Swiss Competence Center for Energy Research
Efficient Technologies and Systems for Mobility

# Towards an Energy Efficient and Climate Compatible Future Swiss Transportation System

## Working Paper

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## Executive Summary

The present report analyzes the status and structure of the Swiss transport system and sketches possible paths for its evolution towards an energy efficient, climate compatible and environmentally friendly mobility future. The report was motivated by the need to provide strategic directions, primarily to the research carried out within the Swiss Competence Center for Energy Research - Efficient Technologies and Systems for Mobility (SCCER Mobility). Moreover, it aims to communicate insights from engineering/natural as well as social/economic sciences to policy makers, opinion leaders and the interested public in general. It serves as a platform for reflection and synthesis of views from a variety of disciplines.

In accordance with the Swiss Energy Strategy 2050 and recognizing the importance of the overarching goal of climate change mitigation, we focus on **energy demand** and in particular on **CO2 emissons** as a proxy for the overall sustainability of future mobility. The core of our analysis concentrates on **road transport**, as it is the dominant contributor to both energy demand and CO2 emissions of the Swiss transport sector. We focus on motorized individual transport, which accounts for about two-thirds of CO2 emissions stemming from transportation, and in selected cases, we comment on the development of the even faster growing freight transportation sector as well. However, the report does not closely consider international aviation – despite its growing worldwide importance – since corresponding policy is a matter of international cooperation. Closer consideration of this mode will be important in the future.

### CO2 emission in the transportation sector: main drivers (the method)

This document develops a systemic framework for decomposing the required energy and CO2 output based on the major drivers of both the demand and supply side of the transport sector. Their development during the past 25 years reveals some interesting dynamics of the Swiss mobility system structure. Following recent scenarios for exogenous and endogenous drivers realized by the Federal Office for Spatial Development (ARE), Swiss Federal Office of Energy (BFE) and the Federal Statistics Office (BFS), etc., we eventually draw possible trajectories for the time frame until about 2050. The CO2-budget projections of the Intergovernmental Panel on Climate Change (IPCC) for keeping global warming within 2°C with a 66% probability are then translated into targets for the Swiss transport sector for this same period. Combining the demand side projections and the transport related CO2-budget, reveals the need for a massive reduction of specific CO2 output per travelled distance, essentially to zero within about 50 years.

### Recommended trajectory toward an energy efficient and low CO2 emission transportation system

The highly ambitious target of a zero-CO2 transportation system can only be achieved by employing a combination of **evolutionary** (short-to-mid-term, **efficiency driven**) and **disruptive** (mid-to-long term, primarily **electrification driven**) strategies. Synthetic and renewable fuels are also expected to play an essential role towards fulfilling this target. Such strategies will require very high investments in the energy sector and other infrastructure, which must be designed and implemented effectively. The rate at which CO2 emissions are reduced will in any case depend crucially on the CO2 footprint of the required marginal electricity for transportation and therefore on the coevolution of the electricity and transportation sector. Thus, the assessment of sector coupling within the overall energy system is mandatory.

Compounding this challenge is that the demand for mobility is expected to grow due to a growing population and income per capita. This additional mobility demand will probably be satisfied by cars for most part, despite a hoped-for shift to public transport. Even if new technological solutions are and will be available, **routines and behavioral habits are still major barriers to change.** However, it is also evident that new attitudes towards the use of cars and public transport are emerging in young generations. In addition, advances in information and communication technologies can foster multi-modal use of means of transport and ride sharing. **Smart political measures could support the convergence of new technologies with these dynamics of behavioral change.** However, the potential impact of such measures on the CO2 emissions reduction are not easy to quantify. Despite these uncertainties, we

anticipate in the present report that demand side measures will play an important role in enabling a faster CO2 reduction trajectory.

**Evaluation of possible interventions and their outcomes**

In order to illustrate specific CO2 reduction potentials quantitatively, we investigated targeted interventions through selected socio-economic and technology side measures in a "what-if" manner, thus identifying areas where priority must be given. Because of the growing complexity of the transportation system and its interaction with the electricity sector as well as with economic and social developments, we believe it is important to continue developing tools able to guide policymakers and opinion leader towards effective decisions and policies.

**Life cycle analysis of different technology options**

The assessment of operational powertrains and vehicles is then expanded to include total life-cycle analysis of climatic, environmental and cost effects to give a holistic evaluation of the impacts of the proposed potential improvements to the future mobility system. One important outcome is that electrification of mobility has a high potential to make the transport system more energy efficient and climate friendly, but attention must be paid to some other criteria. When considering other environmental indicators (e.g., human toxicity potential), life cycle emissions both in Switzerland and abroad, and the footprint of the "upstream" processes (invested energy for infrastructure, etc.), electromobility does not necessarily have a lower environmental impact compared to conventional technologies.

