the renewable and traditional generation sources, the electric vehicle charging loads, and the electricity network) important in analysing the contribution that electric vehicles can have on integration of renewables, but the method of control also plays a critical role.

A proper control strategy for electric vehicle charging needs to meet energy demands for transportation (Electric Vehicle Loads) while it minimizes need for network reinforcements (Network Constraints) and improves efficiency of the electricity generation system (Renewable Energy Sources).

RENEWABLE ENERGY SOURCES

Electricity generation systems have traditionally been supplied by fossil fuels, but are likely to rely increasingly on wind, sun and biomass in the future. However, as seen in Figure 9.1, the electricity generated by wind or solar power varies in time and is non-dispatchable, whereas thermal units are most efficient if run continuously at rated power.

In a thermal electricity generation system complemented with wind or solar power, variations in load and renewable generation can be managed with three different strategies: *part-load operation* of selected thermal unit(s), *start-up and shut down* of selected thermal unit(s), and *curtailment of renewable power*.[2]

Operating thermal units at part-load is associated with an increase in costs and emissions per unit of electricity generated, since the efficiency of a unit decreases with the load level. The start-up of a thermal unit may take hours to days, during which time the unit consumes fuel without generating electricity. Curtailment of renewable power implies unnecessary costs due to discarding the zero marginal cost energy, as well as excess emissions at some thermal unit in the system.

Inclusion of electric vehicle charging in the power system demand represents yet another source of potential load variations which the electricity generation system needs to manage. However, the inclusion of electric vehicles in the electricity generation system presents an opportunity for a fourth option for variation management: *regulated vehicle charging*. Utilizing an appropriate charging strategy,

2 Göransson, L. (2009). Wind power in thermal power systems. Licentiate Thesis. Chalmers University of Technology

electric vehicles have the potential to reduce the need for part-load operation and thermal cycling of thermal units, and decrease the likelihood of curtailment of renewable generation.

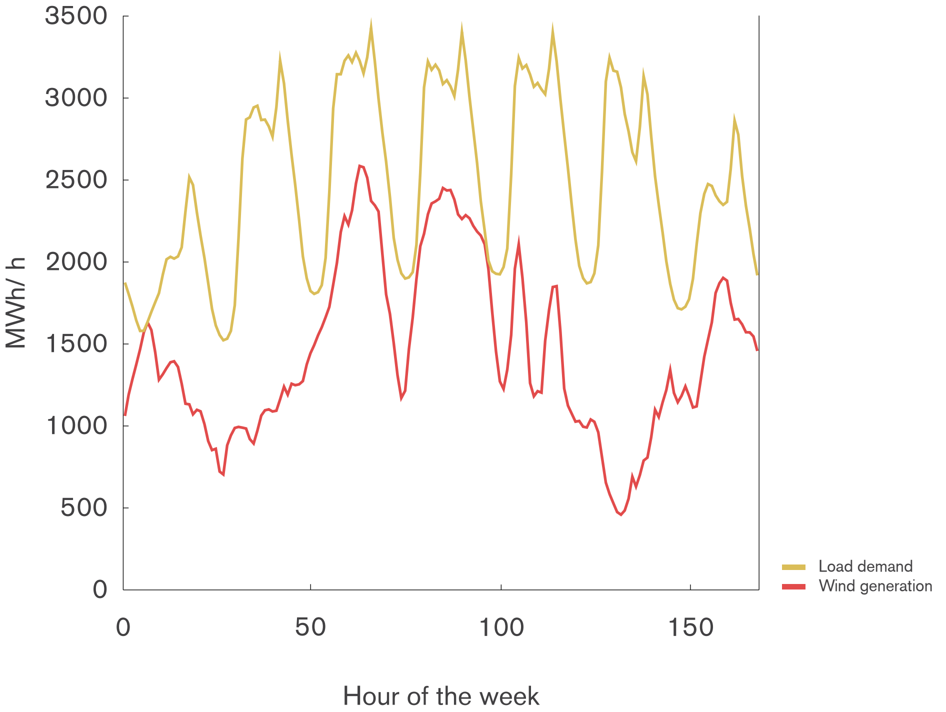


Figure 9.1 Weekly load demand and wind generation fluctuation sample data from Western Denmark. The intermittent variation of the wind output is seen to be uncorrelated to the daily load variations, which can thus reduce reliability and efficiency of the electricity system.

The potential of electric vehicle charging to manage variations in the electricity generation system depends on the charging strategy and the nature of the variations. Variations in demand for electricity follow a diurnal pattern with low demand for electricity at night-time. Electricity generation systems are designed to manage the diurnal variations in demand by letting some thermal units have better cycling properties, at the expense of higher running costs. These units are only operated during the day, when demand is highest. At night, only units with low running costs and poor cycling abilities are left in operation.

By utilizing electric vehicle charging as a method of managing variation, cost-effective integration of renewable generation is facilitated. During the daytime, quick cycling thermal units can adapt to renewable generation output at little expense in terms of efficiency in operation. At night, when demand is closer to base load generation output, an excess of renewable generation would be likely to require part-load operation of the base load thermal units, or curtailment of the renewable generation. Through night-time charging of electric vehicles, the competition between wind power and base load units can be avoided.[3] There are also seasonal variation in wind and solar power output, but variations spanning over time horizons longer than 24 hours are unlikely to be managed by vehicle charging, since it requires an overinvestment in battery capacity in the vehicles.

3 Göransson, L. et al. (2010). Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. Energy Policy, 38 (10) pp. 5482-5492.

ELECTRIC VEHICLE LOADS

In order to understand how electric vehicles may interact with intermittent electricity production through grid connection, an understanding of how electrified vehicles may be used must also be established. The availability of the energy storage resource in electric vehicles will have a probabilistic variance which will depend strongly on factors such as the quantity of electric vehicles in use, the geographic layout of a particular location, and the time of day. The typical user of a personal electric vehicle will tend to use the vehicle to commute from home to work in the morning, and return to home in the evening. Depending on the charging strategy used, the vehicle usage pattern, along with the physical location of residential and commercial areas within a city, may have a strong influence on the availability of storage resources throughout the day. Additionally, the desired charging pattern for the typical user involves charging the vehicle at home, which implies an increased availability of storage resources in residential areas during the evening and night time. Owing also to the investment costs and bureaucratic obstacles related to charging infrastructure, home recharging is likely to remain the predominant option, especially in the near future. For commercial electric vehicles, both the timing and location of charging is likely to follow a more predictable pattern.

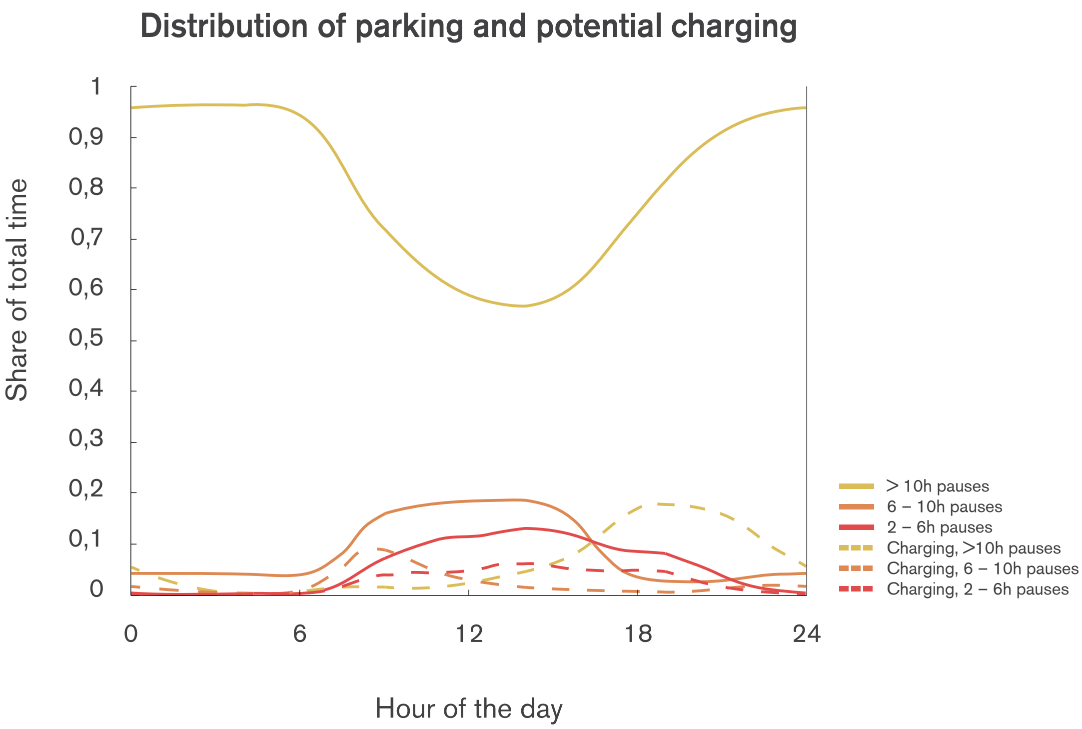


Figure 9.2 The distribution in time for parking of different lengths and potential charging during these pauses. Assumed: PHEVs with 2 kW charging immediately after parking which continue until battery is full (10 kWh) or pause ends. Energy use 0.2 kWh/km in Charge Depletion mode. (From Kullingsjö and Karlsson, 2012)[4]

To actively utilize the storage capacity of electric vehicles, there must be both the possibility and a willingness from the vehicle owner to accept an alteration of the time period over which the charging occurs. An estimate of the usage and charging patterns for electrified vehicles can be obtained by observing movement pattern data for the current conventional vehicle fleet. Figure 9.2 displays the

4 Kullingsjö, L-H, S Karlsson, 2012. The Swedish car movement data project. In Proceedings to EEVC 2012, Brussels, Belgium, November 19-22, 2012.

parking patterns for privately driven conventional vehicles in Sweden. The figure also displays potential charging loads derived from these driving patterns, assuming that the cars are PHEVs and are plugged in and charged immediately upon parking. The charging is assumed to have a consumption of 2 kW per vehicle, and lasts until either the battery is full or the parking is ceased.

From this data, it is seen that parking for periods exceeding 10 hours occurs primarily during the night, but may also occur during the day, due to the presence of vehicles which are not used daily and may remained parked for several days. These extended parking periods typically take place within residential areas. Without some method of control, the charging will be concentrated in the evening, when many commuters arrive home. There is a risk that this charging will coincide with the typical evening peak in residential electric load, if some control method is not applied to delay charging. Parking for periods of 6 to 10 hours is highly connected to commuter driving patterns, where the charging would occur in the morning when the driver arrives at work, mainly in commercial or industrial areas. There is additional charging risk because commuter vehicle charging at work coincides with commercial power demands. Shorter parking periods between 2 to 6 hours is distributed more evenly over the day, as would be the corresponding charging.

If the charging time of electric vehicles is not actively controlled, the charging load can do little to benefit the integration of renewables. However, customer willingness to provide a flexible charging demand alters from customer to customer, and may also vary based on customer circumstance. The greatest opportunities for flexibility exist when the next instance the vehicle will be needed for transportation are well known, such as residential charging when the vehicle is needed the following morning, or commercial charging when the vehicle is needed at the end of the work day. Future developments in battery technology may have a strong impact on the possibility of flexible charging, because expensive batteries will motivate a vehicle having a small battery which will need to be charged often. When cheaper battery technologies become available, it becomes more reasonable that flexible charging could occur overnight at home.

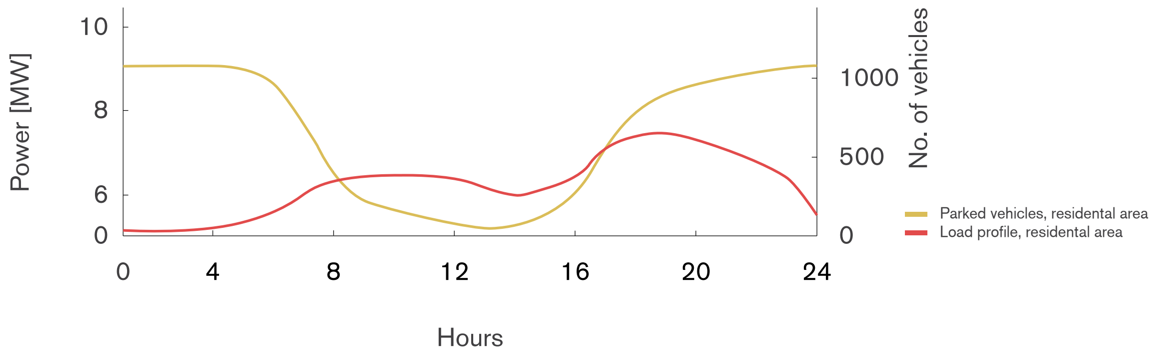
For a more detailed description of expected usage patterns of electric vehicles, please refer to Chapter 10. In this case, it is sufficient to mention the underlying pattern of electric vehicle usage, without explicitly defining the detailed properties of electric vehicle charging and storage availability.

NETWORK CONSTRAINTS

When analysing the impact of electric vehicles within the energy infrastructure, it is important to consider not only the way in which the vehicles will interact with generation sources, but also to consider what impacts electric vehicles will have on the electric grid. In some cases it may be necessary to select a charging strategy for the present EV penetration level in order to reduce stresses on the network. If this coincides with the need for a more intelligent charging strategy, the additional intelligence may be utilized simultaneously to facilitate further integration of renewables. Thus, even though a charging control strategy may be selected based on addressing network constraints, an increase in renewable penetration may be yielded from the control infrastructure.

Essentially, an increase in the penetration of electric vehicles within a network will be accompanied by an increase in the net electricity demand placed on that network. From a network perspective, the additional demand poses little problem, because the network is designed to handle peak load conditions, and the majority of the time operates below this limit. However, while providing the net energy demand of a fleet of electric vehicles is feasible, both the timing and location of the electric vehicle charging loads can have significant impact on network operation.

As shown in Figure 9.3, most vehicles are parked during the time when the electricity demand is high. If a vehicle owner starts charging the electric vehicle immediately after each journey the total power demand may exceed the peak capacity of components in the network.[5] Though it is highly dependent on the individual network, the increased load from electric vehicles has the potential to cause thermal stresses and under-voltage conditions, which has the potential to accelerate component aging or cause service interruption. It is clear that in these cases, it is not the energy demand of charging the vehicle which can lead to these complications, but it is the net power demand in the network due to the timing of the vehicle charging load. Thus the utilization of electric vehicle charging for energy storage must be managed in an intelligent way, through the use of appropriate market models and communications technology.



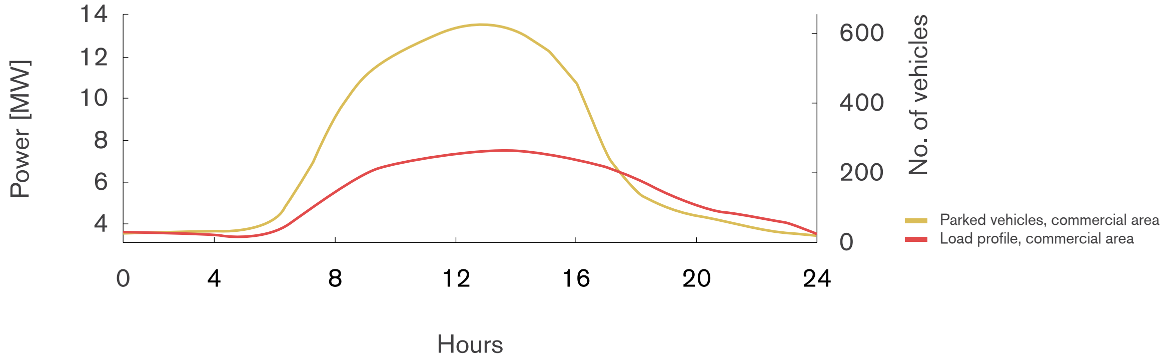


Figure 9.3 Parked vehicle and load profile comparison for a selected residential and commercial area. Note the correlation between peak loading and vehicle parking in these areas, indicating that uncontrolled charging strategies will increase peak loading constraints.

5 Steen, D. et al. (2012). Assessment of Electric Vehicle Charging Scenarios Based on Demographical Data. IEEE Transactions on Smart Grid, 3 (3), pp. 1457-1468.

In many cases, variable pricing is proposed as a signalling method for promoting electric vehicle charging during hours in which electric power is cheaper to produce which often coincides with periods where the network is uncongested. Locational pricing provides a convenient method of reflecting both the availability of supply and the effects of network congestion in a single price signal. However, while locational pricing may provide an effective method for promoting system-beneficial vehicle charging, it is important to understand the limitations of these price signals. Between any areas which have separate price signals, stress in the network can be properly reflected in the price. However, within a single price area, there is no way to reflect network stress in the price signal. In effect, the resolution of the price signals is identical to the resolution at which network stress can be included in the price signals. To achieve higher resolution, the network may be divided into several small price areas, which may be difficult to implement due to legislation and fairness considerations. While locational prices are an important step in enabling vehicle charging, further control mechanisms may be necessary to avoid distribution network stresses.

The geographic distribution of electric vehicles is also important to consider, as this has a significant effect on how the grid may be stressed. Using modern battery technology, the relatively short travel range of electric vehicles (relative to conventional vehicles) will by necessity limit the usage of electric vehicles to situations which involve short commute distances between recharging opportunities. This would seem to imply that electric vehicle penetration may grow significantly in urban areas, but without significant progress in battery technologies, utilization of electric vehicles in a rural setting is likely to remain low. This implies that while the high-voltage electricity transmission network is unlikely to experience appreciable strain from the inclusion of electric vehicle loads, there is a much greater potential for medium-voltage distribution network stresses, especially near urban centres.

The influence of the geographic distribution of electric vehicles on facilitating the integration of renewable generation will thus be affected significantly by the relative location of the intermittent generation to the flexible load. A large-scale renewable generation plant will be constructed at the site which provides the most favourable conditions for generation, which often implies the generation is located a significant distance from the load. In these cases, there is no choice but to connect the renewable generation to the transmission grid to deliver power to the load centres. As renewable penetration increases, if a significant portion of the renewable energy is derived from distantly-located sites, the only available alternatives for ensuring network security will be reinforcement of the grid or construction of dispatchable energy storage facilities. Unless a vehicle-to-grid infrastructure is in place, electric vehicles will not be capable of contributing to network security. However, the presence of a night-time electric vehicle charging load will improve the load factor of the network, improving the utilization of the network.

In the case of locally-placed distributed renewable generation, electric vehicles may be able to contribute much more to network security. The presence of renewable generation in a distribution grid can lead to voltage regulation issues[6] and

6 Masters, C.L. (2002). Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines. Power Engineering Journal, 16 (1), pp.5-12.

the flexible charging load of a fleet of electric vehicles can be utilized to promote voltage stability. This implies that through the proper coordination of the electric vehicle charging load, the renewable energy which is produced can be consumed locally, promoting the security and efficient utilization of the distribution grid.

CHARGING STRATEGIES

As mentioned previously, while an increase in the number of electric vehicles has the potential of providing benefits to the network as a flexible load or even a source of energy storage which can complement intermittent renewable generation sources, this is not without its caveats. Unless the charging of the vehicles is handled appropriately, the potential benefits of the resource may never be realized, and in fact their presence may even lead to detrimental effects within the operation of the distribution network. In this section, a number of charging strategies relating to penetration of both EVs and renewables, as shown in Figure 9.4, will be discussed which each involve different technical and economic approaches for addressing the management of electric vehicles within a network.

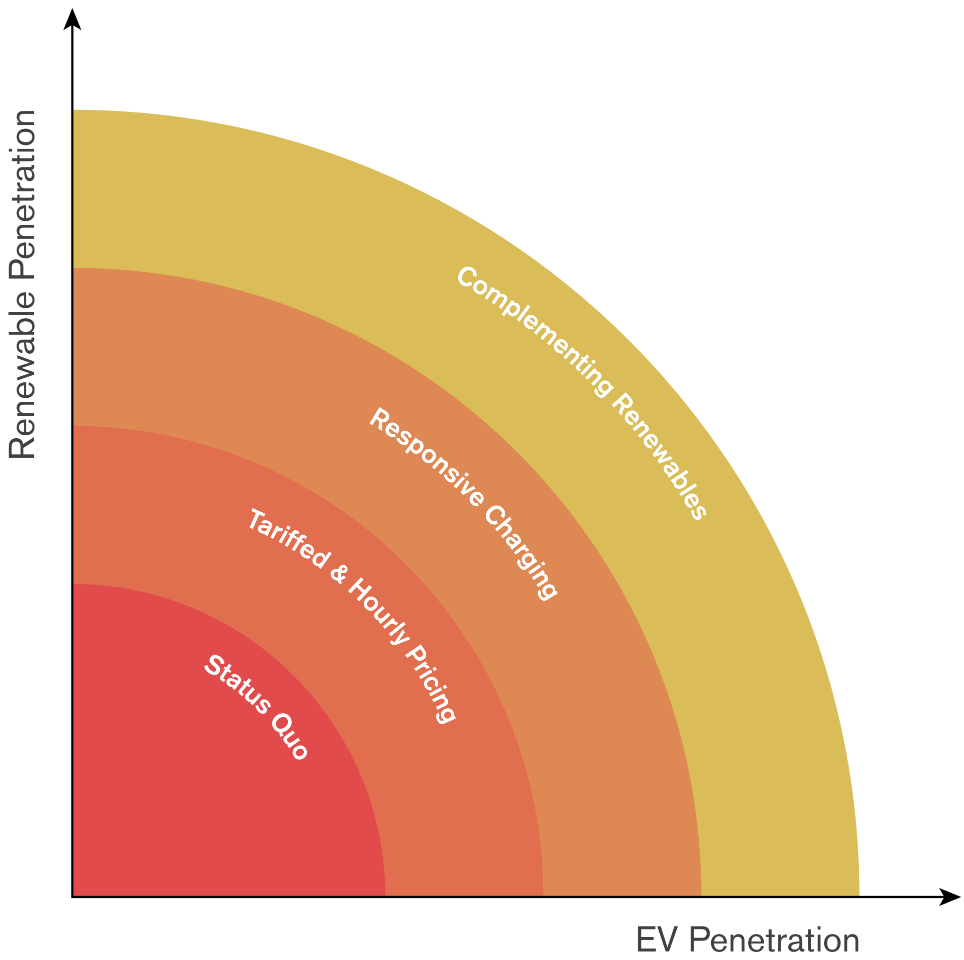


Figure 9.4 Guideline for the evolution of schemes for controlling electric vehicle charging to become a participant in the energy system. With increasing penetrations of either EVs or renewables, more advance controls are required.

STATUS QUO

The simplest option available for managing the charging of electric vehicles is to maintain the status quo of the current method of grid operation. This would require no alterations to the current market for consumer electricity, and would also require no capital investment in infrastructure changes. Essentially, the owner of electric vehicle would plug in the vehicle whenever they desired to charge the batteries, and the vehicle would simply appear as an additional load placed on the network when connected. The batteries would charge at a pre-determined rate until they reach their storage capacity, at which point charging would cease.

This option is the most readily available solution for systems incorporating electric vehicles, as it requires no alterations to the present market structure or electricity distribution systems. Because the vehicle charging is simply added to the inelastic demand or the electricity consumer, all that may be necessary is an analysis of the network to ensure there is sufficient capacity to handle the addition of these charging loads into the network. Note that due to the simplistic nature of such an approach, the grid is not able to extract any benefit from the presence of vehicle-based energy storage. It is also likely that the scheduling of generation to meet these evening peaks will lead to a decrease in efficiency and increase in cost of electricity generation.

This approach is likely the most suitable for addressing networks with low penetration of electric vehicles, and due to the moderate rate of increase in electric vehicle utilization, this is the preferred approach for near-term scenarios. When only a small percentage of the total energy demand of a network comes from electric vehicle charging, the vehicles will have negligible impact on the efficient and safe operation of the electricity network. However, as electric vehicles become a more popular and cost-effective technology, their usage will likely increase, motivating some alteration to the current operation infrastructure.

As electric vehicle utilization within a given area increases, the probability of the load demand exceeding network capacity increases correspondingly, and will eventually motivate an alteration in network operation to address these potential problems, as shown in Figure 9.5. The concern in these cases is that there is a chance that the instantaneous peak power demand in a network may exceed the network's capacity, and the risk of such an event is greatest when home charging of vehicles is performed immediately upon arrival at a residence, as the charging load will add to the early evening energy demands, for which there is already a significant peak.[7] Compounding on these issues are the stresses placed on the thermal generation units in the system, where accentuated evening peaks lead to greater strain and reduced efficiency of the thermal units supplying electricity. To alleviate the risk of such an over-capacity event, a charging strategy should be used which attempts to shift the charging demands to a more fortuitous time in the daily schedule, while still meeting the energy needs of the vehicle over this period.

7 Jardini, J.A. (2000). Daily load profiles for residential, commercial and industrial low voltage consumers. IEEE Transactions on Power Delivery, 15(1), pp.375-380.

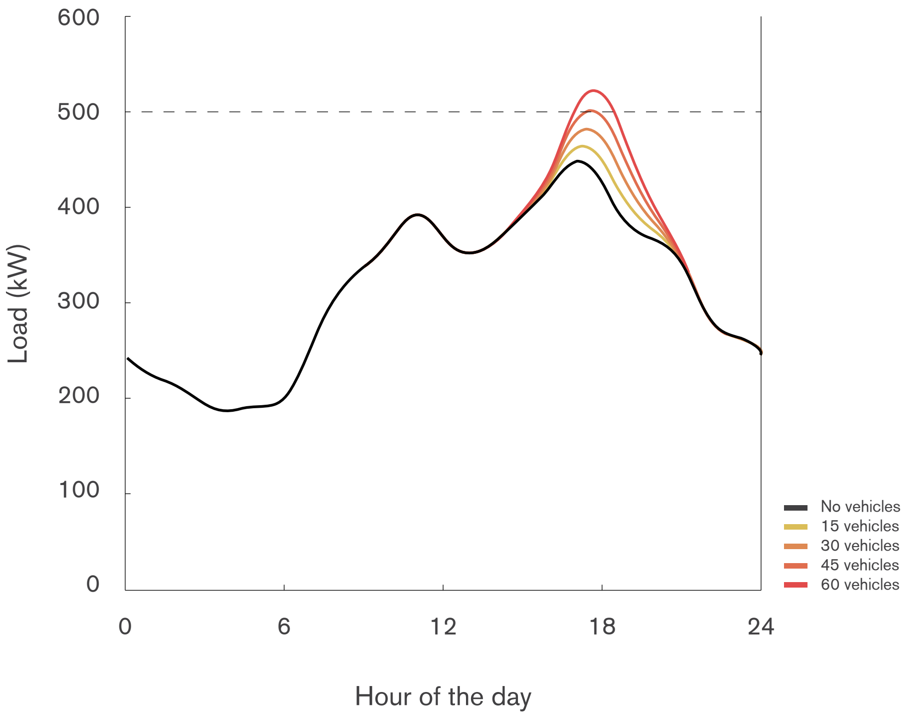


Figure 9.5 In the status quo case, the vehicles begin charging immediately upon arrival in the residential area. In this example, various numbers of EVs with 2 kW charging are connected in an area served by a 500 kVA transformer. It is seen this strategy can lead to overloading with significant EV penetrations. Note that the capacity for EV penetration will vary greatly from network to network.

TARIFFED & HOURLY PRICING

The challenges presented by the increased presence of electric vehicles in the system can be handled with relatively little change to the method of grid operation by modifying the energy pricing scheme, where variable pricing would be established in order to encourage the sale of energy to consumers during a time which is favourable for system operation. The desire of consumers to charge their vehicle at home, along with the typical daily energy use pattern, implies that a pricing structure may need to be established which encourages electric vehicle owners to charge overnight, during the late-night or early-morning time period. This would allow vehicle owners to meet their daily transportation energy requirements through home charging, as well as reducing the peak load on the grid by encouraging charging during lightly-loaded hours, as in Figure 9.6. Thus, establishing an energy pricing scheme which accurately reflects reduced overnight energy prices can simultaneously promote consumer energy cost savings, and a more secure and efficient system.

Another key benefit of establishing such a pricing structure to facilitate the integration of electric vehicles is the low cost of implementation for such a scheme. From a market perspective, very little needs to be changed, as the only difference is that customers will be charged a different rate for energy use based on the hour of consumption. The communications infrastructure required to implement variable pricing is relatively simple, where no communications to the customer are necessary for a fixed-price overnight tariff, and only once daily communications are required if the customers are charged the day-ahead spot market price. From a technological standpoint, in order to accomplish a variable price billing scheme, it will be necessary to collect hourly measurements of energy consumption from customers so that they can receive these price incentives. Smart meters which can collect and communicate this hourly data to the customers' energy supplier are the key technology for enabling this method of electric vehicle charging.

The variable pricing method will motivate customers to charge their vehicles during non-peak hours, and in the aggregate will shift demand to a more favourable time of the day for grid operation while yielding a monetary benefit to the customer. For moderate penetration of electric vehicles (whose level of penetration is grid-dependent) and for a system dominated by thermal generation where wind power supplies up to around 20% or solar power supplies up to around 30% of the load this scheme is expected to be effective. Night-time charging permits a more evenly distributed load on the thermal generation units. With wind power in the system, night-time charging of EVs will reduce competition between base load units (with poor cycling abilities) and wind power, resulting in reduced reduction of wind power curtailment and thermal cycling costs as a result. With less than 30% solar generation, solar power will not compete with base load during the day. Additionally, the charging demand will lead to better utilization of existing grid infrastructure while alleviating stress caused by evening demand peaks.

