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# Illustrating Perspectives of Energy and Mobility

Timur Gül, Hal Turton

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# Illustrating Perspectives of Energy and Mobility

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## Executive summary

This paper analyses current and future trends in energy and mobility on a global, European and regional level. In the case of the latter, we focus on the German-speaking countries Austria, Germany and Switzerland.

In the first step, the analysis shows the implications of business-as-usual developments with regard to how mobility is achieved, and of energy consumption for achieving mobility. In doing so, it discusses the impact of business-as-usual trends on global carbon dioxide ($CO_2$) emissions and future fuel consumption.

In a second step, the paper outlines potential alternative futures in terms of energy and mobility. "Alternative future" in this context refers to alternative energy system and transport sector developments, where climate policy promotes technology change in transport by creating more favourable markets for technologies and fuels with lower greenhouse gas emissions. For this purpose, technology options for achieving mobility are briefly reviewed, both in terms of drivetrain technology and fuel supply. By looking into available transport scenario literature, the paper analyses the conditions—in terms of both technological development and climate policy—under which technologies can become competitive in the marketplace, and discusses key barriers and key drivers for their implementation. Moreover, it aims at providing additional insights into the implications of the scenarios reviewed by discussing what the results mean in practical terms, and quantifying fuel and infrastructure needs for achieving an alternative mobility in the future. Thereby, the paper illustrates what it takes to achieve a shift to alternative technologies in personal transport.

Finally, the paper derives recommendations for policy-makers. In addition, it also identifies gaps in scenario literature with regard to additional scenario work, which should be conducted to gain additional insights and provide a more holistic framework for assessing technology options in energy and mobility.

The analysis presented in this paper is based on statistical and literature reviews, complemented by some own calculations, to explore the current state of and future trends in energy and mobility. The statistical review of the current state of energy and mobility shows that mobility today is mostly achieved by personal cars running on petroleum fuels, and OECD countries dominate global car usage. Recent trends in Austria, Germany and Switzerland show an increased use of diesel fuel, thus gradually replacing gasoline.

The analysis of scenario literature finds that in the absence of considerable policy efforts current trends in mobility are likely to continue, resulting in a strong increase in demand for mobility, in particular in developing countries; nevertheless, the demand for mobility in OECD countries is expected to maintain a highly important role in future overall transport.

It is expected that future mobility is likely to continue being covered by personal cars. Despite the fact that the fuel mix, for example in Europe, is tending towards an increasing use of diesel fuels, the increasing demand for mobility is likely to offset efficiency gains associated with the higher efficiency of diesel engines and lead to an increase in overall $CO_2$ emissions.

Numerous technology options exist for changing the current trends in energy use in transport, and they include alternative drivetrains and/or alternative fuel technologies. The review of scenario literature on alternative transport futures shows firstly that almost any alternative technology will alter energy provision in transport in the long-run, as the utilization of new fuels will require new production and distribution systems. Secondly, the analysis indicates that the competitiveness of alternative technologies is directly linked to the stringency of any future climate policy target, i.e. achieving a strong climate policy target will likely require different technology options than required to achieve a mild climate policy. In addition, the analysis shows that the attractiveness of particular technologies may also be determined by regional circumstances, e.g. the availability of low-cost biomass, or the availability of $CO_2$-free electricity production. Finally, the analysis supports the notion that achieving major technology change in personal transport is likely to take considerable time, given the scale of effort required to establish new fuel production, distribution and refueling infrastructure; in addition to establishing the vehicle manufacturing capacity, and finally realizing significant levels of market penetration.

This analysis is complemented by some own calculations, which seek to quantify the magnitude of the challenge for achieving an alternative future in personal transport by the year 2050. Through quantifying the requirements for achieving an illustrative share of 20% of alternative fuels in transport in Austria, Germany and Switzerland by the year 2050, the analysis finds that these countries will be limited in applying biofuels by their domestic biomass potential. Without imports of biomass or biofuels, these countries are unlikely to be able to satisfy demand for mobility by biofuels alone.

Hydrogen and electricity are other potential alternative fuels in transport. Both, however, face major obstacles to achieve significant market shares in the long-run. For hydrogen, these obstacles include among others the current costs of fuel cells, which need to be reduced to levels of around US$ 50/kW to be competitive; and the requirement to build up a hydrogen supply infrastructure for providing hydrogen to consumers.

For electricity and the use of electric cars, the main obstacles include the cost of battery storage (and related issues of size and weight), along with the need to develop a supply infrastructure. However, while the latter seems less severe due to the availability of existing electricity distribution grids, achieving competitive costs for batteries has been found to be one of the key challenges for the future application of electric cars in transport. As a matter of fact, electric cars rarely appear as a potential cost-effective solution for meeting climate policy targets in the scenario literature, despite their attractiveness as a potentially $CO_2$-free mobility option (particularly in countries such as Austria and Switzerland with low $CO_2$ emissions from power production), and recent media interest in such vehicles.

The paper concludes that realizing the benefits of alternative options for energy and mobility requires early and clear signals from policy-makers. In particular, clear signals on climate policy are necessary for promoting technology change in the personal transport market. Early signals are needed given the long timeframe and substantial investment efforts needed to deploy new fuel production and distribution systems to replace existing systems; and establish alternative vehicle manufacturing capacity.

In addition, the paper calls for additional scenario analysis accounting for more spatial detail at the level of major vehicle markets. This will provide a better understanding about the importance of regional circumstances—e.g. the availability of $CO_2$-free power production—for technology deployment, which is lacking in the literature. In addition, the disconnect between recent interest among manufacturers, consumer and the media in electric mobility options and the findings of scenario analyses warrants further technology assessment focusing on possible niche applications or new markets and better representation of hybrid vehicle variants.

# 1. Energy and mobility today

The term "mobility" has many facets. "Being mobile" can be interpreted as to have the possibility to move from one place to another. Thus, "mobility" can be achieved by any person through taking the train, a plane, a bus, a car, a bicycle or simply through walking. These different ways of achieving mobility obviously differ by the speed at which they advance an individual, and since time is an important factor in modern societies, people tend to choose the quickest modes of transportation, especially for long distances.

Mobility as such is required for various aspects of life. People commute from their homes to work, and companies operating globally expect their employees to "be mobile". Besides, mobility has also become an important aspect of private life, where mobility shapes people's activity in their leisure time and provides the possibility to vacation anywhere in the world.

Figure 1 presents a breakdown of the modes of transport people choose globally to cover their demand for mobility, excluding non-motorized transport. It shows that almost 50% of personal transport is covered by light duty vehicles (LDVs), i.e. cars and light trucks, followed by buses, minibuses, airplanes, two-&three-wheelers and trains.

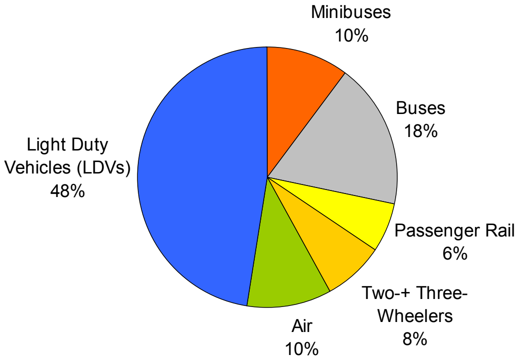

**Figure 1. Global personal transport activity by mode in the year 2000 (Source: IEA/SMP 2004)**

The widespread use of cars, but also buses, for personal mobility has a number of undesired implications, ranging from increasing congestion problems in urban areas to problems of local air pollution. This is particularly the case in industrialized countries, where cars cover a large share of personal transport activity. This is illustrated in Figure 2, which shows the modal split of personal transport activity for the case of the European Union (EU-25). As a consequence of the high utilization of cars in industrialized countries (compared to the global average), these countries account for a large majority of global car travel, e.g. 81% of all kilometers traveled by car are in OECD countries (see Figure 3).

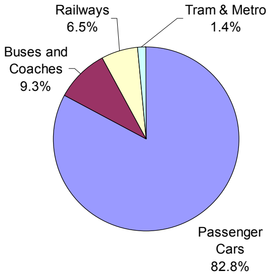

**Figure 2. Modal shares in EU-25 in 2004 (Source: EC 2006).**

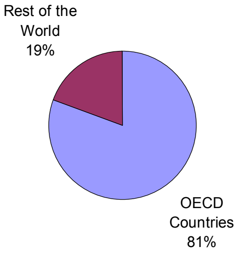

**Figure 3. Global shares of LDV utilization in the year 2000 (Source: IEA/SMP 2004).**

Increasing problems with congestion in OECD countries has led to a development where several cities have adopted measures to reduce traffic in urban areas, e.g. toll-based systems such as in Stockholm, London or Trondheim. Such measures have their merits in that they locally reduce traffic and support a change of transport modes. However, they only partly contribute to solving one fundamental problem of transportation. That is, the transport sector is one of the major global consumers of energy, accounting for 27% of all energy consumed by end-use activities (see Figure 4). Due to the composition of the transport sector, i.e. how mobility is achieved, the energy consumed consists mostly of oil and its products. According to the latest report by the Intergovernmental Panel on Climate Change, petroleum fuels today account for 95% of all energy consumed by global transport (IPCC 2007), and transport accounted for about 66% of all petroleum products consumed in the year 2005 (IEA 2008a).

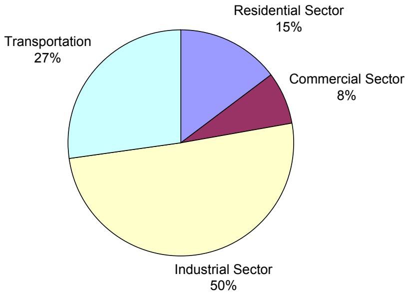

**Figure 4. Global end-use sector energy consumption (Source: EIA 2007).**

The heavy reliance of global transport on oil products brings along two important challenges. Firstly, it makes transport vulnerable to events that may affect the availability and price of oil resources; that is, the oil dependence raises challenges with regard to energy security and the affordability of individual mobility. Oil prices have experienced high volatility over the past years, and there is indication that the global economy is unlikely to see very low oil prices again. Thus, achieving mobility at affordable costs becomes an ever more important challenge. Secondly, the use of any fossil energy carriers is inevitably linked to the production of greenhouse gas (GHG) emissions at all steps of the fuel chain, i.e. from extraction of resources to conversion of primary energy carriers to the use of final energy products, and is thus an imminent threat to the global climate. Today, the global transport sector is responsible for carbon dioxide ($CO_2$) emissions equivalent to 23% of all energy-related $CO_2$ emissions (IEA 2008a).