**Interplay between the electricity and transport sectors**

Increasing electrification levels of the car fleet leads to important interfaces between the electricity and transport sectors; therefore, the CO2 emission associated to the marginal electricity demand needed for mobility plays a crucial role in decarbonizing the transport sector. This means that even if the operational CO2 output of mobility were close to zero, the lowest achievable CO2 emission level of the transportation sector will still not be negligible, at least within the next decades.

International **energy prices** are also a key uncertainty affecting the future configuration of the car fleet. Low energy prices do not push electromobility, nor do they trigger major shifts from conventional technologies and thus new ones (gas, electric vehicles, etc.) will likely require additional policy intervention. On the other hand, higher energy prices induce accelerated deployment of electromobility (and indirectly support climate change mitigation). Overall, policy makers and society must be aware of the fact that even under the most favorable conditions a significant decarbonization of the transport sector will take several decades to realize.

**Supporting the transformation of the transportation sector: adequate policy measures**

A conceptual model was used to identify promising fields of actions for a successful system transformation towards sustainable mobility. Based on this analysis and with regard to transformation processes, the required measures need hierarchal structure (individuals, organizations, state and institutions) so that interventions can be designed according to the influence level. Among the most promising measures, **consistent internalization of external costs** is of decisive importance.

**Some limitations of the present analysis and outlook**

One major limitation of the analysis framework, which is based on the Kaya-type decomposition of CO2 emission drivers and introduced here, is that **the rebound-effect** (efficiency gains lead to higher available income and thus to higher demand for transportation services) is not included. This issue requires primary attention as a major next step. In the future and in addition to engineering science research, a better understanding of the demand side and economic aspects of the system need to be addressed more closely through dedicated research efforts within our competence center. All told, the present report must be considered as a working paper within a systematic framework reflecting the knowledge currently available within our scientific community. It will be further developed as our research and system understanding evolves, thus serving as a "living document" for the elaboration of outreach papers in the future.

# 1 Scope and content of the report

The global Energy System is expected to undergo major changes in the decades to come. It is generally agreed that climate change mitigation, security of energy supply, minimization of environmental pollution and wide access to energy services important for human well-being are highly relevant criteria for sustainability. Population growth and the need to substantially raise living standards for the majority of people living in developing countries and emerging economies will lead to rapid growth of global energy demand according to virtually all projections. This stands in severe conflict particularly with the firmly expressed consensus of the international community (as given in Paris/COP 21) to combat climate change, which is considered to be a major threat for the planet`s ecosystem. At a national scale, the Swiss Government and Parliament – additionally motivated by the major Fukushima accident – have formulated a long-term Swiss Energy Strategy 2050 that has set the transformation of the energy system towards the massive reduction of energy demand and CO2 emissions as strategic goals. If the public vote on May 21, 2017 approves this strategy, it will serve as the compass for the above-mentioned transition.

Given the need to substantially increase the capacity of the country to address this "grand challenge", several SCCERs (Swiss Competence Centers for Energy Research) have been established in 2013, with a first phase already completed (2014-2016) and a second phase just started (2017-2020). Among them, one is exclusively dedicated to the transportation sector (hereafter called the SCCER Mobility for brevity).

At both the global and individual county level, it is widely recognized that the rapidly increasing demand for transportation services and electricity constitute the major drivers for the future evolution of the energy system. Together these two sectors account for more than 50% of the overall CO2 emissions worldwide. In principle, the decarbonization of both sectors must therefore proceed in a synchronous way. This constitutes a major challenge in view of the anticipated sector coupling associated with the projections of an increased share of electric vehicles in the fleet during the next decades.

Specifically for Switzerland, it is worth mentioning that the transportation sector (including international aviation) currently contributes about 1/3 to the overall Swiss energy demand and 50% to the total CO2 emissions. Even more important is that these contributions keep increasing, in contrast to the decreasing trend in the building and industry sectors.

The present report has been motivated by the need to provide strategic directions, primarily to the research carried out within the SCCER Mobility, but also in order to combine insights from engineering/natural as well as social/economic sciences in order to provide consolidated knowledge to policy makers, opinion leaders and the interested public in general. Having started with the mandate to elaborate "Visions for Future Mobility", the document has turned out to be even more useful as a method to analyze and assess both the status and the future perspectives of the Swiss mobility system. In this manner, it serves as a platform for reflection and synthesis of views from a variety of disciplines contributed by i.a. the different Capacity Areas (CA) of the SCCER Mobility.

In its current form, this document should be considered as a working paper with the primary scope of dialogue with and dissemination to a scientific/professional community. As a next step, however, we intend to develop a concise version of this document for effective communication with policy makers and the general audience, potentially followed by dedicated "White Papers" on specific issues of relevance for the transportation sector.