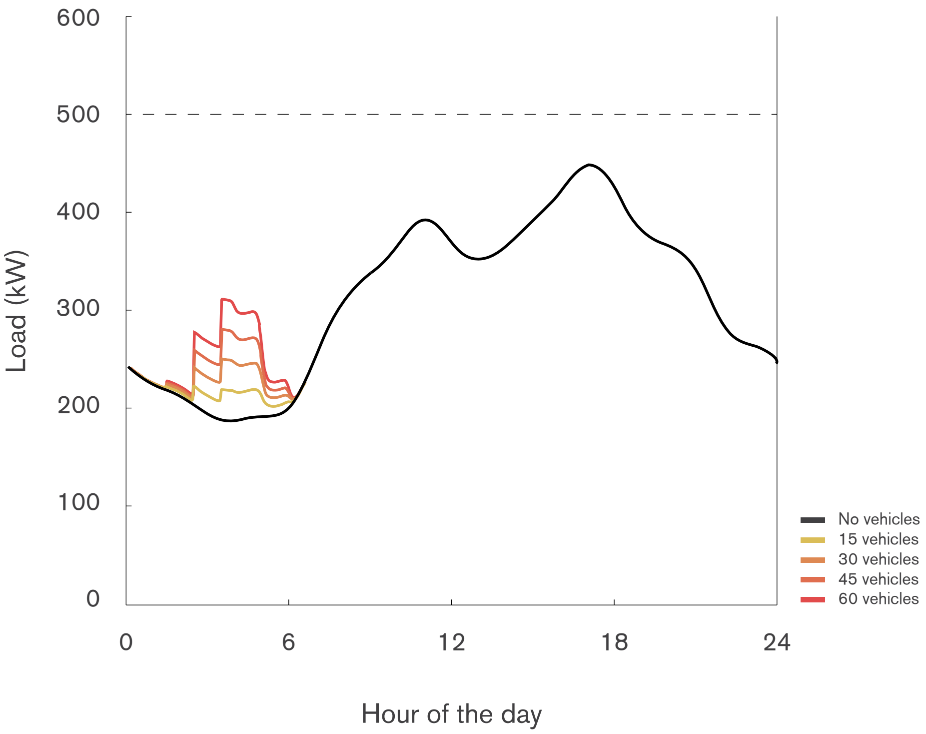


Figure 9.6 In the hourly pricing scheme, customers will charge their vehicle to meet its transportation energy needs by scheduling to charge during the cheapest available hours. Note that this may cause a localized night-time peak, as is shown for this distribution network. However, if there is system wide adoption of electric vehicles, the price advantage of the cheapest night-time hours will be diminished, and the peak displayed above will tend to flatten.

This approach, while effective for moderate quantities of electric vehicles and renewable generation in the system, is still limited in its efficacy for future scenarios with higher penetration of electric vehicles and renewable generation. Due to the relatively simplistic nature of the communications and market infrastructure, the demand of the vehicles is unresponsive to real-time renewable generation intermittency or system stress. Addressing this will require further advancement of infrastructure to permit more flexible customer demand response.

RESPONSIVE CHARGING

With increasing electric vehicle and wind penetrations of 20-40%, a more active charging control strategy must be employed to ensure reliable delivery of energy resources. Some further advancement of the control scheme is necessary to ensure that not only does the vehicle charging load get shifted to the low-demand hours of the night, but that there is also an effort to actively distribute the charging load over this time period in an effort to prevent night-time wind generation from interfering with base load generation, and to avoid network stresses. While there may be many available options for implementing this control scheme, two in particular will be presented here as alternatives for achieving this goal.

The first alternative involves a technological advancement of the fixed overnight price tariff. While the system would continue to utilize the fixed overnight tariff along with collecting hourly usage data, it would be upgraded to allow unidirectional communication signals to be sent to the consumer. The signal sent to the consumer would be used to indicate the time at which electric vehicle charging could begin. By being allowed to control the initiation of charging, a network operator could ensure that the number of vehicles charging at any given time would not exceed the capacity of the network, while also promoting charging at time which prevents renewable generation from negatively impacting base load generation. While the communications structure necessary to implement this system is relatively simple, the nature of customer interaction becomes more complex. Since the customer is giving up the right to independently initiate charging, some quality-of-service assurances must be provided to the customer to guarantee their daily transportation energy needs are met.

The second alternative also involves the implementation of unidirectional communication to the customer, but in this case the goal is to provide the customers with real-time energy price information so that they can independently choose the most favourable time to consume energy. In this implementation, rather than being offered energy priced by a predetermined set of tariffs, the price of energy for a given time period would be communicated to the customer and their energy consumption over this period would later be used to bill the customer appropriately. This method does not require the customer to forgo their right to select when their vehicle will charge, but it does assign to the customer the responsibility of selecting the optimal charging time. Since only the knowledge of past and present energy pricing information is known to the customer, it becomes the responsibility of the customer to attempt to forecast whether a more favourable price may become available, and then attempt to schedule vehicle charging according to this estimate. Forecasting in this manner will inevitably contain errors, which means the customer is forced to assume the price risk of charging their vehicle at a non-optimal time. Additionally, this requires significant attention from the electric vehicle owner, beyond what they may be willing to contribute.

Thus, a solution containing real-time pricing will almost certainly involve some sort of intelligent element in the vehicle which will seek to optimize the charging behavior. A device performing this function would likely employ some sort of statistical learning algorithm (such as a neural networks or support vector machines), using historical pricing information and current price trends to attempt to schedule the charging of the vehicle both optimally and autonomously. The need for an autonomous intelligent control agent leads to a system with more complexity and, due to the interactions that these control systems may have when operating simultaneously, could also lead to concerns about system reliability.

In either of the two cases mentioned, a modification to the current energy pricing structure and implementation of frequent unidirectional communications is required. The hourly energy usage data of a customer needs only to be measured, and the data can be collected once for each billing period. Figure 9.7 displays that by implementing these changes, a network will be capable of hosting a greater number of electric vehicles relative to the tariffed or hourly pricing cases, because unidirectional communications allows information to be sent to customers which subsequently enables an efficient control of load demand during the off-peak hours.

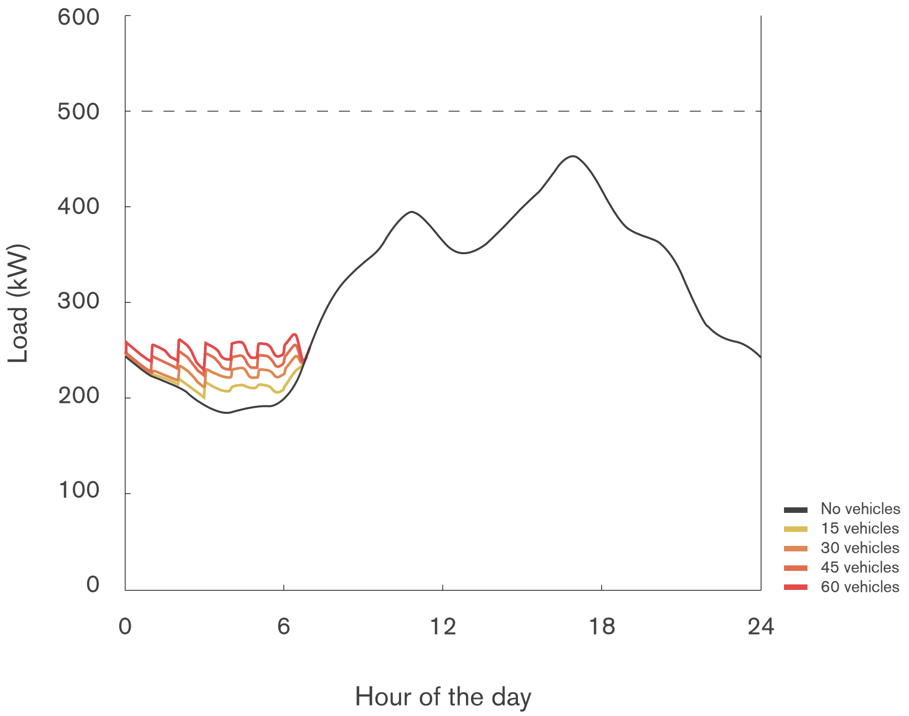


Figure 9.7 In the responsive charging case, an intelligent agent schedules the charging, whether it be some form of centralized or aggregator based control, or through real-time hourly pricing. The case shown here has the charging schedules optimized to minimize charging costs by selecting the appropriate hour in which to begin charging. Note that time resolutions finer than hourly scheduling are of course possible. While the effect here is displayed at the distribution level, note that a system wide increase in the night-time base load will be realized as a result of implementing such a control scheme at large scales.

COMPLEMENTING RENEWABLES

The goal of the charging strategies mentioned in the previous section was to develop the energy pricing and communications infrastructure used for the charging of electric vehicles, such that when customers leave their vehicles connected to charge overnight, not only will the charging be managed to ensure that the charging demand does not exceed the network capacity, charging will also be regulated to promote system efficiency. Those methods were promoted as a method of controlling the charging to facilitate the leveling of the off-peak load, utilizing the most economically produced energy when it is the most readily available. It would therefore be a straightforward extension of these charging strategies to control the charging of electric vehicles throughout the entire day to respond to the intermittency in a system with solar power corresponding to more than 30% of the demand or wind power corresponding to 40% or greater of the electricity demand.

This is essentially an extension of the off-peak charging control schemes to operate for all twenty-four hours of the day. This would imply possible billing complications, as the vehicle owners are likely to have used their vehicles to travel to a place of work or to a commercial centre during the daytime hours, which will require an enhancement of billing capabilities and an expansion of charging locations, if the customers are to participate in the real-time response of vehicles as energy storage.

In general, the use of electric vehicle energy storage as a controllable unidirectional demand seems to be the most practical implementation for the foreseeable future. These systems will require a much more modest investment in billing and communication infrastructure development when compared to electric vehicle charging schemes which also attempt to implement vehicle-to-grid energy flow. The unidirectional schemes are capable of achieving the goals of allowing electric vehicle storage to complement intermittent renewable generation, while facilitating favourable customer energy pricing and ensuring the stored energy in an electric vehicle will always be greater than or equal to the amount which remained upon its last use.

While unidirectional charging strategies are likely to dominate near-term scenarios, owing to its capabilities to address renewable intermittency with relatively little infrastructure investment, there may come a time in the future where the integration of renewable generation and electric vehicles in the electrical network is significant enough to warrant vehicle-to-grid energy flows. With increasing penetration of renewable sources comes the caveat of having increased variance in the amount of energy produced by these sources, owing to their non-dispatchability. There may be instances in networks with high renewable penetration where a shortage of generation motivates the use of the energy stored in the electric vehicles to support the network.[8]

Implementing a system which includes vehicle-to-grid will require significant investment, both in terms of alterations to the current market structure to allow

8 Saunders, C.S., et al. (2012). Congestion Management in Active Distribution Grids: Optimal Reserve Scheduling Under Distributed Generation Uncertainty. CIRED Workshop 2012, 1(1), pp.278-281.

electric vehicle owning customers to potentially sell generation capacity, as well as development of the bidirectional communications infrastructure[9] which would be required to support such a market. While vehicle-to-grid seems to be both infeasible and impractical for the current system, in future scenarios if there is substantial economic benefit to be yielded from avoidance of network investment or from retiring peak load generation units, it may warrant the implementation of such a system.

CONCLUSIONS

In this chapter, one of the key challenges of increasing quantities of renewable generation, namely that these sources are intermittent and non-dispatchable, is discussed along with the concept of how electric vehicles in a network can help address this intermittency. Electric vehicles inherently require some form of energy storage, which makes them a potential candidate to act as a complementary element to renewable generation. In electricity generation systems with a significant amount of thermal generation and a moderate EV penetration, a charging strategy implying night-time charging at low load hours is likely to be the cost optimal option. In systems with wind penetrations of 20%-40% and/or large EV penetration, the night-time charging should be actively scheduled to fit the forecast wind generation and EV energy needs in an optimal way. In systems with a large share of wind and/or solar power, solar and wind power generation may compete with base load generation or even exceed daytime demand which necessitates a 24-hour charging strategy.

However, there are certain complications which arise when attempting to use electric vehicles for energy storage, because unlike a fixed energy storage unit, an electric vehicle has a distinct daily usage pattern which dictates certain energy needs and a likely geographic relocation during daytime hours. Due to the diurnal pattern of usage, electric vehicles cannot address the weekly or seasonal variations of renewables. In an electricity generation system with a high renewables penetration, electric vehicles would thus be one of several variation management strategies.

9 Pahlavan, M, et al. (2011). Gulliver: a Test-bed for Ddeveloping, Demonstrating and Prototyping Vehicular Systems. Proceedings of the 9th ACM International Workshop on Mobility Management & Wireless Access, MOBIWAC 2011, pp. 1-8.

10
ELECTRIC VEHICLES AND DRIVING PATTERNS

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INTRODUCTION

Neither the magnitude of travelling, nor travelling patterns, are given. The movements of people are developing in interplay between demand for mobility, available transport technology and general economic and environmental constraints in society.

The magnitude of personal travel in the industrialised society has increased tremendously. In Sweden, the average travelled distance per person is currently around 40 km per day (see Figure 10.1). Travelling distances are related to speed. Studies show that the time spent on travel tends to be relatively constant at around one hour a day on average. The historical development of new transport technology such as trains and cars has increased the speed and comfort of travelling, and hence also the distances travelled. Airplanes make it convenient to travel even up to tens of thousands of kilometres for business meetings, visits or vacation. Globalised industries and charter tourism rely to a large extent on the speed of airplanes. And increased globalisation spurs further demand for air traffic.

This development demonstrates that technology and travelling patterns are not independent, nor is one causing the other in a linear way, rather they cause each other and coevolve. It is obvious that the use of oil has had an impact on our travelling patterns. To what extent could a change in technology such as electrification of vehicles reshape our travel behaviour and choice of transport modes? Electric high-speed trains already compete successfully with air transport on medium distances. Can electrification of bicycles lead to an upheaval of biking? Will new types of small electric vehicles transform urban transport? (See also Chapter 2 and 11 on the coevolution of technology and user practices.)

As mentioned above, the causality also goes the other way around; travel behaviour has an effect on technology choice. This chapter takes the current travelling patterns as starting point. To what extent can the vehicles, now fuelled by oil, be electrified, or, to put it differently, how much of our travelling is suitable for electrification?

Some travelling modes are already extensively electrified, such as various rail traffic systems, which are bound to a track system, making energy supply by electricity technically convenient. Also some vehicles frequently operating specified routes, such as city buses, are already electrified or are now considered for electrification. Personal vehicles, on the other hand, which dominate passenger transport (Figure 10.1), are characterised by their irregular and mostly non-frequent driving pattern. And even if some vehicles are used regularly on specific routes, for instance when used extensively for commuting, the option to also use it for possible upcoming specific, irregular or infrequent trips, is a highly valued feature of the personal vehicle.

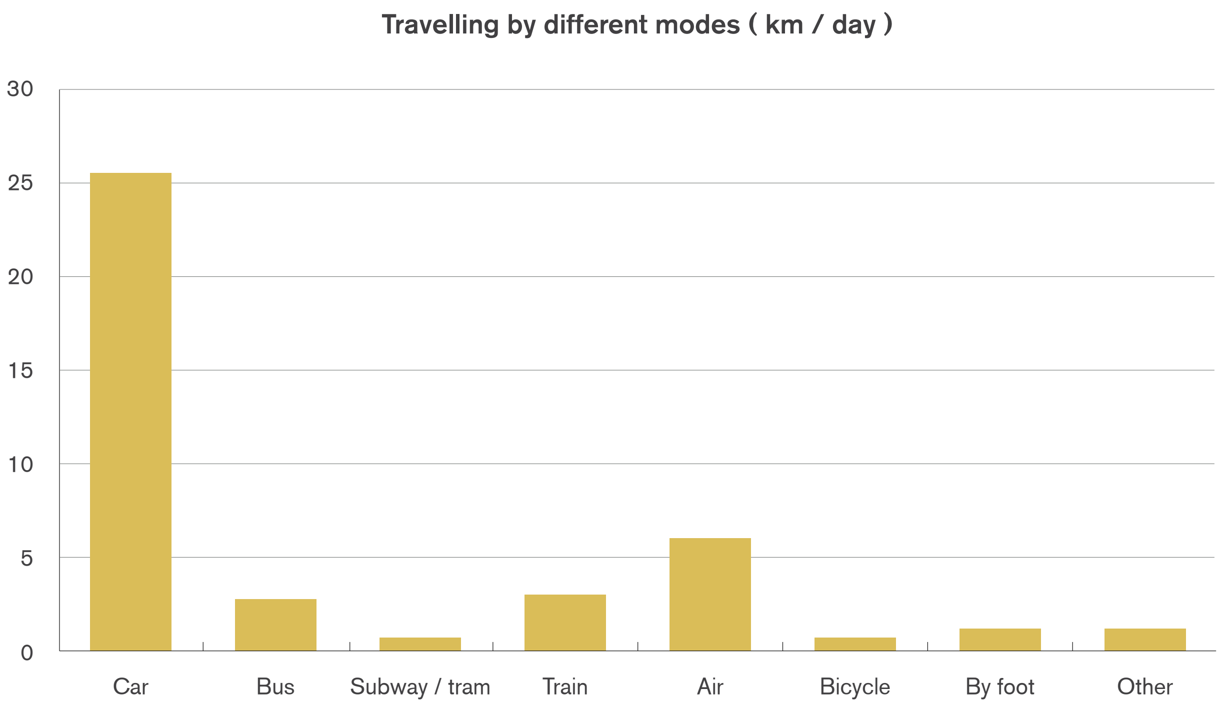

Figure 10.1 Travelling in Sweden divided by transport mode. (Source: RES 2005-2006, The national travel survey. SIKA Statistics 2007:19)

Today the technical option for electrification of personal vehicles is by an on-board battery. The battery cost and energy density limit the range of pure battery electric vehicles. Currently the range for commercially available electric vehicles is often around 150 km under favourable conditions.

The use of bicycles and mopeds is less sensitive to these range limitations. Bicycles are therefore the fastest expanding category of electromobility, with over one hundred millions of electric bicycles in China today. In Europe, a total of 700 000 were sold in 2010.[1] Some cars are not used privately, but are part of fleets with

1 Electric bicycle (Wikipedia)

specific forms of utilization. It can be cars used in various services provided by the municipality, for instance, elderly care. This often implies a reasonably well-known upper limit of the daily driving as well as parking in a specific place during the night. Due to these inherent limitations and the predictability of movements, such fleet vehicles are in many cases among the most appropriate for electrification.

The range limitations of current electric vehicles may also be circumvented by transforming the organisation of passenger transport. Car sharing schemes are now increasingly attracting attention in different cities in the world. By such schemes the user may have access to a range of vehicles more suitable for each specific occasion. For instance, electric vehicles could be used for the many short trips demanded and a fuel-driven car for the few long journeys (compare the discussion on business models in Chapter 12).

In the remainder of this chapter we focus on privately owned cars which make up the major share of travelling. Instead of reorganising transport, there is an option to adapt vehicle technology to prevailing driving patterns. Plug-in-hybrids (PHEVs) is a technology that allow for some adaptation and partial electrification. Taking departure in the current use of cars, we discuss the opportunities to electrify car travel with a focus on PHEVs.

CAR MOVEMENT DATA AND ELECTRIFICATION

What pattern characterises the movement of our cars? Information about vehicle movements over longer periods of time is of major importance for the sizing of batteries, estimation of the economic viability from a consumer perspective and assessment of the potential of electric vehicles to replace fuel-propelled cars. We need data on the distribution of trip lengths and trip characteristics, such as speed and topography, to be able to determine the energy use for individual trips and the need for battery capacity. Moreover, the knowledge of timing and duration of trips and parking between trips is required to evaluate the availability of charging capacity and potential impact on the electricity grid (see Chapter 9 for a discussion on the interaction with electricity production and the grid.) Since the travel patterns of individuals vary considerably over time, which will influence the discharging and recharging patterns and options, data needs to be collected over a long time period.

It can be argued that measurement of today's car movement will not be representative for the near future's battery electric vehicles, which have a limited driving range and hence will impact the travel behaviour of drivers (see introduction above and Chapter 11). However, for plug-in hybrid electric vehicles, a reasonable assumption can be that these vehicles will be used in a similar way as today's cars.

Publicly available data of good quality on car movement patterns are generally lacking. National or regional travel surveys are regularly gathered in many countries. However, in most countries, including Sweden, there is no tracking of the movements of cars, only of persons. It has also been recognised that this often self-reported data (using questionnaires or interviews) provide an underestimate of the travelling, due to a certain share of non-reported trips. Nor does this type of data give the exact position of vehicle movements. Finally, the measurement period in travel surveys is often limited to one day.

GPS-assisted travel surveys have been discussed in several countries. Continuous measurement of position, speed, and time with GPS equipment offers the possibility to gather more thorough information on car movements, although it lacks explicit information on trip purposes, often available in travel surveys. This can to some extent be derived from the available positioning data.

Measurements of car movements with GPS equipment have been scarce, and when done it has been for specific purposes or focusing vehicles in specific areas. For instance, in Australia, cars have been tracked for the purpose of investigating driver behaviour such as speeding. In Italy, a unique commercial dataset of car movements are derived by the company Octotelematics from the GPS tracking of around 650 000 cars (in 2009) in order to inform insurance profiling. In the USA (Seattle area), a GPS logging of 450 vehicles from around 275 households was performed in an assessment of road tolls. In the Atlanta area, 445 cars owned by 273 households where tracked for up to one year in order to assess the effects of different cost schemes on travel behaviour.

In Sweden, in a project in 1998 (Körsätt 98) with the purpose of verifying the role of driving behaviour in emission models, GPS equipment was installed in specifically prepared vehicles. These were placed in 29 families for two weeks, replacing cars of similar size. In another project (LundaISA) about 200 cars in Lund were tracked for about 100 days during 2000-2002. The purpose was to evaluate the impact and acceptability of Intelligent Speed Adaptation (ISA) equipment.

In Canada, a measurement was specifically devoted to electrification. 126 cars in Winnipeg and rural vehicles often commuting into Winnipeg were logged with GPS for up to a year, to be able to, for instance, assess the prerequisites for electric propulsion of PHEVs. Also the data from the two US studies mentioned above have later been used for assessment of electrification opportunities.

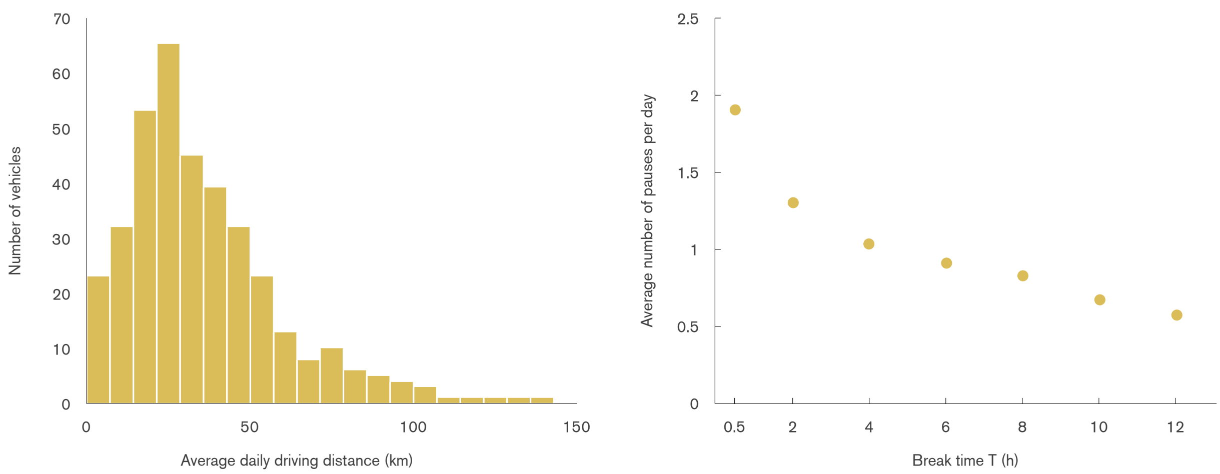

Figure 10.2 For the logged 212 vehicles, the average daily driving distance and the average number of daily breaks between consecutive trips longer than *T* hours. Source: Kullingsjö, L-H, S Karlsson, 2012. *The Swedish car movement data project*. In Proceedings to EEVC 2012, Brussels, Belgium, November 19-22, 2012.

To improve the data situation, a GPS measurement project was recently carried out in Sweden.[2] The aim was to get representative data for privately driven cars in Sweden. The cars come from the positive responses to a request for participation in the project sent to a random selection of owners/drivers of newer cars (≤ 9 years old) from the motor-vehicle register in a region composed of the county of Västra Götaland and Kungsbacka municipality. This project resulted in movement data for around 500 cars for at least one month each. In the following we will use results from this project.

Figure 10.2 shows the distribution of the average daily driving distance. The distance driven by the different vehicles varies considerably, which will affect their individual viability for electrification. Depicted is also the average number per day of stops longer than a certain minimum break time *T*, a parameter, which influence the type of charging that is possible. The frequency of breaks naturally decreases for successively longer breaks. Breaks longer than around six hours, occur less than once a day. This is mainly due to the fact that not all vehicles are driving every day. A knee in the curve can be seen at eight hours, corresponding to the frequent occurrence of break lengths around normal parking times at work places.

POTENTIAL ELECTRIFICATION OF CAR MOVEMENTS

By using the car movement dataset, it is possible to get an estimate of to what extent the movements fit electrification. It is the total distances of all the trips in between the charging occasions that are of importance to electric propulsion. This is determined by the movement pattern as well as the possible utilisation of charging options. Figure 10.3 gives an exemplary yearly distribution of the driving distances between charging options. The driving is sorted with the longest distances at the bottom. The curve therefore shows the annual accumulated number of charging occasions as a function of trip distance, where trip distance means the distance between charging occasions. The area (*S*) under the curve corresponds to the annual distance driven.

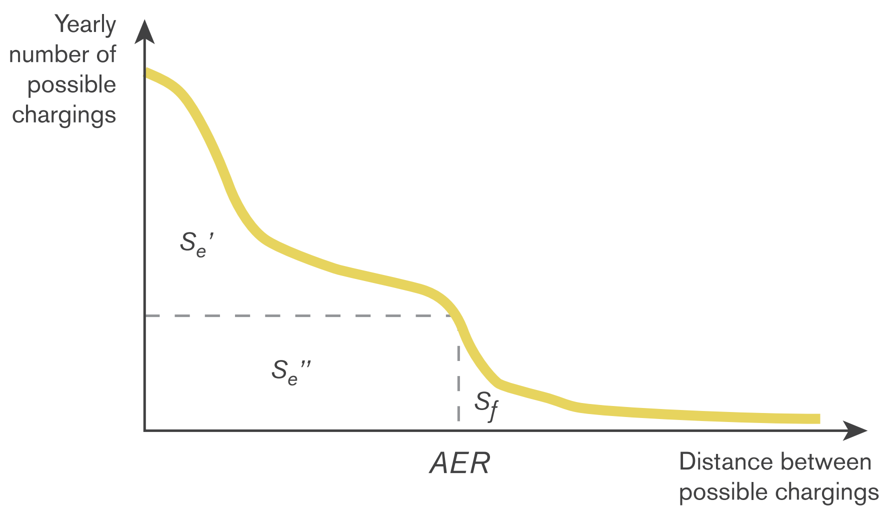

Figure 10.3 A schematic illustration of a vehicle's distribution of distances driven between charging occasions. The vertical axis is the annual accumulated number of charging occasions followed by a driving above a certain distance before next charging option.

2 Karlsson, S. (2013). The Swedish car movement data project, Final report. Energy and Environment, Chalmers University of Technology. See also project website

First we look at a PHEV. We assume it is first propelled by electricity only, and when the battery is emptied it turns to fuel. Hence, it uses a so called Charge Depleting – Charge Sustaining (CD-CS) mode (see Chapter 3) and that the battery is fully charged whenever charged. The battery limits the range the vehicle can drive in the all-electric mode, here termed the *All Electric Range (AER)*. It is then possible to propel the car the yearly distance S_e' with only electricity from the battery.[3] For trips longer than *AER*, the yearly distance S_e'' can be met by battery energy, while S_f must be covered by fuel combustion. The potential share of the yearly distance driven propelled by electricity, the *Electric Drive Fraction* (*EDF*),[4] is thus

$$EDF_{PHEV} = S_e/S$$

where $S_e = S_e' + S_e''$. A battery electric vehicle (BEV) can only be used for trips shorter than the *AER*. The share of the yearly driving in Fig 10.3 possible to cover with a BEV is thus

$$EDF_{BEV} = S_e'/S$$

Generally, for the same battery range (*AER*) and charging options the share of the annual driving distance covered by electric propulsion is thus larger for the PHEV than for the BEV. Of course, a similar relationship holds for the number of trips; the PHEV can with help of the fuel engine cover all trips, while the BEV has to be complemented with another car for trips longer than the battery range. For a specified charging pattern, Figure 10.4 gives the share of current driving in Sweden possibly propelled by electricity as a function of battery range (*AER*) for PHEVs and BEVs, respectively. Here and in the following we assume that data from the Swedish car movement data project is representative for Sweden.[2]

To reach the same *EDF* a BEV needs a battery range more than twice as large as a PHEV. For instance, a PHEV with a range of 60 km can propel roughly half the driven distance with electricity. A BEV will need a range of 130 km to cover the same amount of driving. For the BEV this range must also be a practical utilised range excluding any backup range for the avoidance of running out of battery energy. We must note though, that Figure 10.4 represents the average driving. As demonstrated later in this section, the individual variations are considerable. Many cars may in practice be used in such a way that they never, or at least very seldom, move longer than the BEV range on a daily basis. The suitability of the BEV in such cases is then determined very much by the value of the option to be able to drive longer anyhow.

