Conditions for the successful deployment of electric vehicles – a global energy system perspective

Martin Densing, PSI
Hal Turton, PSI
Georg Bäuml, Volkswagen AG

Conference paper STRC 2012

STRC | 12th Swiss Transport Research Conference
Monte Verità / Ascona, May 02-04,2012

Conditions for the successful deployment of electric vehicles – a global energy system perspective

Martin Densing
Paul Scherrer Institute
5232 Villigen PSI

Phone: +41 56 3102598
Fax: +41 56 3104411
email: martin.densing@psi.ch

Hal Turton
Paul Scherrer Institute
5232 Villigen PSI

Phone: +41 56 3102631
Fax: +41 56 3104411
email: hal turton@psi.ch

Georg Bäuml
Volkswagen AG
38440 Wolfsburg

Phone: +49 5361 972961
Fax: -
email: georg.baeuml@volkswagen.de

May 2012

Abstract

In the study, we analyze scenarios of car technology deployment and the global energy system using the Global Multi-regional MARKAL (GMM) cost optimisation model. We consider some of the conditions under which new drivetrain technologies, particularly battery electric vehicles (BEVs), may be more cost competitive under different hypothetical states of the world. We focus on the role of a potential niche market for cars with a limited travel range and how this may affect overall deployment of alternative drivetrain technologies and fuel choice. The results show that assuming a market of substantial size for such short-range cars leads to technologies such as BEVs being deployed more readily. In addition, we show the important role of other factors, such as stringent climate change policy and possible limitations to resource availability, in supporting alternative technologies. This analysis thus identifies potential technology targets for support by decision makers.

Keywords

Transport – Energy System Analysis – Electric Mobility – Global Multi-regional MARKAL model

1. Introduction

Passenger car transport today is highly dependent on petroleum fuels and represents a significant source of greenhouse gas emission. On a well-to-wheel basis, passenger cars account for approximately 11% of global carbon dioxide (CO2) emissions [Turton, 2006, Fig. 6; [WBCSD, 2004, Fig. 2.13; EIA, 2008, Tab. 11.19], and the share of oil fuel in road transport is currently at 96% [IEA, 2010c, Fig. 14.12]. However, new drivetrain technologies, such as electric, hybrid and fuel cell options or alternative fuels like CNG or biofuels, may play an important future role in reducing the use of oil and greenhouse gas emissions in the transportation sector. Alternative drivetrains currently account for only a small market share, which can be partially attributed to their high prices. In the future, prices could be lowered by appropriate policy support, technology learning and economies-of-scale in production.

Battery electric vehicles (BEVs) are, at first glance a promising alternative vehicle technology because they produce no tank-to-wheel (TTW) GHG-emissions, and their TTW energy efficiency is higher than that of other drivetrains. In addition, an extensive electricity distribution network exists in many parts of the world. A drawback of BEVs is their relatively high cost of energy storage in the electric battery, leading to a high capital cost.

Aside the relatively high investment costs for many alternative drivetrain technologies, another factor limiting deployment may be their lower performance on some criteria when compared with conventional technologies. In case of BEVs, for example, without a prohibitively expensive battery the driving range is likely to be limited to well below the distance provided by conventional internal combustion engine (ICE) vehicles. Despite this shorter driving range, such vehicles may still be appealing to some groups of consumers with compatible driving patterns. For instance, average daily trip lengths for many consumers fall well below 100 km (e.g. [Santini and Vyas, 2008, Hu and Reuscher, 2004]). In addition, possible developments in urban traffic regulations, like restricted car access to city centres and more stringent emission reduction targets may support the market for alternative drivetrain vehicles, despite the limited range of some systems. The potential market for shorter-range travel, which could represent an early niche for deployment and technology learning, is often not fully represented in studies on future transport technology choice (see e.g. [Azar et al., 2003, Turton and Baretto, 2007, Gül et al., 2009, Schäfer et al., 2009]). Much of the previous analysis of transport technology learning in niche markets deals with other technologies, like hydrogen fuel cells, or other niche markets, like light-duty bus or commercial fleets [Rogner, 1998, Adamson, 2003]).

Critically, the deployment of alternative drivetrain technologies depends not only on the characteristics of possible vehicle technologies and their attractiveness to consumers, but also on the availability of appropriate fuels. These fuels need to be extracted, refined (e.g. oil), converted (e.g., electricity or hydrogen) and delivered through the energy system. For example, the attractiveness of BEVs will depend on electricity production costs, including the costs of decarbonising the power sector in the case of an active climate policy and thus on the costs and availability low emission generation capacity, especially carbon capture and storage (CCS), nuclear power and renewables. Further, certain primary energies, esp. biomass or natural gas, can be used in multiple applications – heating for residential sector, industry, electricity or transport [Gül et al., 2009, Grahn et al., 2009]. The interplay between production of hydrogen and other alternative fuels may influence fuel choice [Hedenus et al., 2010, Wallington et al., 2010]. Thus, a broad perspective that considers the dynamics of the full energy system is needed to analyse the overall viability of drivetrain technology choice in car transportation.

In this study, we investigate the cost-effectiveness of alternative car technologies, focusing on BEVs, from a long-term global energy system perspective. We use a global technology-rich energy system MARKAL model, called GMM (Global Multi-Region MARKAL) [Gül et al., 2009, Rafaj and Kypreos, 2007], to develop and quantify a number of scenarios to identify possible drivers for future energy and transport technology deployment. This model determines the cost-optimal combination of technologies and resources to meet an exogenous level of energy and transportation demand, subject to a given set of constraints. GMM also accounts for some elements of technological change by accounting for learning-by-doing—that is, the process by which technologies improve with increasing experience. To account for the possible role of short-range vehicle technologies, we introduce explicit short-range technologies and demands.

The scenario analyses are selected to explore some of the uncertainty about key market, technology, resource and policy drivers that may affect deployment of alternative drivetrains, particularly BEVs in a cost optimal energy system. In terms of policy, the stringency of future climate policy represents a major uncertainty which we expect to influence alternative drivetrain deployment and fuel production. However, this may also well depend on the availability of low-carbon fuel production pathways, including the uncertain availability (and public acceptance) of CCS technologies. Among market uncertainties, the size of the hypothetical short range car (SRC) niche market may influence opportunities for technology learning, and thus future competitiveness of different drivetrain options. Finally, the size of the total extractable global crude oil resource is another uncertainty likely to affect technology choice.

The analysis is conducted for scenarios covering the 21st century, enabling us to analyse the longer-term effects of technology learning, resource depletion and policy measures. Although we pay particular attention to the short-range car niche-market and the BEV technology, the analysis also considers perspectives of possible contenders, like hydrogen fuelled cars (both fuel cells and ICE), forms of hybridisation, like plug-in hybrid electric vehicles (PHEV), CNG and biofuels.

The paper is organized as follows. In the next Chapter 2, the modelling methodology of the energy system is outlined, emphasising the SRC niche market. In Chapter 3, the assumptions of the scenarios are presented. In Chapter 4, we provide results of the scenario analyses. In Chapter 5, we conclude with a discussion including potential policy implications.

2. Methodology

2.1 Overview of the GMM Model

The analysis uses a modified version of the Global Multi-Regional MARKAL (GMM) energy system model ([Barreto, 2001, Rafaj et al., 2005, Rafaj et al., 2006, Rafaj and Kypreos, 2007, Krzyzanowski et al., 2008, Gül et al., 2009]). MARKAL-type models are technology-rich perfect-foresight cost-optimisation models ([Fishbone and Abilock, 1981, Loulou et al., 2004]). Given external constraints and costs, the model determines the optimal combinations of technologies and resources that minimise the total cost of the energy system.

GMM incorporates a detailed representation of the energy system in terms of resource extraction, flows of energy carriers, energy conversion and end-use demand technologies which satisfy different sectors of energy demand: residential, commercial, industrial and transport. Each sector is divided into subsectors, for example transport consists of personal car transport, other surface transports (trucks, buses, trains, ships etc.) and aviation.

GMM is a multi-regional model such that each world region has separate technology and resource parameters with possible different dynamics. Most of the main energy carriers can be traded[1] across regions, subject to transportation costs. The model compromises six regions: (i) North America; (ii) EU-27, Switzerland and Norway; (iii) the remaining OECD countries[2]; (iv) countries of the Former Soviet Union and non-OECD/EU Europe, (v) Asia; and (vi) Latin America, Africa, and the Middle East.

Empirically, unit investment costs of new energy technologies decrease exponentially as a function of the cumulative installed capacity (see e.g. [McDonald and Schrattenholzer, 2001]). This relationship is represented in GMM by endogenous technology learning (ETL). Technologies in GMM are represented as a combination of non-learning and learning components, and may comprise several such components. Different technologies may incorporate the same key component (e.g., gas turbines are used in a natural gas combined cycle plant and in a coal-fired integrated gasification combined cycle plant)—the set of technologies using the same component is called a cluster. Thus, in GMM the unit investment cost of learning component is an exponentially decreasing function of the sum of installations

[1] Not tradable are electricity, biomass feedstock, and captured CO_2.

[2] excluding recent members such as Chile, Israel, Korea, and Mexico

of the component across all the technologies in the corresponding cluster [Barreto and Kypreos, 2004]. Although the energy system is generally allowed to develop differently in different regions, it is assumed that technology learning spills over globally. A drawback of ETL is the non-linearity of the optimisation model, which makes it harder to solve numerically. Thus, we apply a piece-wise linearization using mixed integer programming.

As mentioned in the introduction, the time horizon of the GMM model is 100 years, with 10 year time steps. All future expenditures are discounted by a 5 % p.a. interest rate. The model is calibrated to base year 2000. Generally, sectoral final energy demands are calibrated to the statistics of the IEA [IEA, 2002b, IEA, 2002a, Gül, 2008]. For future demand assumptions, the demographic, economic, and technological developments of the SRES-B2 scenario were chosen as the basic framework, with some updates to account for recent developments and trends [IPCC, 2000, Gül, 2008, World Bank, 2011]. The B2 scenario represents a 'dynamics-as-usual' scenario in the sense that economic growth rates remain similar to long-term historical rates, and current regional divergences disappear only slowly. However, it is not necessarily our objective to reproduce all elements of the B2 storyline. Car travel demand (vehicle-km per year) is projected using the growth rates from the IEA/SMP model [Fulton and Eads, 2004, p. 34], ranging for example from approximately 0.3% p.a. in European OECD countries up to 6 % in the Asian region (China) for the first half of the century. The resulting global fleet stock is 1.6 billion vehicles in 2050. This growth may be compared to 1.6 billion in 2035 in the 'New Policy' scenario in the latest World Energy Outlook [IEA, 2010c, Fig. 3.5] and 1.8 bio in 2050 in the ETP BLUE scenario [IEA, 2010a, p. 282]. GMM has a fixed allocation of personal travel demand and does not model modal shifts.

In GMM, fossil resources (oil, gas, coal) are categorised by different extraction costs and by probability of existence: ranging from easily extractable, proven reserves, through more cost-intensive reserves or speculative resources, to unconventional resources. Assumed volumes are based on [Rogner, 1997], and are in the same range as newer estimates of the IEA or BGR [IEA, 2008b, Tab. 9.1], excluding unconventional sources; [Rempel et al., 2009, Tab.12.1]. More details are provided in Sec. 3.4. In the baseline, the storage potential of CCS is assumed to be greater than 3500 Gt CO_2 with technology-specific costs for CO_2 capture, separation and storage [Gül, 2008].