The following chapter (Chapter 2) gives an overview of both national and international reports, which give a vision and/or strategic plan for shaping future mobility. These include documents from Swiss, European and international governmental agencies as well as from independent organizations from business, research/academia and interest groups.

Chapter 3 introduces the Kaya equation, which allows understating the influences of several different factors driving energy demand and supply as well as CO2 emissions of the transportation sector. Furthermore, it is a tool to analyze possible approaches towards moving to a more environmentally friendly and climate-compatible transportation system. It is used throughout the report to illustrate and couple various aspects of the transport system.

Chapter 4 deals with the evolution of the CO2 output and energy demand in the past 25 years to reach its current state, subdivided into the major terms of the Kaya equation. Subsequently projections in the future are compiled based on different research-based sources (Prognos, ARE, Infras) using the same categories but without the effects of specific additional interventions for transforming the mobility system in the desired direction. Such targeted interventions are described in the subsequent chapters of the report.

In Chapter 5 terms associated with the demand (mega-trends) and supply side, including interfaces with the overall energy system and potentially game-changing effects of digital technologies are examined with regards to the corresponding potential for making the transition to a low-energy demand, minimal CO2 output mobility a reality.

In order to give the reader a flavor of quantitative estimates of what is realistically feasible, CO2 reduction effects originating from a few selected – mainly technology oriented – first order interventions are presented in Chapter 6.

A more holistic and detailed approach for an integrated assessment of future technologies developments, including life cycle analysis (LCA), and economic aspects is then described in Chapter 7 along with first interesting results.

How this transformation path can be actively shaped through policy and innovation measures is then examined more closely albeit in rather qualitative terms in Chapter 8.

It is worth mentioning that the individual chapters of the present report do not only correspond to individual drivers according to the right-hand-side of the Kaya equation, but also have clear links to specific topics within the Capacity Areas, which delineated the type of research conducted within the SCCER Mobility.

For instance, Chapter 5 is associated with CA B2 (Section 5.1), CA B1 (Sections 5.3 and 5.4) and CAs A1, A2, A3 (Section 5.2), while the Future Joint Initiative CEDA will support research described in Section 5.4 as well.

Chapter 6 is based on the outcome of the Strategic Guidance Project, while *Chapter 7* has greatly benefited from research in Capacity Area B2. The latter two modelling-based approaches, together with the learning lab will form an interface with the Joint Activity of all SCCERs "Simulation and Modeling (JA-S&M)" as well as with the Join Activity between SCCER CREST and SCCER Mobility focusing on socioeconomic aspects of mobility.

Chapter 8 draws on research from a Capacity Area B2 and related work will strongly benefit from the Joint Activity with CREST in the period 2017-2020.

Further, in Chapter 9 we comment on the challenges associated with the huge complexity of the mobility system and the limited potential for robust predictions over a time frame of several decades. In order to cope with the inherently non-linear and highly dynamic behavior of such systems we make the case for the establishment of a dedicated **Learning Lab for Future Sustainable Mobility**. Additionally, we envision that the learning lab will aid in integrating the widely distributed knowledge of the SCCER Mobility in the second funding period (2017-2020).

Finally, in Chapter 10 we conclude with the insights obtained from the development of this document and provide an outlook to future research priorities.

## 2 Review of selected national and international transportation visions

For planning a coherent program of transportation research, this program must be set in the context of a comprehensive, integrated vision of what the Swiss future transport sector can and should be. To develop such a vision, it is also important to understand the international context of other countries' visions and planning efforts. This section attempts to give an overview of both Swiss and international transportation visions, focusing first on the ETH Zurich/HSG study *Vision Mobilität Schweiz 2050* (Weidmann et al., 2015), then on government strategies/policies in and beyond Europe, and then finally more generally on visions presented by independent organizations from business, research/academia, and interest groups. This section attempts to identify components or themes within these visions, and to compare the common and complementary elements that are present very broadly. In this context, this section will then outline how the SCCER research program vision is structured given the analytical and technical strengths of the research partners.

In general, organizations' vision statements can exhibit a spectrum of specificity. Some, like the European Commission (EC), may have goals in specific areas, e.g. emissions, and intercity, global (aviation & maritime), and urban transport. Other visions focus on the characteristics of transport systems (e.g. cost, access, equity, safety, environmental quality, etc.). Moreover, goals and methods (policies, technologies, etc.) can also have fuzzy boundaries: for example, efficient markets may be both a goal and a policy. In general, this section focuses on the goal characteristics, rather than on areas or means.

This survey is based primarily on the official visions expressed by different governments, including strategic plans, goal statements, white papers, policies, and invitations for public comment or debate. As noted above, visions from business, academia and interest groups were also surveyed more narrowly, but these were selected based more on bibliographic links and prior knowledge. Sustainability remains a dominant goal in the surveyed visions. Sometimes this is explicitly expressed, and sometimes the focus is more or less on specific areas within the three sustainability pillars: economy (e.g. adequate, affordable transport capacity), society (e.g. safety, equity, etc.) and the environment (emissions and energy use).