That being said, it is worth recalling that the transport sector is essentially the only sector in which most of the energy consumption and GHG emissions occur in a mobile and dispersed fashion. This limits the possibility to capture GHG emissions from cars, unlike in the power or fuel production sectors, for example.

These challenges together impose the question: how do we maintain affordable mobility for everyone, while at the same time reducing GHG emissions from transport? This question is made even more important because there is a general expectation that demand for mobility will grow over the next years, especially in developing countries (WBCSD 2004). If developing countries—driven by economic growth—start perceiving mobility in a similar way as in industrialized countries, i.e. as an "acquired right" according to the European Commission's white paper on transport policy, then energy security and climate change mitigation are at stake. To give a simple example: if China alone had the same degree of motorization as does Switzerland today,[1] then this would result in roughly 675 million vehicles on the road in China alone, compared to the current global level of 900 million vehicles (IEA 2007).

In principle, there are several options to cope with this challenge. First and foremost, these could include behavioural changes and a switch to other transport modes, i.e. public transport by railway. This option is very appealing in that it would not only solve the oil-dependency of mobility, but it would also go some way towards solving problems of urban congestion as well as local air pollution. Nevertheless, it may entail a substantial increase in power generation capacity for the purpose of mobility alone, thus not avoiding *per se* the issue of climate change, although greatly increasing the flexibility to reduce emissions. Besides, and probably more problematic, it is highly uncertain whether the necessary behavioural changes are ever going to materialize—experiences in industrialized countries have thus far been discouraging. The main reason is probably that public transport generally lacks flexibility and convenience as compared to the private motor vehicle and is, thus, not very attractive to consumers.

The second main option is technology change in personal transport. Technology change in this context can mean simple measures such as improving vehicle efficiency, but it could also mean switching to alternative fuels (options being discussed include liquid fuels derived from coal or biomass; natural gas; hydrogen; electricity), combined with changes in drivetrain technology (hybrid vehicles, battery cars, fuel cells).

This paper intends to explore the challenge of satisfying increasing demand for mobility in a sustainable way by looking into available scenario literature on the prospects of future mobility. In doing so, it will first seek to summarize trends on a global, European and regional scale, there focusing on Austria, Germany and Switzerland (see Figure 5 for an overview on the current state of mobility in these countries), in order to understand the scale of the challenge and regional differences

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[1] Vehicles on the road per 1000 inhabitants; in the year 2007, Switzerland had 519 vehicles per 1000 inhabitants (BfS 2008).

(Section 2). Thereafter, a brief review of the current policy context will be given addressing personal transport and the challenge of making mobility convenient, affordable and clean at the same time (Section 3), again with a focus on the countries mentioned above. This is followed by a discussion of the implications of different future energy and mobility perspectives in Section 4, again drawing on available scenario literature. This literature review is accompanied by a discussion of the practical implications of scenario results, illustrating what potential changes in personal transport mean in practical terms. The paper will round up by discussing the insights gained and by looking into necessary future work in Section 5.

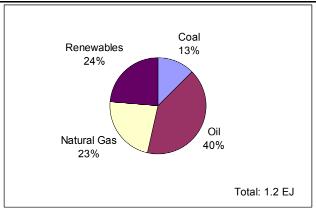
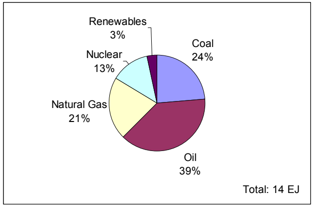
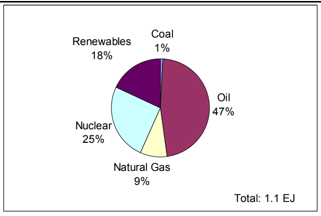
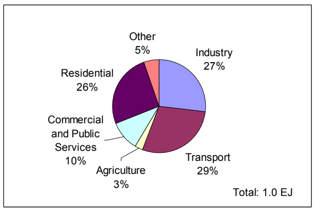
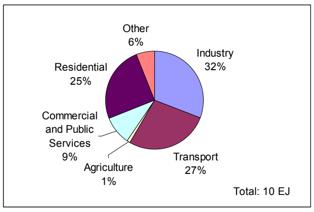
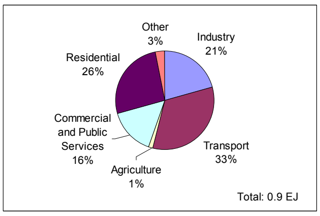
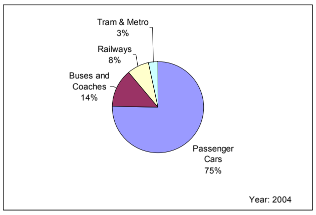
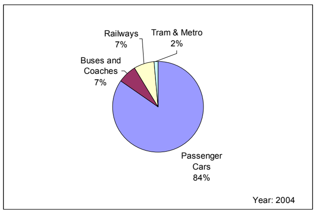
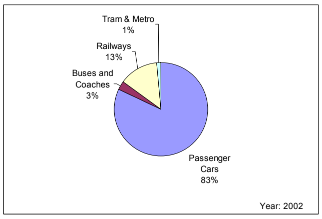
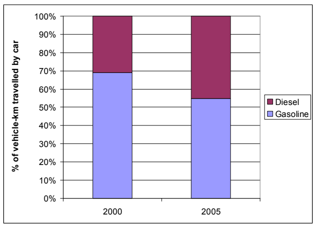
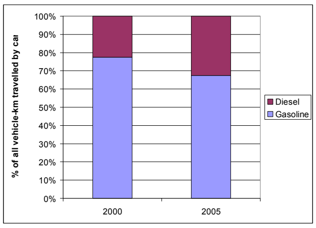
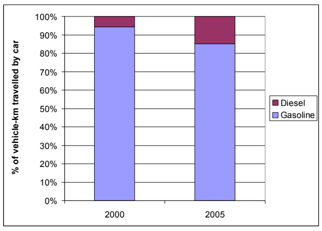
| | **Energy and Mobility today in…** | | |
|---|---|---|---|
| | **Austria** | **Germany** | **Switzerland** |
| **Total Primary Energy Supply** (IEA 2002) |  |  |  |
| **Final Energy Consumption by Sector** (IEA 2002) |  |  |  |
| **Modal Split in Transport** (EC 2006, BfE 2005) |  |  |  |
| **Vehicle Shares in Car Transport** (TREMOVE 2007) |  |  |  |
| **Motorization rate** (WKO 2008, UBA 2007, BfS 2008) | 517 vehicles / 1000 inhabitants | 550 vehicles / 1000 inhabitants | 519 vehicles / 1000 inhabitants |

**Figure 5. Current state of energy and mobility in Austria, Germany and Switzerland.**

# 2. Energy and mobility tomorrow

Numerous studies have been conducted investigating future trends of energy and mobility on various levels, reaching from global studies down to the regional or even country level. This section aims to provide an overview of some relevant studies and their insights into potential future trends in energy and mobility. In "scenario language", the studies discussed here present so-called "baseline" scenario developments assuming a continuation of existing trends, where no radical changes in technology, policy or societal behavior occur.

## 2.1 Global energy and transport trends

A widely recognized study was published by the World Business Council for Sustainable Development (WBCSD 2004). One important feature of this study is that it projects the development of demand in transport for the next decades until 2050. It provides the following key messages:

- Global demand for mobility is likely to increase over the coming decades.
- Even though air travel is likely to experience the most significant growth, automobile transport will remain the most important mode of individual transport.
- Energy use in transport is likely to follow a similar pattern as demand for mobility. If the described trends are to materialize, then total energy consumption from global transport is likely to reach about 175 EJ per year by 2050, compared to about 75 EJ in the year 2000—an increase of 133%.

Two prominent studies are released every year analysing current and future transport trends on a global level, embedded in an energy system-wide context. These studies are the World Energy Outlook, published by the International Energy Agency IEA/OECD, and the US Energy Information Administration's International Energy Outlook. Last year's publications provide important insights for the development of global energy demand in general, and transport in particular until the year 2030. Some of the key messages include the following:

- If current trends continue, then global primary energy demand is likely to increase by about 55% in the period between 2005 and 2030, driven by strong growth in China and India (IEA 2007; EIA 2007). Most of this demand is expected to be covered by fossil fuels.
- The IEA expects 2.1 billion vehicles on the world's roads by 2030 (excluding 2-wheelers), up from today's 900 million (IEA 2007). In this scenario, oil remains the most important single fuel in primary energy supply, and the transport sector is the principal driver of oil demand in most world regions.

The IEA additionally publishes the Energy Technology Perspectives report, which looks in depth into the role of different technologies in a future energy system until the year 2050 using a bottom-up energy system model. In the most recent analysis (IEA 2008b), the baseline scenario presents global energy demand in transport exceeding 197 EJ by the year 2050. This analysis builds upon the IEA's World Energy Outlook in terms of underlying assumptions (e.g. oil price projections) and shows that in absence of policy support to reduce greenhouse gas emissions or actively manage energy security, oil products will account for 75% of this demand, liquid synfuels from coal or gas for 22%, and biofuels will remain marginal, accounting for only 3%.

### 2.2 European energy and transport trends

On a European level, the above studies project that demand for personal transport is likely to increase only modestly within the coming decades, i.e. most of the above described global growth is likely to take place in developing countries, in particular in China and India (WBCSD 2004). The growth in developing countries is mostly driven by their gradual economic catch-up, facilitating increased demand for mobility (since income growth is understood to be the most important driver for personal vehicle ownership and demand for mobility). In developed regions, a certain saturation of demand is anticipated as a result of only little growth in population and incomes and because vehicle ownership is already very high. By way of an example, the WBCSD actually assumes for the European Union a slightly decreasing population (-0.1%/year).

Nevertheless, future mobility and energy provision remain important challenges, and in an effort to understand options for Europe, the European Union commissioned a study that analysed these challenges in depth for the time period until 2030 (EC 2007a). The study expects passenger transport demand in the European Union (EU-25) to increase considerably (by 1.4% per year), but also suggests that this development is accompanied by trends towards faster transport means, i.e. high-speed rail and aviation. Still, individual mobility remains dominated by cars by 2030, see Figure 6.

The study also envisages a gradual reduction of energy intensity in transport, in particular in personal road transport. Importantly, this does not include the impact of the Commissions targets on specific $CO_2$ emissions for new cars from 2008 (see Section 3). Still, the study reports a reduction in average vehicle consumption to 7.5 litres per 100 km by 2030, down from 10.3 litres in 2005. Nevertheless, the study expects transport to continue to account for around 31% of final energy consumption (EC 2007a).