2.2 Personal Transport in the GMM Model

2.2.1 Short-Range-Car Niche Market

Empirically, mean car travel distance is short in relation to the technical driving range of conventional cars. In the USA, approximately 81% of all daily trips are below 64 km and average vehicle trip length is around 16 km [Santini and Vyas, 2008, Tab. 1; [Hu and Reuscher, 2004, Tab. 3]. In Switzerland, 66% percent of all trips are not longer than 10 km, and daily average personal car travel distance is 26.2 km [BfS, 2007, p. 17 and 38]. The short travel distances mainly result from daily commuting for work, shopping and leisure. Thus, short range cars (SRCs) have in principle the potential to satisfy a large share of current driving needs. In comparison, the driving range of today's cars is between 350 and 850 km [DoE, 2010].

Short distances are also favoured by urbanization: More than 48% of people globally live in urban settlements now and this number is expected to rise to 61% in 2030 [UN, 2004]. Urban areas are generally subject to traffic congestion and to relatively stronger emission restrictions, such that future legislation may favour small and low-emission cars especially in these high density areas. Political initiatives to promote alternative and low-emission vehicles in urban areas started more than a decade ago [DoE, 1993, Bonnel, 1995]. Legislative actions to restrict access into city centres by prohibiting the use of high-emission cars are already in place and will perhaps become more prevalent (e.g. Germany's pollution control act for city centres[BImSchV, 2006]; for an overview of current legislation in the European Union, see [PwC, 2010]). Hence, localized restrictions may help to promote SRCs and low-emission vehicles even in the absence of a stringent general climate policy.

In this study, we assume that a certain share of car owners is willing to buy SRCs which have a limited driving range. Costumers may buy such vehicles because of the following reasons: (i) the purchase, operating and maintenance costs are lower, (ii) they seldom drive longer trips, (iii) smaller SRCs may be more convenient for parking in congested urban areas; and (iv) the use of SRCs is politically encouraged or even forced in city centres. We assume that on the relatively rare occasions that owners wish to make a longer trip either the SRC is used with interim refuelling, or these trips are executed by other modes (bus, train, aviation), or with a secondary standard-range car (possibly rented). In the energy model, the SRC market is represented by a split of the yearly vehicle-kilometre personal transport demand into a short-range and a standard-range demand (for each world region). The future share of a SRC market depends on several factors: On the distribution of trip lengths, on the subjective inconvenience of not owning a standard-range car, and on the share of owners that own both short and standard-range cars (see Sec. 4.1.2 for the discussion of assumed shares in the scenario analysis).

2.2.2 Car Technologies

In GMM energy system, car technologies are categorised by drivetrains and their associated fuels from the viewpoint of energy flows; different vehicle sizes are averaged into a single category, separately for standard-range and for SRCs. The first category comprises internal combustion engine vehicles (ICEV) with different fuelling options, like gasoline, diesel, gas, ethanol and hydrogen. The other vehicle categories use an electric motor as the primary or secondary engine: hybrid electric vehicles (HEV) with different fuelling options, plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), hydrogen fuel cell vehicles (HFCV), and fuel cell vehicles with on-board reforming equipment. Detailed technology data for the standard-range cars can be found in [Gül, 2008] and [Kasseris and Heywood, 2007].

The categories of SRCs represent scaled-down variants of the standard-range cars with a limited actual drive range of approximately 100 km. Because we assume a similar use in urban areas throughout the world, the yearly driven vehicle distance is assumed to be uniformly 15’000 km, which is a daily average of 41 km. For this initial study of SRCs from an energy system perspective, a reduced (though representative) set of future SRC technologies was selected (see Table 1).

Table 1: Vehicle technologies for short and standard range

Vehicle Category	Availability as Short-Range Vehicle
Liquid Fuel ICEV	gasoline fuelled
Advanced ICEV	gasoline
Gas Fuel ICEV / Hybrid	–
Hybrid Electric Vehicle (HEV)	diesel / gasoline fuelled
Hydrogen Fuel Cell Vehicle (HFCV)	✓
Hydrogen Hybrid	–
Gasoline Fuel Cell Vehicle	–
Plug-in Hybrid Electric Vehicle (PHEV)	✓
Battery Electric Vehicle (BEV)	✓

As an approximation, conventional ICEV SRCs have the same tank-to-wheel efficiency as standard range cars; we assume that the decreased weight and smaller engine is outweighed by the increased share of urban driving. Hybrid drivetrains in the SRC sector are assumed to have a higher efficiency than their standard-range counterparts, on the basis that a larger proportion of driving will take place using the more efficient electric motor and the better braking-energy recuperation, due to urban short-distance trips and urban stop-and-go traffic. The assumed efficiency increase for hybrids is around 15% (note, the HFCV is assumed to be a FC-battery hybrid). The SRC-version of the PHEV is assumed to execute 75% of km-travel in electric mode (standard-range: 50%) with an efficiency increase of 20-30%. Engines, FC and battery sizes are generally smaller (see Table 2). For BEVs, we assume that short and standard range have the same efficiency.

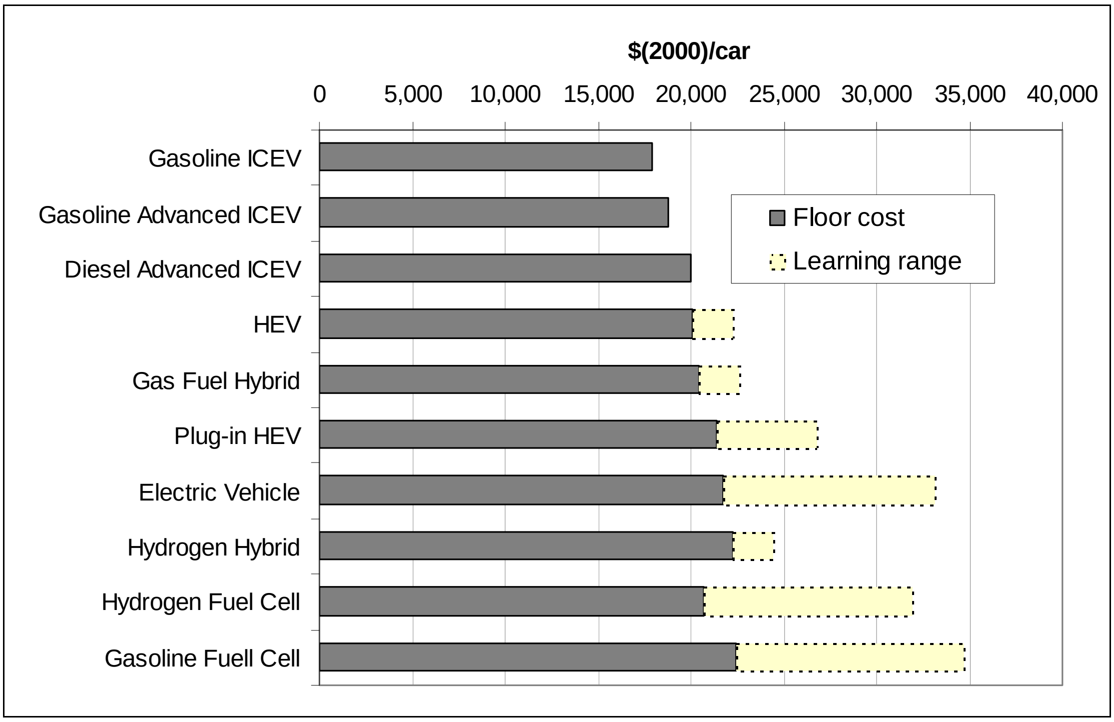
Table 2: Investment cost assumptions for learning components

Key Component	Size in Vehicle	Learning Cost in 2010	Floor Cost	Unit (US$2000)
Fuel Cell	–	250	50	$/kW
Reformer	–	90	25	$/kW
Long Range Vehicles:				
Hybrid Battery System	28 kW	2,500	320	$/car
FC Battery System	42 kW / 1.5 kWh	3,750	480	$/car
Battery Electric System	48 kWh	16,250	4,800	$/car
Plug-in Hybrid System	42 kW / 8.2 kWh	6,500	1,120	$/car
Short Range Vehicles:				
Hybrid Battery System	28 kW	2,000	256	$/car
FC Battery System	42 kW / 1.1 kWh	2,600	333	$/car
Battery Electric System	18 kWh	6,094	1,800	$/car
Plug-in Hybrid System	42 kW / 6.15 kWh	5,200	896	$/car

Source: [Gül et al., 2009] and own assumptions

Table 2 shows also the car components that are subject to learning (ETL). The learning rate[3] is generally assumed to be 15%[4]. The allowed cost reduction is bounded from below by floor costs. The initial battery storage costs of 300$(2000)/kWh may be compared to other energy system studies with similar ranges: 300$ to 500$/kWh [IEA, 2009b, p. 16; IEA, 2010a, p. 284]. The assumed floor costs of 100$/kWh are comparable to a recent study with long-term cost estimates in range of 90$/kWh to $200/kWh [Baker et al., 2010].[5] For hydrogen technology comparison, a long-term estimate for FCs is 95€(2005)/kW [Schoots et al., 2010], whereas a relatively low estimate is the US Department of Energy high volume target of 30$(2005)/kW [Marcinkoski et al., 2008]. Note that GMM includes also an advanced, more efficient ICEV without hybridisation. An illustration of possible investment cost reductions for the example of the standard range cars is given in Figure 1.

Figure 1: Investment costs of advanced and alternative car technologies (standard-range). The floor cost is the minimal achievable cost (by endogenous technology learning and other production improvements).



[3] Unit cost decline when the cumulative installed capacity is doubled

[4] learning for battery power ($/kW) is 20% (model results showed lagging w.r.t battery storage if 15%)

[5] Note that batteries for PHEV have usually higher costs per kWh than for BEV (cf. [IEA, 2009a, p. 16].

2.2.3 Fuel Chains

The electricity to charge the battery of electric vehicles is assumed to be taken from the electricity grid with the generation mix of the corresponding world region. There is uncertainty about the future temporal load pattern of electricity vehicles. In this study, we assume that the average evening/night electricity demand of electric vehicles is the same as the averaged demand during day-time. The pattern is a simple approximation for combined daytime public charging and evening/night private charging. The potential application of smart-grid technologies for improved demand side management may change the load patterns substantially and thus also the respective electricity mix used in electric vehicles.

GMM has a comprehensive set of current and future options for electricity generation. For example coal-fired plants come in different flavours: with and without carbon capture and storage (CCS), with combined cycle turbines or with heat co-generation (and as energyplexes capable of producing electricity and hydrogen). For more details, see [Rafaj et al., 2005].

Liquid and gaseous fuel options in GMM compromise gasoline, diesel, ethanol, methanol, FAME (fatty acid methyl ester, biodiesel), FAEE (fatty acid ethyl ester), Fischer-Tropsch-diesel, bio-SNG (synthetic natural gas), DME (dimethyl ether), and hydrogen. Apart from gasoline and diesel, all fuels have an option to be generated by biomass. GMM includes different first and second generation (cellulosic) biomass. Hydrogen can be produced in addition from different fossil fuels with CCS options, from dedicated nuclear plants, and from non-biomass renewable sources. For details on the different generation and distribution options of biomass and hydrogen, see [Gül, 2008].

3. Scenario Definitions

3.1 Selection of Scenarios

The purpose of the scenarios is to analyse a selection of uncertainties likely to affect the deployment of alternative fuels and drivetrains (in particular BEVs).