3 The battery energy use in the driving can vary depending on prerequisites such as driving style, speed, and use of auxiliaries (see Chapter 5). The analysis can be extended to include this but for simplicity we here assume that the driving has one specific energy use per distance.

4 The electric drive fraction is also designated Utility Factor (*UF*) especially in the US, after the concept of (public) utilities providing electricity or other goods based on a (natural monopoly) infrastructure. The electricity may however as well be charged with electricity from a local off-grid, thus non-utility, source. Generally, there are good reasons to avoid concepts that have been framed in a specific historical and socio-economic context in a vocabulary used for discussions on future technologies.

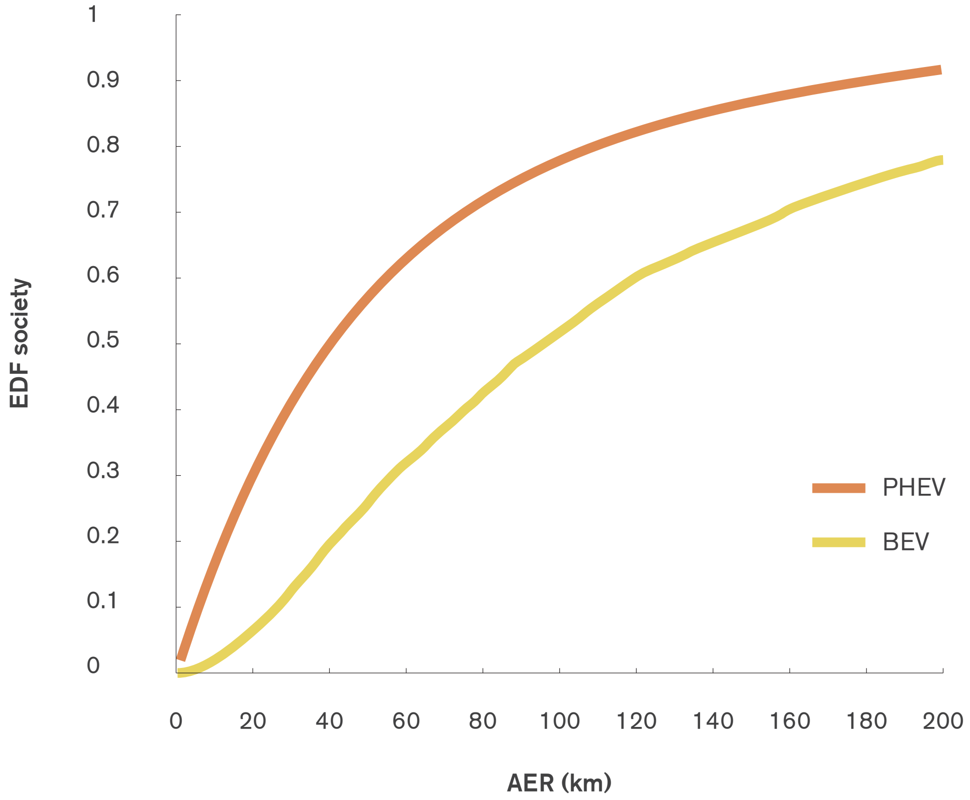

Figure 10.4 The share of current private driving in Sweden possibly propelled by electricity (Electric Drive Fraction, *EDF*) as a function of battery range (*AER*) for PHEVs and BEVs, respectively. The charging is assumed to take place whenever a pause between trips is at least 10 hours ($T = 10$ h).

The range of the BEV can of course be increased by equipping it with a larger battery, but unlike for the conventional car, that comes at a non-negligible cost. Other solutions could be fast charging, battery swapping or charging while driving (see Chapter 2 and 3), all requiring matching infrastructure. If these options are not at hand, the limited range has to be handled by restricting driving to short distances. As mentioned in the introductory section much driving may be facilitated conveniently with BEVs when restricted to specific fleets or when combined with access to other cars: for instance, by membership in a car pool or by renting (see Chapter 12).

Many households have more than one car. In Sweden, almost half of all privately owned cars (not accounting for company cars) belong to households with more than one car. When substituting one of the cars in such a household with a BEV, in many cases the BEV range restriction will be much less of a problem. If the vehicles are really pooled within the household, the BEV can be chosen for the trips that are within its range and the fuel vehicle can be used for longer trips. Moreover, the much lower operational costs, due to the lower energy use per km of the BEV (Chapter 5, 12 and 13), will probably make it the preferred vehicle whenever possible, increasing its share of the household's driving (Chapter 11).[5]

While a BEV battery hopefully never is completely emptied, a PHEV battery can be dimensioned in such a way that its full capacity is frequently utilized. An

5 Measurement of these opportunities are made within a project logging both cars in two-car households in Sweden

important measure or indicator of the utilization of a PHEV battery is the *Marginal Recharging Frequency* (*MRF*). The *MRF* is the number of times a year the PHEV battery is fully emptied and fuel propulsion starts, i.e., how many times a year the last unit of battery capacity is actually used. Besides the driving pattern, the *MRF* is determined by the battery range and the recharging options. Actually, the curve in Fig 10.3 can be interpreted as a movement pattern's *MRF* (y-axis) for different battery ranges (x-axis).

Figure 10.5 illustrates the *MRF*s as a function of battery range for the individual movement patterns of the vehicles in the dataset. The battery is assumed fully recharged every time there is a pause with a length of at least *T* hours (10, 4 and 0.5 hours, in figure a, b and c, respectively). The requirement of a 10 hours pause for charging to occur effectively singles out charging at home during nights. Pauses of 4 to 10 hours length occur particularly at work places when commuting. Thus *T* = 4 hours roughly corresponds to charging at home and at work. Full recharging every time there is half an hour pause (*T* = 0.5) may be seen as an extreme case where fast charging is available and utilised at every stop. (See also Figure 9.2, which shows the distribution of pauses of different duration over the time of day and corresponding possible charging patterns.)

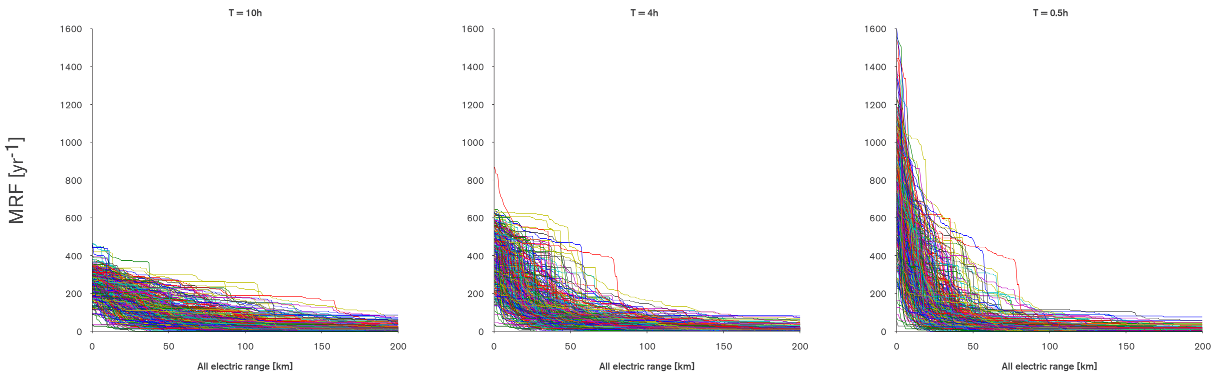

Figure 10.5 For the individual cars driving pattern, the marginal recharging frequency (*MRF*) as function of the battery range (*AER*) and recharging expressed as minimum required break time *T* for recharging the battery. a) *T* = 10 hours; b) *T* = 4 hours; c) *T* = 0.5 hours.

There is apparently a large variation in the *MRF* between different cars depending on their individual movement patterns regardless of charging option; movement patterns matter! For any car movement pattern the *MRF* decreases with larger battery range. That is, all else being equal, the larger the battery in the PHEV the lower the frequency of changes to fuel use due to an empty battery. We can also note that the individual *MRF* curve falls steeply in the cases where the specific movement pattern has a large number of trips around a certain *AER*. This can occur for instance when the driving is dominated by the regular commuting between home and work.

In general, better charging opportunities (here shorter *T*) lead to more recharging occasions and thus to shorter distances covered in between recharging and a higher *EDF*. When the battery range, *AER*, is long, the battery is empty less frequently, that is a smaller *MRF*. For shorter battery ranges, the charging and also the emptying of the battery are more frequent, which implies a larger *MRF*.

FITTING PHEV BATTERIES TO DRIVING PATTERNS

For a PHEV to be economically viable, the higher initial capital cost due to the expensive battery should be compensated for by the lower operational costs due to the higher energy efficiency of the electric drivetrain (see Chapter 5, 12 and 13). A larger battery increases the capital costs, but also the possible share of electric propulsion and therefore lowers the energy costs. Thus, there is a trade-off between battery cost and energy cost. The battery should therefore neither be too large nor too small. Optimally, an extra unit of battery should be (exactly) paid for by the saved operational costs.

Any given set of technical and economic conditions that determine battery cost and saved operational costs corresponds to an optimal marginal recharging frequency, MRF_{opt}. In Table 10.1 some examples derived with help of a simple model are given.[6] With expensive batteries and a relatively small difference between electricity and fuel costs it is economically optimal to switch to fuel more often. The parameters behind an MRF_{opt} of 800 yr^{-1} can be thought of as fairly close to today's situation, while an MRF_{opt} of 200 yr^{-1} requires development of cheaper batteries. A cost somewhere in the vicinity of that predicted for 2020 is required. Similarly, an MRF_{opt} of 50 yr^{-1} corresponds to a possible state further into the future where considerable improvement of battery parameters has taken place, as well as an increase in the energy prices.[7]

Table 10.1 Examples of combinations of techno-economic parameters, which give certain optimal marginal recharging frequencies MRF_{opt}.

	Optimal marginal recharging frequency MRF_{opt} (yr^{-1})				
Techno-economic parameter	**800**	**400**	**200**	**100**	**50**
Annuity (yr^{-1})	0.15	0.15	0.15	0.15	0.15
Utilized share of the nominal battery capacity (-)	0.5	0.5	0.61	0.75	0.8
Marginal battery cost [EUR/kWh)	600	300	185	120	75
Electricity and fuel price (EUR/kWh)	0.11	0.11	0.13	0.15	0.19
Quota of specific energy uses of fuel and electricity [-]	3.0 (0.51/0.17)	3.0 (0.45/0.15)	2.8 (0.42/0.15)	2.6 (0.39/0.15)	2.5 (0.35/0.14)

The optimal battery sizes (ranges), $AER_{opt,i}$, can now be deduced from MRF_{opt}, charging prerequisites and individual driving patterns. Under certain conditions the optimal battery size is zero and hence a HEV (no charging) is preferred over a

6 For further details on the model and the derivation see for instance Karlsson, S. and Jonson, E., (2012). Electrification potential of the car – an estimate from a mid-size Swedish town. *World Electric Vehicle Journal,* 4, 82-90. (2012)

7 Some remarks are in place. Estimated or stated costs of batteries are often given in EUR/kWh for the battery, i.e. total cost divided by the (nominal) energy capacity. But the specific cost of the current PHEV batteries depends on the capacity for both power and energy. For a given power, the additional cost for energy capacity, that is, what is interesting here, can be considerably lower than the specific cost for the whole battery. The marginal cost for battery energy capacity can thus be lower than the today's stated battery specific cost of 450-600 EUR/kWh. On the other hand, stated costs are often production costs and do not include the mark up costs seen by the car buyers. The assumed annuity of 0.15 corresponds to a levelized capital cost over a relatively long depreciation period and/or an assumed low rent. In most countries the actual depreciation in cars' value can be considerably higher in their first years and then decrease for older cars. An assumed doubling of the annuity would result in a doubling of the MRF_{opt}, corresponding to a shifting of one column to the left in Table 10.1.

PHEV. Figures 10.6 and 10.7 show the distribution of optimal battery ranges, and the number and shares of PHEVs in the car fleet. The result is given for different MRF_{opt} in compliance with Table 10.1, and different minimum break times T required for charging to take place.

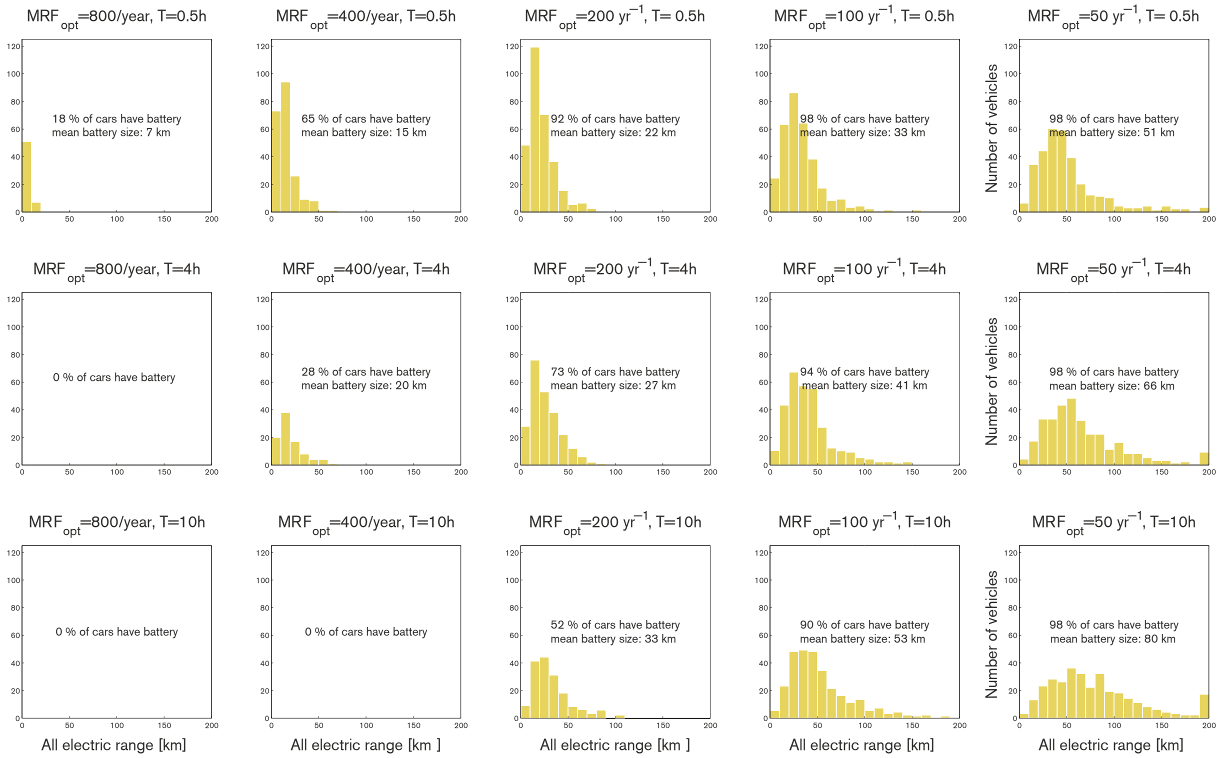

Figure 10.6 For a total of 326 investigated vehicle movement patterns, the distribution of optimal individual PHEV battery ranges *AER*. From left to right: increasing economic viability, that is, decreasing MRF_{opt}. From bottom to top: better recharging options, that is, shorter minimum break time T for recharging.

The viability of PHEVs is strongly dependent on the techno-economic prerequisites, as expressed by the MRF_{opt}. In general, the better the economics of PHEVs, i.e., the smaller the MRF_{opt}, the more viable are PHEVs and the larger are the optimal battery size. Given the conditions of today, if viable at all the optimal battery needs to be small, in the range of 10-20 km, to be able to recover its costs. In a future with possibly very favourable economic conditions, i.e. very small MRF_{opt}, it could be optimal that almost all cars are PHEVs. But their batteries could vary considerably in range due to diverging driving patterns (column to the right in Figure 10.6).

The charging options are of importance for the viability of electromobility. Figure 10.6 demonstrates that for increasing charging opportunities (lower T) the share of viable PHEVs in the vehicle fleet increases. This is especially true for less favourable economic conditions. For PHEV competitiveness, the different charging options are thus most important in the transition from low to high economic viability of batteries. Therefore, development of recharging options is critical to achieve a considerable share of PHEVs in the near future. In addition, the battery should be kept small. For someone not having the ability to charge frequently, PHEVs are unlikely to be an economically viable option without subsidies (Chapter 13).

When charging can take place more often the optimal battery range generally tends to decrease, especially at very benign economic conditions. For instance, our estimates give that for an MRF_{opt} of 50 yr^{-1}, a change of *T* from 10 to 0.5 h makes the average battery shrink in range with about a third: from 84 to 54 km.

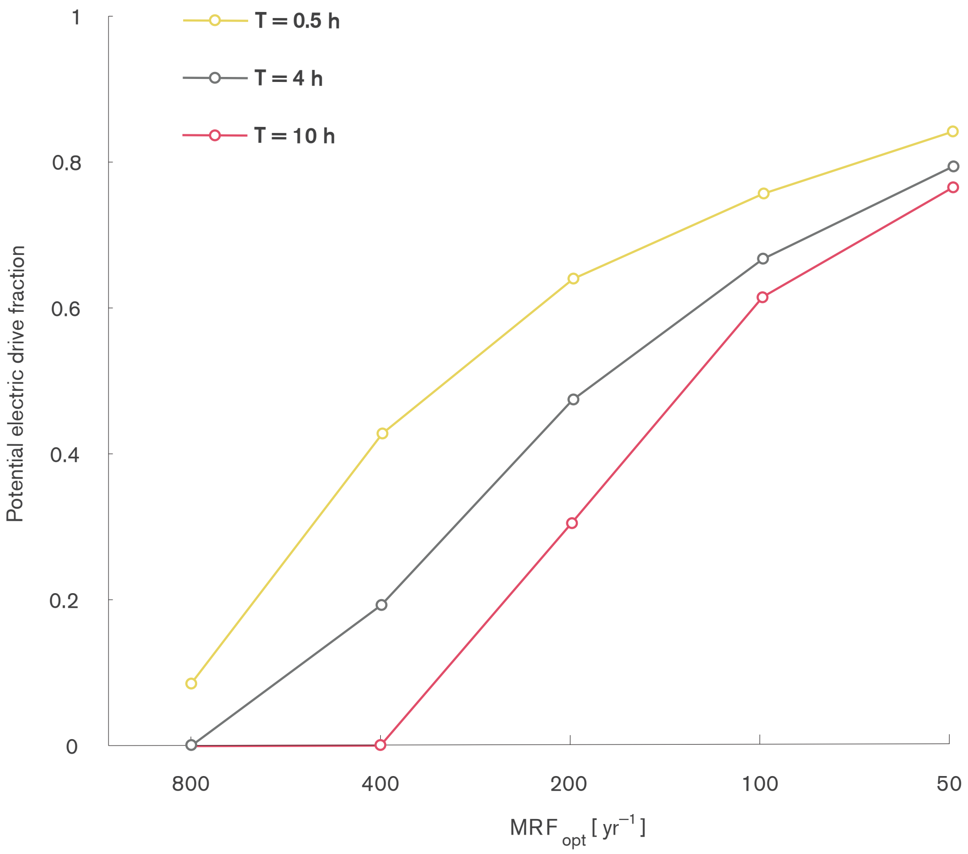

Figure 10.7 The share of the car fleet being PHEVs as a function of the viability parameter MRF_{opt} and charging options expressed as pause time *T* between trips.

Figure 10.8 gives the estimated overall potential for economically optimized PHEVs to replace fuel with electricity, the fleet *EDF*. Naturally the achieved fuel substitution is smaller than the corresponding share of vehicles being PHEVs, shown in Fig 10.7. For instance, with 60 % of the cars being PHEVs, the electric drive fraction is around 35 %. For conditions when practically all cars are PHEVs and have larger batteries, the substitution of fuel is still limited to around 80 % of the distance driven.

Also the electric drive fraction is very dependent on charging options. Actually, compared to the number of PHEVs, the electric drive fraction is more sensitive to charging condition and battery economics also at very benign economic conditions. Even for MRF_{opt} of 100 or 50 yr^{-1}, the EDF increases considerably for better recharging options and/or further improvements in battery economics. In reality there will not be totally individualised and optimised batteries. We have shown elsewhere that introducing a few battery sizes can be enough to harvest most of the gains achieved by fully individual batteries.[8]

8 Karlsson, S. and Jonson E. (2011). *The effect of PHEV battery range distributions on competitiveness: Implications for design strategy and energy-efficiency policy*. In: Proceedings of Energy efficiency first: The foundation of a low-carbon society, European Council for an Energy Efficient Economy (ECEEE) 2011 Summer Study, 6–11 June 2011, Belambra Presqu'île de Giens, France, pp 1015-1013.

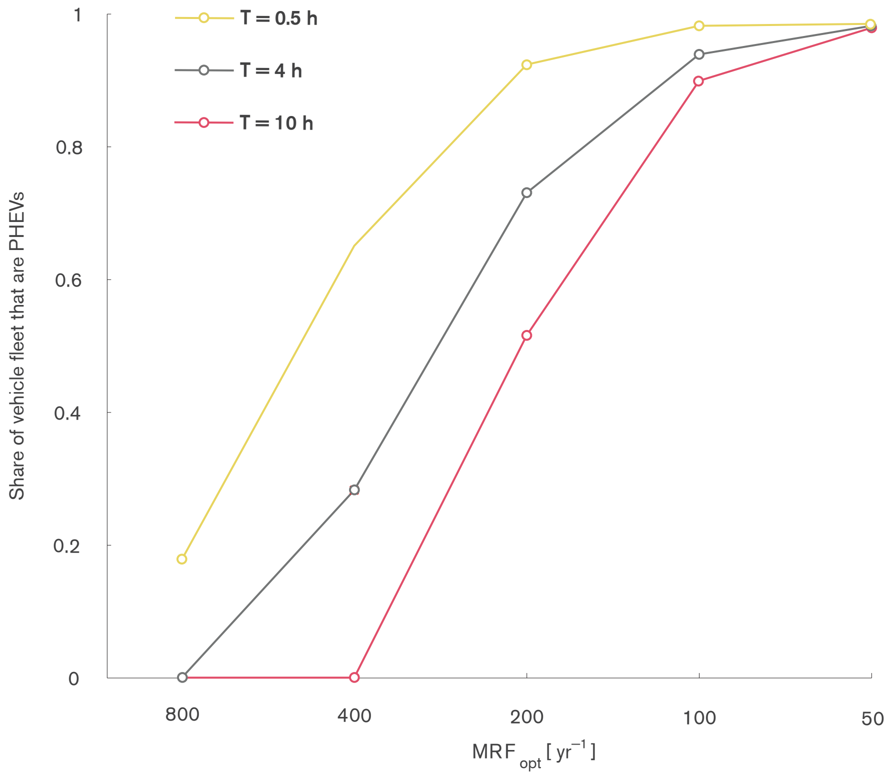

Figure 10.8 Potential electric drive fraction (EDF) for the car fleet as function of the viability parameter MRF_{opt} and charging options expressed as pause time T between trips.

DISCUSSION

We have introduced a simple model for assessment of the design, viability and potential for electrified vehicles based on the movement and charging patterns as well as some techno-economic prerequisites related to battery and energy costs. It should be noted that the analysis in the previuos section is restricted to the evaluation of PHEVs with different battery range in comparison to a car with a zero-range battery, that is, the corresponding HEV. To which extent the HEV and the PHEV are superior to the conventional car is of course very important for the competitiveness of vehicle electrification. The conventional vehicle is quickly developing when it comes to energy efficiency and the gap to electrified vehicles is shrinking (see Chapter 5 on energy efficiency). Part if this development is due to the partial electrification of the conventional vehicle by the introduction of for instance stop/start systems and other electric hybridisation technologies (Chapter 2).

The movement patterns in the dataset utilised here cover about one to two months of driving for each car. Still cars can have a movement pattern which varies over the year with season, vacations etc. The pattern could also change over the vehicle lifetime, for instance due to the fact that most cars have several owners during their lifetime.

It is also worth noting that for very small PHEV batteries the power to energy requirements can be prohibitively large if driving in CD/CS mode is what is aimed for. Moreover, turning an HEV into and PHEV will require a charger, a motor and power electronics with higher power rating to avoid blending mode in various normal driving conditions. For viability these extra costs need to be recovered by a high *EDF* in the driving, i.e., a larger battery. PHEV batteries with very short ranges should therefore probably be avoided altogether which to some extent contradicts a conclusion made in the previous section. Still we think that on an aggregated level, the results presented here are valid.

There are now PHEV models available on the market with a long range (≈ 60 km) as well as models with smaller batteries (≈ 20 km). We have pointed to the favourability of relatively small batteries in an introductory phase and then a turn to larger batteries when the costs have decreased further. This conclusion does not rely on an analysis of the current market, but on an assessment from a "rational" total cost of ownership (TCO) perspective. There may still be niche markets for PHEVs with larger batteries targeting specific groups, for instance persons less sensitive to a high TCO. Different forms of subsidies, not least through favourable conditions for company cars may as well be very important for the early development of vehicle electrification (Chapter 13).

CONCLUSIONS

While electrification of vehicles in the longer term may change our driving patterns (Chapter 11), this chapter has analysed how current driving patterns affect to what degree electrification is economically viable.

It can be concluded that data on vehicle movements is useful for assessments of the impact of different techno-economic parameters on market penetration of PHEV, fraction of electric propulsion and optimal battery size.

While PHEVs technically can replace conventional cars, the limited range of current BEVs severely restricts their ability to be an alternative to current cars given the irregular driving patterns of today and occasional long-distance driving, especially in one-car households. However, in car fleets and car pools, the range may not be a problem.

In assessments of economically viable electrification with PHEVs, the marginal recharging frequency is a central concept linking vehicle movements to techno-economic properties. The marginal recharging frequency is determined by the individual vehicle's battery range, movement and recharging opportunities.

From the perspective of a consumer's total cost of ownership an initial electrification by plug-in hybrids should mainly rely on relatively small and therefore cheaper batteries. The focus should be on customers with driving patterns characterised by frequent driving such as commuting. Frequent recharging is also of importance, for instance, by charging not only at home but also at work. Hence, infrastructural investments directed towards workplaces could be beneficial to an introduction of PHEVs. However, without some form of subsidy or other financial alleviation the potential for PHEV for private driving is currently small.

11

HOW WILL CAR USERS SHAPE ELECTROMOBILITY AND HOW WILL ELECTROMOBILITY SHAPE USERS?

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INTRODUCTION

In the early beginnings of the car, there were three propulsion systems that competed on more or less equal terms: the steam car, the electric car, and the petrol car. In 1900, 40% of all cars in the US were steam powered, 38% electric powered, and only 22% IC engine powered. Electric cars were perfect for city use as they were silent, clean and easy to manage, while their short range and low top speed made them less suitable for intra urban use. For example, a Detroit Electric had a range of approximately 130 km and a top speed of 30 km/h. Nevertheless, it was an electric car that was the first to break the 100 km/h speed barrier in 1899. Steam cars, on the other hand, offered reliable known technology, and high performance in terms of power. Steam was the propulsion of choice for many lorry manufacturers.

Early petrol cars were by comparison difficult to operate, and quite unreliable. They were, of course, mostly toys for very rich people and as such not expected to be of much real use. A major drawback to the petrol car was the lack of fuel infrastructure. While coal and electricity were readily available, at least in the cities, it was quite difficult to buy petrol.

The ultimate win for the internal combustion engine car was caused by many factors, e.g. the invention of the electric starter in 1912 (the year electric car sales peaked), gearboxes that were easier to operate and more reliable, and the discovery of large petroleum reserves in Texas, drastically lowering the price of petrol. Nevertheless, the most important factor was probably that the IC engine became engine of choice for Henry Ford. Thanks to mass production, the Ford Model T was sold at a much lower price than comparable electric cars ($650 compared to $1750 in 1912). Additionally, while electric cars got more expensive for each year, the Ford Model T got cheaper for each year (A model T roadster had a list price of $360 in 1916).

As cars became increasingly reliable and less expensive, new demands were put on them. To be of good use for travel, the car needed to be more practical. It needed, for example, boot space, sides and roof. With every improvement of the car, new uses were found and with them came new demands for further improvements to better suit the new uses. At the same time, the motorcar made demands on the world around it. Roads that worked fine for horse drawn carriages were not up to the challenges posed by cars capable of ever increasing top speeds. New roads, paved with asphalt or concrete, had to be built; networks of fuel stations had to be set up; guide books such as Guide Michelin had to be written so that the new motorist knew where to fix their car and where to eat while waiting.

When cars spread to larger groups of people it had consequences for the way people lived their lives. City planning changed as people started living in suburbs; the car allowed them to travel to work with ease and comfort. Shopping centres sprung up outside of the cities with new roads and great parking lots that offered all amenities in one place. This is a clear example of how technology shaped society and the way of life. And as the habits of people changed, the infrastructure and cars were developed to better meet these new demands.

Today, we live in a society shaped by the opportunities provided by the car as well as the demands this has placed on infrastructure. In many cases, we live far from our workplace, we drive our children to school and activities and we go by car on holidays. This is of course affects the reintroduction of the electric car and electromobility. New electric cars are compared to the concept of the car formed by our experiences of ICE cars, and it is found lacking (see also Chapter 12).

However, it is usually not acknowledged that electromobility might not be necessarily worse, but just different. This chapter elaborates on both the benefits and the drawbacks of electric vehicles from a user perspective and highlights some important areas for development in order to get users to adopt electromobility. Further, building upon the historical review of the ICE vehicle, it discusses how electromobility and its users may co-develop in the future.