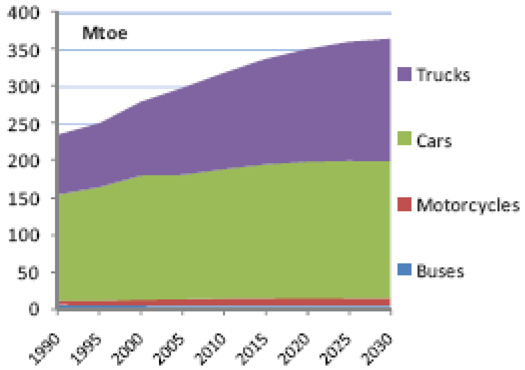


**Figure 6. Energy consumption in road transport by vehicle type (EC 2007a).**

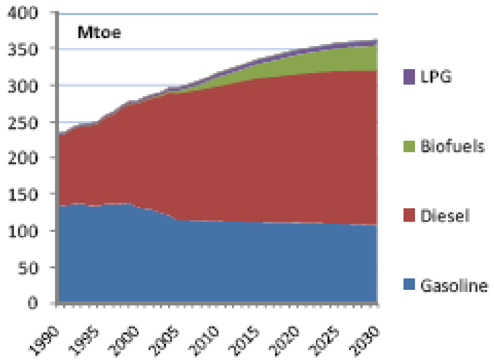


**Figure 7. Energy consumption in road transportation (EC 2007a).**

On the fuel side, the study expects the transport sector to remain the largest consumer of oil products in the EU energy system. However, current trends towards higher dieselization are expected to continue, making diesel the most important fuel in European road transport by 2030 (Figure 7). Alternative fuels are likely to play a minor role, and only biofuels (mostly biodiesel) are expected to take a more significant share by then with 9.5% of in road transport. Under baseline conditions, alternative drivetrains such as hybrid electric cars, plug-in hybrids and fuel cell vehicles are suggested to play at best a marginal role (EC 2007a).[2]

## 2.3 Current technology trends in energy and transport

The European baseline scenario in the Commission study discussed above (EC 2007a) seems "reasonable" from today's perspective. The main trend in terms of energy and mobility—the dieselization of the fleet—is already occurring in several European countries. A continuation of this trend will lead to more efficient mobility, given the higher efficiency of diesel-fuelled compression ignition engines, and hence lower $CO_2$ emissions. In terms of energy provision, this development requires at most adaptations in petroleum refinery performance, at least up to a certain point. The main factors driving this trend, however, are lower taxes on diesel fuel in many countries (e.g. Germany), and higher rates of vehicle utilization. In the case of the latter, consumers are driving more kilometers per year, and even though diesel cars are more expensive to purchase than gasoline cars, the higher efficiency and cheaper fuel make diesel cars more attractive. Such developments will offset many of the efficiency gains, and, thus, total $CO_2$ emissions from transport remain a challenge.

Moreover, energy efficiency improved only slowly between 1990 and 2000, because car sales became dominated by larger and more powerful models with more energy-consuming systems (e.g. air conditioners, power steering, etc.). This development largely offset efficiency gains from improved engine performance. It is only very recently that significant improvements in average fleet energy efficiency have occurred, with the specific consumption of cars decreasing from 11.0 litres/100 km to 10.3 litres/100 km between 2000 and 2005. This improvement results from the combined effect of efficiency gains on the one hand, and increasing fuel prices motivating fuel-saving driving behaviour, on the other hand (EC 2007a).

Despite this mixed contribution from efficiency since 1990, there remains a large potential for further improvements in vehicle efficiency in the coming years. There exists potential in terms of improving engine efficiency, employing light-weight materials, shifting to more compact vehicle designs, and improving many other vehicle characteristics. Nevertheless, many of these potential improvements are only likely to by adopted if fuel prices remain at recent high levels and thus provide an incentive for customers to buy smaller and fuel-efficient vehicles—in such a case the efficiency improvements anticipated by EC (2007a) could be achieved. Otherwise, policy incentives will be required to mandate the adoption of fuel efficient technologies and discourage the trend towards the purchase of larger vehicles.

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[2] Fuel cells are electrochemical devices that convert hydrogen and oxygen into water and produce electricity. Thereby, a fuel cell vehicles uses hydrogen as a fuel for achieving motion.

### *Energy and transport trends in Austria, Germany and Switzerland*

Focusing on the German speaking countries Austria, Germany and Switzerland, it is clear that similar energy and mobility challenges are faced as in the rest of Europe. The European study quoted above gives a detailed breakdown for anticipated future demand for mobility in Austria and Germany, showing an increase in passenger-km traveled throughout the period extending to 2030 with private cars remaining the predominant transport mode (EC 2007a). For Switzerland, a detailed analysis of future demand for mobility has been conducted by INFRAS (2005), showing similarly an increasing use of personal cars. These increases are displayed in Figure 8 showing the change relative to the year 2000 until 2030.

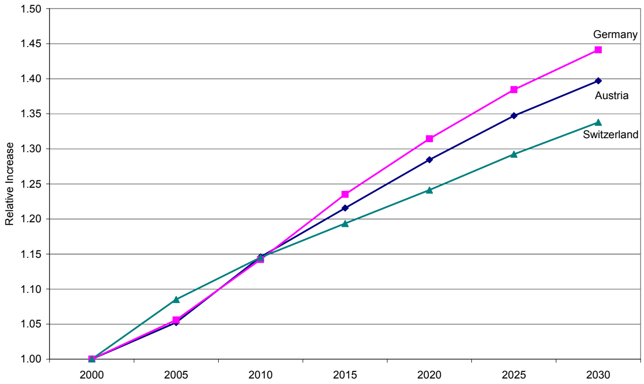

**Figure 8. Relative increase in individual mobility (EC 2007; INFRAS 2005).**[3]

It is worth noting once again in this context that the increasing utilization of personal cars is usually driven by the assumption of growing affluence. A more detailed consideration of other factors such as regional and urban form or the age structure of a population, however, may lead to different results. For instance, a study conducted for the German ministry of transport (BMVBS 2006) shows that accounting for such factors may, in some scenarios, actually lead to a slight decrease in the use of personal cars towards the year 2030. This indicates not only that there is a wide degree of uncertainty and that further analysis needed, but hints that trends in age structure and urban form may provide more flexibility in how to address challenges from transportation.

In terms of future fuel choices, most studies anticipate a trend towards increased utilization of diesel instead of gasoline, with little to no room for alternative fuels under baseline conditions. These potential future developments are in line with recent trends in personal transport. While Austria and Germany already today use significant amounts of diesel in personal transport, this is not the case in Switzerland. If present trends were to continue, however, this situation could alter in the long-run, and Schultz (2007) suggests that diesel could replace gasoline as the most important fuel in Swiss transport after 2030.

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[3] "Mobility" in this graph is understood as the use of personal cars and motorcycles.

Another important option for efficiency improvement is the gasoline-electric hybrid drivetrain, which use batteries and an electric motor as well as an internal combustion engine (ICE). This technology has gained a lot of attention in recent years, with a number of car manufacturers releasing hybrid cars. These include various hybrid vehicle types, including models able to operate using different combinations of the ICE and electric motor, depending on conditions. These vehicles achieve higher efficiencies by recapturing energy during breaking; using the electric motor to assist the ICE (allowing the latter to operate under more optimal load conditions); shutting off the ICE during idle; and operating solely on the electric motor. All hybrids commercially available today use batteries that are recharged either from ICE or through regenerative breaking. Future hybrid vehicles are expected to allow battery recharge from the electricity grid (plug-in hybrids), or even to serve as a means to release electricity to the grid if required during peak load times (vehicle to grid concept, see e.g. Turton and Moura (2008)).

Despite the attention received, hybrids have not yet achieved significant market shares in personal transport. One of the main manufacturers of hybrid vehicles, Toyota, has achieved global cumulative sales of over 1.5 million vehicles in 2008 (CBN 2008). Many scenario analyses of personal transport reveal a much more important role for hybrid vehicles, as will be discussed in Section 4, but so far, the effect on the global fleet's fuel economy is limited.

As a matter of fact, there are numerous technologies that deserve attention in future personal transport. Technology development is taking place not only in terms of improved or even new drivetrains, i.e. internal combustion engine-electric hybrids, pure battery cars and fuel cell vehicles. Technology development also targets alternative fuels for transport, in particular coal-to-liquids, natural gas, biofuels, hydrogen and electricity. While a detailed discussion of alternative fuels and drivetrains is beyond the scope of this paper—the interested reader is referred to e.g. Bardt (forthcoming), WEC (2007), IEA (2008b), Gül (2008)—it is essential to know which fuels can be used by which drivetrain technology for understanding future perspectives of mobility. Potential drivetrain/fuel combinations are, thus, illustrated in Table 1.

As Table 1 shows, there are numerous drivetrain and fuel technology combinations that are potentially feasible. Their competitiveness and their suitability for meeting policy objectives is the subject of Section 4 of this paper. For setting the framework, Section 3 will first outline some of the major policy initiatives that target energy and mobility.

**Table 1. Potential drivetrain/fuel combinations.**

| Fuel | Drivetrain technology | | | | |
|---|---|---|---|---|---|
| | internal combustion engine ICE | ICE electric-hybrid vehicle | electric vehicle | fuel cell-electric hybrid vehicle | fuel cell vehicle |
| gasoline/diesel | X | X | | X | X |
| coal-to-liquids | X | X | | X | X |
| natural gas | X | X | | X | X |
| Biofuels | X | X | | X | X |
| Hydrogen | X | X | | X | X |
| Electricity | | X | X | X | |

# 3. Policy context

It is apparent that the developments described in the various baseline scenarios presented in Section 2 are likely to have severe impacts on global climate. For illustration, the WBCSD study concludes that global baseline scenario developments are likely to more than double greenhouse gas (GHG) emissions from transport to about 14 Gt of $CO_2$-equivalents per year by 2050, up from about 6 Gt in the year 2000. In addition, energy security may become an even more important issue than it is today, as increasing demand for mobility in countries with emerging economies places further pressure on oil supplies.

As mentioned before, policy-makers are confronted with the challenge to maintain and improve current levels of mobility, while at the same time ensuring affordability and environmental sustainability. On a European level, this challenging task has been translated into policy action. That is, the European Commission has released its “20 20 in 2020” strategy, which calls for a reduction in $CO_2$ emissions from the European energy systems of 20% by the year 2020. The most important measures for achieving this target are include achieving a share of 20% of renewable energies in European energy consumption and a share of 10% biofuels in transport fuels (EC 2008).