Clearly, one important uncertainty is the future cost of alternative drivetrains. However, our interest is primarily to understand the conditions affecting deployment *assuming that it is possible to realise moderately optimistic drivetrain costs* in the future if sufficient experience and economies of scale are realised (and not, whether it is possible *at all* to realise such costs). Accordingly, in these scenarios costs are determined via endogenous technology learning, with moderately optimistic assumptions about ultimately achievable floors costs (see Sec. 2.2.2). If, for example, battery costs would stay persistently high with respect to the floor costs of competing technologies like fuel cells, BEVs are not deployed even under strong climate policies [Gül et al., 2009].

As discussed in the introduction, one uncertainty that may be particularly important for alternative drivetrains is consumer willingness to adopt shorter-range vehicles. Thus we analyse scenarios considering a range of possible market shares for SRCs.

In addition, climate change policy measures may be important for deployment of alternative drivetrains, including BEVs, because the power sector could be –in principle– decarbonised, and thus electricity as the fuel of BEVs may become more attractive than fossil fuels. In this study, we consider scenarios including policy measures meant to reduce energy-related CO_2-emissions.

In the presence of a climate policy, electricity production from fossil fuels may be discouraged if CCS technologies are not available. The political and technical feasibility of CCS is still uncertain, and the estimated storage potential ranges over more than three orders of magnitude [Bradshaw et al., 2007, Fig. 1]. Hence, we also include a scenario where CCS is not available.

The use of fossil fuels in car transport may be discouraged not only by climate policy, but also by scarcity of fossil resources, making extraction more costly or infeasible. Hence, we consider also a scenario with low fossil resource availability. Details of the scenarios are provided below.

3.2 Climate Policy Scenario

While some climate protection measures are already active in legislation in some countries, other proposed measures as well as the nature of long-term policies is still debated. In this study, we try to incorporate current legislation together with future projected policies. We assume three different measures: (i) For the whole energy system, we consider an increasing price on carbon emissions, which can be interpreted as a proxy for comprehensive climate policy, (ii) for the transport sector, we assume targets for the use of biofuels, and (iii) for the personal transport sector, we incorporate current and possible future legislation for limits on carbon emissions intensity (per kilometre). These sectoral targets reflect current policy trends. In addition, they could be expected to continue in some form even with an economy-wide carbon pricing mechanism, given some of the barriers to the transmission of a carbon price, and because some of these policies support additional goals related to energy security, agriculture, and industry policy.

We assume that different world regions will diverge in the short to medium term in terms of climate policy, but in the long term will converge to carbon price of 200$/t$CO_2$, which corresponds to the marginal carbon price in the ETP BLUE scenario in 2050 of the IEA [IEA, 2008a, Fig. ES.1].[6] In the medium term, we assume that the developed world takes stronger action than the economies-in-transition and developing world. The carbon price also applies to fossil diesel and gasoline fuels despite the efficiency targets and biofuels targets. Thus, in the long-term the carbon price signal may outweigh the other targets and drive deployment.

The biofuels targets are based on announced targets (EU Directive 2009/28/EC, USA Energy Independence and Security Act 2007, China's NDRC targets [Yang et al., 2009]) which are extrapolated into the future. For example, the targets for Europe are 10% and 25% in the years 2010 and 2050, respectively, whereas North America has an absolute amount of 5070 PJ/y in year 2050. We also assume that other world regions will adopt similar targets in the future, with some delay.

The targets on car emissions are based on the EU-Regulation 443/2009 (European standard for new passenger cars) and the USA Energy Independence and Security Act 2007, and are assumed to become increasingly stringent at a gradual rate over the longer term, with developing countries following with a delay. For example, in Europe, the target is 95g/km in the year 2020 and reaching around 73g/km after 2045-2050.

[6] The assumed long-term carbon price leads in the ETP BLUE energy system model to a 50% reduction of GHG emissions in the year 2050 with base year 2000.

3.3 Emission Cap Scenario

The climate policy described above incorporates a relatively stringent carbon price. Nevertheless, initial modelling analysis indicated that such a policy was not sufficient to achieve some of the more ambitious mitigation targets that may be necessary to avoid serious climate change. Accordingly, we also consider a scenario with a strict 50% CO_2-emission reduction target in the year 2050 (relative to 2000 levels), decreasing to 80% by 2100.[7]

We assumed that efforts to achieve such a target would be accompanied by increased end-use energy efficiency (which is not represented endogenously in GMM). Hence, for this scenario, energy end-use demands were scaled in proportion to the ratio between the demands in IIASA's B2 Baseline and 480ppm-CO_2eq scenarios [Riahi et al., 2007]. This equates to a 10-25% reduction in thermal energy demand by 2050 compared to baseline demands, a 0-10% reduction in specific energy (mostly electricity) demand, and approximately 15-25% for other surface transport. Personal transport demand (in vehicle-kilometres) is not altered, since stringent efficiency measures are already included in the scenario and because stringent climate policy may encourage a substitution away from air travel [Turton, 2008, Schäfer and Victor, 2000, Zahavi and Talvitie, 1980].

3.4 Low Resources Scenario

Fossil energy resources in GMM follow a supply curve categorised by different geological assurance and by different economic feasibility of extraction: Proven or highly probable reserves, uncertain resources, and costly sources, like unconventional reserves/resources and enhanced recovery of existing fields [Rogner, 1997]. In the baseline scenario, total fossil resources in the base year (sum over all categories) consist of approximately 500 Gtoe (21'000 EJ) of oil, 840 Gtoe (35'000 EJ) of gas and 6200 Gtoe (166'000 EJ) of coal [Rogner, 1997]. Excluding the unconventional sources[8], the assumptions are in the range of recent IEA and BGR estimates [IEA, 2008b, Rempel et al., 2009].

However, there is a degree of uncertainty regarding these estimates, and other groups are much less optimistic about resource availability [EWG, 2007]. Accordingly, we consider a low

[7] It should be noted that the IEA's ETP BLUE scenario presents a 50% reduction scenario with the same marginal carbon price used here (see Sec. 3.2). However, the ETP BLUE scenario incorporates extensive end-use efficiency.

[8] The most speculative category VI of Rogner is not included in GMM.

resource scenario with substantially lower estimates of oil and gas resources (coal is still assumed to be abundant). In this scenario, we assume that the more speculative and costly categories of oil –that is, enhanced recovery and unconventional sources– are unavailable or prohibitively expensive to extract. In addition, we adopt a pessimistic estimate for conventional oil categorized as either ‘additional reserves’ or ‘speculative resources’, reducing the available resource by 50% in developed countries and by 25% in the developing world (on the basis that there has likely been less thorough geophysical exploration). In summary, the low scenario has roughly 50% less fossil oil available than in the baseline. For natural gas, the most speculative category of unconventional resources is removed, reducing gas availability by approximately 30%.

4. Results of the Scenario Analyses

4.1 Relevance of SRC Market and Climate Policy

4.1.1 Scenarios without SRC Market

As a starting point, we first present a scenario assuming no short-range cars (SRCs) and no climate policies. Figure 2 reports the development of the global car technology market over the 21st century under this scenario. One of the most notable results is that almost no BEVs or PHEVs are deployed, despite the moderately optimistic assumptions about future battery costs (Sec. 2.2.2); hydrogen powered cars are absent as well.

Figure 2: Car technologies without SRC market and without climate policy

0% SRC, no Policy

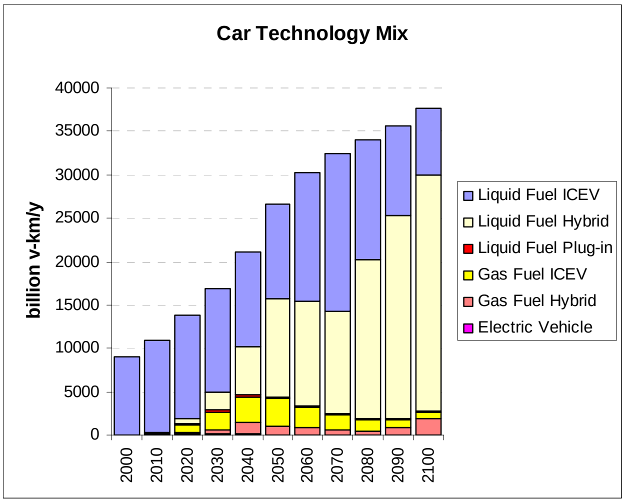
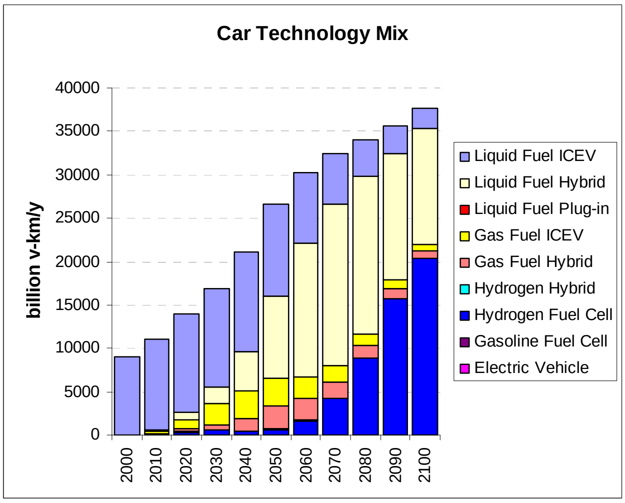


Figure 3: Car technologies without SRC market and with climate policy

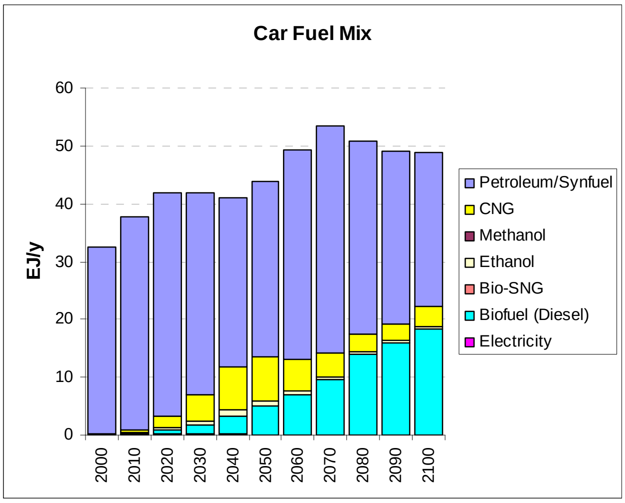
0% SRC, with Policy



Instead, we see conventional vehicles and HEVs playing a major role; hybrid drivetrains have the largest share at the end of the century, mainly driven by cost reductions due to technology learning and due to more efficient fuel-use, which is triggered in turn by rising fuel costs caused by fossil resource depletion. The resource depletion is more pronounced for oil than for gas, such that gas fuelled vehicles can gain a significant market share at least in intermediate years of the next century (approx. 15% of the oil potential is left in the year 2100; whereas 60% of the gas potential remains, with some of the unconventional gas resources used starting from 2050). The depletion of fossil resources also supports the use of biofuels in personal transport (Figure 4).