This chapter is focused on full electric cars, i.e. battery electric vehicles, BEVs, except where specifically mentioned. Quite often, plug-in electric hybrid vehicles are included when one discusses electric cars. However, the plug-in hybrid electric vehicles, PHEVs, are quite different in terms of mobility and how the driver can use and interact with the vehicle. Plug-in hybrids are in a way much easier to adopt since they essentially can perform the role of an ICE car (Chapter 10). On the other hand, they are immensely more complex in terms of how they function (Chapter 3) and how their user interface has to be designed in order for the user to understand how to drive them in an eco-efficient way.

PERCEIVED BENEFITS OF ELECTROMOBILITY

A good starting point for understanding electric cars and how these may shape future mobility is to study what people who already own one has to say about them. In studies of electric vehicles where people have actually spent their own money to buy or to lease an electric car, the involved drivers have stated many reasons for doing so. Among the reasons stated are: economic reasons, technology interest, environmental concerns, political reasons, as well as the excitement of friends and family.

While electric cars in general are quite much more expensive to buy, the running costs are low, at least when you don't consider depreciation and cost for replacing worn out batteries (Chapter 12 and 13). However, in France for example, where the government made substantial investments in electric vehicles during the 1990s, there exist a relatively large amount of used electric cars. These cars can be acquired at low cost, which makes them economically attractive.

Many participants in the different electric car tests that have been made state a high interest in the technology. There are people who are interested in cars in general and therefore want to test what is viewed as the upcoming technology for cars, as well as people with a general interest in technology such as electronics and electric power and want to test what these technologies can do for the car. Participants also state that the excitement of colleagues, friends, and their children was an important reason for acquiring an electric vehicle since electric vehicles are being seen as novel and cool.

Another often-claimed reason for choosing an electric vehicle is environmental concern. This could involve local issues such as reducing the pollution in the city you live, or concerns about global warming. A final reason for acquiring an electric vehicle is related to resources and international politics. There seems to be a growing concern, not least in the USA, that the dependency of foreign oil leads to political instability and to war.

One can assume that the people belonging to either of the latter two categories will be more inclined to give up some of the ICE car convenience than people in the former categories. Indeed our research indicates that this is the case. For example, in one of our studies on electric vehicles there was a participant with a strong interest in environmental issues. He worked with measuring mobile phone base station signals from a car. He stated that the standard procedure was that two people did this from a van since there was so much equipment involved. He, on the other hand, for environmental reasons used an ordinary estate car. During the test he forced his co-workers to join him in a small two seat electric car with much of the measuring equipment in the lap, and he claimed that he intended to continue with this even after the test period.

Whatever the reason for adopting the electric vehicle, all studies seem to indicate that the ownership of an electric car drives interest in environmental and energy issues. There are many examples of users of electric cars, previously not very engaged in energy or environmental issues, e.g. installing solar panels.

Electric cars also offer some unique benefits that become apparent when you try them out. All electric cars on the market use re-generative braking in order to reduce energy use. Typically, they offer different settings with the standard setting allowing coasting much like with an ICE car and one or two settings with harder braking force, intended for driving down hills or at high speed. Users, however, reports that this hard re-generative braking is very useful and relaxing in city traffic as it allows the car to be driven with one foot on the accelerator at all times. For the drivers, this then becomes a feature that increases their comfort, rather than a feature that offers a means to increase range.

Another benefit of the electric car is the performance in everyday driving. Although electric cars in general have quite low top speed, the torque characteristics of electric motors gives electric cars high acceleration at slow speeds, leading drivers of even such low powered cars as the "Think" to describe its performance in city traffic as quite nippy. The Mini-E that was used as test car in a couple of studies has some real performance advantages in terms of acceleration and handling, outperforming most cars in the segment.

PERCEIVED PROBLEMS OF ELECTROMOBILITY

Even if the electric car can be viewed as an eco-friendly, fun, technological marvel, it also has some drawbacks. One very real problem is people's *perception of electric power, electronics, and batteries as being complex* and out of reach for common people. Research has shown that drivers have problems understanding how electricity can power a vehicle.[1,2] Electricity is a concept hard to grasp to start with and batteries offer further problems.

In addition, people are inexperienced with electric energy measurements and ways of displaying that information. This causes problems in understanding important aspects of driving an electric vehicle. Studies have shown that drivers new to electric vehicles do not know how to relate to information displayed and wonder such things as "Why is the amount of electricity in the battery constantly changing?"

The uncertainty this causes is manifested in both concerns about the feasibility of the technology, concerns about how to treat the battery in the best way, but mostly in what is popularly described as "*range anxiety*". When asked about electric vehicles, many people express concerns regarding range anxiety, i.e. they are

1 Strömberg et al., (2011), Drivers, Electric Cars, and HMI: A Human Factors Approach, EEVC Brussels, Belgium, October 26-28, 2011

2 Cocron, P. et al. (2011), Methods of evaluating electric vehicles from a user's perspective – the MINI E field trial in Berlin, ET Intell. Transp. Syst., 2011, Vol. 5, Iss. 2, pp. 127–133 doi: 10.1049/iet-its.2010.0126

worried about getting stuck in the middle of the road with no power left. Taking into account that most car trips are local and not very long at all, this appears somewhat surprising. Possibly, motor journalists fuel this anxiety when they cannot refrain from putting any electric vehicle they test through some trial that involves long distance driving.

In a test where we let people have access to an electric car for free during three months this aspect was typically expressed as: "I was constantly worried that the electricity would run out, even though I never saw less than half power left on the meter". Similar results can be found in all short-term tests of electric cars.

On the other hand, in studies that report on long-term use of electric cars, such as the Mini-E studies[2,3,4] and Magali et al.[5], this anxiety seems to diminish with use. The participants in those studies still desired longer range, but they did not express any anxiety. Instead they learned how the car behaved in different conditions and what types of journeys are possible in different circumstances. Cocron et al. described it as users appraised range as a resource to which they could successfully adapt and that satisfied most of their daily mobility needs.[2] On average the participants in that study used 82% of the available range.

The importance of the user interfaceIt is a known fact that people use their experience of similar things when they assess new technology. Most people's experience of battery-powered devices is probably that they are unpredictable and never reach the performance stated in the advertisements. If you are used to computers advertised as having seven hours of work time on battery and are never able to reach more than three, you are bound to be anxious about the performance of car batteries. There is, however, lots of evidence that when they are offered control and adequate feedback, drivers change their behaviour and therefore are able to exceed the stated technical potential of electric cars.

In the Mini-E study in Germany there was a trend that people who had tried to reach the range limit were more confident in driving closer to the range limit.[6] The authors concluded that user interfaces that helped the drivers to test the limitations would be beneficial to reduce concerns about range.

These findings lead us to two important areas of improvement, the infrastructure has to be developed to better suit the characteristics of the electric car and the driver-vehicle interface has to be developed to support the driver to utilize the electric car in the most efficient way.

Careful design of the driver-vehicle interface can facilitate the dissemination of electric vehicles by helping the user gain a better understanding of the vehicle, and thereby reduce range anxiety and recharging issues. Even though the driver

3 Franke, T. et al. (2012). Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior. In Sullman, M., Dorn. L. (Eds.). Advances in Traffic Psychology. Farnham, UK: Ashgate.

4 E.g. Turrentine, T., et al. (2011), The UC Davis MINI E Consumer Study

5 Magali Pierre, Christophe Jemelin, & Nicolas Louvet, (2011), Driving an electric vehicle. A sociological analysis on pioneer users, Energy Efficiency , DOI 10.1007/s12053-011-9123-9

6 Franke, T. et al. (2012). Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior. In Sullman, M., Dorn. L. (Eds.). Advances in Traffic Psychology. Farnham, UK: Ashgate.

interacts with the whole car, the instrument cluster is the most natural place to communicate the specifics of driving electric vehicles to the driver.

According to Biscarri[7] the instrumentation should reflect the vehicle's significant variables (e.g. battery state-of-charge, necessary to see if the car will work) and intended use (e.g. speedometer, necessary to keep within legal limits). As drivers today are familiar with ICE instrumentation and their interpretation, this familiarity can be used to speed up adoption where communality exists (such as with the speedometer).

However, it may also lead to confusion when similar meters and symbols are used for measures that work differently in an electric vehicle (e.g. having state-of-charge meters that look like fuel meters). The relationship between state-of-charge and range is more complicated than the relationship between fuel level and range. As range is limited in EVs, this becomes an important aspect to communicate. A common solution is to include instrumentation for both range and state-of-charge (SOC). However, it is hard to accurately present estimated range as it fluctuates with the driving conditions and driving style. Studies have shown that this may in turn lead to confusion and uncertainty when the driver is given several different ranges for the same state-of-charge on different occasions, or levels that vary greatly within the same trip. Nevertheless, with time, drivers learn the range of their car, as well as gain an understanding of how it varies with the driving conditions.[8]

The EV interface will also need to communicate some unique points that are more naturally understood in ICEVs because of additional sensory cues missing in EVs. One example is that an ICEV will give off some noise and vibrations when the vehicle is started. In EVs this is not the case, and therefore an indication of "vehicle ready to drive" is necessary. A second important example is that some form of feedback is necessary when the vehicle is plugged-in and charging. Again, with ICEVs it is possible to hear that there is fuel going into the tank without a special indicator.

Novel instruments related to battery and the electric drivetrain can also be added. One such instrument is the powermeter, which shows how much power is drawn from, or is regenerated to, the battery. The power drawn from the battery not only affects the range, but also the longevity of the battery through the strain put on it. Therefore, this instrument can help explain the relationship between state-of-charge and range, while also encouraging the use of regenerative braking by showing its positive effects.

As previously noted, electricity is perceived as a difficult concept and people in general are unaccustomed with electricity as a means of propulsion. Therefore, instruments with an educational approach, such as power flow displays, have been suggested. However these have not proven successful, as they have been perceived as unnecessary at a first glance causing drivers to lose interest after a while. In some cases they lead to more confusion than understanding, and they

7 Biscarri, E.L., (2001), Instrument Clusters for Electric Vehicles, SAE Technical papers series E, 2001-01-3959

8 Wellings, T. et al. (2011). Human Machine Interfaces in Low Carbon Vehicles - Market Trends and User Issues, HMI 2.1 Report Low Carbon Vehicle Technology Project: Workstream 13

can even interfere with the driving performance.[9,10] Hence, we argue for simple, or minimalistic, design of the interface, where the instrument cluster should be designed in such a way that the vehicle can be operated with ease and without any safety concerns or inconvenience to the driver. Studies have shown that drivers learn the relationship between state-of-charge, driving conditions, driving style, and range quite quickly without complicated instrumentation. The focus should be on information that is easy to understand, reliable and not distracting.

COEVOLUTION OF TECHNOLOGY AND PRACTICE

The shift from horses to motorcars to electromobility can be compared to other technology shifts. When new technology is introduced, it is often inferior to the existing technology in some aspects, but with time the drawbacks can be dealt with while the benefits stay. Latour criticises the idea that innovations appear suddenly and are adopted by people if they are perceived to offer benefits greater than their costs.[11] Instead, he argues that when technology is introduced, people discover new uses for it which leads to technology development to better serve the new applications, which in turn generate new demand and further development and so on and so forth. There is a coevolution of technology and practice.

To give an example, Latour describes the development of roll film. Before Kodak invented roll film, all photography was done by professionals or by advanced hobbyists. These people prepared their own glass plates and developed the photographs themselves. Kodak started selling pre-prepared glass plates, and then roll film that offered simplicity at the cost of image quality. Professionals did not like this, but it opened a market for amateurs who could now take their own photos. These amateurs, however, did not want go through the trouble of processing film and making paper copies so Kodak had to develop these services as well. One outcome of this was pre-processed photo paper, which the professionals *did* like. Over time, roll film was developed to the point that glass plates became obsolete, not because roll film was inherently better, but because the great demand afforded the development costs. In the last ten years we have seen a similar change of technology where roll film has been phased out in favour of digital photography. At the start, it offered simplicity and speed at the cost of image quality but today it has almost totally superseded roll film for all applications.

When the car was introduced it was an expensive plaything for very rich people, but within a quite short period of time it was faster, more convenient and perceived as more environmentally friendly than a horse, and within economic reach for middle class people. One could imagine that electric vehicles can go the same way, if the industry chooses to focus their development activities on electric vehicles (see Chapter 2 and 15). So far, the traditional car manufacturers have chosen to move quite carefully, adapting existing car platforms for electric propulsion. The benefit of electric propulsion that is communicated is that of lower emissions (a "common good"). With use, people seem to find other benefits that have the character

9 Kurani et al. (2009), Plug-In Hybrid Electric Vehicle (PHEV) Demonstration and Consumer Education, Outread, and Market Research Program, UCD-ITS-RR-09-21

10 Wellings et al. (2011). Human Machine Interfaces in Low Carbon Vehicles - Market Trends and User Issues, HMI 2.1 Report Low Carbon Vehicle Technology Project: Workstream 13

11 e.g. Latour Bruno, (1998) Artefaktens återkomst: Ett möte mellan organisationsteori och tingens sociologi, Nerenius & Santérus Förlag, Stockholm

of "private goods", such as driver experience and comfort. We argue that these benefits have to be picked up, developed, and marketed, if the electric vehicle shall have a chance to replace the ICE vehicle (see also Chapter 12).

If we are to change from a liquid fuel transport system to a system that to a large degree is based on electromobility, we have to adapt the infrastructure so that it fits the electric car in much the same way that we adapted the infrastructure from a horse-driven transport system to a motorcar based system (see also Chapter 9 and 10 on issues related to charging infrastructure). Electric cars need electric power outlets placed close to parking spaces. This fact will put some demands on the infrastructure. Today, most discussion surrounds public charging stations, and while convenient in some situations, this is clearly a thought coming from an old system where fuel is tanked on special petrol stations away from home. Electric cars, on the other hand, are pre-dominantly charged at home, just as your smartphone is charged at home during the night. As long as the charge is enough for a day's use, you do not have to bother with how much electricity is still in the battery. Looking at long-term studies of electric car use this has proven to be a big advantage of electric cars: "You never have to fill the tank". This is of cause only true if you live in your own house, or if you have a rented parking space with a power outlet. For most people living in apartments, the lack of power outlets is a major hurdle to electromobility (if based on car ownership, see Chapter 12 for alternatives).

Several studies on long term effects of electric car use shows that the electric car triggers the interest in environmental issues, regardless of the initial reason for acquiring an electric car. Electromobility therefore has the potential for a positive impact on the environment that is greater than just the direct effects of changing propulsion system. On the other hand, there are also indications that electric car users transfer their trips from other modes of transport to the electric car. In a test where 40 people leased a Mini E for 6 months, 70% of all trips were made with the Mini E. ICE car use was lowered from 71% of all trips to 21%. Biking, walking, and public transport use was almost non-existing when the participants had access to an electric car.[12] This can to some extent be explained with the electric car being trendy and something that you want to be seen in. This effect will probably disappear as electric cars get more common. On the other hand, if it is an effect of people believing that they have done their contribution to improving the environment and therefore don't have to take the bus, or bike, it might constitute a problem.

The marketing of electric cars as a "secondary car" is questionable. Instead, we would argue that the electric car would make an excellent "first car" for everyday commuting, shopping etc. Hence, it should be comfortable, good looking, have a premium feeling, and therefore also possible to sell at a premium price. The petrol car could then be relegated to second car. There are several signs indicating that such a strategy could viable. One is that there is a clear trend for premium car manufacturers, at least in Europe, to introduce small premium cars. The BMW 1-series, Audi A1 and the new Mercedes A show that customers accept the idea

12 Franke, T. et al. (2012). Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior. In Sullman, M., Dorn. L. (Eds.). Advances in Traffic Psychology. Farnham, UK: Ashgate.

of an expensive car that isn't very big. Another fact supporting our argument is that the US Mini E study showed that the participants shifted the application areas of their cars, preferring to do as much driving as possible in the electric car. This way, they found the Mini E (a strict two-seater car with limited boot space) practical for 90% of their trips, and it was space as much as range that was the limiting factor.[13] Similar figures were noted for a long-term test of the same vehicle in the Berlin area. It was also noted in these studies that the participants adapted to the smaller car by e.g. changing cars with their neighbours in those few occasions they actually needed a bigger car.

To conclude, manufacturers of electric cars market their cars as "technical wonders who are good for the environment" with big displays that show how complex and novel they are, but looking at what people who actually has bought or leased an electric car say about them, what they should focus on is "fun and easy to drive, and very comfortable".

13 Turrentine, T., et al. (2011), The UC Davis MINI E Consumer Study

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DOES ELECTROMOBILITY REQUIRE NEW BUSINESS MODELS?

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INTRODUCTION

Chesbrough and Rosenbloom stated in 2002 that *The inherent value of a technology remains latent until it is commercialized in some way; obviously, the extent to which its value is realized is contingent upon the manner in which that takes place.*[1] This statement shows in a condensed expression the fundamental and critical role business models have in exploiting a technology's value. Business model innovation is therefore an important area that deserves legitimate attention from anyone interested in seeing a certain technology commercialized. There is a substantial interest in decarbonizing the transport sector and electromobility is seen as one important element to move in that direction (see Chapter 2).[2] Hitherto the commercialization of electric cars has not met expectations. Therefore there are good reasons to ask the question: Is there a need for new business models?" and to look into business model options.

Business models combine the technical features of an offering with consumers' perception of value. Developing business models hence comprise several inhomogeneous research areas like consumer attitude and behaviour, marketing, technology and economics. The scope of this chapter therefore allows for only a brief discussion on some and will, beyond the technical aspects of electromobility that is covered elsewhere in this book, focus on consumers and business model

1 Chesbrough, H. and R. S. Rosenbloom (2002). "The role of the business model in capturing value from innovation: Evidence from Xerox Corporation's technology spin-off companies." Industrial and Corporate Change 11(3): 529-529.

2 See Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system (2011) (read 2012-10-09)

concepts. The potential value of electromobility to freight companies is discussed in Chapter 13.

Electric vehicles can come in many variants like battery electric vehicles (BEV), plug-in hybrids (PHEV), range extender and fuel cell vehicles (see Chapter 2 and 3). This chapter focus primarily on the BEV to illustrate if and how new business models can help commercialize electric vehicles on a consumer market. The approach used for the BEV can be applied to any of the electric vehicle variants although their different attributes may affect how a detailed solution is designed.

PERCEIVED PROS AND CONS OF ELECTRIC VEHICLES

An electric car differs in many attributes compared to a traditional ICE car in ways that hitherto has created hesitance among car buyers. In many countries, the market doesn't "take off" as expected. One reason may be that the main benefits are common goods while the private goods are not so obvious (see also Chapters 11 and 13).

Some attributes are perceived as *worse* than those of an ICE. First, a BEV is significantly more *expensive* than a comparable ICE car. The price is often almost twice as high, mainly due to a costly battery pack.[3] Second, the distance between refuelling is mostly within the *range* of 100 km to 200 km, dependent on for instance ambient temperature and auxiliary equipment in use, like AC, stereo, and navigation system (see Chapter 5). Many BEV drivers experience range anxiety due to the uncertain range. Third, it normally takes many hours to fully *charge* an empty BEV battery compared to a few minutes to refuel an ICE car. There is currently no fast charging infrastructure in place and not yet a common fast charging standard. At the current BEV range and fast charger capacity, the BEV can hardly replace an ICE car for long-distance travels. Fast charging for 20-30 minutes charge the battery to about 80% of its capacity. This gives about 1 hour driving on highways, i.e. for every 1 hour of long-distance driving one need to stop and charge for 20-30 minutes. Finally, there is currently a considerable *uncertainty* about the used-car value of BEVs since the expensive battery lose capacity due to calendar time, number of charge cycles, number of deep discharges and full charges, temperature and so forth in ways that are not well known.

Hence, most car buyers do not perceive the value proposition a BEV constitutes as competitive to that of a traditional ICE car. Car manufacturers also seem hesitant. With a limited budget for new car development, should they spend it on developing a BEV based on relatively unfamiliar technology (Chapter 15) and that may sell in volumes dependent on governmental subsidies (Chapter 13), or shall they spend it on developing ICE cars – their home territory?

A BEV also has attributes that are perceived *better* for the owner than an ICE car, for instance its energy efficiency that translates to energy cost of about one third or less than that of an ICE vehicle (Chapter 5), a much better take-off torque, no tailpipe emissions (Chapter 6), and much less noise. As many of these attributes remain unknown to potential customers until electric cars become more common

3 Nissan Leaf (Golf-size BEV) 44 000 EUR (370 000 SEK); VW Golf from 20 000 EUR (170 000 SEK), dealer information 29 Oct. 2012.

in the streets and in car-showrooms, so do the knowledge about customers' willingness to pay for them.

CONSUMER VALUE

Consumers' perception of value, i.e. the factor that influences their consumption choices, is a social construct far from as logical as the traditional utility theory suggests.[4] The issue of consumer acceptance is not only a monetary issue. Convenience, status, and the product as contributor to the individual consumer's identity – these matter significantly. This section lists some issues, highly relevant for new technology and eco-environmental technology, where this perception of value plays an important role.

Climate change and the need to do something about it is increasingly known and accepted by the swedish population.[5] However, knowing and accepting that something must be done can be quite different from knowing and accepting that I personally have a responsibility and have to change my behaviour. Attitude and behaviour doesn't have to be aligned and often are not aligned on eco-environmental issues. Research in *consumer psychology* indicates that consumer behaviour generally follows rational-choice theory in high-private-cost situations, despite consumer eco-environmental concern attitudes. Diekmann et al. note that recycling falls in the low-cost domain while sacrifices in the energy and mobility area are typically seen as high-cost.[6] Hence, there are reasons to expect that consumers maximize their own utility when it comes to the mobility area despite their eco-environmental attitudes.

Within *market theory* it is well known that an established technology, as the ICE car has a defining power in symbolic, organizational and behavioural dimensions, which means the ICE car is and will be the reference point electric cars are compared against in all these dimensions.[7]

In order to be considered by consumers, alternatives to established technological paradigms need to become socially embedded.[14,8] If not embedded, the consumers' perceived *uncertainty* is higher than for established technologies. When people face uncertainties they tend to use a high implicit discount rate, sometimes as high as 800% and often around 30%-50%, especially regarding energy technologies.[9] So from a buyer's perspective, the uncertain technology has to "pay off" quickly or it will not be considered.

4 Dobers, P., & Strannegård, L. (2005). Design, lifestyles and sustainability. Aesthetic consumption in a world of abundance. Business Strategy and the Environment, 14, 324-336. Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. Econometrica, 47, 263-291. Thaler, R. (1985). Mental accounting and consumer choice. Marketing Science, 4, 199.

5 Naturvårdsverket. (2009). Allmänheten och klimatförändringen 2009. In (pp. 28). Stockholm: Swedish Environmental Protection Agency.

6 Diekmann, A., & Preisendörfer, P. (2003). Green and Greenback. Rationality and Society, 15, 441-472. Liebe, U., Preisendörfer, P., & Meyerhoff, J. (2011). To Pay or Not to Pay: Competing Theories to Explain Individuals' Willingness to Pay for Public Environmental Goods. Environment and Behavior, 43, 106-130.

7 Cf. Hård, M., & Jamison, A. (1997). Alternative cars: The contrasting stories of steam and diesel automotive engines. Technology in Society, 19, 145-160.

8 Newton, T. J. (2002). Creating the new ecological order? Elias and actor-network theory. Academy of Management Review, 27, 523-540.

9 Geiler, H., & Attalie, S. (2005). The Experience with Energy Efficiency Policies and Programmes in IEA Countries - Learning from the Critics. In (pp. 47): IEA. Jaffe, A. B., & Stavins, R. N. (1994). The energy-efficiency gap What does it mean? Energy Policy, 22, 804-810.

The value proposition's ability to contribute to the customer's self-image is an important part in the customers' consideration process.[10] People who are about to buy a car mostly care both about the car's status value and environmental performance but tend to maximize their own utility if these two attributes are conflicting. However, the car seems to lose power as status marker, especially among younger generations.[11] This can open up for new business models and value propositions based on mobility services rather than vehicles.

The Nobel Prize winning prospect theory from behavioural economics suggests that there is an asymmetry in customers' perception of gains versus losses. [12] If you win 100 EUR and then lose the same amount, you feel worse off than before. In other words, the perceived joy of winning is less than the perceived punishment of losing an equal amount of value. Outcomes are perceived as gains and losses rather than as states of wealth. Gains and losses hence refer to some kind of reference point. Customers hence disregard alternative technologies even at relatively small product attribute deteriorations versus the reference, which in this case is the ICE car.

When the above issues are applied on the BEV offering from a traditional car sale business model, theory clearly suggests that a BEV will be perceived as an inferior offer for most car buyers.

BUSINESS MODEL BRIEF

A business model is a model of how a company creates, delivers and captures value.[13] All firms have a business model but the vast majority of firms does not articulate it and lack a process for managing it (see also Chapter 2 on technology lock-in).[14] Johnson concludes:[15]

Eventually, the elements of the business model commonly fade into the mist of institutional memory, even as it lives on as a practical matter in the rules, cultural norms, and metrics. This may be the reason why so many companies can operate so effectively without being able to articulate what their business model is. But since they evolve precisely to optimize an existing business model, these guidelines and control mechanisms are powerful inhibitors to the introduction of new business models.

A business model is often quite complex, and therefore difficult to comprehend in all its details. There are several frameworks for how to visualize a business model, with their individual strengths and weaknesses. At least three different categories can be found illustrating a) the internal logic of an organization, b) the interaction

10 Johansson-Stenman, O., & Martinsson, P. (2006). Honestly, why are you driving a BMW? Journal of Economic Behavior & Organization, 60, 129-146.
11 Automotive Landscapes 2025 (2011)
12 Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. Econometrica, 47, 263-291.
13 Osterwalder, A. (2004). The business model ontology: A proposition in a design science approach. Université de Lausanne, Lausanne. Osterwalder, A., Pigneur, Y. (2010). Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. New Jersey: John Wiley & Sons, Inc.
14 Cf. Chesbrough, H. (2007). Business model innovation: it's not just about technology anymore. Strategy & Leadership, 35, 12-17.
15 Johnson, M. W. (2010). Seizing the white space: Business Model Innovation for Growht and Renewal. Boston: Harvard Business School Publishing.

between organizations, or, c) decisions and consequences. There is not one single all-encompassing business model framework that manages to visualize a business model in all its complexity.[16]

The Business Model Canvas has become popular in industry through Osterwalder's successful commercialization of it as a tool for business model generation.[17] The canvas has a focus on the internal logic of an organization, see Figure 12.1. It depicts a business model in nine building blocks. The left half of the canvas depicts how the value proposition is created through own activities, own resources and the organization's network of partners. The creation and distribution of a value proposition incur associated costs, described at the bottom left. The right half is used to depict how the value proposition reaches the customers through customer relationships and channels, and how revenue is created. The notion "value proposition" indicates that it can be a product, a service, a mix of the two, a bundling and so forth.

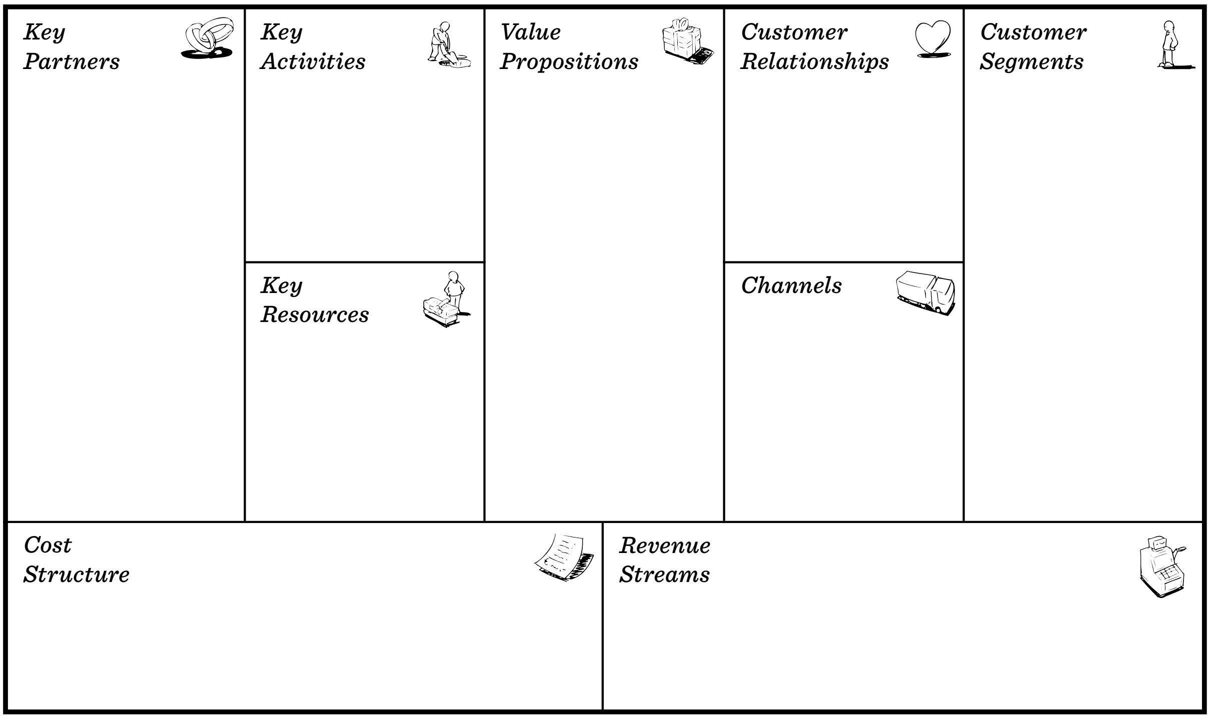

Figure 12.1. The Business Model Canvas. Source: Osterwalder et al. (2010)

The idea with a depiction of a business model is to make it more visible and easier to share. The depiction complements text with pictures, graphs and illustrations. This helps in the understanding of nuances of the business model and in a collective effort to develop and rejuvenate it.