Another policy initiative is the European Emissions Trading Scheme (ETS), aimed at reducing European GHG emissions. Any company that falls under the ETS has the possibility to either reduce GHG emissions, or to purchase tradable certificates from other industrial players. Since the total amount of tradable certificates is capped and reduced over time, the ETS provides a policy framework to reduce total European GHG emissions. The transport sector, however, is not yet part of the ETS, and only air transport will be included as of 2012.

To address emissions from transport, the European Commission has proposed targets to reduce average $CO_2$ emissions from new passenger cars to 120 g $CO_2$ per km by 2012 (EC 2007b). This objective would limit petroleum fuel consumption to about 4.5-5 litres per 100 km. The initiative requires manufacturers to limit the average $CO_2$ emissions of the cars they sell to 130 g per 100 km, and allows for complementary measures to achieve the anticipated 120 g objective.

Further policy efforts within Europe are pursued on a country level, including measures targeting improvements in energy efficiency or encouraging the use of renewable energy, for example. They will not be further discussed in the context of this paper, but they are obviously highly important for reducing GHG emissions from the various sectors of the energy system. Instead, in the following paragraphs we focus on the main energy and mobility policies in Austria, Germany and Switzerland.

In Austria, the most important national policy to curb emissions is the “Klimastrategie 2000-2008/2012” instituted by the Austrian government in 2002 and implemented by the Federal Ministry for Agriculture and Forestry, Environment and Water Management. The plan was updated in 2007, and includes a variety of measures across sectors and industries, targeting supply as well as demand side (Klima 2007). In transport, the strategy seeks to reduce emissions by increasing the share of alternative fuels in transport to 10% by 2010, and 20% by 2020 focusing mostly on biodiesel, bioethanol, E85 and methane.

In Germany, an eco-tax reform introduced environmental taxes on petroleum fuels, the commuter tax allowance was eliminated and a road charge was introduced for freight traffic. An additional recent initiative of the German government seeks to increase the number of hybrid-electric buses for public transport (BMU 2008a). However, no further efforts have been undertaken targeting explicitly the reduction of GHG emissions from the German transport sector and, in particular, from individual mobility. The biofuels decree that aimed at increasing the maximum blend of ethanol into conventional fuels to 10% was modified since this fuel was incompatible with a range of cars available to the German market. The new decree allows for longer transition times towards such blends (BMU 2008b).

In Switzerland, one key policy initiative introduced an "energy vignette" for personal cars. That is, efficiency categories ranging from label "A" (high efficiency) to "G" (low efficiency) are assigned to each car, thus allowing new car buyers to easily determine environmental performance (see e.g. BfE 2008). While this efficiency label is so far only meant to stimulate the purchase of energy efficient cars, there is an ongoing discussion on whether to additionally connect the "energy vignette" to a fee/rebate system, thus further encouraging the purchase of efficient cars. Such a system is used in other countries; for example, in France since January 2008.

Numerous other measures are being pursued in the context of initiative "EnergieSchweiz" launched in January 2001. One main objective of this initiative includes a 10% reduction of $CO_2$ emissions by 2010 compared to 1990 levels. The initiative seeks to reach this goal with a number of different measures, one of these being "energy efficient mobility with low emissions". In this context, three main objectives are pursued:

1. reduction of the $CO_2$ emissions to an average of 140 g $CO_2$ per km until 2010
2. increase the number of natural gas-fuelled vehicles to 30'000, hybrid- and electric vehicles to 20'000 and electric two-wheelers to 30'000 by 2010.
3. increase awareness for energy efficient driving style

Note, however, that the initiative "EnergieSchweiz" is voluntary and, thus, non-binding. The initiative was introduced in 2001 by the Bundesamt für Energie as a result of the $CO_2$ law enacted in the year 2000, which seeks to fulfill Switzerland's commitment under the Kyoto Protocol. Within the $CO_2$ law, the so-called "Klimarappen" was introduced, which taxes fossil fuels. The transport sector, however, is so far excluded from environmental tax.

Considering the range of policies described above, and their limitations and lack of coherence, it must be observed that policy-making rarely appears to take a holistic view of the energy system in the process of policy design.[4] To support a more holistic and effective approach in decision-making, tools such as scenario analysis using system-modeling approaches have been adopted. Such approaches can analyse the impacts of different policies on the energy system as a whole, and on specific sectors of the energy system such as transport in particular. Scenario analyses of energy and

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[4] This is because of a variety of reasons related to the separation of responsibilities across different government departments, a short time horizon for policy-makers, the influence of interest groups and a lack of information. Without a holistic approach, however, sub-optimal outcomes and policy conflicts may occur.

mobility commonly integrate two steps: that is firstly a technology assessment, which is helpful in identifying promising technologies for coping with energy system challenges, and optimal paths for their implementation. Secondly, the scenario analysis is helpful to explore alternative futures and deal with uncertainty. It allows the integration of different key driving forces in a consistent and disciplined way and provides an understanding of how different technological options can be applied to address multiple objectives.

The next section, therefore, looks into the results of some major scenario analyses concerned with the future of energy and mobility in meeting particularly the challenge of climate change mitigation. The section seeks to identify key drivers that shape the results of the various analyses and aims at illustrating the scale of the challenge in creating an alternative tomorrow—i.e. a tomorrow that differs from baseline developments outlined in Section 2.

## 4. Perspectives illustrated—creating an alternative tomorrow

Before looking at the range of perspectives in the scenario literature, let us return to the discussion on current technology trends in energy and mobility in Section 2. There, we introduced the various technologies that have been proposed as a means to cope with the challenges of energy security and climate change. When considering the technology and fuel options outlined in Table 1 in Section 2, two main questions emerge:

1. how could alternative technologies contribute to meeting the challenges of energy security and climate change? Which technology options are best suited for these challenges?
2. when could alternative technologies be deployed and at which pace?

Looking first at question 2, i.e. the timing of alternative technologies in transport, there is an immediate intuitive logic to the possible sequence of future technology transitions, which is presented in Figure 9.

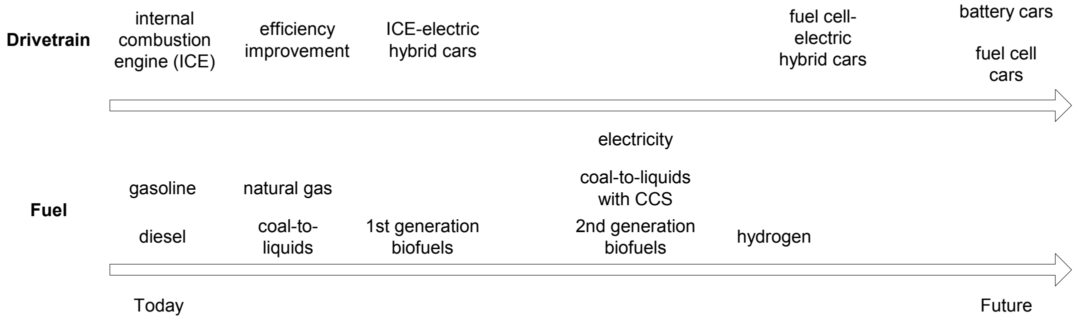

**Figure 9. Illustrative timeline for the introduction of alternative technologies in transport.**[5]

This timeline does not intend to give any prediction of the chronology of market introduction. It is rather thought of as being an illustration of what one may perceive as a logical sequence to the development of alternative technologies in transport. That means for example that hydrogen fuel cell cars are generally thought of as being "future" due to the need for significant technology improvements, while efficiency improvements are seen as measures that could be implemented in the short-term.

The above timeline additionally gives an idea of the complexity of alternative futures in transport. Consistent with the two streams in the timeline, the term "alternative future" in transport encompasses alternative drivetrain technology as well as alternative fuel provision. This means that achieving an "alternative future" in transport requires a holistic approach combining technology development on the demand side (cars) as well as supply side (fuels), accounting also for developments throughout the energy system.

Scenario analysis can help us to understand the scale of efforts to achieve alternative futures and provide answers to the two questions above by quantifying the technology timeline and accounting for interactions between mobility and energy supplies. It can provide insights into the competitiveness of different technology options in response

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[5] CCS = carbon capture and sequestration.

to different policy objectives, targeting for instance climate change or energy security. Further; scenario analysis can facilitate a better understanding of key obstacles for the implementation of different technology options, thus providing a richer answer to our second question about the pace at which these options can enter the market and ultimately achieve a significant market share.

The following subsections seek to draw on available scenario literature that considers transport in the context of the challenges of climate change and energy security. In doing so, it aims at critically discussing the insights gained with regard to the above questions—i.e. “which technologies” and “when”—while at the same time looking behind the analysis and finding an indication as to which assumptions are critical for producing the outcomes presented in the various studies.

The analysis of scenario literature will—as in the above sections—start by looking at analyses pursued on a global level, and will then “zoom in” to Europe and later Austria, Germany and Switzerland as the key countries of the present study.

## 4.1 An alternative global tomorrow

Various studies have looked into an alternative future for global transport. We turn first to those studies that have been presented in earlier sections, beginning with the World Business Council for Sustainable Development (WBCSD 2004) study into alternative futures for transport. One interesting case the WBCSD analysed was called “combined technologies”, which investigates the potential contribution of different technology options to reach an illustrative 50% $CO_2$ emission reduction compared to anticipated baseline trends by 2050—importantly, this analysis does not consider the costs or the probability that a particular option will emerge. The results are depicted in Figure 10, which shows an important role for biofuels in reducing GHG emissions from transport. The second most important technology option is the hydrogen fuel cell, contributing to the reduction of GHG as of 2040 and mostly fuelled with hydrogen from carbon neutral sources. All other options, including dieselization, hybridization of vehicles, efficiency improvements of the existing fleet and GHG reduction due to improved road traffic flow, remain marginal in this analysis.