Figure 4: Fuel mix corresponding to Figure 2

0% SRC, no Policy



In the presence of the climate policies, the transport technology market develops as shown in Figure 3. Once again, standard-range BEVs and PHEVs are not competitive in this scenario under the assumptions of this study[9]; despite technology learning and the climate policy supporting low-emissions fuels. Due to the climate policy, hybridisation is accelerated relative to the scenario without policy, and natural gas remains attractive as a transitional fuel because of its lower emissions. Towards the end of the century, there is strong deployment of hydrogen fuel cell vehicles, mainly due to technology learning and the increased stringency of the policy measures. It should be noted that the learning assumptions (see Table 2.2) mean that the ultimately achievable costs of HFCVs are below those of BEVs at the end of the century (year 2080+).

[9]: with the main cost assumptions as in Table 2.

The following scenarios investigate whether a SRC market enables cost-effective electric vehicles in any of the two personal transport sectors.

4.1.2 Scenarios with SRC Market

The possible future market share of SRCs is uncertain. Considering limited-range electric cars, a recent study estimates a possible market share of 4-11% [Lieven et al., 2011]. In our study, we first assume that 10% of vehicle owners in each world region would be willing to own a SRC, that is, 10% of vehicle-km demand is satisfied by SRCs. For a scenario without climate policy, the resulting technology mix over time for all cars and separately for SRCs alone is shown in Figure 5 and Figure 6.

Figure 5: Car technology mix in scenario with 10% SRC and without climate policy

10% SRC, no Policy

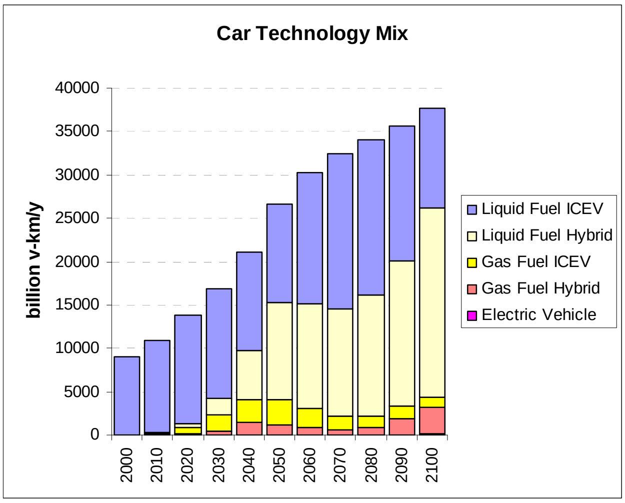


Figure 7: Car technology mix in scenario with 10% SRC and with climate policy

10% SRC, with Policy

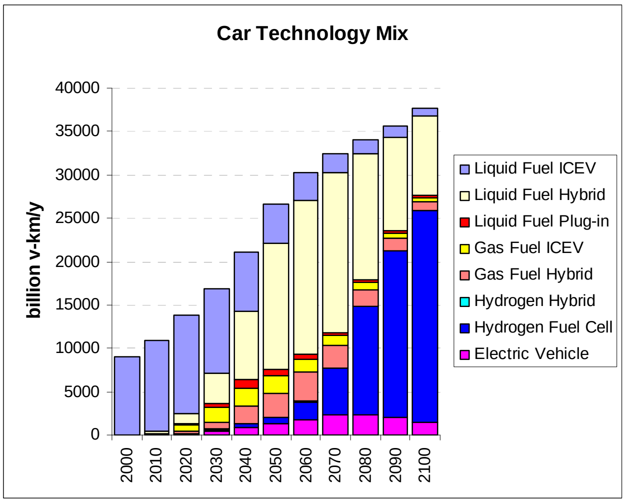


Figure 6: Short-range car technology mix in scenario with 10% SRC and without climate policy

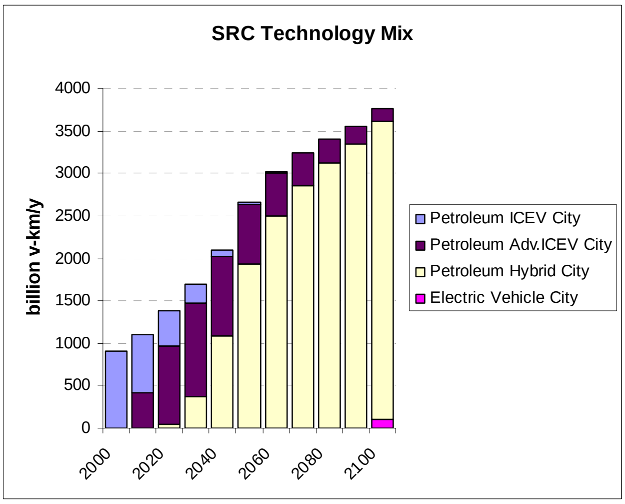
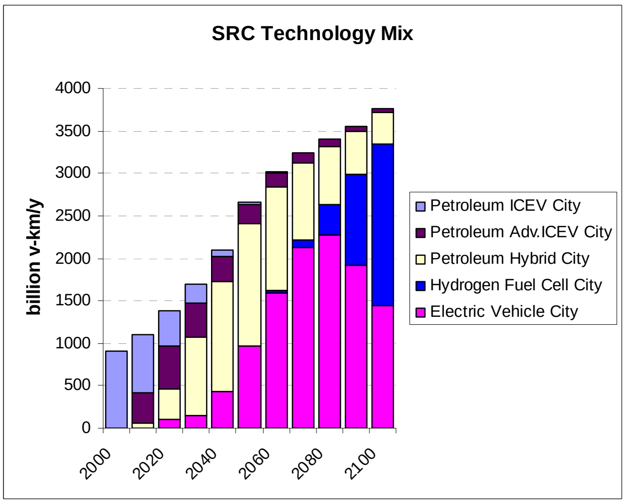


Figure 8: Short-range car technology mix in scenario with 10% SRC and with climate policy



Despite the lowered investment costs of BEVs and PHEVs in the SRC sector, there are still no electric vehicles in personal transport under the assumption of 10% SRCs and without policy measures. The main driver in this scenario is the depletion of oil and gas resources, which supports deployment of hybrids and natural gas, as in the case above without the SRC market. Concerning hybridisation, there is a faster market penetration of hybrids in the short-range market relative to the standard-range sector, which is due to their increased efficiency in urban-like driving cycles assumed for the short-range sector. At the end of the century, the short-range sector is practically entirely hybridised.

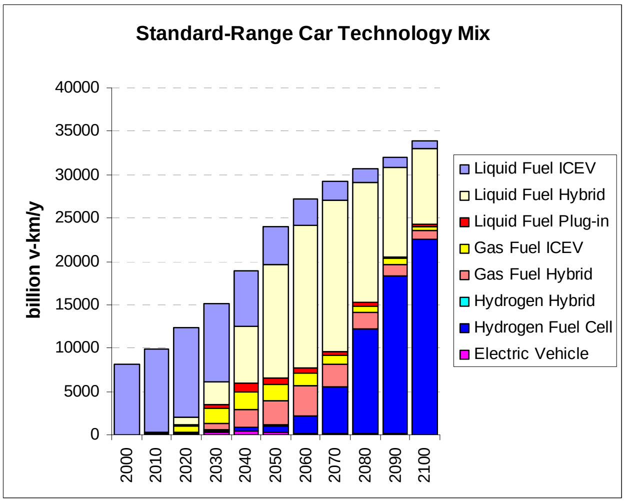
The introduction of the climate policies changes the technology mix substantially, as shown for all cars in Figure 7 and for the 10% SRC market in Figure 8. The figures show that under the assumptions of the climate policy, BEVs are an attractive option in the short-range niche market. There is also a very small share of standard-range BEVs and PHEVs (Figure 9), mostly due to increased technology learning in the short-range car sector (scenario with 10% SRCs: battery storage floor costs are reached in year 2050; scenario with 0% SRC: cost still 20% above floor in 2050). In the scenario without climate policy, marginal electricity and hydrogen costs remain above gasoline costs, whereas with climate policy they fall below in the second half of the century.

We also examined scenarios assuming larger proportions of drivers willing to own SRCs, which resulted in a proportional increase in deployment of BEVs in the short-range market (not shown). Although this larger total market for BEVs supports additional technology learning, accelerating the cost reductions for batteries, there appear to be minimal spillover to the long-range market, shown for the case with a 40% share of SRCs in Figure 10.

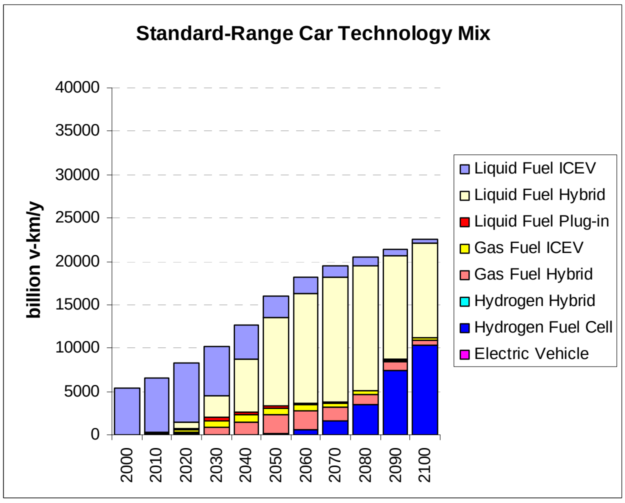
Figure 9: Technology mix for standard-range cars in scenario with 10% SRCs and with climate policy

Figure 10: Technology mix for standard-range cars in scenario with 40% SRCs and with climate policy

10% SRC, with Policy



40% SRC, with Policy

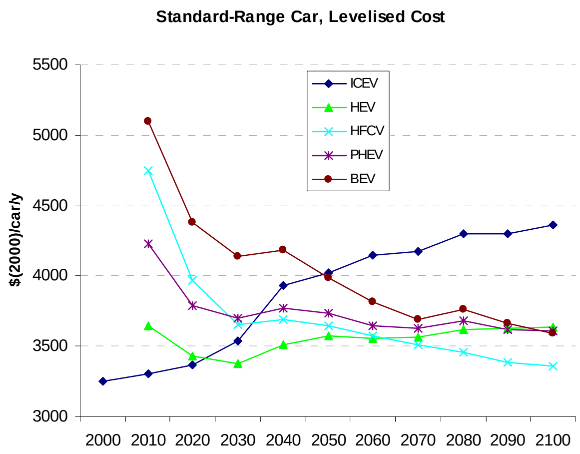


Hence, standard-range BEVs are not a cost-effective option under the assumptions of the climate policy and technology costs. Indeed, battery technology learning is reinforced by deployment of BEVs in the short-range market, but this is not sufficient to make BEVs more competitive than ICEVs before around 2040 and HEVs before 2080 (see Figure 11, Figure 12, Figure 13), by which time HFCVs are more cost-competitive under the assumptions for long-term learning of the fuel cell. With a more stringent (and earlier) climate policy, BEVs may become more competitive than ICEVs and HEVs earlier, leading to higher deployment (which we examine in Sec. 4.3 below).

Figure 11: Selection of levelised costs of standard-range vehicles in scenario without SRCs and with climate policy

Figure 12: Selection of levelised costs of standard-range cars in scenario with 10% SRC and with climate policy.