16 Lindgren, J., & Sundelin, A. (2011). Business Model Frameworks – Review and Applicability. Unpublished Master Thesis, Chalmers University of Technology, Gothenburg.
17 Osterwalder, A., Pigneur, Y. (2010). Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. New Jersey: John Wiley & Sons, Inc.

Table 12.1. Business model analogies.

Type	Example	Description
Affinity Club	MBNA	Partner with membership associations and other affinity groups to offer a product exclusively to its members, exchanging royalties for access to a larger customer base.
Brokerage	Century 21, Orbitz	Bring together and facilitate transactions between buyers and sellers, charging a fee for each successful transaction.
Bundling	Fast-food value meals, iPod/iTunes	Make purchasing simple and more complete by packaging related products together.
Cell phone	Sprint, Better Place	Sell a service through multiple plans featuring a range of prices depending on varying levels of usage.
Crowdsourcing	Wikipedia, YouTube	Outsource tasks to a broad group who contribute content for free in exchange for access to other users' content.
Disintermediation	Dell, WebMD	Deliver directly to the customer a product or service that traditionally has gone through an intermediary.
Fractionalization	Time-sharing condos, NetJets	Allow users to own part of a product but enjoy many of the benefits of full ownership for a fraction of the price.
Freemium	Skype, LinkedIn, Pandora	Offer basic services for free but charge for upgraded or premium services.
Leasing	Xerox, luxury cars, MachineryLink	Make high-margin, high-cost products affordable by having the customer rent rather than buy them.
Low-touch	Southwest, Walmart, Xiameter	Offer low-price, low-service versions of a traditionally high-end offering.
Negative operating cycle	Amazon	Generate high profits by maintaining low inventory and having the customer pay up front for a product or service to be delivered in the future.
Pay-as-you-go	PG&E, metered ISPs	Charge the customer for metered services based on actual usage rates.
Razors/blade	Gillette, personal printers	Offer the higher-margin "razors" for low or no cost to make profits by selling high-volume, low-margin "blades".
Reverse auction	Elance.com, OnForce.com	Set a ceiling price for a product or service and have participants bid the price down.
Reverse razors/ blade	iPod/iTunes, Amazon Kindle	Offer the low-margin "blades" at no or low cost to encourage sales of the higher-margin "razors".
Product-to-service	IBM, Hilti, Zipcar	Rather than sell products outright, sell the service the product performs.
Standardization	MinuteClinic	Provide lower cost standardized solutions to problems that once could only be addressed through high-cost customized products or services.
Subscription club	Magazines, Costco, Netflix	Charge the customer a subscription fee to gain access to a product or service.
User communities	Angie's List	Grant membership access to a network, generating revenue through membership fees and advertisements.

Source: Johnson, M. W. (2010). Seizing the white space: Business Model Innovation for Growht and Renewal. Boston: Harvard Business School Publishing, p 131.

A VARIETY OF BUSINESS MODELS

There has been an increasing interest in recent years for business model innovation as an important and complementing tool to product, service and process innovations for firms to use in their quest for profits and competitiveness. Successful business models like Apple's iTunes store + iPod, TataMotor's Nano city car, Hilti's Power tools leasing and subscription and Spotify's streaming music draw attention to the importance of business models for market success.

The business model's importance for competitiveness and profit is not new. Gillette's razor-blade business model is one of the iconic historical examples (although that specific example may not be as clear-cut as shallow history suggests[18]). It is however not the first example of the "bait and hook" concept (or the more recent notion "freebie"). John D Rockefeller used this strategy successfully when Standard Oil in the early 1880th gave away or sold at loss 8 million kerosene lamps in China to increase the demand for kerosene.[19]

The list of business model analogies provided, from Johnson (2010) will be used as inspiration when addressing the challenges for commercializing electric vehicles.[6]

ENTREPRENEURIAL APPROACHES

Successful entrepreneurial newcomers are said to simultaneously co-develop the value proposition, its market, and the formula for how to serve the market profitably.[20] This co-creation process helps them create a viable business at low cost and to identify superior value propositions to customer segments, often viewed as radical by competitors. Another difference from established firms seems to be in how uncertainty is perceived and managed.

An incumbent firm, normally operating in known territory of customers and technology may manage uncertainty through early business case calculations and precise execution. A car company knows fairly well how much higher a car with better acceleration and top speed can be priced. They can also, based on experience and calculations, estimate what additional costs these performance attributes may incur. Sales volumes may also be predicted based on competitors, focus groups and so forth.

An entrepreneurial approach to uncertainty is learning. When neither the value proposition nor the customer segment is known, uncertainty may hence be reduced through a low cost process of scientific investigation. The saying "fail fast and fail cheap" shows that business model innovation, the co-creation of a value proposition and its market, needs to be a learning process.

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18 The Razors-and-Blades Myth(s) (2010)
19 Freebie Marketing (Wikipedia)
20 Blank, S. G. (2006). The Four Steps to the Epiphany: Successful Strategies for Products that Win (Second ed.): Cafepress.com. Furr, N., & Ahlstrom, P. (2011). Nail It then Scale It: The Entrepreneur's Guide to Creating and Managing Breakthrough Innovation. Johnson, M. W. (2010). Seizing the white space: Business Model Innovation for Growt and Renewal. Boston: Harvard Business School Publishing. Ries, E. (2011). The Lean Startup: How Constant Innovation Creates Radically Successful Businesses: Viking.

What market one intends to act on will significantly affect the requirements for success. There are four market options: act on an existing market; create an entirely new market; resegment an existing market as a low cost entrant; or resegment an existing market as a niche player. Each of these markets carries their specific challenges, conceptually shown in Table 12.2.

Table 12.2. Characteristics of the four market options.

	Existing Market	Resegmented Markets		New Market
		Low cost	Niche player	
Customers	Existing	Existing	Existing	New/New usage
Customer needs	Performance	Low cost	Perceived need	Simplicity & convenience
Performance	Better/faster	Good enough at the low end	Good enough for new niche	Low in "traditional attributes", improved by new customer metrics
Competition	Existing incumbents	Existing incumbents	Existing incumbents	Non-consumption/other startups
Risks	Competition from incumbents	Competition from incumbents	Niche strategy fails	No market adoption

Source: Blank, S. G. (2006). The Four Steps to the Epiphany: Successful Strategies for Products that Win (Second ed.): Cafepress.com, p. 27.

There are many historical examples where initially inferior technologies succeeded to create new markets and later even drove established technologies out of existing markets, i.e. they "hit from below".[21] A common characteristic for those cases was that they didn't chose head-on competition with the established technology. Instead, they used a different business model and often aimed (initially) for a customer segment that was non-customers to the established technology. They started in "New Market" in the Table 12.2, and then, as the technology developed and improved, also became competitive in the "Existing Market". The latter was then a consequence of technology improvement rather than of a business strategy.

POTENTIAL BUSINESS MODELS FOR ELECTRIC CARS

Business model innovation can be a possible means to address certain market issues, i.e. issues where the current value proposition can't meet competition under the given customer perception of value. We will now look upon some issues for electric vehicles and search for inspiration from the existing business models in Table 12.1.

Consumers' tendency to value losses higher than gains works against electric cars with their higher price but lower energy cost. The perceived unproven technology may also lead to consumers' use of a high implicit discount rate, which also works against the higher price and lower energy cost. This can however be changed through *fractionalization* and *leasing* concepts (Table 12.1). The objective is to change the relation between the upfront payments buyers have to make and the running cost they will have so that they both become easier to compare with the

21 Christensen, C. M. (1997). The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Boston: Harvard Business School Press.

current dominant technology (compare the discussion on total cost of ownership in Chapter 13). Renault uses a variant of this business model today for their Zero Emission line of battery vehicles.[22]

A BEV without battery would cost about the same as a comparable ICE car or even somewhat less in high volumes (see Chapter 13 and Figure 13.2 for an alternative view). The typical battery warranty in USA is 8 years or 160,000 km. A battery price of about 10 000 EUR spread over the warranted distance is hence 6.25 EUR per 100 km which together with the electric energy price of about 2.0 EUR per 100 km sums up to 8.25 EUR per 100 km. This cost per 100 km is relatively competitive with the cost per 100 km for an ICE vehicle. At a fossil fuel price of 1.50 EUR per litre, it corresponds to an ICE fuel consumption of 5.5 litres per 100 km. A battery lease can be based on a variety of parameters like annual driving distance, number of charge cycles or any other relevant combination of parameters that influence battery capacity loss. By using a fractionalization business model where the BEV is sold and its battery leased, the price and "energy cost" can be made more ICE-comparable, see Table 12.3.

Table 12.3. Two different ways to compare a BEV against an ICE car.

	ICE Car	BEV
Traditional business model		
Vehicle cost (EUR)	20 000	30 000
Energy cost (EUR/100 km)	10	2
Fractionalized (Battery lease) business model		
Vehicle cost (EUR)	20 000	20 000
Energy cost (EUR/100 km)	10	8.5

Business model changes in one part of the model almost always imply changes in other parts as well. In this case, the value proposition is changed from a complete electric car to one where the battery is leased while the car is sold without the battery. The lease may require a monthly customer relation and invoice, which either can be handled by the company itself as a key activity or through a leasing company as a key partner. If handled by the company itself, the initial battery investment has to be financed, either through own financial resources or through borrowing. How the solution is designed in this case affects the business model in terms of key activities, resources and partners.

The much lower energy cost for a BEV tells us that above a certain annual mileage, the BEV will be an economically better purchase than a comparable ICE car. Potential markets that can benefit from the lower energy cost may be: rental firms, where the annual mileage is about twice that of a private household; taxis (which however may require inductive fast charging at taxi stations); and in car pools.

One may view car rental, taxis and car pool services as variants of the *product-to-service* concept with offerings to non-car customers, i.e. to people who chose to not own a car. As more and more people live in cities where it becomes

22 EV Battery Leasing Could Become Norm in Europe (2012) read 2012-10-12

increasingly difficult and costly to own a car, and as the car loses in importance as status symbol for younger generations,[23] one possible business model may be to offer a type of car-pooling based on free-floating electric cars in collaboration with the cities. The city provides space for parking and charging and the car pool operator provides electric vehicles with zero local emissions. One can find a car through one's Smartphone, pay per minute it is disconnected from the grid, and can get and leave the car in different locations. Such an offering may give non-car owners a very attractive city mobility solution and may also attract those considering a second car. One example of such a business model is Daimlers Car2Go offering. [24]

Compared to the business model for traditional car sale, this one is quite different. The customer segment is non-car owners. The value proposition is access to cars through a pay-per-minute use scheme. Municipalities or parking space owners in cities are key partners. Car maintenance is a key activity. The pool of cars becomes a key resource. Customer relation is more or less continuous, and the distribution channel, i.e. customer access is through dedicated parking places.

Technology uncertainty raises a different issue. Some suggests that electric cars already today have a total cost of ownership (TCO) that is lower than comparable ICE cars (compare Chapter 13).[25] However, under uncertainties, consumers raise their implicit discount rate. In addition, many car buyers don't intend to own the car until end of its life but sell it after some years. One important uncertainty is therefore the car's value on the second-hand market. As long as electric cars haven't been on the market in high volumes for several years, the uncertainty about the second-hand market will remain, and new car buyers will hesitate. This creates a catch-22.

One possible business model solution is a variant of the *product-to-service* concept where ownership is kept and the service is sold (see above), or a *lease* concept where electric cars can be leased out in multiple lease cycles until end of the car's life. Such a business model hence removes the second-hand market risk through a sequence of leases to the different customer segments that today buy used cars of different ages. Both used-car leasing and operational leasing exists today. A combination of the two over the lifetime of the car will help solve the technology uncertainty issue and the potentially competitive TCO can be shared among the lease customers.

A business model based on this concept is relatively similar to traditional car lease business models. The main difference is the need to find and maintain the chain of customer segments that contain customers with preferences that matches all ages of a car from brand new to quite old.

Cars are used for a lot of different reasons and objectives. They can be used for commuting, for vacation, to visit relatives and so forth. The frequency with which one makes these trips varies greatly. When discussing whether BEV can play a significant role in society, there are often references to various studies showing

23 Automotive Landscapes 2025 (2011)
24 car2go (2012) read 2012-10-12
25 Werber, M., M. Fischer, et al. (2009). "Batteries: Lower cost than gasoline?" Energy Policy 37(7): 2465-2468.

that the lion's share of a household's travels have a distance far below the range a BEV can provide (see Chapter 10 and 11). For the individual car buyer who might have only one car, the focus may be less on the travels that the BEV can cover but rather on the travels it can't cover. Referring to our tendency to value losses more than gains, this may hinder a rapid commercialization of BEV. It hence seems fairly unlikely that a BEV have any possibility to completely replace an ICE based on the judgments a car buyer makes today.

One possible solution is to *bundle* a BEV with a car rental or car-pooling service. That combination can not only meet but also exceed the transport utility of one ICE car since the rental or car pool service may have a range of vehicles to choose from. Peugeot Mu is such an offering based on a bundling concept.[26] One issue though is that adding such a service to a BEV makes it look even more expensive. Such a bundling may however also make it possible to *decrease* the range and battery size of the BEV since its use can be set more precisely to cover the required daily range. PHEV and range extenders can be viewed as bundled cars as they are a bundle of a BEV and an ICE.

Combined with *leasing*, the transport utility issue may be solved or at least significantly reduced for a number of potential customers by using a *bundling* business model concept.

A business model based on this concept can be achieved through for instance a partnership between a car manufacturer, a car rental company and a leasing company. With the car manufacturer as the business model owner, the other two companies become key partners. The value proposition's ability to compete with that of owning an ICE car can be tuned through battery capacity, leasing terms for the battery and range of cars provided from the rental company.

DISCUSSION

The headline of this chapter asked if there is a need for new business models to support the commercialization of electric vehicles. ICE vehicles, which currently set the stage for how vehicle buyers compare cars, differ substantially from electric vehicles. Several of the electric vehicle benefits are common goods, like noise and CO_2 emissions. The private benefits, like higher energy efficiency are not appreciated as much as the drawbacks are disapproved when electric cars compete with traditional cars and their traditional business models.

We have shown that new business models have the potential to help make electric vehicles comparable in ways that affect customer perceptions so that they don't discredit them as much as otherwise. There may also be business models for non-car buyers where the electric car can be made superior to an ICE alternative.

We have for a variety of perceived hindrances shown business model concepts that may remove or at least reduce these perceived hindrances and hence improve the competitiveness of electric vehicles. These business model concepts are just variants of already known business models that have proven themselves in other businesses.

26 Mu by Peugeot read 2012-10-29

Then why are there so few alternatives to the traditional and well-established car sale business model? Consumers may be as sceptical to new business models as to new technology. Scepticism can be met through for instance transparent information that clearly compares the economics between buying-owning versus the proposed model's ownership-payment concept. This requires however that the business model owner consider its alternative as superior to traditional buying-owning. If the business model owner currently runs a sell-and-disengage business model, it may be difficult both to run two different business models and to argue for one in favour of the other.

The auto industry has optimized their current sell-and-disengage business models for decades and may perceive considerable risks with new and unproven ones. Their most important customers probably don't ask for electric cars. Since most OEMs also have a range of ICE cars, do they really want to compete with themselves and risk cannibalizing their (more profitable) ICE business? Their current business model is based on a continuous and high flow of cars into a market where they require service and spare parts for their entire life. Although too early to conclude, electric car technology promises lower maintenance costs and some of the suggested business models are based on a higher utility rate, i.e. a higher per-car efficiency. A company used to flow-based thinking may perceive this as a threat. The situation may hence be a typical example of Christensen's "The Innovator's Dilemma", where incumbent industries showed incapable of exploiting closely related business opportunities when based on products with attributes initially perceived as "inferior" and significantly different business models.[27]

27 Christensen, C. M. (1997). The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail. Boston, Harvard Business School Press.

13

POLICY INCENTIVES FOR MARKET INTRODUCTION OF ELECTRIC VEHICLES

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INTRODUCTION

This chapter outlines and analyses the policy options available to stimulate consumers into buying plug-in electric vehicles (PEV or EV), i.e., mainly battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). As seen in previous chapters, PEVs offer the opportunity to mitigate some of the sustainability issues of today's transportation system: propulsion energy supply, energy efficiency, environmental concerns such as emissions of regulated pollutants and greenhouse gases and noise (see Chapters 5 and 6). Thus, if the possible rebound effect[1] due to lower driving costs is curbed, there are societal gains of shifting towards electric mobility. PEVs still face a number of market disadvantages compared to the incumbent technology: there are knowledge gaps for the consumers, PEVs provide a slightly different service (e.g., range limitations) and they are still more expensive (see Chapters 11, 12 and 14 for further discussions on performance dimensions, consumer attitudes and alternative business models).

The standard economic solution to address these issues would be to tax the externality, i.e., the undesired side effect of the activity. An example in this case

1 The rebound effect is a term that captures that with increased efficiency the cost of e.g., driving are decreased and thus may lead to increased driving and thus not all the assumed energy saving is realized.

would be an economy or sector wide carbon tax. While fuel or carbon taxes are cost effective and address both the efficiency of the vehicles as well as distance travelled, they are generally not sufficient to spur the development and market introduction of less mature technologies, at least if the tax increase is to remain politically feasible. Extra policies might be needed to decrease uncertainty, increase learning by using and to be able to tap into economies of scale. Through incentives, part of the risk of a new technology is moved from the individual consumers to the governmental level.

In this chapter we investigate incentives that are directed toward the consumers of PEVs, focusing primarily on private cars and not commercial vehicles such as trucks (Chapter 14). Other options, such as changes in regulations that might simplify the introduction of PEVs, support for R&D (Chapter 15) and other supply side activities are not included. Each section represents perspectives related to: geography, the impact for the consumer and on vehicle sales, the timing on the adoption curve, and the related costs of the incentives.

NATIONAL STRATEGIES AND COUNTRY WIDE INCENTIVES

There is a range of incentives that target different cost components of the PEV. Addressing *purchase price* there are e.g., point of sale rebates (Sweden), income tax credits (USA), registration tax exemptions (Norway and Denmark). Exemptions from the annual circulation tax in Germany targets *annual costs*; while free parking and charging (Norwegian cities) reduce *other costs related to usage*.

Incentives can also be non-monetary but still have a large effect on sales since they might reduce risks such as extended battery guarantees for hybrids in California or provide other benefits such as reducing commute times by giving access to High Occupancy lanes (California) and bus lanes (Oslo).

Looking at the European countries you can find varying strategies on how to promote sales of electric vehicles. The different strategies might depend on issues such as budget constraints (become increasingly important), national car production (was a driver for high incentives in Norway and France), overall climate change related goals and strategies. We chose here to present a few examples that are representative of the different types of efforts.

Denmark has the highest registration tax for new vehicles in Europe (105 % on the price of the vehicle up to 9 500 EUR, thereafter 180 %).[2] PEVs are exempt from the registration tax and the green ownership fee[3] (*grønejerafgift* – max 1 200 EUR), making Denmark one of the countries with the highest incentive levels in Europe. This incentive should balance the much higher purchasing cost of PEVs and make them price competitive with conventional vehicles. This is part of Denmark's strategy to achieve its target of 200 000 EVs on the road for 2020. So far however sales have been moderate and are still below 0.5 % of new sold cars.

The strategy in *Germany* has been to fund R&D and local and regional initiatives rather than give incentives to individual consumers. Now however, as part of the

2 Registreringsafgift for nye køretøjer - satser (accessed 2013)
3 A fee paid every 6 months based on the fuel consumption of the vehicle.

National E-mobility Strategy from 2012 to 2020, with the goal to put one million electric vehicles on German roads, the individual customer can get an exemption from the yearly car tax, which is based on the weight of the vehicle. For a car weighing 1 500 kg the tax equals 45 EUR.[4] The national strategy also includes support to development of vehicle production and infrastructure.

The strategy for promoting EVs in *Norway* has been to facilitate the purchase and usage of PEVs. In this strategy the construction of charging stations has been included, as of September 2012 there were 3 500 of them. The majority of the charging stations are in the capital Oslo, but chargers have been installed even in the most Northern provinces.[5]

Norway has a target of 200 000 electric vehicles on the road in 2020. By the end of 2012, 8 600 electric vehicles had been sold, making it the country in Europe with the largest fleet of PEVs, out of which about 3000 were sold from January to September 2012. The large fleet of PEVs is highly related to the high amount of incentives in place. PEVs are not subjected to registration tax. The tax is based on three characteristics of the vehicle: weight, engine power and CO_2 emissions. E.g., a car weighing 1 300 kg, with a 100 kW engine and 140 gCO_2/km would have a tax of 13 100 EUR.[6] The annual registration fee is also lower. This amounts to 330 EUR for vehicles below 7500 kg.[7] There is no VAT compared to 25 % of the retail price of conventional vehicles. They are exempted from road tolls such as those to enter Oslo. In a number of cities parking in public parking spaces is free and they have access to bus lanes. They also receive free admission on national road ferries, but the driver still has to pay. The mileage allowance is higher and the taxable benefit of company cars is reduced by 50 %. Besides the level of incentives, the time and learning aspect may also be of relevance. Norway has been promoting EVs for at least ten years. Thus, compared to other countries, there may be larger experience amongst all actors.

Sweden has chosen not to be explicit on choice of vehicle technology. The goal of the Government is to have a vehicle stock that is "independent" of fossil fuels by 2030. An official inquiry is currently being made on the meaning of "independent". To promote vehicles with low CO_2 emissions a consumer incentive *supermiljö-bilspremien* (super green vehicle rebate) was presented in September 2011. It reduces the purchase price of environmentally enhanced cars (with tailpipe emissions of maximum 50 gCO_2/km, i.e. only electric vehicles for now) with 4 500 EUR for private owners and 35 percent of the premium cost of such a car for companies (such as car pools). A prolongation of the validity of the present reduction by 40 % of the fringe tax value (max 1 800 EUR) for leased company cars is discussed.

In the *UK*, purchasers of PEVs with CO_2 emissions below 75 g/km receive a premium of 5 800 EUR (maximum) or 25 % of the value of the vehicle.[8] Electric

4 Kfz-Steuer Elektrofahrzeuge (accessed 2013)
5 Grønn Bil (accessed 2013)
6 Kalkulator: import av kjøretøy (accessed 2013)
7 Årsavgiften 2013 (accessed 2013)
8 Must meet a series of eligibility criteria (for example, min. range 70 miles for electric vehicles, 10 miles electric range for plug-in hybrid vehicles). See Plug-in car grant (2010)

vehicles are exempt from the annual circulation tax. This tax is based on CO_2 emissions and all vehicles with emissions below 100 g/km are exempt from it. Electric cars are exempt from company car tax for a period of five years from the date of their first registration. Electric vans are exempt from the “van benefit charge” for a period of five years.

REGIONAL AND LOCAL INCENTIVES

There are examples of *regional cooperation* regarding EVs in the US e.g., in North Carolina the cities of Raleigh, Durham, Cary, and Chapel-Hill are collaborating on a number of EV related initiatives. An example in Europe is the Green Highway connecting Sundsvall-Östersund-Trondheim through a system of linked charging stations to enable longer trips. Many of these charging stations are free. Fast charging stations are also part of the concept.[9] The impact of these regional incentives is hard to evaluate at this early stage.

A number of *cities* are competing around the world to become EV capitals. There are Investments in infrastructure for charging and various consortiums are established. Few cities have given upfront monetary incentives even if examples exist such as Shanghai and Amsterdam. The most common way for a city to support PEVs is through free public charging and parking (e.g., Oslo and other Norwegian cities). Generally, if the city has other policies in place to manage other transportation issues such as congestion charging, these can be used to create special cases for PEVs. A typical example of this is the congestion charging in London. Shanghai caps the amount of vehicles registered per year by auctioning out a limited amount of license plates (prices have reached over 7 000 EUR at times), however EVs can get these for free. Another option is to give access to special roads and lanes such as bus lanes. This can be a major driver as in Oslo where surveys show it has been an important factor in the decision to purchase an EV.

Paris and neighboring municipalities have created a joint EV car sharing scheme, Autolib, providing the possibility for short-term rental of EVs. As of mid-2012, about 1900 EVs are rolling under the scheme, making up 32 % of the EVs sold in France.[10] While this is a service that people actually have to pay for, it promotes EVs by allowing more people to test EV driving without having to invest and take the risk of purchasing their own vehicle. Stockholm city in collaboration with one of the major Swedish utilities have in place a EV procurement project that has gathered 296 organizations and companies from all of Sweden that have signed up for the purchase of totally 1250 EVs during four years.[11]

Evaluating the effect of city level incentives at this stage is hampered by lack of reliable data with the exemption of Norway. Around 52 % of the PEVs in Norway are sold in the Oslo metropolitan area, while only 28% of the population live there, implying that local incentives such as access to bus lanes have spurred sales.[12]

9 Green Highway – En fossilbränslefri transportkorridor (accessed 2013)
10 Présentation d’Autolib’ (accessed 2013)
11 Elbilsupphandling.se (accessed 2013)
12 Income might also have contributed to the higher sales numbers.

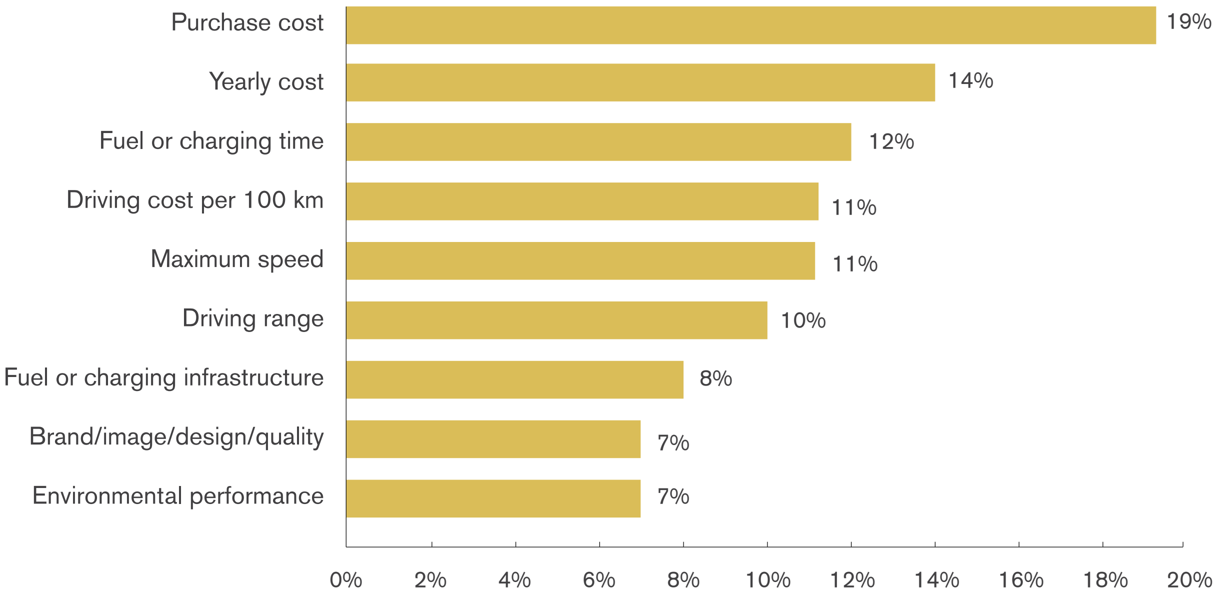

Figure 13.1 Importance of attributes in decision making process of a new car. Source: Lebeau et al., 2012.

THE RELATIONSHIP BETWEEN COSTS, INCENTIVES AND SALES

When purchasing a new vehicle, different parameters are taken into account. A survey with 1196 respondents in Belgium showed that costs are perceived as the most important parameter in the decision making process (see Figure 13.1). [13] For electric vehicles, this is not ideal, as these vehicles are sold at a high initial purchase cost. However, driving an EV is cheaper compared to driving conventional petrol or diesel cars, as the cost of electricity is relatively low. Therefore, a total cost of ownership (TCO) analysis is necessary to understand the cost structure of both electric and conventional vehicles (see also Chapter 10-12).

The costs associated with a vehicle occur at different moments in time. Therefore, in order to calculate a correct TCO, it is necessary to calculate the present value of all costs. The present value methodology makes use of a discount rate,[14] in this case the real discount rate, which does not take into account the inflation. To calculate the present value (*PV*) of future one-time costs, we use the following formula:

$$PV = A_t \times \frac{1}{(1+I)^t}$$

where A_t is the one-time cost at a time t, I is the real discount rate, and t is the time expressed as number of years. To calculate the present value of future recurring costs, we use:

$$PV = A_0 \times \frac{(1+I)^t - 1}{I \times (1+I)^t}$$

where A_0 is the recurring cost.

13 Lebeau, K., Van Mierlo, J., Lebeau, P., Mairesse, O. and C. Macharis (2012). The market potential for plug-in hybrid and battery electric vehicles in Flanders: a choice-based conjoint analysis. Transportation Research Part D 17, 592-597.
14 A discount rate is the interest rate that is used to calculate the present value of future investments or costs.

We use a vehicle lifetime of seven years and a yearly mileage of 15 000 km/year as a starting point.[15] The real discount rate used is 2.5%. The three investigated cars are located in the same segment (medium size) and their initial sales prices are 20 000 EUR (petrol), 22 000 EUR (diesel) and 35 000 EUR (EV). The incentives included in this TCO calculation are an exemption of the registration tax and a direct subsidy of 9 190 EUR (which was applicable in Belgium until December 2012).