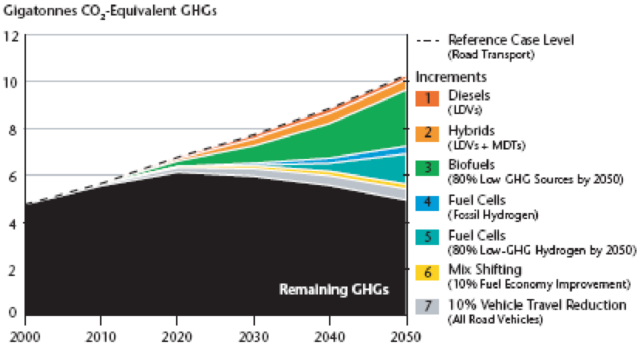

**Figure 10. Combined technology case in WBCSD (2004).**

***What drives the results of this analysis?***

The WBCSD study uses an indicator approach to assess the future of personal transport. Therein, a potential for reducing GHG emissions from personal transport is attributed to each technology in the analysis; and technologies are selected to reach the given emissions target. The results, therefore, reflect the pace at which the technical potential of each option could be exploited under the specific assumptions taken. However, it does not necessarily represent the most economic way to achieving this target.

What this analysis also indicates, however, is that policies targeting the reduction of $CO_2$ emissions in transport are likely to alter substantially energy use in transport. The analysis reveals that both hydrogen and biofuels could contribute substantially in the long run to the decarbonization of personal transport, and the future fuel mix could—even though still dominated by oil products—see substantially different fuel shares than today.

This result is supported by a number of studies conducted by various researchers. Within the present study, we will look into three of them more closely, aiming to specify what drives the results of their analyses: Azar (2003), Turton (2006) and Gül (2008). All three studies use models representing the global energy and transport sector for assessing, among other influences, the impact of climate policy on the penetration of alternative fuels in transport over the course of the 21st century. The studies naturally differ in terms of geographic resolution, i.e. on how many world regions are distinguished, and in terms of the technological detail applied. In addition, although all analyses use optimization modeling approaches, the modeling procedure differs across the analyses.

The results of all three analyses can be summarized as follows: oil is going to remain an important fuel in personal transport during the next decades, but climate policy is likely to induce a shift towards the use of hybrid drivetrains. The analyses differ, however, in terms of the role of different fuels, for instance biofuels: Turton (2006) suggest an important role for biofuels in the decarbonization of personal transport, while in the other studies biofuels are only used in the transition towards the utilization of hydrogen in the second half of the century. The key reason for the observed difference is the stringency of applied climate policy target. For instance, an atmospheric $CO_2$ concentration target of 550 ppmv is used in Turton (2006) while Azar (2003) uses 400 ppmv. Gül (2008) looks into climate policy targets ranging from 650 ppmv to 450 ppmv and finds biofuels to be an attractive option under mild climate policy targets, and hydrogen for more stringent policy.

Accordingly, long term perspectives on energy and mobility identify climate policy to be a key influence on technology choices in personal transport. This is illustrated in Figure 11, which shows the results of the analysis of Gül (2008) for the 650 and 450 ppmv targets. Figure 11 additionally suggest that other important technologies are hybrid drivetrains. The analysis of Turton (2006) as well as Gül (2008) shows that efficient hybrid-electric cars are a highly important technology option during the next decades; with increasing fuel prices and resource scarcity, most global modeling analyses find hybrid-electric cars to be a competitive solution for the decarbonization of personal transport. The higher efficiency of hybrid-electric drivetrains makes this technology competitive at higher fuel prices, irrespective of whether the fuel is petroleum-based or from an alternative source. In addition, hybrid vehicles are expected to undergo significant cost reductions with increasing experience in manufacturing, with the biggest reductions expected in battery costs. This makes their application attractive in the medium to long term.

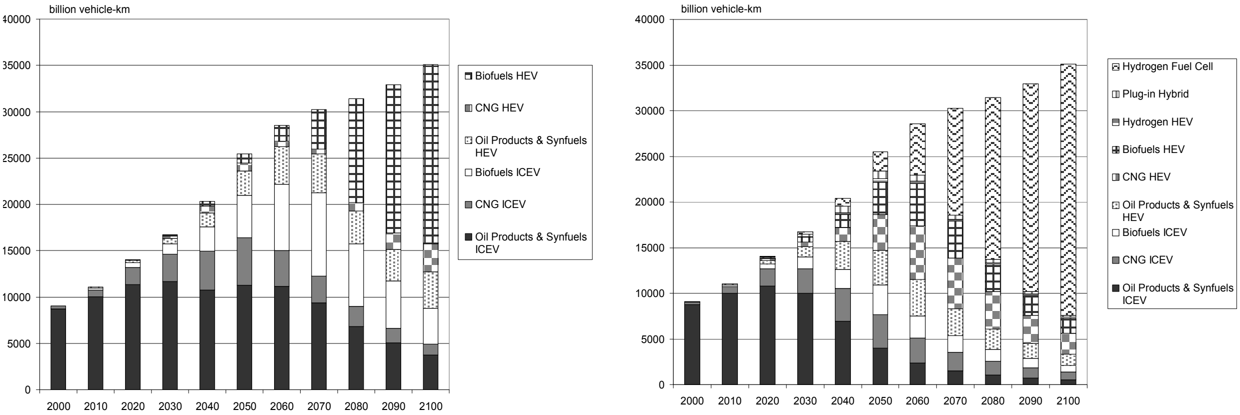

**Figure 11. Personal transport under a climate policy target of 650 ppmv $CO_2$ (left) and 450 ppmv (right) (Gül 2008).**

Other drivetrain options using batteries, i.e. electric cars, plug-in hybrids or vehicle-to-grid technologies, are rarely found to be a competitive solution in the context of global scenario analysis. We return to this observation later in this section.

***What drives the results of these analyses?***

To start with, it is important to note that the discussed analyses are results of an optimization procedure. That means the analysis seeks to identify the "optimal" result—in the case of Azar (2003) and Gül (2008), "optimal" means "cost-optimal", i.e. the model looks for the cheapest societal costs for achieving the climate policy targets, while at the same time meeting fixed energy and transport demands. In the case of Turton (2006), "optimal" refers to "cost optimal" as well, but also accounts for changes in energy and transport demands as a result of variations in fuel prices.

To understand the results of these studies, it is important to recognize that the findings for technology and fuel changes are not meant to represent a forecast or prediction of future developments. Rather, the results show the cost-optimal solutions in order to deal with the challenge of climate change under the assumptions taken for the different analyses, on the supply as well as on the demand side. These assumptions reflect one possible "what if" scenario of the future, which is helpful for understanding possible interactions and trade-offs associated with different options in a consistent framework.

***What factors could change the outcome of these analyses?***

As in all assumption-based analyses, the results are dependent on the input parameters. In a cost-optimization framework, results are, thus, sensitive to assumptions about current and future costs of individual technologies. For this reason, results are commonly supported by sensitivity analyses on the most critical input parameters, and all authors discussed above have conducted such analyses.

The most comprehensive sensitivity analyses have been conducted by Azar (2003). He concludes that the choice of hydrogen as a long-term fuel is not sensitive to general energy parameters, such as cost and availability of biomass, oil and gas resources. That means that the stringency of the applied climate policy target is the main driving force for the choice of hydrogen as a fuel in transport. In some additional analyses, Azar (2003) finds that all variations of supply technology parameters conducted result in a phase-out of 50% of gasoline fuel from the transport sector around 2050-2070. An earlier phase-out of gasoline as a transportation fuel could be facilitated either by more stringent climate policy, or through an earlier depletion of recoverable oil reserves. Azar (2003) suggests that in these cases, transition fuels such as methanol and/or natural gas could then replace gasoline as of 2020, being themselves replaced by hydrogen later in the century.

None of the investigated scenario analyses found significant shares for battery cars. This observation may have many reasons, e.g. Turton (2006) does not consider battery cars in his analysis. Nevertheless, one key reason for this observation is that the expected future costs of batteries are generally too high to make battery cars competitive in cost-optimization modeling frameworks. Given the potential importance of this technology, further work is needed to consider in more detail the uncertainty of future battery costs. We will return to this aspect in the discussion in Section 5 of this paper.

***What do the results mean in practical terms?***

In practical terms, the results of the above analyses mean in the first place that the applied climate policy plays a large role in determining the competitiveness of individual technology options. This calls for decision-makers to set a clear and long-term framework early on, in order to send appropriate signals to industry and the research community. In other words: if global policy seeks to achieve moderate climate targets only, then there may be little point to do further research on hydrogen, as hydrogen is likely to require strong climate policy to become cost-effective. On the other hand, if stringent climate policy is to be pursued, or if societies want to keep open the option for future generations to achieve stringent climate policy targets, then hydrogen represents a prospective technology option in transport. Corresponding climate policy targets, thus, should motivate further research and development on hydrogen as a fuel, and the fuel cell for its application in the transport sector, in addition to other possible applications.

The analyses also suggest that climate policy is likely to induce technology change in terms of alternative fuels as well as alternative drivetrains. However, achieving significant use of alternative fuels is likely to take considerable time for various reasons: firstly, technology development needs to take place. Scenario analyses like the ones presented here are commonly built on assessments of technologies that still require considerable efforts with regard to R&D. Thus, these technologies will take some time until they are sufficiently mature for large-scale commercialization.

Thereafter, the widespread use of these technologies is likely to take time. This can be illustrated by looking at analogies from other sectors, such as the development of wind power in the electricity sector. According to the International Energy Agency IEA, Germany produced roughly 28 TWh of wind power in 2005 (IEA 2008a), up from 0.1 TWh in the year 1990 (IEA 2004), due to considerable policy efforts, thereby facilitating technology development. These figures correspond to a stunning annual growth rate of about 46%. However, and despite these impressive figures, wind power made up for only little more than 4% of total electricity production in Germany by the year 2005 (IEA 2008a).

This analogy is not meant to discourage the application of alternative fuels or alternative drivetrains (neither wind power, of course). Rather, it is meant to emphasize the extent of the challenge of realizing major technology change in transport. Starting almost from scratch and from a lock-in situation with existing systems built on the refining, distribution and use of oil and oil products, alternative transport technologies will require substantial development, facilitated by significant policy support, and time before they can make a significant contribution.

## 4.2 An alternative European tomorrow

A number of studies have been conducted looking at the impact of different policies on the European transport sector in general, and on individual mobility in particular. The study by the European Commission quoted in Section 2 (EC 2007a) investigated the prospects of transport only under baseline conditions, i.e. in absence of any further policy support other than those measures already in place.

The Energy Centre of the Netherlands (ECN), however, created a vision about a future sustainable energy system in Europe (ECN 2007). Therein, they develop a scenario of future European transport, which allows for similar levels of mobility as today, but by sustainable means. The study envisions a European campaign for "100'000 fuel cell cars" in 2020, encouraging manufacturers to produce large quantities of these vehicles, leading to sharply decreasing costs for hydrogen fuel cells. As a result and driven by climate policy that limits $CO_2$ emissions in 2050 to 60% of 1990 levels, hydrogen fuel cells become the dominant drivetrain technology, making up for roughly 50% of the market by 2050.