0% SRC, with Policy



10% SRC, with Policy

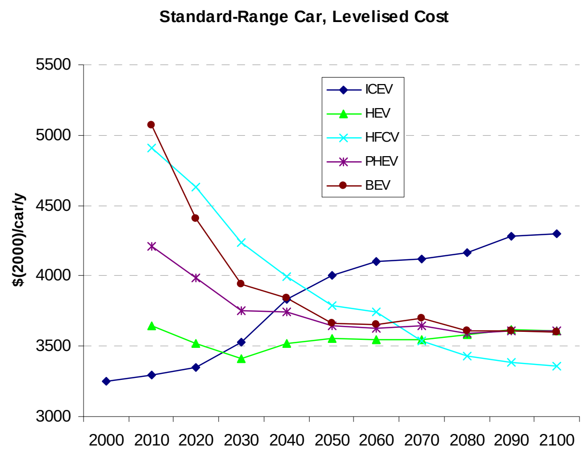
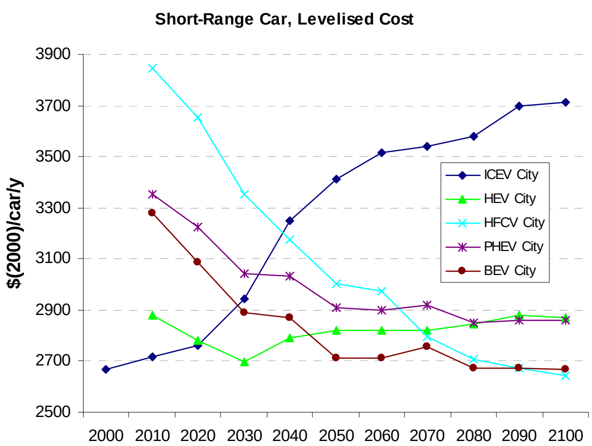


Figure 13: Selection of levelised costs of SRCs in scenario with 10% SRC and with climate policy.

10% SRC, with Policy



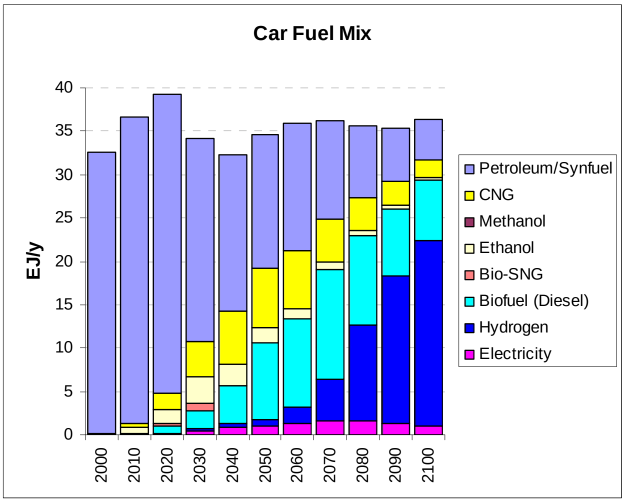
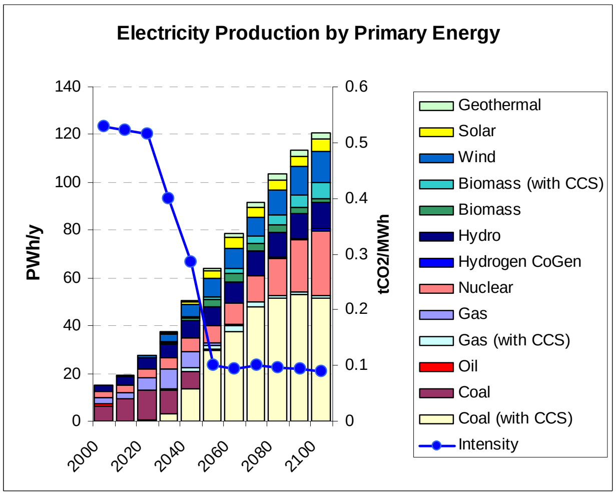
As mentioned, the deployment of PHEVs is marginal, similar to that of BEVs (Figure 9). PHEVs are disfavoured in the purely cost-driven analysis of the study because of their relatively large investment costs under the assumptions of our study for the drivetrain (see Table 2, Figure 1, Figure 11 - Figure 13), whereas other, non-direct-cost factors, for example the convenience of increased refuelling flexibility and range, are not taken fully into account (more in Sec. 5.4), which may however dominate the consumer choice.

4.2 Low-Carbon Fuel Production and Role of CCS

The fuel mix in the personal transport sector for the scenario with 10% SRC market and climate policy is shown in Figure 14 (note, varying the share of SRCs does not affect proportional fuel shares considerably, although the total fuel consumption changes because some SRCs are more efficient than their standard-range counterparts). Consistent with the vehicle technology shares in Figure 7, the share of petroleum fuels decreases, replaced with natural gas, biofuels (predominantly biodiesel) and hydrogen towards the end of the century. Electricity plays a small role in personal transport—accounting for 0.5% of total electricity consumption in the year 2050.[10]

In the presence of climate policy, the advantage of electric vehicles depends on the decarbonisation of the electricity sector, such that the cost of electricity is largely affected by the implicit carbon price. The electricity generation mix in this scenario is shown in Figure 15, along with the average global carbon intensity of the electricity. Figure 15 indicates that carbon capture and storage (CCS) plays a large role in decarbonising the electricity sector in this scenario, especially for coal-fired plants, resulting in heavily reduced CO_2-emissions after 2050.

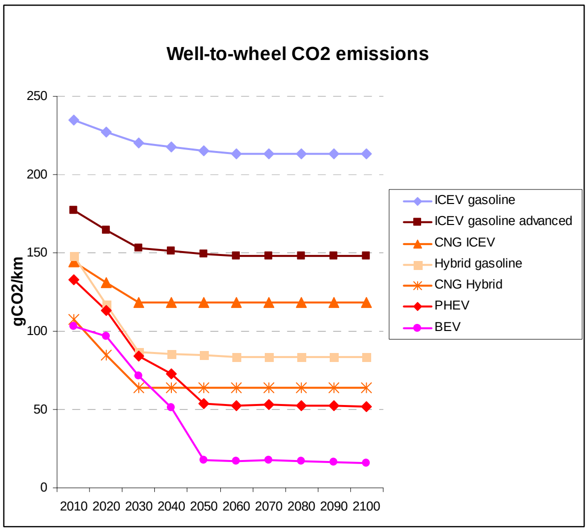
[10] It is interesting to note that if the entire personal transport sector were fully electrified in 2050 this would account for 7% of total generated electricity.

Figure 14: Fuel consumption in the personal transport sector in scenario with 10% SRC and with climate policy	Figure 15: Electricity generation and its CO2 emission intensity in scenario with 10% SRC and with climate policy
10% SRC, with Policy	**10% SRC, with Policy**
	

The decarbonisation of the electricity sector is reflected in the CO_2-emissions of BEVs and PHEVs in relation to other technologies (Figure 16), although it is worth noting that with the 2010-2030 global electricity mix, natural gas hybrid cars have lower emissions per kilometre than electric vehicles.

Figure 16: CO2-emissions of standard-range cars (WEUR model region).

10% SRC, with Policy

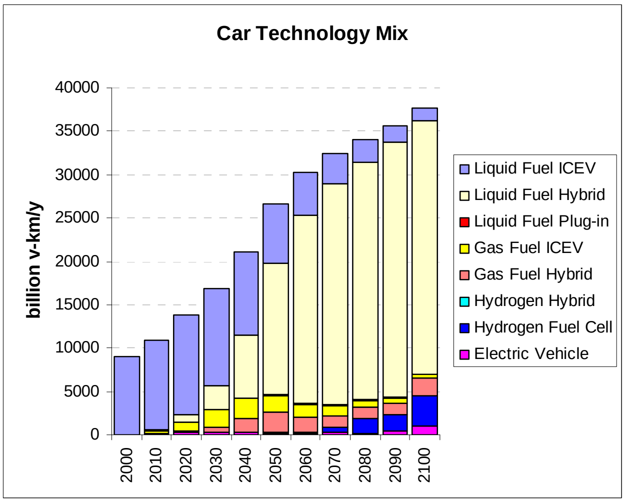


As mentioned above, despite a huge uptake in renewables in electricity generation, coal continues to be cost-effective if CCS is available. Without CCS availability, electricity generation stays carbon intensive, and gas, which has less emissions, is used more (Figure 18). BEVs are discouraged without CCS (Figure 17): Emissions for BEVs are 52g CO_2/km in the scenario without CCS in 2050 and 18g CO_2/km with CCS (as in Figure 16). Therefore, CCS seems to be crucial for cost-effective BEVs under the assumed gradually increasing carbon price. Use of hydrogen is similarly discouraged because cost-effective hydrogen production relies on CSS, too. Figure 19 presents marginal fuel costs for electricity and hydrogen with and without CCS under the climate policy scenario.

Figure 17: Car technology mix in scenario with 10% SRC, with climate policy and without CCS

Figure 18: Electricity generation and CO2 emission intensity in scenario with 10% SRC, with climate policy and without CCS

No CCS, 10% SRC, with Policy



No CCS, 10% SRC, with Policy

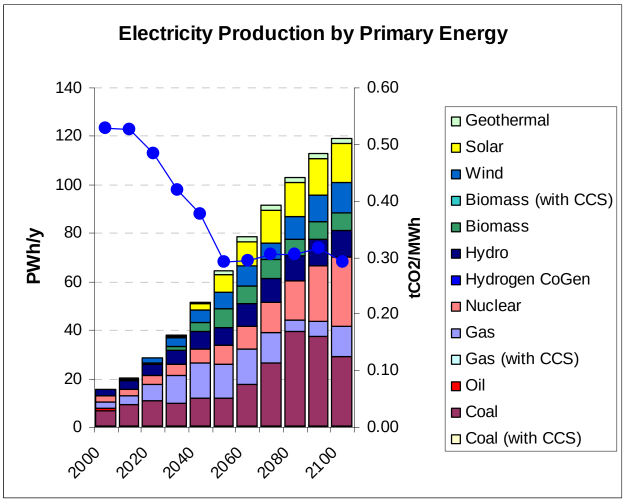
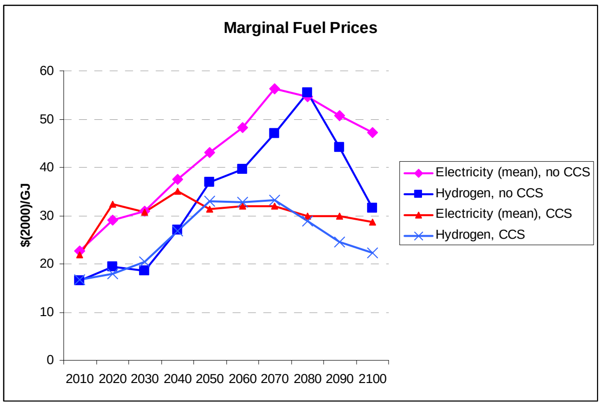


Figure 19: Marginal electricity and hydrogen costs with and without CCS in scenarios with 10% SRC and with climate policy

With/No CCS, 10% SRC, with Policy



4.3 BEVs in the Emission Cap Scenario

The previous results showed that in the presence of a comprehensive climate policy, BEVs are an attractive option in the SRC niche market. But, even with an increased relative size of the SRC market, there are few spillovers to sufficiently promote BEVs to enter the standard-range market. The standard-range market remains dominated by hybridised ICEV technologies in intermediate times of the century, and HFCVs become the most cost-competitive option towards the end of the century.