Figure 13.2 illustrates the cost components of a petrol and a diesel car compared to an EV. The different cost components are: depreciation, registration tax, yearly driving tax, insurance, maintenance (including tires), fuel/electricity cost and battery costs. Below the x-axis, the direct subsidy is shown. We used different depreciation values for the different vehicle technologies. The yearly value lost per vehicle technology is: 15.5% for a petrol vehicle, 17.3% for a diesel vehicle and 28.0% for an electric vehicle.[16] These figures should not be taken as universal facts. There are many factors that influence the depreciation, and hence the residual value of cars, such as vehicle technology, brand and the condition of the car. In the TCO calculation, we replace the battery for the EVs when the amount of years passed exceeds the warranty period. This is a worst-case scenario, but since replacing the battery is expensive, consumers have to take into account that this cost may occur.

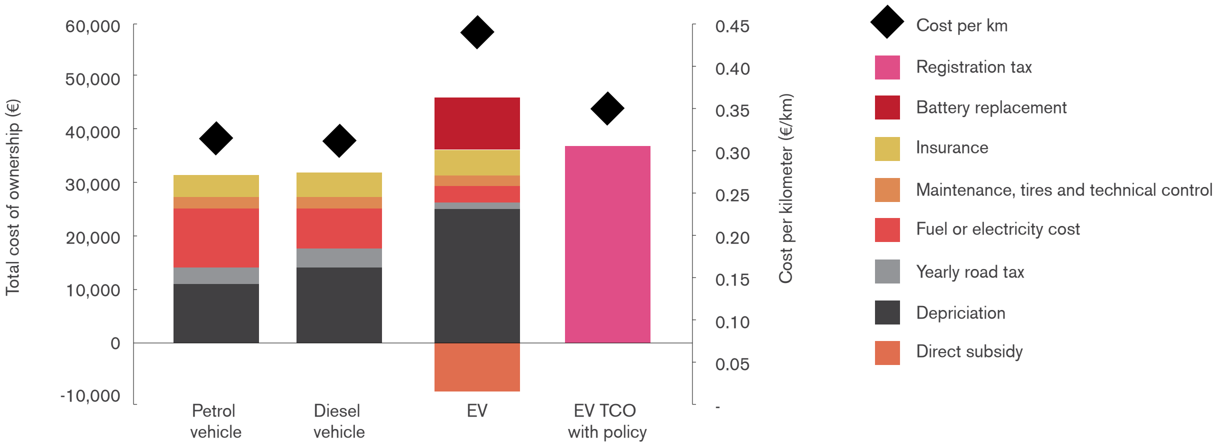

Figure 13.2 Total cost of ownership and cost per km of petrol, diesel and electric car (EV), with and without policy.

For the electric vehicle, two vertical bars are shown: one with the cost structure (left) and one with the final TCO taking the subsidy and tax exemption into account (in red, right). We can conclude that without financial incentives, the EV is not competitive with the conventional vehicles from a financial point of view. Its cost per kilometer is 46% higher than the petrol and diesel counterpart (see Table 12.3 for an alternative view). However, when we take into account the incentives, the difference is lowered to 15%. This is largely due to the governmental direct subsidy. In this model, the exemption of the registration tax has almost no effect on the TCO of the electric vehicles.

15 In Belgium, the average lifetime of a vehicle is 13.7 years. However, the average Belgian consumer only owns the vehicle for 7 years before selling it.
16 Lebeau, K., Lebeau, P., Van Mierlo, J. and C. Macharis, 2013. How expensive are electric vehicles? Working paper.

As seen in Figure 13.2 incentives can lower the TCO and make the PEVs more competitive. The effect of these incentives on sales of PEV however depends on how sensitive the consumer is to prices and costs. Sensitivity to prices are, in economics, normally calculated through so called elasticities, i.e., a measure of how many more vehicles are sold by decreasing the price or increasing the incentive in this case. To calculate the effect of monetary incentives on market shares of PEVs an econometric analysis including income, gasoline, diesel and electricity prices, and monetary incentives was applied to 13 European countries. [17] We collected data for 2010, 2011 and January to September 2012. The effect of incentives was significant and positive but the effect on actual number of cars sold was low. An increase of 1000 EUR in incentives would result in an increase of 12% in the market share, given that all other variables remained constant. Considering that the market share numbers are low this implies a very limit number of vehicles (approximately 70 – 300 PEVs depending on the market share). Previously, similar calculations have been made including sales until June 2011. The results give elasticities of the same magnitude. This means that the effect of the incentives has not changed markedly between 2011 and 2012.

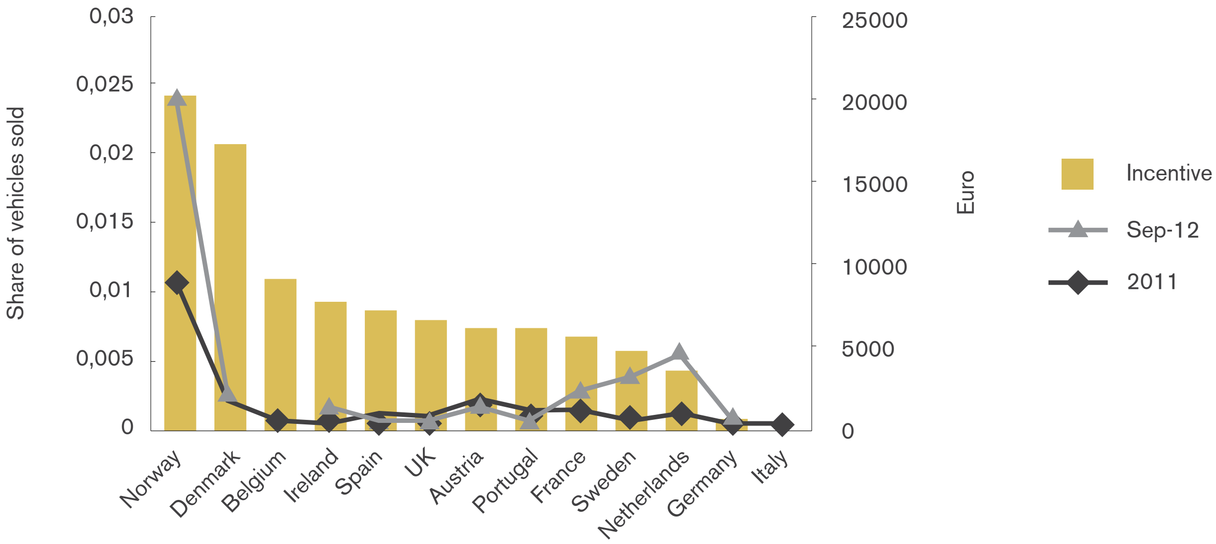

Figure 13.3: Lines and left axis show EVs share of new cars sold in 2011 and 2012 (for Belgium and Italy only 2011). Right axis and bars show incentive levels for each country.

To capture the effect of non-monetary incentives a dummy variable for Norway was introduced,[18] since these types of incentives are most prevalent here. The coefficient for the dummy is positive and significant, implying that the favorable conditions for PEVs in Norway have boosted sales. The coefficient for the monetary incentive remains significant, illustrating that the estimated effect in the previous calculations is not only driven by sales in Norway. The value of the coefficient however is slightly lower meaning that the effect of incentives might be smaller than previously presented.[19]

17 In the econometric model used the share of EVs sold was logged, while the incentive was kept linear to achieve the most reasonable fit. For a full description of the model see: Sprei, F. and D. Bauner (2011). Incentives impact on EV markets - Report to the Electromobility project. Gothenburg, Viktoria Institute.
18 A dummy variable is a variable that is one for Norway in this case and zero for all others. It is introduced to capture the effect of the non-monetary incentives, including infrastructure, available in Norway.
19 Sprei, F. and D. Bauner (2011). Incentives impact on EV markets - Report to the Electromobility project. Gothenburg, Viktoria Institute.

It is also possible that the increase in sales between years may be due to other dynamics of the market, such as increased number of models available and more knowledge about PEVs among consumers. In the model this was tested by introducing a variable for time. The coefficient for this variable was positive and statistically significant, showing that that these other developments have had an impact on sales. However, it does not alter the effect of the incentive. Between 2011 and 2012, Sweden, Norway, France and the Netherlands were the countries with the largest increase in EV shares of new cars sold. The consumer rebate in Sweden was introduced in 2012, partly explaining the increase in sales. In France the higher sales can partially be attributed to the introduction of the Autolib car sharing system.

There are a number of limitations of this analysis: data reliability is an issue; the model does not take into account that the limited supply of electric vehicles on many markets and the limited availability of electric vehicles in different market segments; constraints related to infrastructure are not included; and there might be basic differences in what cars people prefer buying in the various countries that affect the sales of PEVs as well. Thus the results should be interpreted in the light of these limitations and the reader should be aware that the analysis aims at assessing this early market environment and should not be generalised to other market conditions. So far, BEVs and PHEVs available on the market have quite similar characteristics and prices thus aggregating them to one group thus not undermine the results from the analysis.

POLICY TIMING AND TECHNOLOGICAL MATURITY

The adoption of a new technology is traditionally depicted as an S-curve, starting slowly with the innovators adopting the technology and moving on to early adopters. These are followed by the early majority.[20] PEVs today are at the early adopter stage. Early adopters are often characterized by being wealthier and more technology savvy compared to the average consumer and it has been shown that purchase price and TCO are less salient for these purchasers. For early adopters of the Toyota Prius hybrid vehicle the symbolic value of the vehicle was just as important.[21] It is thus plausible to assume that the amount of free-riders, i.e., people that would purchase the vehicle even without incentives would be quite high. This could mean that the role of the incentive as a driver for sales is even lower than what the elasticities show. However, early incentives might have other benefits. For example, it could be a signal to consumers and producers, that this is a good technology, supported by society, and thereby push car manufacturers to put new vehicles on the market. In the US, the Chevy Volt and Nissan Leaf were first launched in states with extra incentives or regulations. Nissan also selected countries in Europe for the market introduction of the Nissan Leaf based on the existence of incentives.

The S-curve has been complemented with concepts such as 'valley of death', 'crossing the chasm' and 'the hype cycle', i.e., the challenge of moving from the early adopters to the more pragmatic early majority and moving beyond initial

20 Rogers, E. M. (2003). Diffusion of Innovations. New York, Free Press.

21 Heffner, R. R., K. S. Kurani, et al. (2007). "Symbolism in California's early market for hybrid electric vehicles." Transportation Research Part D: Transport and Environment 12(6): 396-413.

funding to revenue generation.[22] Maybe incentives at this stage are more effective than earlier for the long term adoption of the technology. In Japan, while hybrids had crossed the line from the early adopters to the early majority, incentives were still in place until September 2012.[23] Pertinent questions related to this are: what incentives are most appropriate at what stage? Does the early majority need other incentives than the early adopters?

Another important question about timing is when to discontinue the incentives. At the moment in Europe budget constraints are posing a threat to many incentives. In Belgium the financial rebate for vehicles emitting less than 105 gCO_2/km was dropped in 2012. The number of vehicles sold in this category decreased with two-thirds during the first nine months of 2012 compared to the same period in 2011. This could be an example of how an incentive removed prematurely (?) can make the market collapse.

GOVERNMENT SPENDING ON INCENTIVES

There can be a concern that subsidising PEVs may be expensive for the state, especially in times of economic crises. In such debates it may be useful to be aware of how much money is actually spent on incentivising PEVs. In this section we calculate the total costs (including loss of revenue) for the government when it comes to financial incentives for PEVs as well as the cost of each additional PEV added on the market.

The annual spending (in 2011 and 2012) for the incentive ranges between 1 and 10 million EUR for the different countries, with the exception of Norway that is discussed in detail below. How large the spending is will of course depend on the number of EVs sold and the size of the incentive. Generous incentives to PEVs could easily reach large sums if the market takes off, however most governments have capped the incentives either by designating a specific pot of money for the subsidies or limiting the total number of vehicles that may receive it. There are as well revenue losses from decreasing sales from fuel taxes. We estimate the net revenue loss from decreased fuel sales from the PEVs sold during one year, based on average fuel consumption of new vehicles, average vehicle kilometres travelled per vehicle and the increased income from electricity taxes. Fuel taxes are fairly similar between countries and thus the differences mainly arise from the number of PEVs sold.

Norway is the country with the highest incentives and the highest penetration rate of PEVs in Europe and thus warrants a closer look at the costs. The calculation of the costs is not straightforward since incentives are based on exemptions from having to pay taxes or fees. Some of these depend on the characteristics of the vehicle and thus the question is what car, if any, the PEV is replacing. The loss of income due to the registration tax during one year may vary between 10.5 million and 20 million EUR (based on sales of 1500 vehicles). Fuel tax losses are in the magnitude of 1 million EUR. The loss of revenue from public parking for one year

22 Moore, G. A. (1991). Crossing the Chasm: Marketing and Selling Disruptive Products to Mainstream Customers. New York, HarperCollins Publisher.
23 Closing the Acceptance of Applications for the Subsidy for Privately-owned Environment-friendly Vehicles (“Eco-cars”) (accessed 2013)

is around 7 million EUR. These give a total of 18 - 28 million EUR.[24] Econ Pöyry calculate the total cost in relation to the CO_2 emissions avoided and find a cost of 3300-4000 EUR / ton CO_2 reduced.[25]

To calculate the cost of adding an extra PEV to the road we use the results from the econometric model. Presume that the incentive would increase with 1000 EUR, how many more PEVs would be sold? Our results give a range between 70 to 300 vehicles depending on the country. The total cost of adding those vehicles to the fleet would be 1000 EUR times the total number of PEVs sold. This total cost is then divided with the number of the number of additional vehicles (70-300), since we presume that the other vehicles sold would be sold at the old level of incentives. Our calculation gives us a price of 9 300 EUR per additional PEV. 9 300 EUR is quite a high subsidy; still it might be warranted at an introductory phase of a new technology. It is also cheaper than the government directly buying the vehicles for demonstration fleets, which may be an alternative.

CONCLUSIONS

Taking a total cost of ownership (TCO) perspective is important for PEVs since their initial cost is higher but the cost of driving the vehicle is lower, due to the price of electricity and the higher efficiency of the vehicle (Chapter 5). New business models that take this perspective into account may increase the competitiveness of PEVs (Chapter 12), but financial policy incentives might also be needed to lower the gap between the TCO of PEVs and conventional cars.

Current incentives have a positive but limited effect on PEV sales. Hence, in order for the market to really take off, more efforts are needed. Denmark, for example, has a strong economic incentive that in principle should make PEVs economically competitive with conventional vehicles. Nevertheless, sales have been moderate. Norway, on the other hand, has made use of a wider variety of policy instruments to stimulate sales and usage of PEVs and has today the largest fleet of PEVs in Europe.

The Norwegian example shows that sales of EVs can be successfully stimulated. However, the total costs for these incentives are high, especially if one only considers short term CO_2 emission reductions. There are, however, long term effects that are harder to quantify today (see discussions in Chapters 5, 6, 8 and 9). Incentives at city level are a strong complement to national policies considering that PEVs will be more popular in urban centres. Some of these, such as access to special lanes can be implemented with lower financial costs.[26]

Incentives for PEVs are not only important from a consumer's point of view, car manufacturers may also react to the national incentives within countries. Car manufacturers have selected the countries with the most PEV friendly institutional setup for the introduction of their first electric cars. Also the stability of the incentive structure system matters. Sudden changes in policy impacts the way car manufacturers estimate the market potential for PEVs within a country.

24 Sprei, F. and D. Bauner (2011). Incentives impact on EV markets - Report to the Electromobility project. Gothenburg, Viktoria Institute.
25 Econ Pöyry (2009). Virkemidler for introduksjon av el- oghybridbiler. Oslo, Econ Pöyry.
26 There might be other drawbacks such as increased congestion.

It should be noted that, despite strong stimuli for a new vehicle technology the market may collapse if there is a shift of public opinion due to e.g., negative news coverage and major improvements of the environmental performance of conventional vehicles. The market for flex-fuel vehicles in Sweden is an example of this. After a promising start with sales reaching almost 25% of new cars sold, the market share relapsed back to 5% in 2011, in despite of the fact that policies to promote flex-fuel vehicles and alternative fuels were still in place.[27]

27 Sprei, F. (2013). Boom and bust of flex-fuel vehicles in Sweden. Proceeding of the eceee 2013 Summer Study on energy efficiency, Toulon/Hyères, France.

14

ELECTROMOBILITY FROM THE FREIGHT COMPANY PERSPECTIVE

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BACKGROUND

In Europe (EU-27), there are approximately 600 000 commercial freight transport companies and 20 million road goods vehicles transporting 1900 billion tonne-kilometres annually.[1] The number of heavy duty vehicles is increasing rapidly. While it has been argued that the market prospects of electrified heavy duty vehicles are improving, it remains to be seen how quickly electrification will be picked up in different market segments. In this chapter we ask the question what benefits, and drawbacks, electromobility has to offer a commercial freight transport company (see Chapter 10, 11 and 12 on similar issues for passenger transport). We present a model that can be used by a freight transport operator to evaluate alternative energy carriers. The model takes a systems perspective and encompasses several dimensions apart from the pure technical.

COMMERCIAL FREIGHT

Typically, road freight companies have a low profit margin, often around 1-2%.[2] The largest share of the costs is staff, ranging from 35% to 55% of the total. The second largest is diesel (10-23%) and the third is depreciation, i.e. vehicle cost

1 Eurostat 2009 "Panorama of Transport", (2009). Some of these vehicles operate outside the commercial freight sector in privately owned fleets, i.e. at companies that use these vehicles to transport their own goods (for instance a manufacturer of office furniture with trucks of their own for deliveries etc.). Since these vehicles exist outside the commercial freight market they are excluded from this chapter, although several of the results and observations should be applicable to them as well.
2 Sternberg, H. (2011). Waste in road transport operations - using information sharing to increase efficiency. Institutionen för teknikens ekonomi och organisation, Logistik och transport,

(10-13%). Overall, the ratio of fixed versus variable costs is high in the transport industry. Between 18-35% of the costs are considered variable (fuel, maintenance and tires), the rest are more or less fixed (staff, insurance, depreciation etc.). This means that the revenues must cover not only the running costs but also a large overhead.[3] As a result of this, there is little room for non-revenue generating activities. In fact, a study of German transporters shows that only 1.1% of their revenue is spent on innovation.[4]

There are some intrinsic properties of the freight transport industry that are worthy of notice. In Sweden, 91% of the road freight (in tonnes) is transported less than 300 km.[5] The transportation industry is very fragmented, both when it comes to company size and services provided. The average number of trucks of a Swedish haulage company is 3.7, and more than 80% of the companies have five trucks or less.[6] Moreover, the transport industry services everything from waste management to agriculture, manufacturing, trade, mining, forestry, and construction industries. These industries have little in common when it comes to the nature of the transportation service in terms of distance, vehicle type, goods type, market situation and administrative processes. The heterogeneity of the companies and of the services they provide leads to difficulties in finding solutions that will fit all needs.

The freight industry acts as an intermediary in supply chains. There are a large number of stakeholders involved, including consignor, consignee, transport buyer, transport company, hauler, driver, governments, municipalities and private citizens, that have demands concerning reliability, security, safety and sustainability. The transport system is not allowed to break down, be delayed or otherwise impeded. Measurements such as uptime, delivery precision and service level are used to ensure reliability. Since the 9/11 attacks, there are also stringent regulations in place guarding against terrorist threats. There is an increasing focus on crime-related security issues.[7] The Swedish government has famously proclaimed that no people should be seriously harmed or killed in traffic related accidents (also called the Vision Zero).[8] Companies, both sellers and buyers of transport services, are now working systematically with transport safety issues.[9] Regarding sustainability demands, both public opinion as well as EU-wide regulations, are forcing the transportation industry towards alternative energy as well as higher energy efficiency.

In order to evaluate an energy carrier like electricity, all aspects above must be considered. Moreover, the evaluation will likely differ between stakeholders. In this chapter the perspective is that of a freight transport company.

3 Swedish Association of Road Haulage Companies, (2012)
4 Wagner, S. M. (2008). "INNOVATION MANAGEMENT IN THE GERMAN TRANSPORTATION INDUSTRY." Journal of business logistics 29(2): 215-231.
5 Swedish Association of Road Haulage Companies, (2012)
6 Ibid.
7 Ekwall (2009) Managing the risk for antagonistic threats against the transport network, Chalmers University of Technology.
8 Road safety (accessed 2013)
9 The newly created standard ISO39001:2012 "Road traffic safety (RTS) management systems - Requirements with guidance for use" is starting to come into use by the transport industry. Först i världen med ISO 39001-certifiering (accessed 2013)

EVALUATION OF ENERGY CARRIER ALTERNATIVES: THE MEET MODEL

The MEET model is a tool that has been used by freight companies to evaluate the consequences of switching to alternative fuels.[10] It was developed to help the companies evaluate alternative fuels from a systems perspective. There are also other similar models[11] but common to all models is that they include several aspects of the fuel or energy carrier, not only environmental or economic effects.

The MEET model takes four perspectives into account: *Money*, what are the economic consequences of choosing the energy carrier? What are the *Environmental* consequences? Are there any *Ethical* considerations? What are the *Technical* specifications?

Each of these perspectives is important when evaluating a technical option, although each individual evaluation will of course be subjective and based upon that single company and their preferences.

When comparing energy alternatives from an *economic* standpoint we may notice that since fixed costs amount to between 65-82% (as mentioned above), the freight company is highly dependent on reliability and uptime in order to maximise the return on investment. It is also of importance that a large part of the variable costs is related to energy (normally diesel). Three separate types of risks can be identified: operational risks, supply risks and investment risks, each with a number of critical issues.

The operational risk - the risk of disturbing or otherwise affecting the operations as a result of energy choice – is affected by three factors. The first is the risk for increased cost per km. The fuel price is, as previously stated, very important. This price is not only affected by supply and demand relations but also by taxes. The government can change the tax on various energy carriers and related emissions and thereby change the price (in the examples below we will leave out this political risk). The second issue is change in maintenance cost. An alternative energy carrier may increase, or decrease, the required maintenance (both total time as well as frequency). The third issue is range. A new fuel may require a higher refill/recharge frequency thereby affecting operations.

The supply risk is the risk of not being able to gain access to the alternative energy carrier in the same quantities and geographical locations as the current alternative. If the number of suppliers are too few, competition may be weak, which in turn may affect prices and quality. The availability of raw material is also an issue here. How and where is the energy carrier produced? What else besides energy carrier production is competing for the raw material (see also Chapter 8)? Another issue is that of infrastructure maturity, i.e. if there is a distribution system in place that is able to supply energy when and where needed. The energy carrier must be available as close to the geographical area of operations as possible.

10 The model was first developed in 2010 together with Jan-Olof Arnäs, then CEO of TRB Sverige (a Swedish company working with the road freight industry in R&D), as a tool to evaluate alternative fuels. The model has since been modified further to accommodate new prerequisites.
11 See for example Konrad (2007), Visual Comparison of Alternative Transportation Fuels, and Alternative Fuels Data Center (accessed 2013)

The Investment risk - the risk of investing in new technology – is hard to quantify. Vehicle price, changes in vehicle life-span and projected second-hand value are all important factors in determining the life cycle cost of a vehicle adapted to or designed for a novel energy carrier.

When evaluating an energy carrier from an *environmental* perspective, some important properties are emissions of greenhouse gases and pollutants, renewability (how much of the energy carrier is produced from renewable energy), degradability (effects when fuel is spilled) and toxicity (how harmful it is to handle or breathe). Also, competition for raw materials (both for energy and components) may lead to a negative environmental effect if the energy carrier is produced from a resource that could have been used elsewhere with greater effect (see Chapter 7 and 8). The local effects of production are important as well as more indirect effects in the well-to-wheel chain (Chapter 5 and 6).[12]

Even if an energy carrier is better technically, economically and environmentally than the current alternative there may still be *ethical* concerns. Marketing is one area that needs to be scrutinized. Not all producers are truthful in their marketing and sometimes statements are made based on assessments designed to clearly favour one alternative, or at least, make comparison difficult. When studying an energy carrier, the origin of the raw material is an issue of great importance. The local social effects of production, treatment of personnel and handling and transportation of materials and the fuel are all areas that may raise ethical concerns.

Assessing the *technical* properties might be more straightforward since they can be measured directly and compared across alternatives. Some important properties are related to the energy carrier itself. The presence of a standardized specification is important, i.e. a range of prescriptions that need to be met in order for the energy carrier to be recognised as valid. Energy density is of particular interest here since a commercial transport vehicle needs to be able to load as much cargo as possible (both by volume and weight). Another thing worthy of note is the temperature properties of the energy carrier. The vehicle should be able to operate during very hot as well as very cold outside temperatures.

Some technological aspects are more related to the engine technology than to the energy carrier *per se*, for instance, the level technological maturity. A newly developed powertrain type may malfunction while a diesel engine is based on a mature technology. The powertrain and its parts can also be affected by the energy carrier in different ways, such as corrosion/oxidation. Many of the liquid fuels require that lubrication is added to the mix in order to keep the fuel pumps from braking down (see also Chapter 4 on safety issues for electric drivetrains).

12 See also Systems Perspectives on Biorefineries 2013 for environmental effects of biofuel use.

TWO EXAMPLES

To exemplify how the MEET model can be used, we evaluate two plausible applications of electric heavy-duty trucks and compare them to diesel trucks. The first is an electric road system (ERS) and the second a battery electric city distribution truck (BEV).

The evaluations are performed from the perspective of the freight company investing in the truck. As previously stated, there are large differences between various types of transport services. The model assumes that the freight company already has a functioning business and that it is confronted with a choice of a new energy carrier. This is not a comparison between the two applications but rather two comparisons for two different companies.

The nature of the transportation service plays a big part in choice of energy carrier. The transportation distance affects the demand for range, size of energy carrier infrastructure and maintenance. A city may have restrictions on noise levels or exhaust emissions. These restrictions affect viable choices for haulers active in city logistics. Some services are unique and one-time-only whereas some are repetitive. This affects the impact of parameters like fuel availability, range etc. Therefore, the choice of energy carrier is specific to the individual company and its situation.[13]

The first example is an ERS which is a technology option for the propulsion of long haul trucks.[14] The principle is to transfer electric energy from the road to the vehicle and use an electric engine for propulsion. The continuous charging could be conductive or inductive (see Chapter 2 and 3). The main strategy is to develop the system in steps. First start with closed localised systems, such as transport from mines or bus systems, and then continue with highways. For long haul the main idea is to use a hybrid vehicle. Where no electric power infrastructure is built into the road the vehicle can use a diesel engine for propulsion. There are several on-going or planned demonstrations in the world. The most known is Pajala (Sweden), KAIST (Korea), LA Harbour and Siemens (Germany).

ERS could have a major impact on the cost of electric trucks. In particular, the size of the battery could be drastically reduced.

13 On the other hand there are other factors that push towards standardisation. Currently, diesel trucks are used in a great variety of applications.
14 ERTRAC Research and Innovation Roadmaps Implementation of the ERTRAC Strategic Research Agenda 2010.

Electric roads vs conventional diesel
Assessment example for long haul road transport

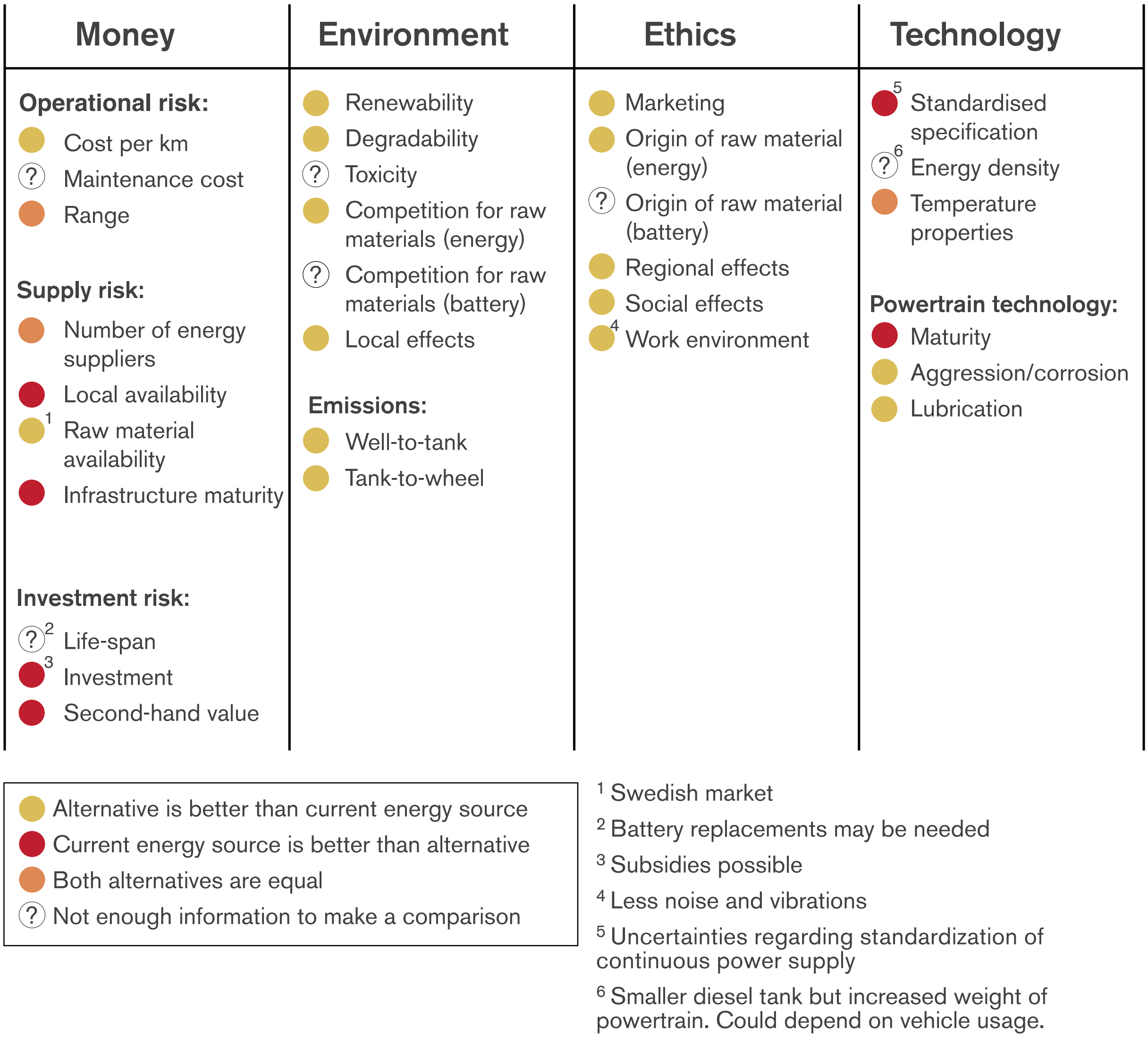

Figure 14.1 Example of how a long-haul freight company can assess the alternative of electric roads in relation to conventional diesel.