Biofuels, in this analysis, serve as a transition fuel, phased out in favor of hydrogen in the long run. The results are depicted in Figure 12.

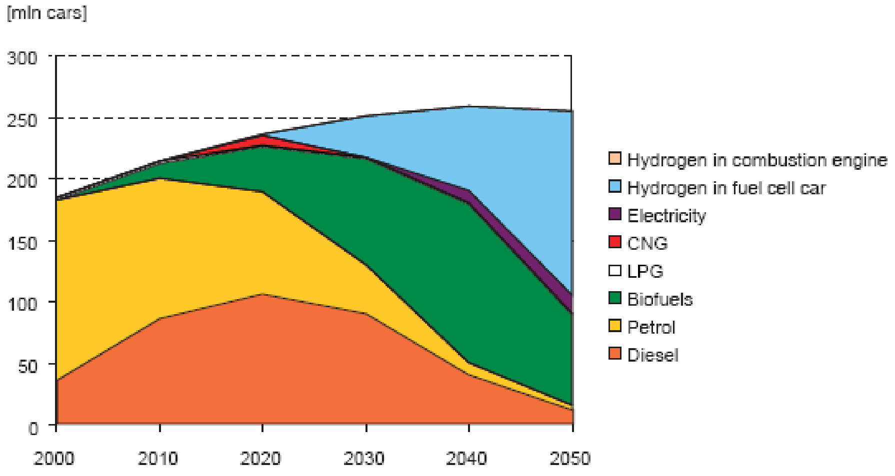

Figure 12. A vision of the European transport system according to ECN (2007).

Another study that looked into the prospects of European transport under climate policy was conducted in Gül (2008). Similar to the above-mentioned study by the ECN, hydrogen fuel cells become the dominant technology in European transport in the long run under a climate policy that limits $CO_2$ emissions to 50% below 1990 levels. However, the study concludes that a transition towards hydrogen in European transport is likely to require longer timeframes than those in ECN (2007), and will need a substantial reduction in fuel cell costs from currently very high levels. The most important means for achieving such cost reductions towards levels of around US$ 50/kW are mass production of fuel cells and learning-by-doing mechanisms, i.e. cost reductions achieved from learning through practical application of fuel cells in the marketplace.

As opposed to ECN (2007), however, Gül (2008) does not envision significant market shares for biofuels as a result of very limited biomass potential in Europe. The results obtained are based on the assumption that only domestic biomass potential can be applied, thus not allowing for imports from other regions of the world. The study finds that limited biomass potential should rather be exploited for the decarbonization of other sectors such as the heat and power sector, if hydrogen can be utilized as a fuel in personal transport. Instead of biofuels, the analysis of Gül (2008) finds hybrid-electric vehicles using petroleum fuels and eventually natural gas to be more competitive solutions for decarbonizing personal transport until 2050.

Other battery-based drivetrain technologies (battery cars, plug-in hybrid, vehicle-to-grid) do not achieve significant market shares in European scenario studies, just as is observed on the global level.

### ***What drives the results of these analyses?***

As in the case of the global studies discussed above, the results are generated with optimization-models, i.e. models that look for the cheapest options under given assumptions and constraints (e.g. climate policy, limited biomass potential, etc.).

Gül (2008) justifies his less optimistic results on the basis of the time needed to achieve the cost reductions required for hydrogen fuel cells to become cost-competitive. In sensitivity analysis, however, he also finds that shares of 20% of hydrogen fuel cells are feasible by 2050 under aggressive cost reduction scenarios for hydrogen fuel cells.

For biofuels, the observed differences in the results of the studies discussed above are directly linked to whether the analysis allows for the importation of biomass and biofuels. This implies that the potential role of biofuels in European transport is ultimately linked to the availability of low-cost biomass for energy and transport purposes.

### ***What factors could change the outcome of these analyses?***

It is implicit that changing the above described assumptions is likely to alter the results. Nevertheless, the analyses have their merits by showing firstly that biofuels can only obtain significant shares in individual mobility if Europe allows for the import of biomass and/or biofuels. Besides, the analyses show that biofuels will likely only be transition fuels, if other options such as hydrogen fuel cells can be developed in the long-run. Such observations are consistent with those observed in the sensitivity analyses conducted by Azar (2003) on a global level, and with discussions that can be found e.g. in Grahn et al. (2007).

***What do the results mean in practical terms?***

The authors of ECN (2007) present their study as a "vision", and propose policy measures that could lead to a sustainable energy system. To understand the practical considerations of achieving their vision: to achieve the anticipated high shares of hydrogen fuel cells by 2050, and starting with the study's suggested program to have 100'000 hydrogen vehicles on the road by 2020, very rapid growth rates are required. For example, if 100'000 vehicles are on the road by 2020, and the target is about 150 million by 2050, i.e. after 30 years, this corresponds to an annual growth rate of more than 27%. Achieving such high growth rates is generally possible during the early phases of technology deployment: by way of example, the global annual sales of Toyota's hybrid vehicles have increased by about 40% on average from 1998 to 2006 (calculated from GCC 2007). Whether such high growth rates can be maintained for a long period is an issue we return to after briefly considering the implications for Germany.

For illustration of this growth rate, consider Germany's car fleet consists of roughly 40 million cars today (SBD 2008), and the average new cars sales between 2003 and 2007 were 3.1 million (KFZ 2008), with the German car fleet growing by around 1% per year (SBD 2008). If car manufacturers were able to realize sales of 20'000 hybrid cars in the German market by 2010, and sales were to grow at the above annual rate of 40% per year, then hybrid cars would eventually reach a share of 19% of all sales by the year 2020 assuming annual car sales remain constant (for comparison, in the United States, hybrid car sales amount to only about 1.5% of total sales 10 years after hybrid vehicle market introduction according to LAT (2007)). Cumulative sales over the 10 years would then amount to almost 2 million cars. Assuming all hybrid cars sold were still on the road by 2020, even after such a rapid period of growth, such vehicles would make up 4.5% of the entire German car fleet.

However, as briefly alluded to, maintaining such high growth rates over the course of 3 decades is likely to be difficult, thus requiring (again) significant policy efforts and a steep learning curve in terms of technology development. While achieving high growth rates over longer time horizons is challenging for any new technology, the challenge is even greater for hydrogen fuel cell vehicles than e.g. for petroleum hybrid-electric cars. The reason for this is that hydrogen will need not only vehicle technology to achieve high growth rates, but also an entire supply infrastructure, while petroleum-based cars can make use of existing infrastructure.

In addition, realizing the results presented in these studies implies significant fleet technology turnover in the decades to come, and requires societies to move away from the use of petroleum in personal transport and adopt transition fuels (biofuels in the case of ECN (2007), and natural gas in the case of Gül (2008)) until more cost-effective technologies are developed and ready for mass utilization. In the past 100 years, such large-scale transitions have taken place, in the case of the replacement of horses by cars and petroleum fuels in the early 20th century (for example, see Grübler et al. 1999). However, ever since, the transport sector has been dominated by petroleum fuels, creating a lock-in situation with regard to fuel supply and corresponding vehicle technology choices, making technology change in transport complicated. Moreover, achieving two distinct transitions into alternative fuels in the course of next 50 years would be especially challenging (and perhaps unlikely)—requiring building up a distribution network for the respective transition fuel first (biofuels or natural gas), before then moving towards hydrogen, which requires a distribution network of its own.

Clearly, synergies can be found. That is, liquid biofuels could be distributed by similar means as petroleum fuels despite differences in energy density, making the distribution of biofuels more costly. Natural gas is already in use in some countries like Germany today, but would require an elaborated pipeline distribution network for achieving significant market shares. The pipeline network could also be used to facilitate the initial distribution of hydrogen in blends with natural gas. For a widespread use of hydrogen in transport, however, further adaptations and parallel infrastructure will be required.

However, such significant technology changes would be taking place without any relevant respective historical experience, and would require very long-term planning. It is important to note in this context that the models applied for such analysis as presented here are perfect-foresight models, i.e. they know what to expect in the end of the time horizon. Such models "know" that by a certain year the hydrogen fuel cell will be the most cost-effective means to reduce $CO_2$ emissions from transport, because they "know" the future cost of this technology. This puts the model in the position to build up the required hydrogen distribution network until when it is required, if it deems this to be the least-cost solution for the energy system.

In reality, we do not possess this detailed information. In fact, there are numerous "targets" for the future costs of the hydrogen fuel cell available (e.g. the target of the US Department of Energy, which is US$ 30/kW by the year 2015),[6] but large uncertainties regarding what will ultimately be achieved and by when. Thus, modeling analyses such as those discussed here should again not be understood as predictions of the future, but rather illustrations of what is potentially feasible. Nonetheless, they help identify technologies that may potentially be promising for addressing challenges associated with energy and mobility; thereby identifying targets for decision-makers and areas for further technology development. Many of these analyses call for further research on advanced drivetrain and fuel technologies, and potential limitations to their application, to overcome uncertainties and bring technologies towards commercialization. Not doing so could result in significant delays in the market introduction of the most appropriate technologies, potentially resulting in double investments in infrastructure because of a requirement to exploit transition fuels and, thus, in a very high cost for society. Or, it could lead to a situation were much hope is placed on one particular technology, but the technology cannot live up to expectations because the required cost reduction cannot be achieved, e.g. because of technical limits that cannot be overcome.

### 4.3 An alternative tomorrow in Austria, Germany and Switzerland

The perspectives on energy and mobility options at the global and European levels illustrate a number of insights that are highly relevant to Austria, Germany and Switzerland. We now turn to related studies focused directly on these countries.

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[6] Compare the FreedomCAR initiative's technology goals of the US Department of Energy on its website: http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/fc_goals.html

## Austria

A recent study conducted by Steininger et al. (2007) looked into the impacts of different policy measures potentially feasible for addressing climate change. The analysis aims at analysing the effectiveness of each policy in reducing $CO_2$ emissions from road transport by means of a global emission model. Some of the policy measures investigated include e.g. road-pricing, increasing the attractiveness of public transport or lower speed limits for road traffic. The study finds among others that road-pricing has the highest potential for reducing $CO_2$ emissions from road transport by 2010, see Figure 13.