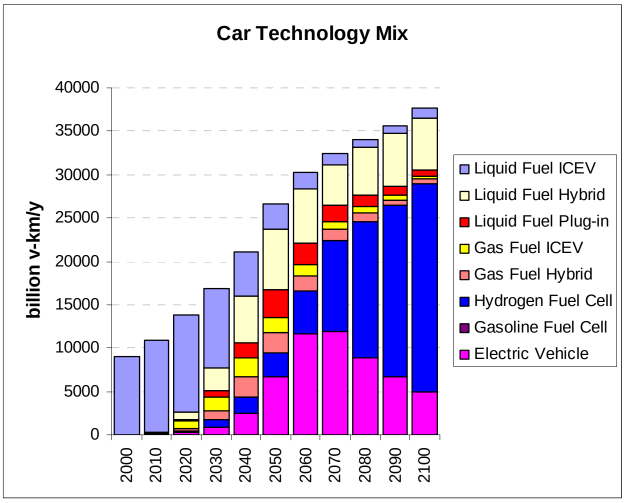
Nevertheless, the results show that climate policies tend to favour BEVs. Hence, in this section, we examine the impact of a more stringent climate policy: specifically, we present the scenario incorporating a 50% CO_2-emission reduction target for year 2050 as defined in Section 3.3.

The resulting technology mix in the Emission Cap scenario shows that even without a SRC market, there is a considerable share of BEVs in the standard-range sector, peaking in 2060 at 39% (Figure 20). Under the assumptions of 10% SRC market share, the deployment of standard-range BEVs reaches higher levels (Figure 21), such that HFCVs play a smaller role towards the end of the century. This is a strong indicator for a spillover from the short-range to standard range BEVs.

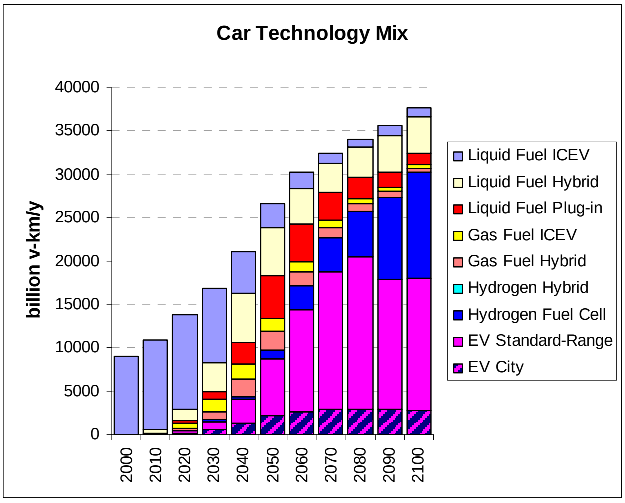
Figure 20: Car technology mix in the scenario without SRC, with climate policy and additional emission cap

Figure 21: Car technology mix in the scenario with 10% SRC, with climate policy and additional emission cap

0% SRC, Stringent Emission Cap



10% SRC, Stringent Emission Cap



The stringent climate policy also supports the deployment of PHEVs: Figure 20 and Figure 21 show a persistent share of PHEVs even in the standard-range sector.

4.4 BEVs with Low Fossil Resource Availability

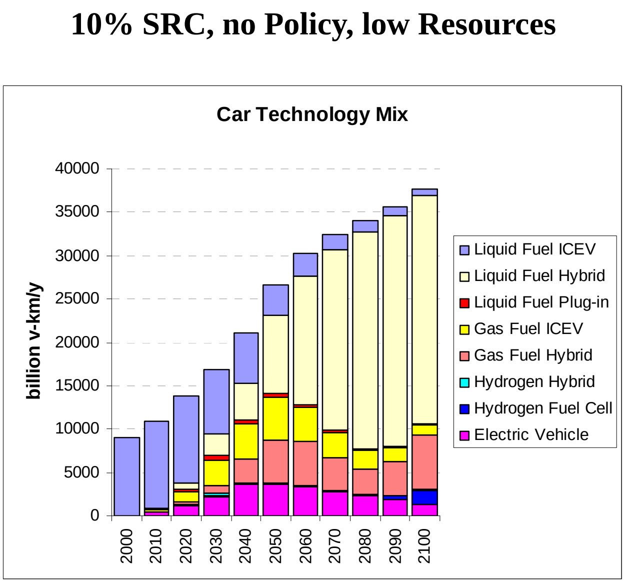
In some of the scenarios presented so far we have observed that depletion of oil and, to a lesser extent, gas resources appears to be driving some of the developments in car transport, even in the absence of climate policy. Thus, conditions that lead to a faster depletion of oil resources may necessitate additional changes in the transport sector, supporting a different set of technologies. We thus consider a scenario of low fossil resources were (as discussed in Sec. 3.4) unconventional oil and gas resources are assumed to be unavailable or prohibitively expensive, and conventional resources are reduced.

Figure 22 and Figure 23 present car technology deployment in a scenario of low resources without any climate policy and with 10% SRCs. The reduced availability of fossil resources makes alternative drivetrains more cost-effective, with hybrids substituting conventional drivetrains more aggressively (cf. Figure 5) and an intermediate shift to gas-fuelled vehicles as a substitute for petroleum-fuelled vehicles (there is still enough relatively cheaply extractable fossil gas in the energy system). There is also a considerable share of BEVs in the short-range market over the medium term, and a small number in the standard-range sector until 2040 even in the scenario without climate policy, which is partially due to the assumption on fast infrastructure deployment in coal-to-liquid capacity (Fischer-Tropsch). Thus, it appears that in the absence of climate policy, low resource availability can promote BEVs. However, liquid fuelled vehicles continue to dominate in this scenario, with coal-to-liquids production making up for lower oil availability. Biofuels also make a larger contribution respect to the scenario with regular fossil resources (e.g. more than a doubling in year 2050).

In a scenario combining low resources and the climate policy (as of Sec. 3.2), we observe deployment of BEVs and HFCVs at only a slightly higher level than in the case with base level of resources, as shown in Figure 24 and Figure 25 (cf. Figure 7 and Figure 8). That is, lower resource availability appears to have only limited additional impact on alternative (including BEV) drivetrain deployment. However, deployment of natural gas fuelled vehicles (ICEVs and HEVs) is substantially higher, replacing liquid fuel HEVs. Similarly to previous scenarios, the most cost-effective option in the long term is the HFCV for standard range and partially taking over also the short range sector towards the very end of the century.

Figure 22: Car technology mix in the scenario with low resources, 10% SRC, and without climate policy

Figure 24: Car technology mix in the scenario with low resources, 10% SRC, and climate policy



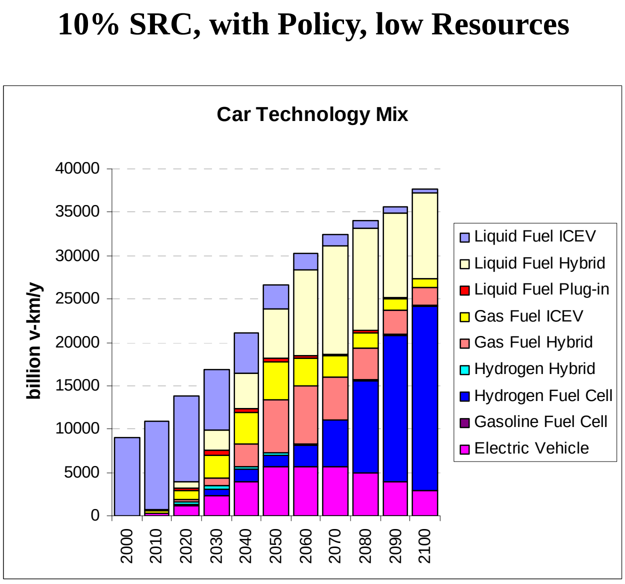
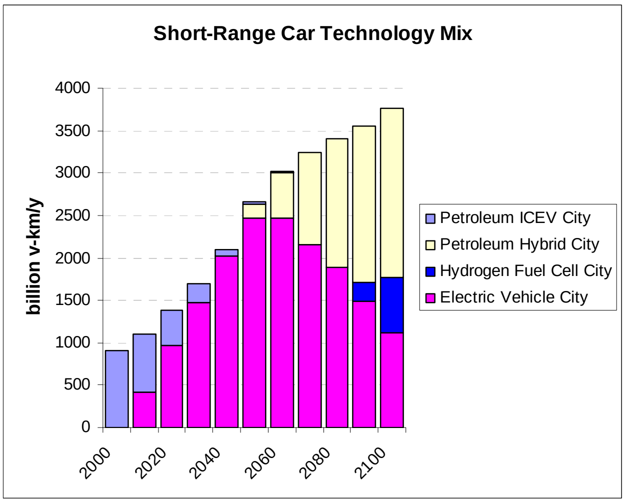
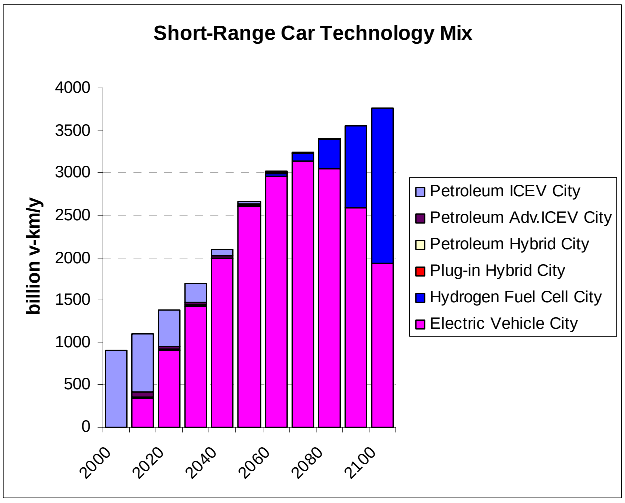


Figure 23: SRC Technology mix in scenario with low resources, 10% SRC, and without climate policy

Figure 25: SRC Technology mix in scenario with low resources, 10% SRC, and climate policy





5. Discussion and Conclusions

The purpose of this paper is to investigate conditions for the successful deployment of alternative drivetrain technologies, focusing on battery electric vehicles (BEVs). Because alternative fuels like electricity have interdependencies with the energy conversion sector and other energy end-use sectors, a global energy system model was used for the analysis. Unlike many earlier studies of alternative drivetrain technologies, the possible role of the short-range car (SRC) market as a suitable niche market for the deployment of new drivetrains was investigated.

5.1 Prospects of BEV and its Competitors

In this study, the SRC niche market in combination with a comprehensive climate policy enables the cost-effective deployment of short-range BEVs. The climate policy (long term price 200$/t$CO_2$) allows BEVs also to gain a relatively small share in the standard driving range market (<10%). In a more stringent policy scenario that additionally achieves a reduction in CO_2 emissions of 50% (and is thus more compatible with ambitious climate change mitigation), BEVs with a standard driving range become also attractive (with HFCVs attractive over the long term).The implementation of a SRC market in GMM helps to better represent an important niche market that can provide opportunities for early experience, thereby accelerating technology learning. Specifically, we see that BEV deployment in the SRC sector accelerates cost reductions for battery storage investment, increasing the cost-effectiveness of standard-range BEVs. However, without stringent climate policy this reduction may be insufficient to make standard-range BEVs more competitive than hybrid technologies until the second half of the century. Importantly, though, there other spillovers that are not modelled, for example shared electric charging infrastructure, which may increase the attractiveness of BEVs.

However, without CCS, electricity is seen to be unattractive for personal transport. Thus, realising the mentioned vehicle shares requires cost-competitive low emission generation, for example from coal with CCS. This importance of CCS is likely to depend on assumptions about other low-carbon electricity generation sources—for instance, a more optimistic learning assumption for renewables may support BEVs even without CCS. The potential role of BEVs in supporting the integration of intermittent renewables by providing additional storage to the grid has not been modelled here, but may well lead to lower overall costs for higher shares of renewables in the electricity mix used for BEVs [Turton and Moura, 2008].