The assessment example above shows the complexity in choosing alternative energy. All of the different parameters are compared to conventional diesel and some of them are (in this example) better and some are worse. The drawbacks of electric roads as an alternative for this haulage company is mainly focused on the supply and investment risks involved. According to this assessment, the transition to electric roads will be expensive and risky, also when looking at the as of yet immature engine technology.[15]

The second example is battery electric city distribution trucks. Several municipalities around the world restrict access to trucks with engines with high emission

15 Initially, the availability of ERS is limited to roads where power is available. This will decrease the number of freight companies that can choose this alternative.

rates. Some cities are even discussing the possibility to only accept zero-emission trucks. Battery electric city distribution trucks with a range of 180 to 200 km could be a feasible solution. They do not emit pollutants in the city, make less noise and could use renewable electricity.

BEV vs conventional diesel
Assessment example for city distribution truck

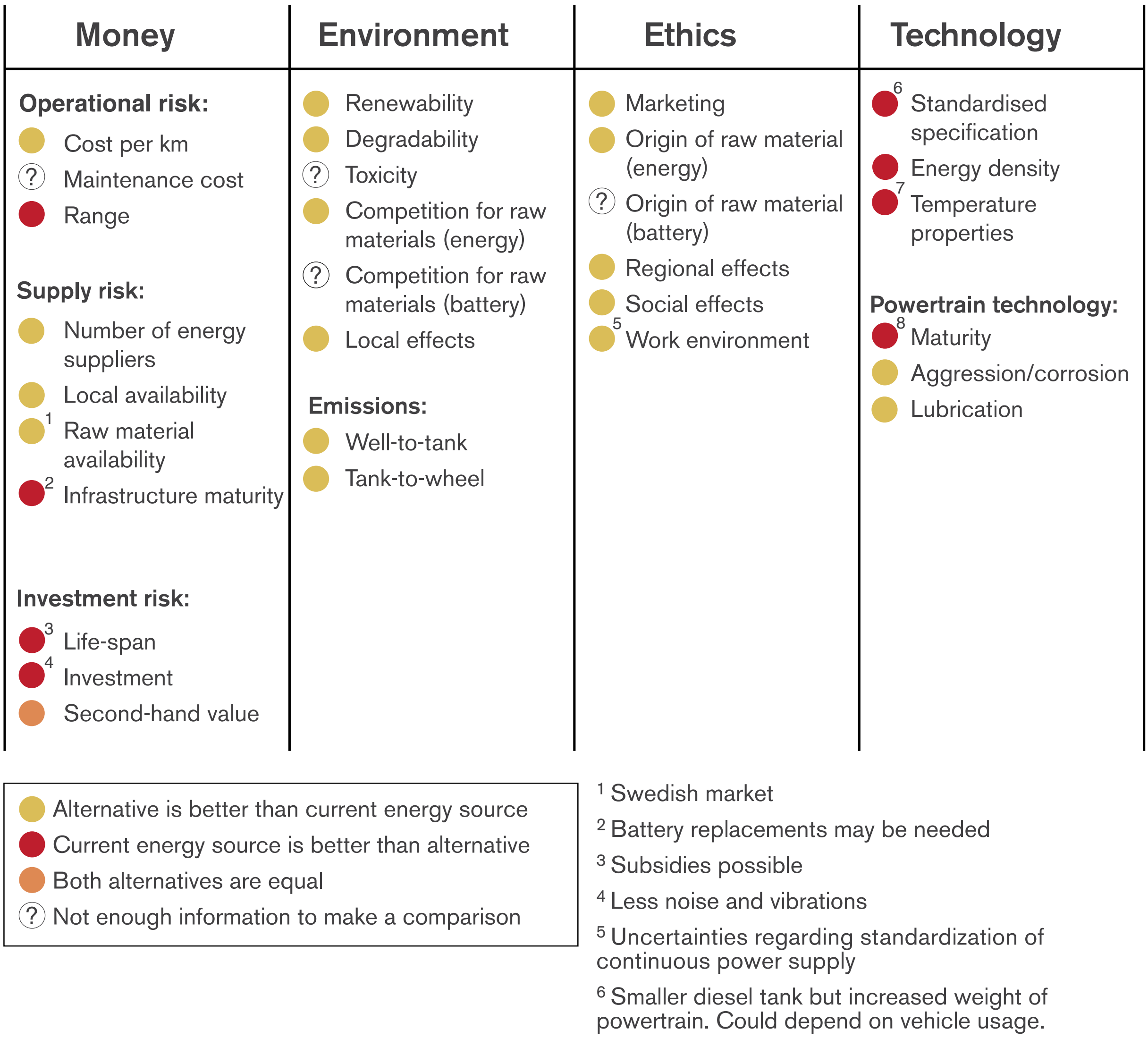

Figure 14.2 Example of how a city distribution freight company can assess the alternative of a battery powered electric vehicle (BEV) in relation to conventional diesel.

In the above example, the negative aspects of the BEV alternative are found to be both economic and technological. The battery technology is clearly a problematic area here, where range, life-span, price, standards and temperature sensitivity are the main arguments against BEV. This is just an example, however, and another transport company may well have a different opinion on what is considered good or bad compared to diesel.

CONCLUSION

Freight companies are part of a low-margin and high-investment industry that is extremely competitive. There is little or no room for investments that do not generate profit (preferably directly). In spite of this, there are frequent demands for the use of alternative fuels and energy carriers. These demands come from customers as well as from society as a whole. The choice of fuel or energy carrier is however quite complex. There are many factors that need to be taken into consideration and the new options will be compared to the existing mature diesel-based system.

There is a need for system models that take various aspects into account. In this chapter, one such model was presented. The MEET model is a checklist encompassing the dimensions Money, Environment, Ethics and Technology. A model like this can be used to construct a subjective "map" of arguments that in turn can be used to guide a decision. The model can also be used as a basis for communication with stakeholders such as customers, suppliers, authorities, trade organizations and competitors. Because of differences in individual preferences and situations, the generated maps will differ between firms.

15

ELECTRIFYING THE AUTOMOTIVE INDUSTRY VIA R&D COLLABORATIONS

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INTRODUCTION

The electrification of vehicles has regained popularity in the last two decades. Staying abreast of the electromobility trend poses challenges for automakers. One challenge is that electrification requires knowledge and competences that are different from those associated with the internal combustion engines (ICE).[1] Integrating components such as electric motors, batteries and regenerative braking systems, for instance, requires that automakers develop more complex systems to control and monitor electrical subsystems and components (see Chapters 3 and 4). Such developments require automakers to further develop competences in fields such as electronics and computing. Connecting electric vehicles to the electricity grid requires developments in ICT and utilises competences from electric power engineering, often in collaboration with utility companies (see Chapter 9). Specifically, electromobility means that automakers must integrate three competences areas that are sometimes described as 'me-chem-tronics' (mechanical, chemical and electronic competences), alongside raw material management.[2] Overall the transition to electromobility means that automakers must increasingly draw on skills and knowhow that are beyond their traditional competence bases (see Chapter 2).

1 Aggeri F, Elmquist, M. and Pohl, H. (2009). Managing learning in the automotive industry – the innovation race for electric vehicles. International Journal of Automotive Technology and Management Vol. 9 No. 2, pp. 123-147.
2 Frick et al. (2011). Boost! Transforming the powertrain value chain – a portfolio challenge. McKinsey.

Automakers may thus find it useful to seek out external partners with competences and knowledge that can assist in the electromobility transition. The strategic alliance between Renault and Nissan, for instance, aims in part to develop 'zero-emission' transportation[3] their most notable achievement hitherto being the Nissan Leaf battery electric vehicle. In practice the alliance allows Renault access to Nissan's joint venture activities such as the Automotive Energy Supply Corporation, whose aim is the development and mass-production of lithium-ion batteries. The alliance is one example of a network strategy designed to help develop and access new and existing knowledge relevant for innovation and which can boost competitive advantage.

This chapter presents some findings of a recent study that examined the structure of collaborative knowledge networks in the automotive industry.[4] In particular, the study utilised quantitative methods based on the analysis of bibliometric and patent data to examine 1) how automakers have collaborated with external partners in terms of their traditional lines of research and development and 2) how automakers and suppliers to the automotive industry collaborate in terms of R&D that is useful for electrification. Whilst quantitative methods produced relatively comprehensive and concrete findings, the conclusions presented here are limited by the fact that qualitative methods based on interviews, for instance, would provide a much more nuanced understanding of the way automakers collaborate on R&D activities. Our conclusions are thus tentative and intended to form the basis for future research in R&D collaboration.

R&D ACTIVITIES IN THE ELECTROMOBILITY FIELD

The recent upsurge in attention for electromobility is reflected in an exponential increase in the number of scientific journal publications focusing on electric and hybrid electric vehicles from the beginning of the 1990s to the present day (Figure 15.1)

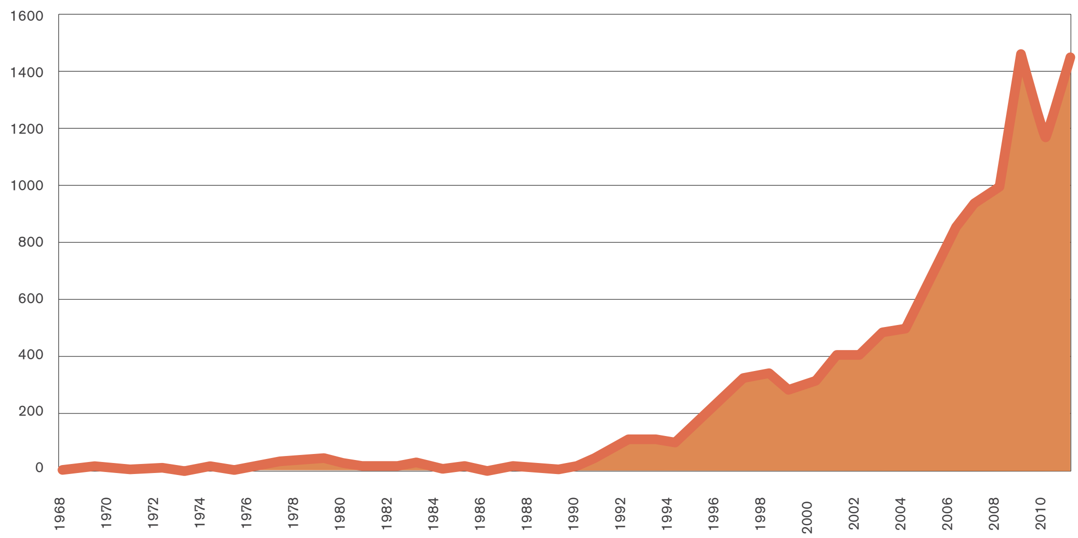

Figure 15.1 Numbers of scientific journal publications on electric and hybrid electric vehicles 1968-2012.

3 See Nissan Zero Emission Website - Partnership. Accessed on October 1, 2012.

4 Sarasini, S. Electrifying the automotive industry: Networks of R&D collaboration. Under review by Environmental Innovation and Societal Transitions.

However, the development of technological knowledge and competences for electrification may be somewhat unevenly dispersed across the globe, with some companies, countries and regions having performed more R&D than others. This is perhaps because countries with strengths in the automotive industry spend varying amounts on R&D for electrification and prioritise different areas. Government R&D funding in Sweden, for instance, has previously prioritised hybrid powertrains and control systems for vehicles, but in the first years after the turn of the century funding for research on batteries, fuel cells and hydrogen infrastructure was lacklustre in comparison to Japan and the USA (Arnold et al., 2007). Bibliometric data suggests that the USA, China and Japan are the most active on electrification R&D (in absolute terms) and that technical colleges universities that focus on engineering sciences and which are located close to automobile manufacturers boast the greatest number of publications (Figure 15.2).

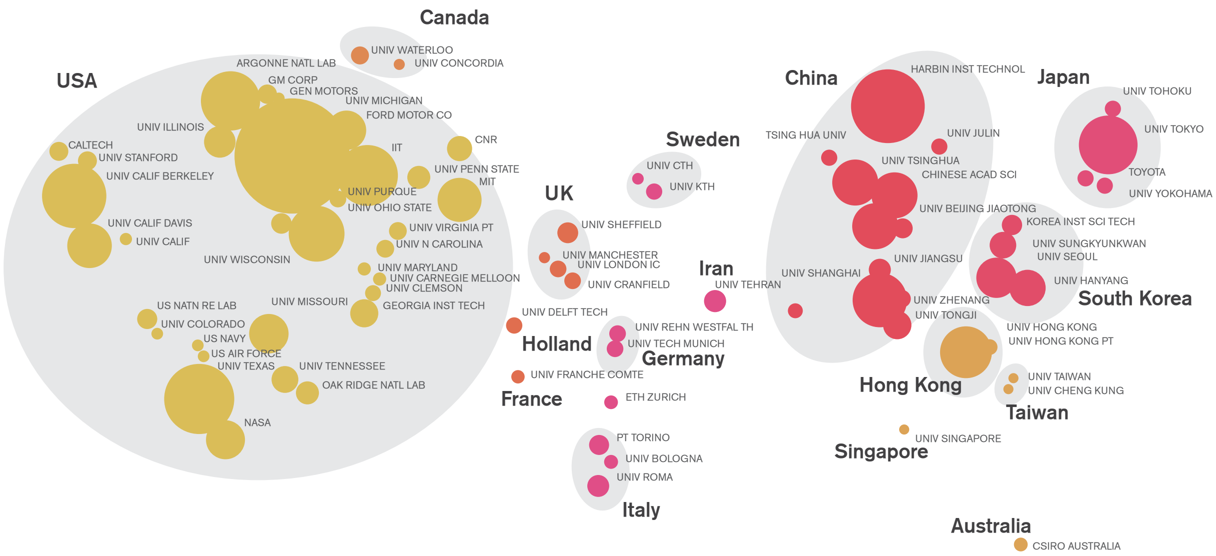

Figure 15.2 Scientific journal publications on electric and hybrid electric vehicles per institution (Only organisations with at least 100 publications from 1968 to 2012 are included.)

Furthermore, countries appear to be variously willing to transform research efforts into innovations, as Japanese companies own more patents associated with electrification compared to companies located elsewhere (Figure 15.3).

Taken together, the data presented here suggest that China, the US and Japan are the most active in terms of R&D in the electrification field. However Table 15.1 shows that, in 2002, Japanese and US-based firms owned the majority of "significant" patents in the field of electrification.[5] China may have emerged as a key player since 2002, and its role is expected to grow in years to come. In 2009, the Chinese government outlined plans to become the global market leader.[6]

5 Pilkington et al. (2002) examined patents and their citations as an indicator of patent significance, which comprises patent quality, key inventions and activity clusters.
6 Bradsher, K. (2009). China vies to be world's leader in electric cars. The New York Times, April 1, 2009.

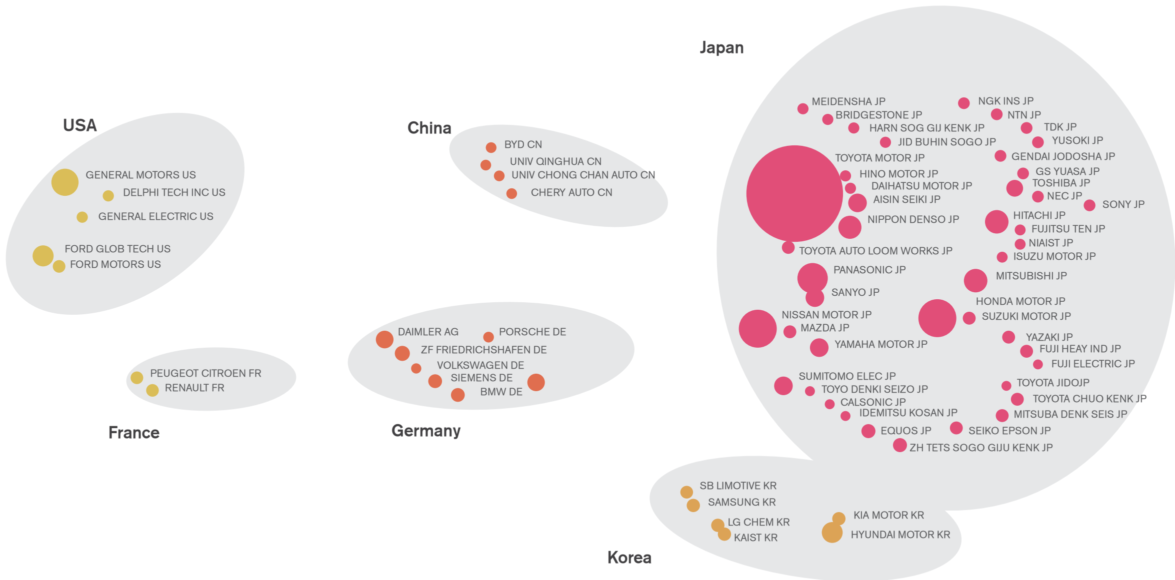

Figure 15.3 Electric and hybrid electric vehicle patents per institution (Only organisations with at least 100 patents from 1963-2012 are included).

The extent to which R&D data can reveal technological leadership in the electrification field is debatable. Whilst Japanese companies are market leaders in the market for HEVs, for instance, there is evidence to suggest that automakers such as Toyota pursue different strategies to US-based companies such as GM as regards accessing technologies that are key to electrification such as batteries. Japanese firms focus more on developing technologies internally whereas US firms tend to work with a broader range of suppliers to access the key technologies such as batteries.[7]

The main implication is that automakers can utilise external sources of knowledge and competences related to key components in order to develop electrified vehicles. Furthermore, automakers initially prefer to focus on architectural (as opposed to component) knowledge and competences as a means to offset the risks and uncertainties associated with paradigmatic technological change.[8] One such risk is that leadership in a rapidly evolving technological field is difficult to maintain, since technologies develop quickly and since electric vehicles are competing with other alternative vehicle technologies. It may be the case that many of the patented technologies shown in Table 15.1 are no longer that 'significant'. R&D collaboration is a means to offset this type of risk. It is thus relevant to consider the ways in which automakers collaborate and the conditions that support collaborative R&D.

7 Pohl, H. And Yarime, M. (2010). Relations between battery suppliers and automakers for knowledge base development during paradigmatic shifts in technology. Paper presented at the Organization Learning, Knowledge and Capabilities Conference 2010, University of Warwivk, UK.
8 Ibid.

Table 15.1 'Significant' patent ownership in the field of electrification.[9]

Assignee Company	Number of patents held
Toyota Jidosha Kabushiki Kaisha	24
General Electric Company	14
Mitsubishi Jidosha Kogyo KK	5
Ford Motor Company	4
Nippondenso Co., Ltd.	4
Nissan Motor Co., Ltd.	4
Aisin Aw Co., Ltd.	3
Daimler-Benz AG Chrysler	3
Fuji Electric Co., Ltd.	3
General Motors Corporation	3
Honda Giken Kogyo Kabushiki Kaisha	3
Lucas Industries Limited	3
Newport News Shipbuilding and Dry Dock Company	3
USA Government	3

FORMS OF R&D COLLABORATION

Scholars have known about the importance of interaction and collaboration for innovation for a long time. Over a century ago, Alfred Marshall argued that innovation is a collective act having noted that internal processes within firms account for only a fraction of their development.[10] In recent decades, scholars have increasingly recognised that firms are dependent on regional clusters and innovation systems, where a range of actors develop knowledge, competence, infrastructure, regulation, norms and markets collectively. This chapter focuses on the knowledge dimension of innovation systems. The systemic, or 'open', nature of innovation means that firms may find it useful to collaborate with rival firms, suppliers, customers, universities and research institutes that can assist in generating ideas and knowledge for new innovations.[11]

9 Pilkington, A. Dyerson, R. and Tissier, O. (2002). The electric vehicle: Patent data as indicators of technological development. World Patent Information Vol. 24 No. 1, pp. 5-12.

10 Marshall, A. (1890). Principles of Economics. (First Edition). London: Macmillan.

11 Gilsing, V., Nooteboom, B., Vanhaverbeke, W., Duysters, G., and van den Oord, A. (2008). Network embeddedness and the exploration of novel technologies: Technological distance, betweenness centrality and density. Research Policy, Vol. 37 No. 10, pp. 1717-1731. Christensen, J.F. (2006). Whither core competency for the large corporation in an open innovation world? Chapter 3 in H. Chesbrough, W. Vanhaverbeke and J. West (eds.) Open Innovation: Researching a new paradigm. Oxford University Press: Oxford UK. Chesbrough, H. (2006). Open innovation: A new paradigm for understanding industrial innovation. Chapter 1 in H. Chesbrough, W. Vanhaverbeke and J. West (eds.) Open Innovation: Researching a new paradigm. Oxford University Press: Oxford UK. Langlois, R.N. (2003). The vanishing hand: the changing dynamics of industrial capitalism. Industrial and Corporate Change, Vol. 12 No. 2, pp. 351-385. Sturgeon, T.J. (2002). Modular production networks: a new American model of industrial organization. Industrial and Corporate Change, Vol. 11 No. 3, pp. 451-496.

Collaboration is important because it facilitates technology transfer and allows firms to access partners' technologies and competences.[12] In other words, collaborations between two firms can help them swap knowledge and skills whilst innovating together. Firms also pursue collaborations in order to reduce or share the costs and risks of R&D activities.[13] Furthermore, given the increasing complexity of technology, firms find it difficult to maintain all of the knowledge and skills required for innovation. Collaboration allows firms to access interdisciplinary sources of knowledge and monitor developments in different technological areas.[14]

R&D collaboration and knowledge acquisition can be organised in different ways. A general categorisation of organisational types that is useful for this particular study distinguishes between hierarchies, markets and networks.[15]

Hierarchical organisation could imply that firms develop new knowledge within their own organisation, but it could also involve acquisition of other companies or joint ventures and formalised strategic alliances. Compared to markets, hierarchical organisation is suited to situations with high uncertainties and risks. An example of such a risk is knowledge spillover – the process whereby actors that do not sponsor R&D activities nonetheless benefit from gains in knowledge or competence. In such situations it is beneficial for firms to internalise R&D activities and where necessary protect themselves from knowledge spillovers via bureaucratic means (e.g. the use of confidentiality agreements).

An alternative to internal, or internalised, R&D is to buy knowledge and innovations on a *market*. Markets are suited to actors that can make exchanges with low uncertainties and risks. Market relations are typically arm's length and made on a contractual basis. Licences present one option to buy knowledge and modularisation opens a complementary pathway. A passenger car contains thousands of components that are designed and manufactured in a complex tiered system of suppliers. Modularisation means that automakers outsource the responsibility for designing key components and subsystems to suppliers. One of the main advantages of modularisation is that automakers can utilise value chain competences to boost their own competitive advantage.[16]

12 Lynn, L. H. (1988). Multinational joint ventures in the steel industry. In D. C. Mowery (ed.), International Collaborative Ventures in U.S. Manufacturing. Ballinger. Cambridge, MA. Mariti, P. and R. H. Smiley (1983). Co-operative agreements and the organization of industry. Journal of Industrial Economics, Vol. 31, pp. 437-451.
13 Mowery, D. C. (1988). Joint ventures in the U.S. commercial aircraft industry. In D. C. Mowery (ed.), International Collaborative Ventures in U.S. Manufacturing. Ballinger, Cambridge, MA. Mytelka, L. and M. Delapierre (1987). The alliance strategies of European firms in the information technology industry and the role of Esprit. Journal of Common Market Studies, Vol. 26, pp. 231-253.
14 Porter, M. E. and Fuller, M. B. (1986). Coalitions and global strategies. In M. E. Porter (ed.), Competition in Global Industries. Harvard Business School Press, Boston, MA, pp. 315-344. Hagedoorn, J. and Schakenraad, J. (1990). Inter-firm partnerships and cooperative strategies in core technologies. In C. Freeman and L. Soete (eds.), New Explorations in the Economics of Technical Change. Pinter, London, pp. 3-37.
15 Powell, W.W. (1990). Neither market nor hierarchy: Network forms of organization. Research in Organizational Behavior, Vol. 12, pp. 295-336.
16 Howard, M. and Squire, B. (2007). Modularization and the impact on supply relationships. International Journal of Operations & Production Management, Vol. 27 No. 11, pp. 1192-1212. Morris, D. and Donnelly, T. (2006). Are there market limits to modularisation?. International Journal of Automotive Technology and Management, Vol. 6 No. 3, pp. 262-275.

Although R&D activities are outsourced to suppliers, automakers must retain some level of competence regarding these activities or risk their competitive advantage. Automakers thus face a significant challenge in that they must develop and maintain technical competences that complement those in the value chain.[17] Automakers also face the risk that key competences are made available to competitors via shared suppliers.

Networks are more relational and trust-based than markets and hierarchies, and actors collaborate in networks due to mutual benefits and complementary strengths. Networks are suitable when uncertainty about performance, costs and value is very large, making market arrangements, as well as costly and bureaucratic hierarchal organisations, less attractive.

There are various known barriers to collaboration in networks. First, firms seeking to collaborate in order to access technology must know that the technology exists, which is a challenge given the complexities of global markets. Alternatively, individuals within firms may be aware of such opportunities but lack personal contacts with relevant individuals in partner organisations. In other words, whilst workers may boast a lot of *know-how*, they may not have the necessary *know-who* to facilitate effective collaboration. Know-who means that individuals' social networks can be important for collaboration.[18]

Second, opportunities to collaborate via networks may be constrained by the system of intellectual property rights (IPR). Whilst patents, for instance, create incentives to innovate, the patenting system creates incentives to trade inventive knowledge in a competitive market setting rather than via more open systems of collaboration.[19]

Third, opportunities for collaboration may be constrained by the types of knowledge that is to be shared between actors. A distinction can be made between tacit and codified knowledge (Polanyi, 1967). Tacit knowledge refers to competences and skills that are hard to codify with the result that knowledge transfer requires face-to-face collaboration. In contrast, codified knowledge can be exchanged more freely between individuals without interpersonal contact. Some scholars have argued that these features influence the geography of innovation in that industries operating primarily on tacit knowledge pursue collaborations on a more localised scale.[20] Other factors that reinforce the importance of the local scale include the costs of collaboration over longer distances, language and cultural/institutional differences.[21]

17 Takeishi, A. (2002). Knowledge Partitioning in the Interfirm Division of Labor: The Case of Automotive Product Development. Organization Science, Vol. 13 No.3, pp. 321-338. Morris, D. and Donnelly, T. (2006). Are there market limits to modularisation?. International Journal of Automotive Technology and Management, Vol. 6 No. 3, pp. 262-275.
18 Lundvall B.A. and Johnson, B. (1994). The learning economy. Journal of Industry Studies, Vol. 1 No. 2, pp. 23–42.
19 Hall, B.P. (2007). Patents and Patent Policy. Oxford Review of Economic Policy, Vol. 23 No. 4, pp. 568-587. Hall, B.P. and Hellmers, C. (2010). The role of patent protection in (clean/green) technology tranfser. Santa Clara High Technology Law Journal, Vol. 26, pp. 487-532.
20 Martin, R., and Moodysson, J. (2011). Comparing knowledge bases: on the geography and organization of knowledge sourcing in the regional innovation system of Scania, Sweden. European Planning Studies, Vol. 19 No. 7, pp. 1183-1203.
21 Tidd,J., Bessant,J. and Pavitt,K. (2005). Managing Innovation: Integrating Technological, Market and Organizational Change, Hoboken: Wiley (3rd edition).

AUTOMAKERS' R&D COLLABORATIONS

The following figures map automakers' R&D collaborations. The maps are generated from bibliometric data (co-authorship) and patent data (co-invention). Generally, bibliometric data show that whilst automakers are capable of establishing collaborations with different types of organisations across the globe, they collaborate mainly with organisations that are located in the same country as their own headquarters. Furthermore, a pattern can be observed in data on publications where automakers have the strongest ties with a single organisation, usually a university, technical college or polytechnic that is located close to the firms' main development or manufacturing operations. This is shown in Figure 15.4. Volvo Cars' main partner is Chalmers University of Technology. Like Volvo, Chalmers is located in Gothenburg, Sweden and collaborations between the two account for 25% of the 288 publications accessed for Volvo Cars.