**Abbildung 1-1: Übersicht über die berechneten $CO_2$-Reduktionspotenziale der untersuchten Maßnahmen**

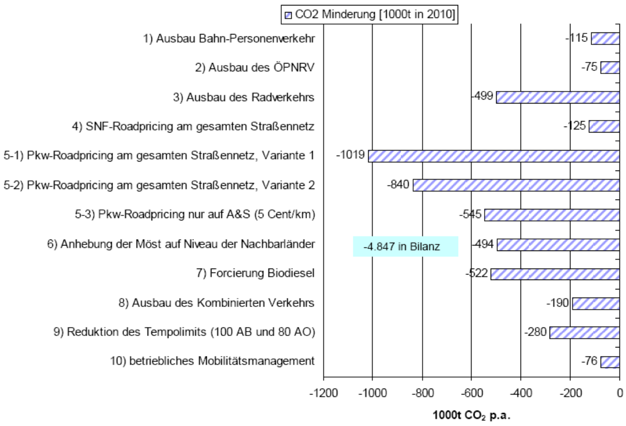

**Figure 13. Overview of $CO_2$ reduction potential of policies in Austria (Steininger et al. 2007).**

Recent studies in Austria have looked at the potential of electric cars as a means of achieving mobility in particular in urban areas (see e.g. Brauner (2008) and Leitinger and Brauner (2008)). A country like Austria, where hydropower accounts to 66% of electricity generation, leading to low $CO_2$ emissions, is almost inevitably likely to consider this option.

Battery cars stand to benefit from existing electricity distribution networks, despite some necessary adaptations. However, the main problems with battery cars are: their driving range, which is significantly lower than for most other transport technology options; the durability of the battery; the long recharging times; and their cost. Nevertheless, if applied in urban areas where the driving range of battery cars is sufficient to cover urban mobility demand, battery cars could be an attractive mobility option, if consumers are willing to accept vehicles with a limited operating area.

Some interesting calculations in Brauner (2008) illustrate some further challenges associated with battery vehicles. He investigates the number of recharging systems required at each fueling station for different market shares of electric cars and a recharge time of 60 minutes (see Figure 14 below). The figure shows that establishing a refueling infrastructure is challenging for electric cars, requiring significant numbers of reloading systems per fueling station. The author, however, also shows that the number of facilities required is directly proportional to the loading time of the battery and, thus, could by reduced roughly by a factor of 6 for batteries with only 10 minutes loading time. Naturally, these numbers could potentially be reduced even further if recharging could be made available at home or in office parking areas.

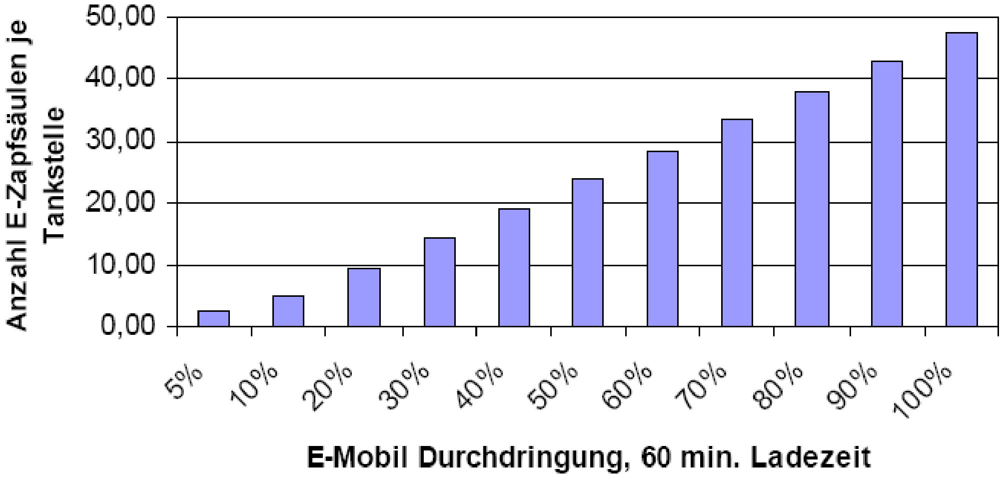

**Figure 14. Number of recharging facilities per fueling station in Austria (Brauner 2008).**

## Germany

A number of studies have been conducted in Germany looking into the future of personal transport and the impacts of climate policy. Among those are studies discussing the effects of very specific policy measures (e.g. speed limits, see Schallaböck et al. (2007), Schallaböck et al. (2006)) that are beyond the scope of the present study. More relevant is a modeling-based analysis of the introduction of hydrogen in Germany conducted by Ramesohl and Merten (2006). The analysis suggests that a forced introduction of hydrogen in German transport before the year 2050 is a less effective way to achieve benefits in mitigating GHG emissions than implementing efficiency measures in other sectors of the energy system and introducing renewable energy.

The option of electric mobility has recently received significant attention in the media due to various electric mobility fleet projects initiated by the German power and automobile industry as well as the German government (see e.g. BMU 2008c). However, the German power sector is heavily reliant on fossil fuels. Thus, a positive impact on German $CO_2$ emissions from transport is not guaranteed. The strong focus on electric cars is, thus, rather motivated by concerns about energy security on the one hand, and the need to integrate increasing shares of fluctuating renewable energies, especially from wind power, on the other. Much hope has been placed on electric cars to buffer peaks in electricity supply by storing surplus production; or even feeding back electricity into the grid if intelligent vehicle-to-grid concepts can be developed.

Despite the $CO_2$ emissions from the German power sector, electric cars could, thus, be an interesting option for German transport. A recent study commissioned by the German environmental ministry calculated that $CO_2$ emissions from current electric cars fuelled by electricity from hard coal power plants would be in the order of emissions from a conventional gasoline internal combustion engine vehicle with a mileage of 5 to 6 litres per 100 km (Pehnt et al. 2007).

## Switzerland

Among the studies conducted on the Swiss transport sector, the one of Schultz (2007) is the most comparable with those presented in previous sections of this study, because it also makes use of a cost-optimization framework. In his analysis, Schulz (2007) showed that hydrogen fuel cell cars could achieve a market share of more than 20% by the year 2050, if fuel cell costs declined to 50 US$ per kW and Swiss policy was aiming at reducing $CO_2$ emissions by 10% per decade (equivalent to a reduction of more than 40% compared to 2000 levels by 2050) and reducing primary energy consumption per capita to 3.5 kW (down from about 5 kW in the year 2000). Other important fuels for Switzerland would be natural gas and diesel, used in highly efficient hybrid vehicles. The results of the analysis are depicted in Figure 15.

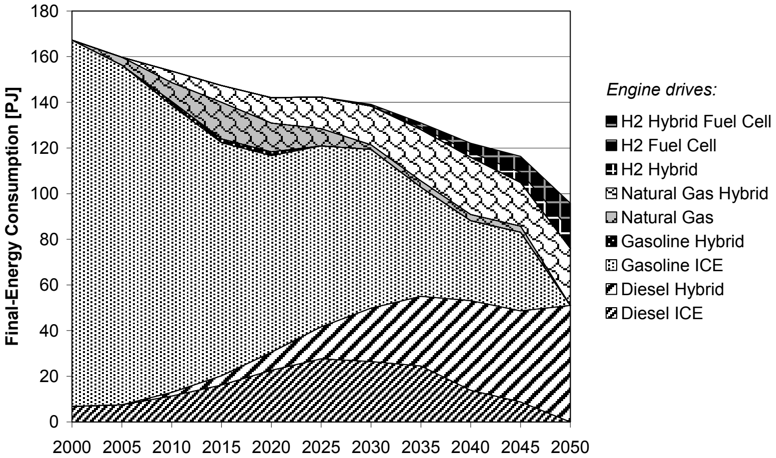

**Figure 15. Final-energy consumption of passenger cars at an oil price of $75US_{2000}$/bbl, 3.5 kW/Cap primary energy and a $CO_2$ reduction constraint of 10 % per decade (Schulz 2007).**

Battery cars have not received the same public attention yet in Switzerland as in Germany, despite the country's $CO_2$-free electricity supply from hydropower and nuclear energy. In some Swiss mountain villages such as Saas-Fee or Zermatt, however, local traffic is restricted to the use of public transport and electric cars only, reducing local air pollution and urban traffic. Nevertheless, no modeling-based studies are available to the knowledge of the authors, which look into the prospects of electric cars in Switzerland.

### 4.3.1 Illustrating alternative futures in Austria, Germany and Switzerland

The above sections have looked into different studies on the future of personal transport in different regions of the world. Where possible, we have tried to illustrate the factors driving the outcome of the analyses and the implications in practical terms. For the latter, this subsection will try to further elaborate on the implications of pursuing alternative futures in personal transport in Austria, Germany and Switzerland.

Most of the discussed alternatives for personal transport will require profound changes in how we achieve mobility. In particular, the energy carrier that actually fuels our demand for mobility is likely to change—as result of climate policy or for reasons of energy security. This result is the common outcome of all modeling analyses we looked into in this paper. Which fuel is likely to dominate the future may ultimately be determined by regional circumstances (e.g. availability of low-cost biomass, or $CO_2$ emissions from the electricity sector), but it is worth looking into what it takes to achieve certain shares for individual mobility in the future.

### *The role of the consumer in future technology choices*

The studies reviewed in the context of the present paper are primarily based on cost-optimization. That is, they seek the least-cost solution for certain constraints, e.g. climate policy that limits $CO_2$ emissions from the energy system to certain policy targets. The analysis then identifies technologies that are under the assumed conditions cost-optimal to meet such targets.

It is, however, obvious that the technology mix of the future in particular in transport will be determined not only by cost-effectiveness of each technology. There are other factors which require due attention, and a very important one is consumer preferences. Consumer preferences are not necessarily driven by cost-competitiveness alone. Rather, they are a result of complex interactions of different influences. By way of example, the availability of refueling stations is an important factor for the market success of any new fuel, as drivers are accustomed to being able to refuel their cars almost anywhere and anytime.

The impact of consumer preferences on the choice of future technologies has been studied within system dynamics modeling frameworks, which are able represent the most important influences and feedbacks determining the choice of technology—for example, such models seek to represent the impact of increasing the number of refueling stations for a new fuel on the attractiveness of the fuel to consumers. By varying the factors influencing consumer preferences such models can therefore determine e.g. critical masses required to be reached for the success of new technologies in the market-place. These models are commonly calibrated to reproduce historical market trends, and take account of consumer surveys.