Regarding other alternative drivetrains, a sufficient climate policy is also a prerequisite for the deployment of HFCV, as well as a decarbonised hydrogen production (e.g. with CCS). Hence this is comparable to the conditions for electricity in personal transport. In the longer term (i.e. years 2050-2100), HFCVs represent a competitive option in most scenarios where a climate policy is present. Independent of climate policy, fossil resource depletion alone promotes the deployment of hybrids (HEVs), and alternative fuels such as natural gas and biofuels, triggered by increased marginal costs of fossil fuels. For instance CNG is a competitive option for intermediate periods due to its relative abundance and low emissions compared to fossil gasoline. Under more pessimistic assumptions about the size of the oil and gas resource base (50% less oil, 30% less natural gas) and without any climate policy, conventional ICEVs are rapidly replaced by hybrids and gas-fuelled vehicles.

Achievable long-term costs play an important role in the deployment of alternative drivetrains. Larger deployments of BEVs (and HFCVs) depend under all scenarios of this study on the underlying rather optimistic assumptions for technology learning, particularly the floor cost. The floor costs for both technologies are chosen such that considerable reductions are possible, which conforms to most recent studies (Sec. 2.2.2). Sensitivity analysis with elevated floor costs showed negligible deployment of the respective technologies. The modelling also indicates that if hydrogen and electricity are cost-effective, they are deployed even more heavily in other parts of the transport sector. However this requires further analysis with a more detailed representation of end-use technologies in the commercial vehicle market.

5.2 Comparison to Other Studies

The 50% emission-cap scenario has a comparable greenhouse gas reduction goal as the BLUE MAP scenario of IEA's Energy Technology Perspective (ETP) [IEA, 2010a] and as the 450 scenario of the World Energy Outlook (WEO) [IEA, 2010c]. Table 3 shows a comparison of vehicle deployment across these scenarios.

Table 3: Comparison of car technology shares with to studies (ETP 2010, Fig. 7.16; WEO 2010, Fig. 14.13)

Scenario	WEO 450	GMM (50% Cap)	GMM (50% Cap)	ETP (BLUE Map)
Year	2035	2040	2050	2050
Gasoline/Diesel ICEV	30%	21%	10%	10%
HEV	31%	27%	21%	10%
PHEV	28%	12%	18%	30%
NGA-Vehicle	2%	20%[a]	14%[a]	3%
BEV	11%	19%	33%	25%
HFCV	0%	2%	4%	20%

[a]: includes hybrids and biogas

The IEA-studies reported a somewhat lower share for BEVs, and consider PHEVs and HFCVs more promising in the first half of the century. Purely on the basis of cost-effectiveness (which is the basis of GMM), a dual-fuel vehicle like a PHEV may be less attractive because it includes both an expensive storage battery of a BEV and all the systems of a HEV. However, the fuel flexibility may make this vehicle more appealing to a wider range of customers, particularly before extensive refueling infrastructure is available for BEVs (see below more on flexibility). This factor is not represented in GMM. However, in Table 3 total shares of PHEVs and BEVs are still of comparable size (more in Sec. 5.4 for issues in PHEV's cost modelling) Another deviation illustrated in Table 3 is that gas-fuelled vehicles are deployed in GMM on a much larger scale than in the other studies. This deserves further analysis to determine if barriers to the deployment of gas may preclude such an outcome. It is worth noting that other studies also report higher deployment of biofuels (ETP BLUE Map: 29% in total transport in 2050 (Fig. 7.7), GMM: 13%). The use of biofuel is then declining in ETP after 2030 in personal car transport (GMM after 2050). The differences in results may be attributed to different modelling assumptions. For example, future shares in WEO are calculated based on a logit growth model rather than uniquely on pure cost minimization [IEA, 2010b, p. 10], and for example ETP's deployment of BEVs and of HFCVs belongs to the scenario definition [IEA, 2010a, Tab. 7.1]; an indication for their vehicle assumptions is [IEA, 2009b], which shows also a set of different driving ranges (150 to 400 km).

In GMM, availability of CCS in the climate policy scenarios encourages both the use of electricity and hydrogen in personal transport. Other studies ([Grahn et al., 2009, Hedenus et al., 2010]) found that CCS allows for larger cost reduction for hydrogen and for biofuels than for electricity (in terms of total costs with carbon price). Our results show rather similar cost reductions (Figure 19). PHEVs are also assumed to operate more in electric-drive in these studies, bringing their average efficiency closer to that of costly BEVs; in contrast, BEVs (200 km driving range) are generally unattractive under all conditions, even with battery costs below 150$/kWh [Grahn et al., 2009]. This appears to indicate that such intermediate-range BEVs are still too expensive. Indeed, shortening the range decreases costs, but decreases also the possible market share.

5.3 Support for Alternative Drivetrains

This paper shows that alternative drivetrains and fuels play an important role in climate change mitigation, for managing resource depletion, and thus potentially for increasing energy security by possible diversification. We try to highlight areas of the energy system that could represent possible targets for policy support with respect to alternative drivetrains and fuels.

In the area of car technologies, hybrids and gas driven vehicles may be cost-effective even without climate policy because of fossil resource depletion. As with many cost-effective options for increasing energy efficiency policy has to overcome esp. non-financial barriers for these technologies. However, those cannot be analysed with a cost-optimising model like GMM. BEVs and HFCVs on the other side in both the standard and short range sectors may need sector-specific and/or broad-based climate policy support. We have also seen, however, that short range BEVs may be attractive even without climate policy support in the case of more pessimistic resource assumptions. These results suggest that promotion of HEVs, natural gas and short-range BEVs may represent a means to manage resource depletion and some of the uncertainty regarding ultimate resource availability.

Note that the modelling with endogenous technology learning and with perfect foresight assumes that actions will happen early by anticipating long-term cost reduction potentials. To realise the same levels of learning in practice, direct policy support for BEVs (and HFCVs) may be needed, both at the level of drivetrain R&D and support for deployment / commercialization. Another area in which policy intervention may be necessary relates to fuel cost: Currently, in many countries fuel taxes on electricity (and hydrogen) are small in comparison to fossil fuels; this kind of passive subsidy may need to be retained to support early deployment (similarly for natural gas).

In this analysis, we applied a policy package consisting of carbon intensity targets for cars (gCO_2/km), biofuel targets for the transport sector, and a carbon tax for the overall energy system. The modelling analysis showed, however, that the efficiency and biofuels targets are largely superfluous in most regions and time-steps—that is, the price signal from the carbon tax appears to be sufficient to promote the deployment of low-carbon drivetrains and the use of biofuels. However, there are likely to be market imperfections that may warrant the application of more sector-specific policies such as gCO_2/km and biofuel targets. These may also help support other objectives, including energy security and agricultural policy (in the case of biofuels), and industry policy (in the case of vehicle targets).

A SRC market can contribute to GHG-emission reduction and to energy security (through increased deployment of alternative drivetrains and fuels), as well as to global mobility needs in increasingly urbanised environments (by lowering costs and size). We have seen that a dedicated SRC market enables a considerable share of alternative drivetrains—that is, hybrid vehicles without climate policy and additionally BEVs if a climate policy is present or if the fossil resource base is relatively low. Given these advantages, there may be some scope to promote (or avoid discouraging) consumer uptake of short-range vehicles. This could be supported by measures encouraging the provision of refuelling infrastructure for short-range BEVs (and PHEVs). Improvement of rental and car sharing infrastructure can increase modal flexibility to overcome the some of the lowered convenience of SRCs. Such measures may help to avoid or delay the need for more politically controversial measures such as increasing fossil fuel taxes. Support in SRCs may also help to increase the range of competitive options in the broader standard-range market. For example, for BEVs we observed some spillovers from the short-range market in the case of stringent climate policy.

Some complementary measures for the broader energy system may be important for promoting alternative drivetrains that decarbonise the energy system and support energy security. CCS (if technically and politically feasible) in fuel production enables the production of relatively inexpensive carbon-free electricity and hydrogen, which increases significantly cost-effective deployment of BEVs and HFCVs. This appears to warrant further R&D and pilot projects to determine the long-term feasibility of CCS. Low-carbon electricity without CCS requires large shares of renewable or nuclear generation[11]; and thus support for these technologies may also contribute to a strategy of decarbonising transportation and increasing energy security. Providing an appropriate investment and regulatory environment for developing a capital-intensive fuel distribution infrastructure, especially for natural gas,

[11] subject to possible other policy constraints.

electricity and hydrogen, may also be important, most prominently in developing countries (though, see [Dickinson et al., 2010] for using existing infrastructure).

Regional differences may, in addition, influence future development pathways and technology choices. In particular, differences in the local resource base may affect both fuel choice and energy security over the long term. For example, approximately 70% of the global biomass potential is located in non-OECD countries, while our analysis identifies large import flows of ethanol and biodiesel into OECD countries as a cost-effective way to respond to climate policy needs, especially for the second half of the century. This has the potential to undermine energy security, and thus OECD countries may find other options (such as electricity and hydrogen) more attractive than indicated here. Another important regional difference between developed and developing regions is that the latter are experiencing a rapid expansion in travel demand which may facilitate a more rapid market penetration of new, alternative technologies. Moreover, they are not locked in to a particular set of technologies and infrastructure, and thus may be able to leap-frog to more sustainable options. The large use of two and three wheelers in some developing countries (more than 20% in China in 2007 [IEA, 2010a, Fig. 7.3]) also suggests that consumers in these regions may have different expectations about personal transport in terms of vehicle costs and flexibility, and thus may be more receptive to shorter-range vehicles.

Note that any direct or indirect support for low-carbon fuels and for high-efficiency vehicles can increase the demand (rebound effect), which may have to be counterbalanced by appropriate policies (although historical rebounds in road traffic seems to be small [Goodwin et al., 2004]).

5.4 Limitations of the Model and Extensions

The scenario analysis in this study determines an optimal global least-cost solution for the energy system under perfect foresight assumptions. Thus, our analysis does not account for behavioural dynamics of individual economic agents, which are also driven by non-monetary aspects like convenience and social status, and for other 'real-world' developments, like imposed market power, myopic decisions (see for example [Turrentine and Kurani, 2007, Peters et al., 2011] for idiosyncrasies in fuel economy).

Vehicle technologies that can be fuelled by two or more energy carriers have the flexibility to use the lowest-cost fuel option. An example is the PHEV, which can use gasoline or electricity. In this analysis, the fuel input ratio is assumed to be fixed for the PHEV, and fuel costs represent a time average. In reality, the ratio may be elastic to a certain degree with respect to the cost differences of the two fuels. Moreover, given a fixed ratio, actual fuelling costs can be lower than with timely averaged fuel costs, because consumers will exploit short-term price fluctuations. PHEVs also offer convenience and reliability in terms of refueling (particularly before infrastructure is developed).

Electricity fuel cost reductions for BEVs and for PHEVs may be achieved through active load management of the electricity-grid by smart metering. More speculative vehicle-to-grid technologies may help to manage the load further [Turton and Moura, 2008]. However, benefits from load management (such as through reduced grid expansion) depend largely on the share of intermittent (renewable) generation, and may be relatively low for vehicle-to-grid technology even in the presence of large shares of wind power [Ekman, 2011]. The uniform day-and-night charging assumed in GMM accounts for a simple type of load management, such that charging is not exclusively at costly electricity peak hours. Therefore, it is not clear that major changes in BEV/PHEV deployment would result if active load management was represented in our analysis.