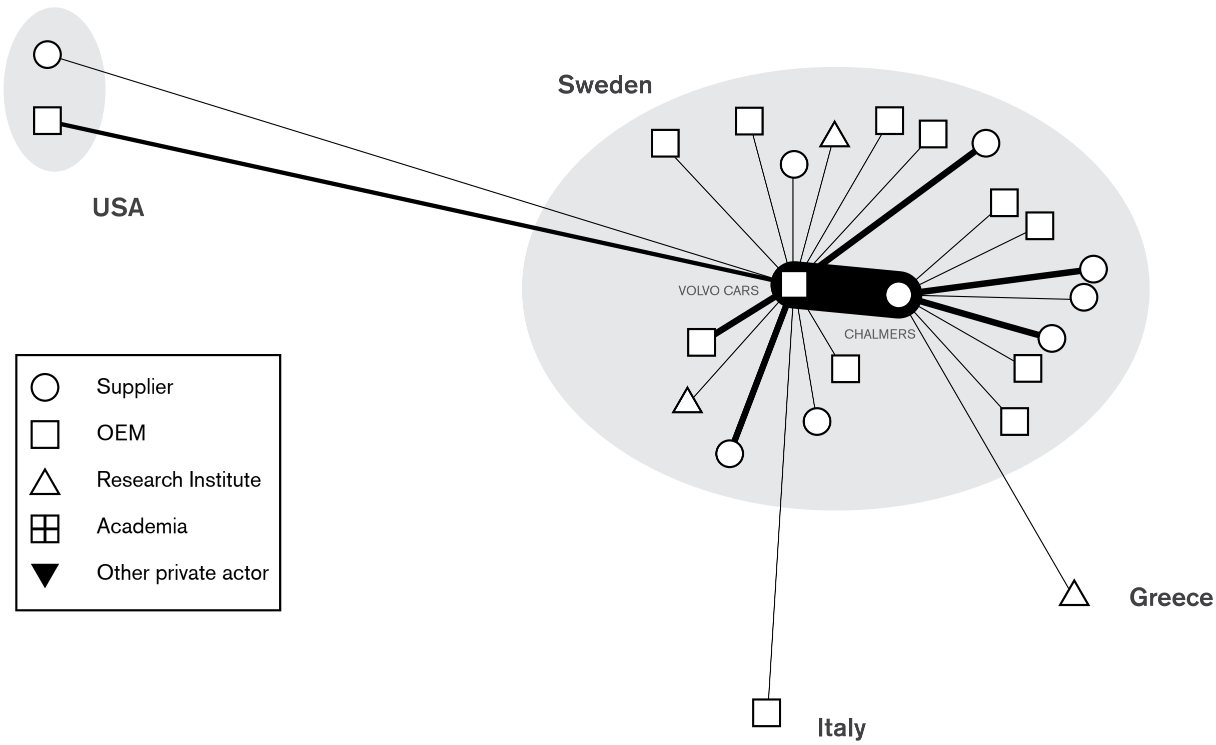

Figure 15.4 Bibliometric network data for Volvo Cars.

This pattern, whereby an automaker demonstrates strong ties with a local academic partner, was observed for each of the automakers that featured in the study (including Ford, FIAT, Hino, Renault, Scania and Volkswagen). Overall, publications records also show that automakers collaborate mainly within national borders, although several collaborations exist with foreign partners (Table 15.2). Furthermore, and as expected, automakers collaborate mainly on publications with academic partners.

Table 15.2 Geography and diversity of partners for collaboration in the automotive industry (bibliometric data collected between 1899-2012). 'Local' partners are those within national borders; 'regional' partners are from the same continent; and 'global' partners are from a different continent than the automaker in question.

	Geography of collaboration			**Type of partner**			
	Local	*Regional*	*Global*	*Academia*	*Corporate*	*Research institute*	*Gov't/ NGO/other*
FIAT	253	240	46	297	104	79	59
Ford	2453	113	717	2662	260	191	154
Hino	31	0	1	12	12	10	9
Renault	472	33	13	313	47	156	2
Scania	100	9	8	96	16	1	4
Volkswagen	266	67	25	184	94	71	4
Volvo Cars	187	4	7	152	38	8	0
Total	**3744**	**466**	**817**	**3716**	**569**	**515**	**228**
Percentage	**75%**	**9%**	**16%**	**74%**	**11%**	**10%**	**5%**

Patent data shows that whilst local factors appear to influence R&D collaborations, automakers are also capable of collaborating across borders, mainly via organisational hierarchies. For instance, patent data for Renault shows that its main collaborations are within France, with 5.3% of its 11,000 patented inventions developed in collaboration with Peugeot. The two companies have a history of collaboration having developed various engines together. However, Renault has also collaborated significantly with its subsidiary, Renault Trucks (now owned by Volvo – 4.4% of patents) and more recently with its subsidiary Renault Samsung Motors, which is located in South Korea (Figure 15.5). These also represent organisational hierarchies, the latter being an example of cross-border collaboration.

FIAT's (Figure 15.6) main partner for patents is *Centro Richerche FIAT* (the FIAT research centre – 5% of 2500 patented inventions), which serves "as a centre of expertise for the [FIAT] Group's innovation and development activities".[22] The centre is located in Turin, which reinforces the importance of the local scale. FIAT Automobiles has also collaborated significantly with Alfa Lancia (2%) and Bosch (1.5%). Alfa Lancia was purchased by the FIAT Group in 1986,[23] with headquarters also located in Turin. Bosch, however, is located in Germany and has served as a significant supplier to FIAT having provided its popular start-stop system for the FIAT 500, for instance.[24]

22 FIAT S.p.A - Centro Ricerche Fiat. Accessed on October 4, 2012. The centre is treated here as an external organisation since it serves the entire FIAT Group, not just FIAT automobiles.
23 Alfa Lancia was split into two separate subsidiaries of FIAT in 2007.
24 The start-stop system prevents engine idling when vehicles are not in motion – a significant feature for some electrified vehicles.

Taken together, these patterns of collaboration reinforce the importance of the local scale, but FIAT's history of collaboration with Bosch suggests that cross-border ties can also be of significance.

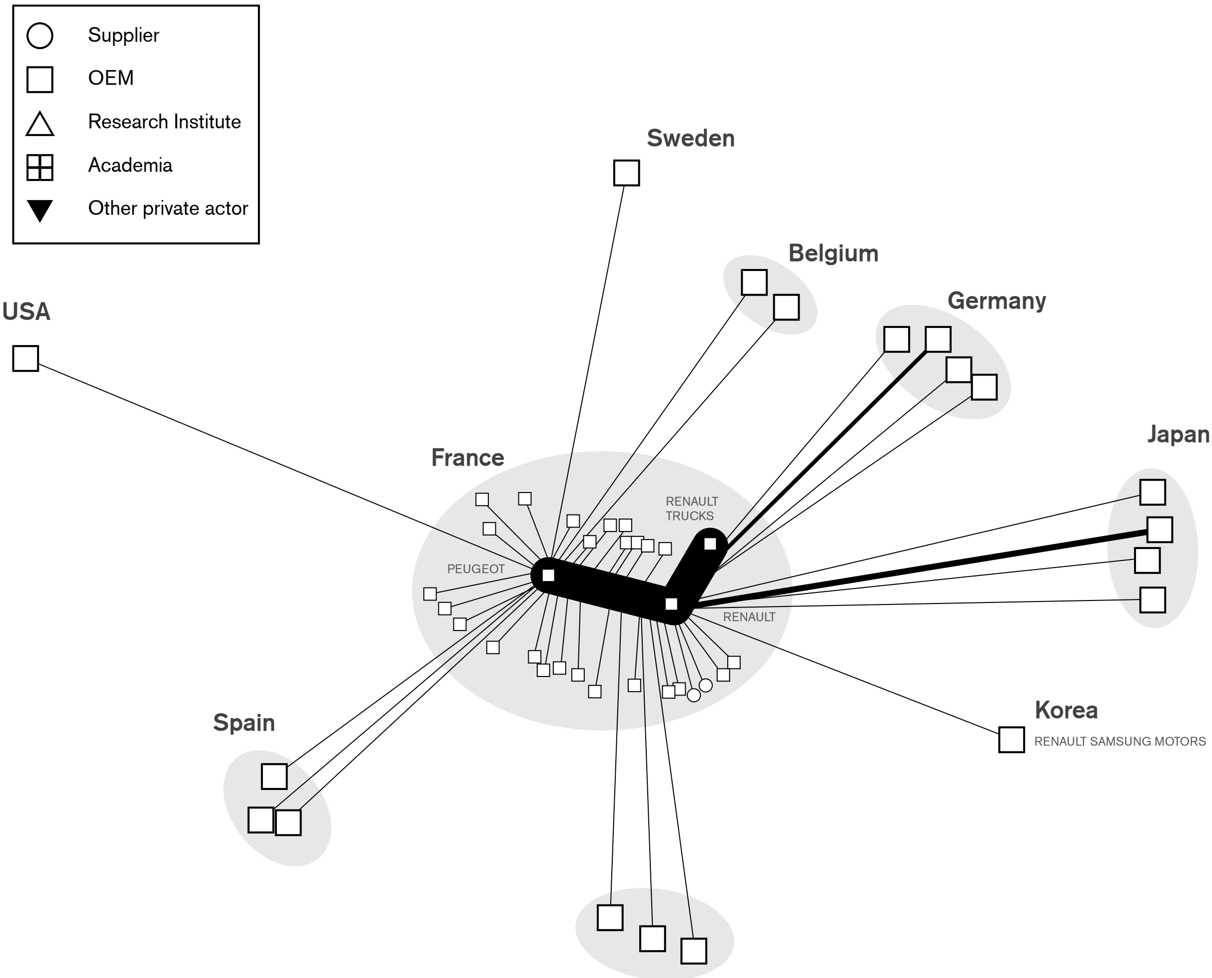

Figure 15.5 Network data for Renault (patents)

Ties with FIAT's research centre and Alfa Lancia suggest that organisational hierarchies are important for collaboration, whereas ties with Bosch are less easy to evaluate. Whilst Bosch is a significant supplier to the automotive industry, there is no evidence of a hierarchical relationship with FIAT. However it may be the case that FIAT and other automakers have engaged in network partnerships since Bosch's start-stop technology appears in vehicles manufactured by several companies.

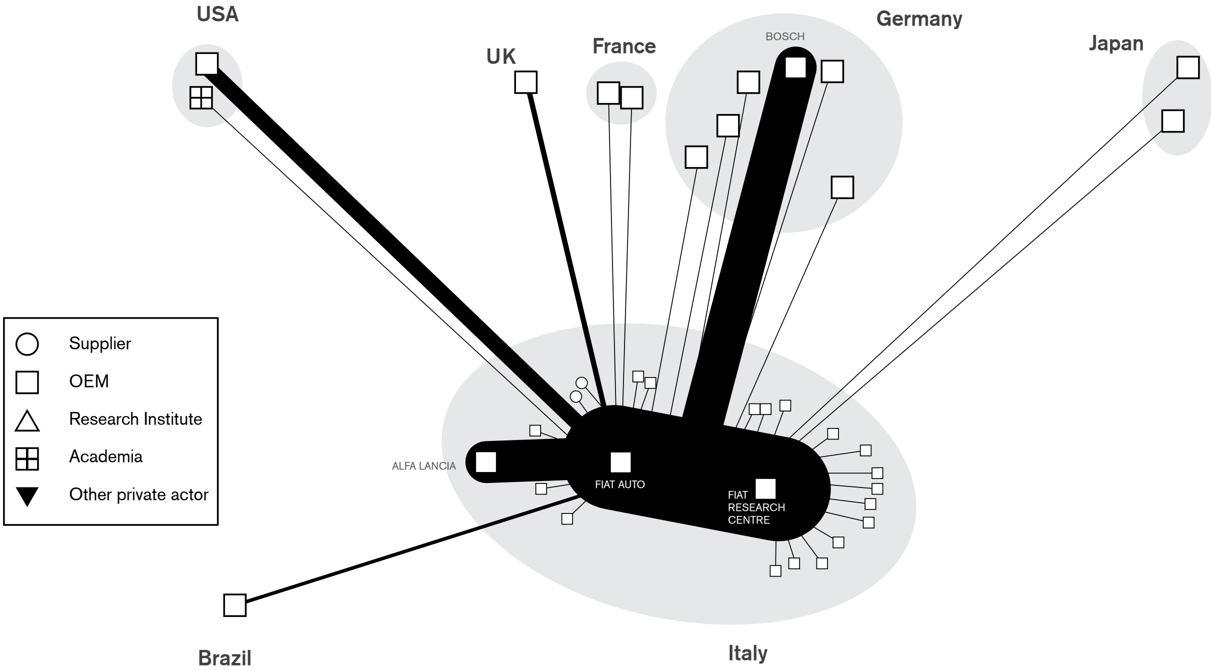

Figure 15.6 Network data for FIAT (patents)

R&D COLLABORATIONS IN THE ELECTROMOBILITY FIELD

Since the current interest in electrification is a relatively recent phenomenon, and given that creating new knowledge networks requires considerable time, effort and resources, it is likely that automakers prefer to collaborate with established partners rather than seek out new ones based on their knowledge and competence within this field.

In the field of electrification, both bibliometric and patent data suggests that Ford prefers to collaborate with established partners. Ford's main partners in terms of publications are the University of Michigan (6.3% of 79 publications) and Wayne State University (3.8%). Whilst the University of Michigan has performed a significant amount of research on electrification, Ford has traditionally collaborated with these two universities. The extent to which collaborations are singularly based on motives to access technology and skills/competences is thus questionable. Patent data on Ford shows that it has one main partner, Daimler Motors, which is located in Germany (Figure 15.7 – 9.3% of 1300 EV patents). Ford owned Daimler between 1989-2007, and this is likely a hierarchical tie.

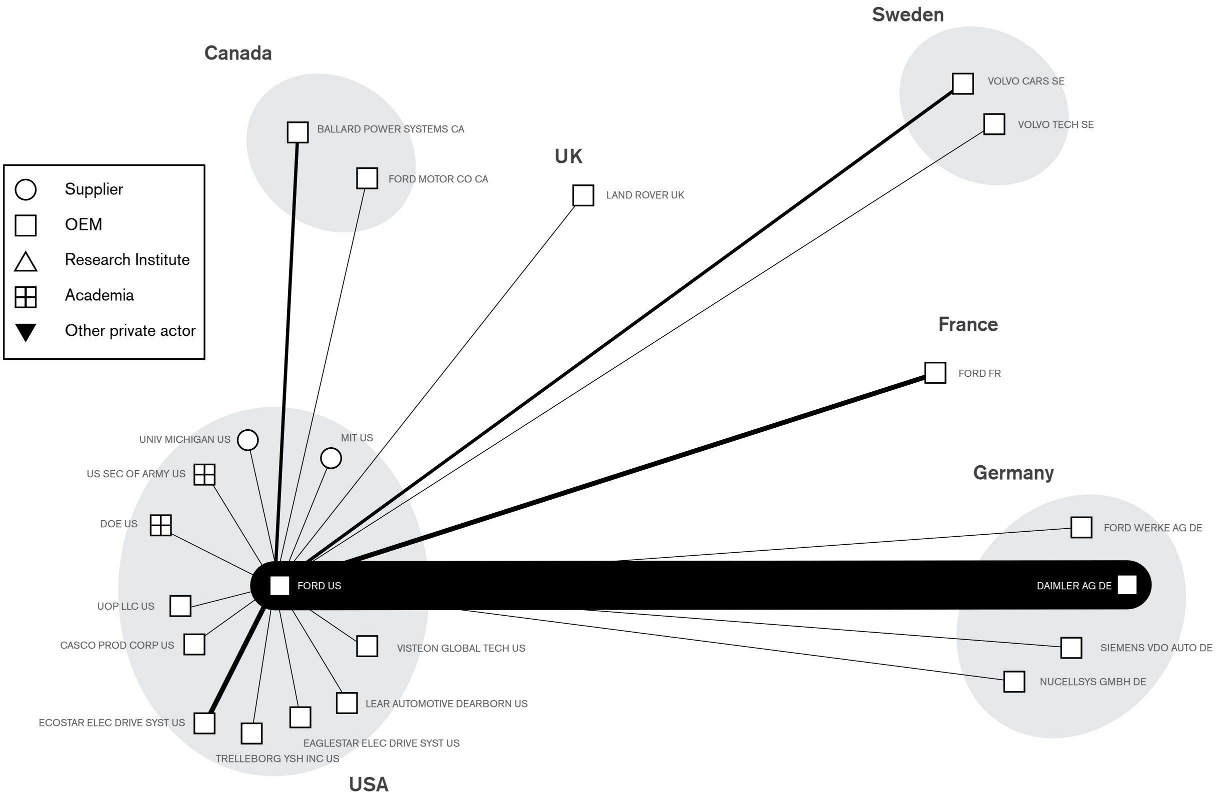

Figure 15.7 Network data for Ford (EV patents)

Similarly, FIAT has collaborated mainly with the Polytechnic University of Turin (20% of 10 publications) and with the FIAT research centre (8.7% of 23 patents). The latter represents a hierarchical tie, and like Ford, FIAT has a history of collaboration with these organisations. FIAT's relatively small number of electrification patents and publications suggest that it is perhaps a laggard in this field.

Patent data for Volvo Cars (Figure 15.8) add further credence to the observation that companies prefer established partners within the field of electrification and that hierarchical ties underpin patenting activities. Volvo Cars, which has only 9 patents in this field, has collaborated with the two former owners, the Volvo Group (22% of 9 patents) and Ford (56%).

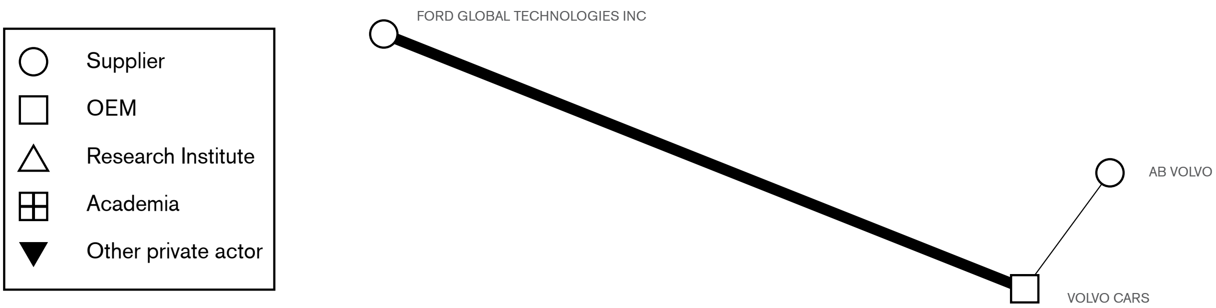

Figure 15.8 Network data for Volvo Cars (EV patents)

Similar patterns can be found elsewhere. Volkswagen's main partner in terms of electrification publications is the University of Leibniz (19% of 21 publications), with whom Volkswagen has collaborated historically. In terms of electrification patents, Volkswagen's main partner is its subsidiary Skoda, located in the Czech Republic (8.7% of 263 patents), again reflecting the importance of hierarchical relationships for patented inventions.

Taken together, the data on collaborations within the field of electrification suggest that 1) automakers collaborate within established networks with academic partners; 2) automakers tend to enter collaborative relationships with private companies via existing hierarchical organisations; and 3) automakers occasionally establish ties with suppliers with competences in the field of electrification. The latter is the only real evidence of an access-to-technology driven strategy whereby automakers seek partners with competences that are of benefit in the field of electrification. The prospects for European automakers in the field of electrification may thus hinge partially on the development of knowledge and competences in Europe, given the apparent importance of collaborations with local partners. It may also depend on suppliers' abilities to collaborate with leading electrification hubs on a more global level.

SUPPLY CHAIN R&D COLLABORATIONS

This section examines collaborative trends associated with two major European suppliers, Bosch and Siemens, that boast competences in the field of electrification and which could potentially facilitate knowledge transfers from foreign locations. Both Bosch and Siemens are headquartered in Germany, where the bulk of their operations are also located. However both companies have subsidiaries in Japan and the US, which could potentially help in facilitating the transfer of valuable knowledge and competence in the field of electromobility. Bosch has 888 patents in the field of electrification and Siemens has 374. Figure 15.9 shows that Bosch collaborates mainly with a subsidiary, SB LiMotive, which is located in Germany and Korea, and which was a joint venture between Bosch and Samsung. This again suggests that hierarchies facilitate cross-border collaboration. Furthermore, Bosch's subsidiary in Japan is key to collaborations with the Nippon Electric Works and Bosch's subsidiary in the US means that collaborations span three continents. Collaborations with automakers are relatively weak, as Bosch has patent ties with only two automakers, both located in Germany.

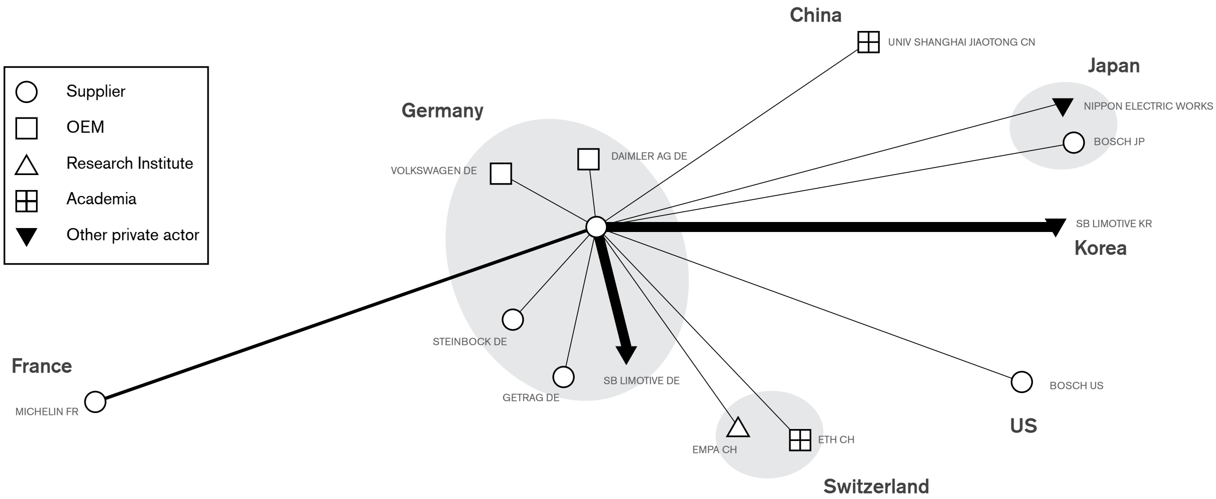

Figure 15.9 Network data for Bosch (EV patents)

Despite the fact that Siemens has fewer patents in the field of electromobility, Figure 15.10 suggests that it is embedded in a more complex collaborative network. Again, ties with the US and Japan are mainly due to the fact that Siemens has subsidiaries in these locations. And again, foreign collaboration appears to be facilitated by hierarchies. Siemens does however boast strong ties with two other suppliers within Germany (Continental and Emitec). Whether these are also due to hierarchies is unclear. Note that Siemens has only one patent collaboration with an automaker, Ford, via it's subsidiary in the US.

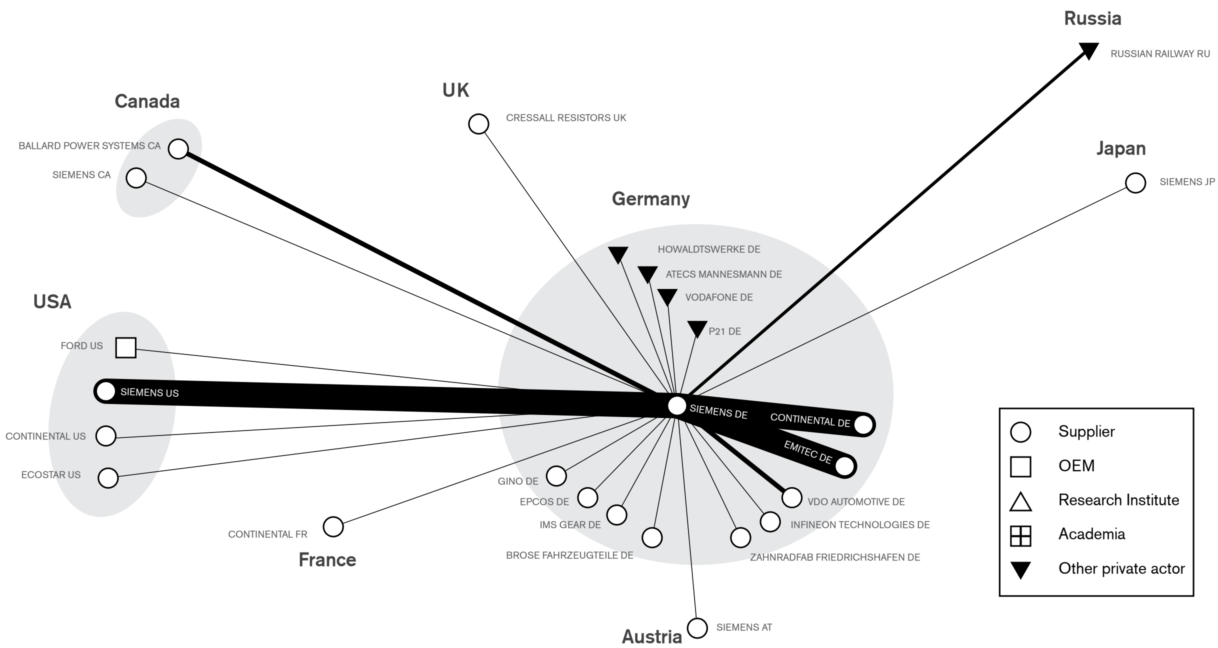

Figure 15.10 Network data for Siemens (EV patents).

CONCLUSIONS

A number of tentative conclusions can be drawn from the bibliometric and patent data examined in this chapter. First, as regards publications, automakers tend to collaborate with academic partners that are geographically close their main operational hubs. It may be the case that academia acts as a supplier of skilled labour to the automotive industry, as a source of ideas and/or as a site for experimentation. Academia is perhaps even an indirect source of innovation for automakers even though this is difficult to measure using patent records. Despite the expansion of licensing practices and technology transfer offices that seek to create incentives for 1) university-based invention and 2) university-industry collaboration, there is evidence to suggest that academic researchers rely more on their personal social networks than formalised technology transfer practices for collaborations with industry.[25] These types of collaboration are thus likely governed by network types of organisation, and thus take a long time to establish and change.

One implication for policymakers is that the provision of targeted and strategic funding for academic research may be of benefit for automakers in terms of competence enhancement and innovation. Here it may be beneficial to sponsor research on electrification within academic institutions that are based in the same localities as major automakers. Whilst the exact impacts of such research are unknown, some sort of positive spillover is likely given the strong ties between these two sets of actors. Furthermore, this type of policy intervention may be of paramount importance for the European automotive industry given that Japan and the US appear to be leading in the field of electrification. The provision of funding to academic institutions that have a history of collaboration with automakers is a good start and should perhaps be complemented by mechanisms that stimulate knowledge transfer between European universities and their academic partners in the Japan and US. This type of policy intervention may also be key to ensuring the long-term sustainability of the automotive industry given pressures to find alternative, environment-friendly technologies and given the current economic climate where automakers find it hard to justify the costs of R&D on alternative technologies.[26]

Second, patent records suggest that inventions are more likely to occur between companies that share some type of hierarchical organisational structure than between other types of organisation. This appears to be the case for both automakers and suppliers to the automotive industry. Records suggest that openly innovative network structures are not the primary structures for inventive collaborations, as most occur within existing corporate structures (i.e. with parent or subsidiary companies) or with companies that are part of a strategic alliance or joint venture. This suggests that the risks and uncertainties associated with open innovation pose a significant obstacle for collaborations.

However, and in contrast to bibliometric data, patent records do suggest that geography is not a significant barrier for collaboration. Companies are capable of establishing strong ties with foreign partners where the above conditions are

25 Siegel, D.S., Waldman, D.A., Atwater, L.E. and Link, A.N. (2003). Commercial knowledge transfers from universities to firms: Improving the effectiveness of university-industry collaboration. *Journal of High Technology Management Research*, Vol. 14, pp. 111-133.

26 Wells P.E. (2010). *The automotive industry in an era of eco-austerity*. Edward Elgar: Cheltenham UK.

satisfied. This brings us to a third tentative conclusion. Whilst it is widely acknowledged that trust is an important precondition for efficacy in collaborations, the findings shown here suggest that trust is realised through different organisational structures. In publication networks it appears to be the case that proximity is the key to strong ties, which may be due to individuals' own social networks and the propensity for individuals within these networks to meet more often and participate in the same collegial communities. In contrast, patent collaborations appear to require different sorts of mechanisms to ensure reciprocity in that organisational hierarchies perhaps compensate for a lack of trust given the uncertainties and risks attached to cross-border collaboration.

The good news for automakers is that geography appears not to be a significant obstacle for patent collaborations. It is either the case that the knowledge that underpins inventive collaborations in the automotive industry is to a large extent codifiable and thus renders geography unimportant, or that automakers have found ways to overcome the need for proximity when collaborating on new inventions. Although organisational hierarchies appear to facilitate cross-border collaboration, the extent to which these ties represent true collaboration and not, for example, instances where parent companies appropriate patentable inventions from their subsidiaries is not clear. This is a topic for further investigation.

Notwithstanding, practitioners may benefit from establishing hierarchical agreements with companies in countries such as the US, China and Japan that appear to be at the forefront of the electrification field. The extent to which it is necessary for Swedish automakers to pursue such an approach is however unclear. It may be the case that market modes are sufficient in that Swedish automakers can simply purchase components and sub-systems such as batteries and hybridised powertrains from key suppliers as part of a modularisation strategy. However, such an approach has been noted for its risks, as by simply purchasing key technologies 'off the shelf', automakers can lose the architectural competences that are key to competitive advantage.[27] A precautionary approach would thus be to ensure that automakers retain and build competences that are relevant to electrification, which we assume will play a significant role in years to come. This further emphasises the point made above that strategic and targeted academic funding is required to match the needs of automakers in terms of competences and skilled labour, given the prevalence of local academy-industry ties.

27 Takeishi, A. (2002). Knowledge Partitioning in the Interfirm Division of Labor: The Case of Automotive Product Development. *Organization Science*, Vol. 13 No.3, pp. 321-338.