A recent study by Bosshardt (2008) investigated the penetration of alternative technologies in different European car markets (among those the German and Swiss markets) as a result of consumer choices. The study looks into a great variety of influencing factors, and not all of them can be mentioned here. A few key messages, though, include that fiscal incentives for individual consumers are not sufficient to overcome the dominance of gasoline-ICE vehicles in personal transport, since the lack of required infrastructure for alternative fuels is a severe obstacle. A more promising approach, which showed a much larger impact on the market penetration of alternative technologies in particular in Switzerland and Germany, is to increase the attractiveness of alternative technologies, e.g. through regulative measures, campaigns and marketing instruments. This can facilitate a shift towards alternative drivetrains and also towards fuels other than gasoline (e.g. diesel). For alternative fuels, however, the highest market penetration is observed where multi-incentive policy packages are initiated, comprising both fiscal incentives as well as raising technology attractiveness. This is particularly the case of hydrogen fuel cell vehicles, which faces the most severe obstacles for market penetration due to high purchase cost for the vehicles and the lack of supply infrastructure.

For this purpose, we present some simple analysis, which aims to illustrate the implications of achieving an illustrative share of 20% of each alternative fuel in personal transport for the year 2050 in Austria, Germany and Switzerland. The analysis looks into biofuels, hydrogen and electricity as potential future fuels, and builds upon future demand projections for individual mobility found in various literature sources (EC 2007; WBCSD 2004; Schulz 2007), complemented by some own calculations using technology data from Gül (2008) and some conservative assumptions about future vehicle efficiencies (Kromer and Heywood (2007) and Gül (2008)). The analysis should be considered as being indicative only, since it simply calculates from mobility demand via vehicle and fuel production efficiencies back to the required fuel supply capacities. However, the analysis has its merits in showing the order of magnitude required in terms of fuel supply and number of vehicles on the road by 2050. The results of these calculations are presented in Table 2.

**Table 2. Implications of a 20% alternative fuel target in Austria, Germany and Switzerland.**

| | **20% of vehicles by 2050** | **In 2050 required amount of** | | |
|---|---|---|---|---|
| | | Hydrogen | Electricity | Biofuels |
| **Austria** | ≈ 1 million | 275 t/day in 185 large fueling stations | 0.3 GW power plants | 15 PJ/year, about 10% of the biomass potential |
| **Germany** | ≈ 9.5 million | 2’800 t/day in 1’850 large fueling stations | 3.5 GW power plants | 153 PJ/year, about 40% of the biomass potential |
| **Switzerland** | ≈ 1 million | 280 t/day in 190 large fueling stations | 0.4 GW power plants | 16 PJ/year, about 1/3 of the biomass potential |

The results highlight a number of important messages with regard to each fuel option.

***Biofuels:*** Especially in Germany and Switzerland, the application of biofuels is severely limited by the available potential of biomass. While there is always a strong debate on what is the “real” biomass potential for energy purposes, the numbers shown in Table 2 are pretty clear in their message, especially when considering that calculations are made for a share of only 20% of personal transport—that is, only in Austria are domestic biomass resources sufficient for a possible large-scale deployment of biofuels in transport. For the application of biofuels in Germany and Switzerland, the above figures suggest that without reductions in transport demand (i.e. behavioral changes), or without the import of biofuels from other regions, biofuels are not going to become the one fuel replacing petroleum fuels in the long run. Their use is rather motivated by reasons of an early reduction of $CO_2$ emissions from transport, or by short-term energy security considerations. In addition, there is strong competition surrounding the use of biomass, as it may also be used in the electricity or heat sector. Most cost-optimization modeling analyses actually reveal that biomass is rather utilized there instead of in fuel production, at least if other fuel alternatives such as hydrogen can be developed (see e.g. Grahn et al. 2007 or Gül 2008).

***Hydrogen:*** Hydrogen has a good potential as an alternative fuel, because it can be produced by many different means. However, its application will require substantial efforts in terms of supply infrastructure, as illustrated in Table 2 by the number of fueling stations required in each country. Along with the numerous other R&D challenges concerning e.g. the cost and performance of the fuel cell, the convenience demanded by consumers, or the question of on-board hydrogen storage, deploying hydrogen before 2050 will require significant efforts beyond what one may deem as "normal". Nevertheless, the technology holds good prospects for a carbon-constrained future, if development targets can be met, thus justifying further R&D efforts.

***Electricity:*** Deploying electricity as an energy carrier in transport seems, in light of the conducted spreadsheet calculations, the most straightforward option. If electricity was provided from large-scale power production units such as coal or nuclear power plants, the need for additional capacity would be modest. If power was produced from renewable energy sources instead, the need for additional capacity would become significantly larger because of lower availability and higher variability, i.e. a shift to electric cars may eventually become more challenging. However and as briefly outlined above, it could also entail significant additional benefits by enabling the successful integration of fluctuating renewable generation in electricity networks.

One additional key indicator presented in Table 2 is the number of alternative vehicles corresponding to a market share of 20%. This share converts into about 1 million cars in Austria and Switzerland, and almost 10 million in Germany. For comparison with recent sales of another alternative vehicle, global cumulative sales of hybrid cars by Toyota were 1 million within 10 years (GCC 2007), as mentioned before. In 2006, about 250'000 hybrid cars were sold in the United States alone. In this light, the values for Austria and Switzerland do not seem too drastic given that the year 2050 is still more than 40 years away from today. Again, however, it is important to keep in mind that hybrid cars benefited from tax credits (for example, in the United States) and other policy support. In addition, their market penetration was enhanced by increases in oil prices and the fact that hybrid-electric vehicles can make use of existing fuel supply infrastructure. The latter is not the case for alternative fuels, which will require the development of a full supply infrastructure. For comparison, while hybrid cars experienced such strong growth in the United States, compressed natural gas vehicles experienced an average annual growth over 10 years of only about 9%, reaching about 120'000 vehicles in use in 2005 (DoE 2008). While these comparisons are only illustrative, they nevertheless shows that achieving fairly modest targets for the year 2050 for Austria, Germany and Switzerland represents a big challenge, and require early action and substantial policy support.

# 5. Discussion and outlook

This study has investigated the future of energy and mobility by looking into available scenario analyses conducted on a global, European and regional level, with the latter focusing on Austria, Germany and Switzerland. The study shows that under business-as-usual assumptions, the demand for mobility is likely to increase over the next decades. Without significant policy initiatives, however, most studies expect future mobility to remain dominated by the use of personal cars, fuelled by conventional petroleum fuels for decades to come.

Policy initiatives promoting reductions in $CO_2$ emissions from the energy and transport system are likely to alter this situation though. For instance, climate policy regimes that seek to limit emissions or internalize the costs of climate change are likely to reduce the cost-competitiveness of petroleum fuels and conventional internal combustion engines in the long run. Prospective fuels that may dominate future transport under such circumstances include biofuels, hydrogen and electricity. Their competitiveness and, thus, their application in the marketplace are closely dependent on a number of factors. For biofuels, the main factor is the availability of low-cost biomass for energy purposes, and the extent to which this is more suitable for other sectors of the energy system. For hydrogen, critical factors include the time and effort required to build up a hydrogen supply network and the cost of the fuel cell, which needs to be reduced to roughly US$ 50/kW to become cost-effective. Whether either of these two fuels can potentially become the dominant choice for transport is, thus, uncertain. In the case of biofuels, the choice will likely be dependent on regional circumstances. Where low-cost biomass is plentiful and no conflicts with other land-uses (food production) exist, biofuels are likely to have an important future. If obstacles to hydrogen can be overcome in the future, however, it is likely that biofuels will serve as a bridging fuel, until hydrogen and fuel cells are ready for commercialization. In any case, however, hydrogen can at best be expected to be a long-term technology option (in absence of major technology breakthroughs), potentially being a dominant fuel in transport in the second half of the century.

In some additional simple calculations, electricity was also found to be an interesting fuel option due to the fact that, in principal, a supply infrastructure is already in place in industrialized countries. Even though there is evidently still a need to establish "refueling" stations, the requirements in terms of infrastructure are potentially lower than for hydrogen. Despite this attractiveness, electric cars have not been found to be a viable option in the scenario analyses considered in the context of this study. This observation has one main reason: in order for battery cars to achieve comparable performance to other technology options, e.g. in terms of loading times, and in particular in terms of driving ranges, batteries with high storage capacity are required. As storage capacity is the main determinant for the costs of batteries, electric cars with comparable performance represent a very costly option. Where only short driving ranges are required, e.g. in urban areas, electric cars may have better prospects.

The findings on electric vehicles identified an important limitation of many scenario analyses exploring future energy and mobility, which generally do not account for different car travel markets (e.g., intra-urban *versus* inter-urban travel). In order to get a clearer understanding of the prospects of electric cars as compared to other technology options, additional scenario and modeling accounting for these factors is needed. For example, this could comprise scenario analysis of the competitiveness of alternative transport technology options separating urban from highway traffic and accounting for different trip length and travel behaviour. To the knowledge of the authors, only Shiga et al. (2007) have performed analysis in this direction for the discussed technology options. Further analysis on this topic should also consider transition period aspects, e.g. technology choices in transitions towards the use of battery cars (what is the role of plug-in hybrids and vehicle-to-grid systems?) or hydrogen fuel cell vehicles (are there potential synergies to the use of natural gas in transport?).

In any case, the search for different storage media is and will remain important during the years to come. Storage is required for many aspects of the energy system, be it for accommodating increasing shares of renewable energies in the power sector or for transport. As a matter of fact, it is likely that even hydrogen fuel cell vehicles will require additional battery storage capacity, i.e. they will be implemented as hybrid vehicles. Therefore, further research in advancing the development of batteries and reducing their costs, as well as the search for alternative storage options is an intelligent R&D strategy. It is a safe investment, keeping open various development pathways for the energy system and technology choices of future generations. In transport specifically, it could support a shift towards hydrogen as well as electricity.

In addition to R&D strategies, policy-makers need to set early and clear market signals to industry and consumers in order to foster the necessary technology shift in transport required for realizing future climate change objectives. The challenge in transport is complex, and will require technology change not only in terms of the types of vehicles we drive, but also in terms of which energy is used and how this energy is provided. This will require a long-term effort that requires a transparent, foresighted and stable policy framework with clear signals. In particular, the stringency of the long-term climate mitigation target is an important signal for industry as well as research since it is an important determinant for the competitiveness of different passenger car technology options.

Importantly, these policy initiatives should be implemented in a way that reduces the costs of adoption. By way of an example, the European Union's measures to reduce average new vehicle fleet emissions to 120 grams of $CO_2$ per km until 2012 could be combined with an emission trading scheme between manufacturers (rather than a charge on each gram by which new cars exceed this objective, as it has been proposed in the EU). This would allow reductions in $CO_2$ emissions to take place where they are cheapest and provide stronger incentives to over-perform, fostering further technology development in the transport sector.

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