It should also be noted that the current study focuses on the personal transport sector. Other surface transport is represented by aggregated end-use demand technologies, and air transport is assumed to be entirely fuelled by fossil oil products (although other options are under consideration, like biofuels [ATAG, 2009]). The possibility of biofuels in aviation may increase biofuel marginal prices through fuel competition, but allow a slower, more cost-effective technology transition in the surface transport sector to meet the overall carbon targets for the whole energy system, delaying the deployment of BEVs and HFCVs.

Finally, the applied bottom-up modelling uses a variety of parameter assumptions based on extrapolation of historical and current technological dynamics and institutional drivers (notably for technical key components such as batteries). The future development of these drivers is of course uncertain, and thus a range of other possible outcomes need to be considered to identify robust pathways to a sustainable personal transport system. The ultimate contribution from each of biofuels, electric vehicles, hydrogen and improved conventional drivetrains in addressing challenges of climate change, energy security and regional pollution, while facilitating increasing global mobility remains uncertain. However, this analysis has reduced the scope of this uncertainty and has identified some of the conditions under which different alternative drivetrain technologies are likely to be attractive.

6. References

Adamson, K. A. (2003). An examination of consumer demand in the secondary niche market for fuel cell vehicles in Europe. *International Journal of Hydrogen Energy*, **28** (7):771–780.

Air Transportation Action Group (ATAG) (2009). *Beginner's Guide to Aviation Biofuels*.

Azar, C., Lindgren, K., and Andersson, B. A. (2003). Global energy scenarios meeting stringent CO2 constraints-cost effective fuel choices in the transportation sector. *Energy Policy*, **31** (10):961–976.

Baker, E., Chon, H., and Keisler, J. (2010). Battery technology for electric and hybrid vehicles: Expert views about prospects for advancement. *Technological Forecasting and Social Change*, **77** (7):1139–1146.

Barreto, L. (2001). *Technological Learning in Energy Optimisation Models and the Deployment of Emerging Technologies*. PhD No. **14151**, ETH Zurich, Switzerland. doi: 10.3929/ethz-a-004215893.

Barreto, L. and Kypreos, S. (2004). Emissions trading and technology deployment in an energy-systems "bottom-up" model with technology learning. *European Journal of Operational Research*, **158** (1):243–261.

Bundesamt für Statistik (BfS) (2007). *Mobilität in der Schweiz - Ergebnisse des Mikrozensus 2005 zum Verkehrsverhalten*.

Bundes-Immissionsschutzverordnung (BImSchV) (2006). Federal ambient pollution control act for city centres – 35th BImSchV. Germany.

Bonnel, P. (1995). Urban car policy in Europe. *Transport Policy*, **2** (2):83–95.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N. P., and Mathiassen, O. M. (2007). CO2 storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control*, **1** (1):62–68.

Dickinson, R. R., Battye, D. L., Linton, V. M., Ashman, P. J., and Nathan, G. G. J. (2010). Alternative carriers for remote renewable energy sources using existing cng infrastructure. *International Journal of Hydrogen Energy*, **35** (3):1321–1329.

Department of Energy (DoE) (1993). Clean Cities - energy efficiency & renewable energy. U.S. Department of Energy.

Department of Energy (DoE) (2010). U.S. Department of Energy, Energy Efficiency and Renewable Energy.

Energy Information Administration (EIA) (2008). Annual Energy Review (AER) - international energy. Technical Report DOE/EIA-0384, U.S. Energy Information Administration.

Ekman, C. K. (2011). On the synergy between large electric vehicle fleet and high wind penetration - an analysis of the danish case. *Renewable Energy*, **36** (2):546–553.

Energy Watch Group (EWG) (2007). Crude oil - the supply outlook. EWG-Series 3.

Fishbone, L. G. and Abilock, H. (1981). Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. *International Journal of Energy Research*, **5** (4):353–375.

Fulton, L. and Eads, G. (2004). IEA/SMP model documentation and reference case projection. Technical report, IEA. WBCSD, Sustainable Mobility Project (SMP).

Gül, T. (2008). *An energy-economic scenario analysis of alternative fuels for transport*. PhD No. **17888**, ETH Zurich, Switzerland. doi: 10.3929/ethz-a-005699807.

Gül, T., Socrates, K., Turton, H., and Barreto, L. (2009). An energy-economic scenario analysis of alternative fuels for personal transport using the global multi-regional MARKAL model (GMM). *Energy*, **34** (10):1423–1437.

Goodwin, P., Dargay, J., and Hanly, M. (2004). Elasticities of road traffic and fuel consumption with respect to price and income: A review. *Transport Reviews: A Transnational Transdisciplinary Journal*, **24** (3):275–292.

Grahn, M., Williander, M. I., Anderson, J. E., Mueller, S. A., and Wallington, T. J. (2009). Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO2 targets: connections between transportation and other energy sectors. *Environmental Science and Technology*, **43** (9):3365–3371.

Hedenus, F., Karlsson, S., Azar, C., and Sprei, F. (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):4638–4651.

Hu, P. S. and Reuscher, T. R. (2004). *Summary of Travel Trends - 2001 National Household Travel Survey*. U.S. Department of Transportation.

International Energy Agency (2002a). *Energy Balances of Non-OECD Countries 1999-2000*. OECD Publishing.

International Energy Agency (IEA) (2002b). *Energy Balances of OECD Countries 1999-2000*. OECD Publishing.

International Energy Agency (IEA) (2008a). *Energy Technology Perspective (ETP)*. IEA.

International Energy Agency (IEA) (2008b). *World Energy Outlook*. OECD Publishing.

International Energy Agency (IEA) (2009a). *Technology Roadmap – Electric and plug-in hybrid electric vehicles*. International Energy Agency.

International Energy Agency (IEA) (2009b). *Transport, Energy and CO2 – Moving Towards Sustainability*. OECD Publishing.

International Energy Agency (IEA) (2010a). *Energy Technology Perspective (ETP)*. IEA.

International Energy Agency (IEA) (2010b). World energy model – methodology and assumptions.

International Energy Agency (IEA) (2010c). *World Energy Outlook*. OECD Publishing.

IPCC (2000). *Special Report on Emissions Scenarios*. Cambridge University Press.

Kasseris, E. P. and Heywood, J. B. (2007). Comparative analysis of automotive powertrain choices for the next 25 years. *Journal of Materials and Manufacturing*, **116**:626–648.

Krzyzanowski, D., Kypreos, S., and Barreto, L. (2008). Supporting hydrogen based transportation: case studies with global MARKAL model. *Computational Management Science*, **5** (3):207–231.

Lieven, T., Mühlmeier, S., Henkel, S., and Waller, J. F. (2011). Who will buy electric cars? an empirical study in germany. *Transportation Research Part D: Transport and Environment*, In Press:–.

Loulou, R., Goldstein, G., and Noble, K. (2004). Documentation for the MARKAL family of models.

Marcinkoski, J., Kopasz, J. P., and Benjamin, T. G. (2008). Progress in the us doe fuel cell subprogram efforts in polymer electrolyte fuel cells. *International Journal of Hydrogen Energy*, **33** (14):3894–3902.

McDonald, A. and Schrattenholzer, L. (2001). Learning rates for energy technologies. *Energy Policy*, **29** (4):255–261.

Peters, A., Gutscher, H., and Scholz, R. (2011). Psychological determinants of fuel consumption of purchased new cars. *Transportation Research Part F: Traffic Psychology and Behaviour*, **14** (3):229–239.

PwC (2010). Study on urban access restrictions. Technical Report TREN/A4/103-2/2009, European Commission – Mobility and Transport. Institute of Studies for the Integration of Systems (ISIS) and PwC.

Rafaj, P., Barreto, L., and Kypreos, S. (2006). Combining policy instruments for sustainable energy systems: An assessment with the GMM model. *Environmental Modeling and Assessment*, **11** (4):277–295.

Rafaj, P. and Kypreos, S. (2007). Internalisation of external cost in the power generation sector: Analysis with global multi-regional MARKAL model. *Energy Policy*, **35** (2):828–843.

Rafaj, P., Kypreos, S., and Barreto, L. (2005). *Flexible Carbon Mitigation Policies: Analysis with a Global Multi-Regional MARKAL Model*, chapter 9, pages 237–266. Springer Netherlands.

Rempel, H., Schmidt, S., and Schwarz-Schampera, U. (2009). *Annual Report 2009: Reserves, Resources, and Availability of Energy Resources*. Federal Institute for Geosciences and Natural Resources.

Riahi, K., Grübler, A., and Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, **74** (7):887–935.

Rogner, H. H. (1997). An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment*, **22**:217–262.

Rogner, H. H. (1998). Hydrogen technologies and the technology learning curve. *International Journal of Hydrogen Energy*, **23** (9):833–840.

Santini, D. J. and Vyas, A. D. (2008). How to use life cycle analysis comparisons of PHEVs to competing powertrains. Technical report, Center for Transportation Research, Argonne National Laboratory, Washington DC, USA.

Schäfer, A., Heywood, J. B., Jacoby, H. D., and Waitz, I. A. (2009). *Transportation in a Climate-Constrained World*. The MIT Press.

Schäfer, A. and Victor, D. G. (2000). The future mobility of the world population. *Transportation Research Part A: Policy and Practice*, **34** (3):171–205.

Schoots, K., Kramer, G., and van der Zwaan, B. (2010). Technology learning for fuel cells: An assessment of past and potential cost reductions. *Energy Policy*, **38** (6):2887–2897.

Turrentine, T. and Kurani, K. (2007). Car buyers and fuel economy? *Energy Policy*, **35** (2):1213–1223.

Turton, H. (2006). Sustainable global automobile transport in the 21st century: An integrated scenario analysis. *Technological Forecasting and Social Change*, **73** (6):607–629.

Turton, H. (2008). ECLIPSE: An integrated energy-economy model for climate policy and scenario analysis. *Energy*, **33** (12):1754–1769.

Turton, H. and Baretto, L. (2007). Automobile technology, hydrogen and climate change: a long term modelling analysis. *International Journal of Alternative Propulsion*, **1** (4):397–426.

Turton, H. and Moura, F. (2008). Vehicle-to-grid systems for sustainable development: An integrated energy analysis. *Technological Forecasting and Social Change*, **75** (8):1091–1108.

United Nations (UN) (2004). *World Urbanization Prospects: The 2003 Revision*. United Nations, New York.

Wallington, T. J., Grahn, M., Anderson, J. E., Mueller, S. A., Williander, M. I., and Lindgren, K. (2010). Low-CO2 electricity and hydrogen: A help or hindrance for electric and hydrogen vehicles? *Environmental Science & Technology*, **44** (7):2702–2708.

WBCSD (2004). *Mobility 2030: meeting the challenges of sustainability*. World Business Council for Sustainable Development.

World Bank (2011). Global economic prospects – navigating strong currents. Technical Report 2, The World Bank.

Yang, H., Zhou, Y., and Liu, J. (2009). Land and water requirements of biofuel and implications for food supply and the environment in china. *Energy Policy*, **37** (5):1876–1885.

Zahavi, Y. and Talvitie, A. (1980). Regularities in travel time and money expenditures. *Transportation Research Board*, **750**:13–19. National Research Council, Washington DC.