### Switzerland

The study *Vision Mobilität Schweiz 2050* authored by ETH and the University of St. Gallen (Weidmann et al., 2015) takes an approach that develops thematic areas ("Themenbereiche") and target concepts ("Zielbildthesen"), and uses a reference scenario and the effects of transportation trends ("Referenzszenario und Trendwirkungen") to develop policy recommendations ("Handlungsempfehlungen"). It is a relatively qualitative and value-driven study (e.g. including equity and availability of access) that is comprehensive in its survey of issues, its consideration of the multiple criteria and inclusion of different stakeholders/actors. The thematic areas include international integration, social justice and equity, resources (energy, emissions and land use), demand, finance, planning and organization, infrastructure, supply and service. The study presents numerical results by sector and mode for 2030 and 2050, and back-casts policy measures needed to achieve the 2050 goals, but does not discuss the numerical methodology used to quantify these results. Overall, this study is much more of a comprehensive "vision" compared to any of the government policies surveyed below.

The study *Vision Mobilität Schweiz 2050* uses and cites various official Swiss governmental planning documents, including the Federal Office for Spatial Development's (Bundesamt für Raumentwicklung, ARE) perspectives on personal and freight mobility ("Güter- u. Personenverkehr") from 2004 and 2006, as well as the update in 2012. These "hypotheses and scenarios" are more forecasts and modeling than policy planning or vision documents. As with other countries, scenarios are split by transport sector (personal v. freight, although road/rail are combined). In general, transportation visions and policy have strong connections to both urban/city planning and energy policy. In Switzerland, the Swiss Energy Strategy 2050 focuses more on an electricity strategy than on an overall energy strategy. Transport is chiefly addressed by the assumption that there will be increasing electrification of vehicles, either directly [battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV)] or indirectly ($H_2$ electrolysis).

### European Union (European Commission / Joint Research Centre)

Within the EU, the European Commission's (EC) department of Mobility and Transport has the chief executive responsibility, while the Joint Research Centre (JRC) supports transport-related research. Particular reports of interest include *A Sustainable Future for Transport* (2009), the *TRANSvisions* (2009) report about transport scenarios with a 20- and 40-year horizon, and the *Roadmap to a Single European Transport Area* (2011). The *TRANSvisions* report has specific goal areas related to emissions, intercity transport, global aviation and maritime transport, and urban transport, plus further specific strategic goals for implementation along with goals for system characteristics. Its roadmap also includes a strong emphasis on the goal of furthering European integration. The EC's *Energy Roadmap 2050* and the resulting strategy will of course also affect transport sector.

The *JRC Strategy 2010-2020* does not include transportation specifically within its seven major thematic areas (open and competitive society, low carbon society, sustainable use of natural resources, consumer and food safety, nuclear safety and security, security and crisis management, and reference materials and measurements). However, the JRC supports technical research topics related to strategic transportation concerns (e.g. sustainable transport and fuels, transportation modeling, and support of the transport and innovation initiative). Sustainable transport and fuel research areas include e-mobility, biofuels, and hydrogen and fuel cell research, based on the strategy set out in the 2010 European strategy on clean and energy efficient vehicles.

### UK Department for Transport

The focus of the UK department was not particularly long-term or strategic, but generally divided by mode (road v. rail) and with more emphasis on the elements of infrastructure, investment, etc. The *Single Departmental Plan 2015 to 2020* (2016) is short-term with a very brief vision and objectives, and two reviewed sample reports from 2013 (*Transport – an Engine for Growth* and *Strategic Road Network and the Delivery of Sustainable Development*) were likewise limited. The first of these two reports in a very concrete "nuts and bolts" way on the six principles of budgetary restraint, balanced investment, maximum economic benefits, environmental protection, private sector participation, and local partner participation and control. The second deals with sustainability issues, but is a consultation outcome based on public input.

### US Department of Transportation

The major effort related to a future vision within the US Department of Transportation (DOT) is the draft publication *Beyond Traffic 2045*, with the purpose of soliciting public comment and feedback. The DOT has a separate strategies page that lists various goals and policies, but it is rather short-term to be termed a vision. For example, *Transportation for a New Generation 2014-2018* (2013) focuses on the three major areas of safety, infrastructure renewal, and technology and process innovation. The passenger and freight strategic plans are sector specific, short term, and focused.

A number of other, non-governmental strategies or vision plans were also reviewed. Various sources included the International Transport Forum (ITF), World Energy Council (WEC), the International Energy Agency (IEA) and the World Business Council for Sustainable Development (WBCSC). More academic vision reports included the MIT report *On the Road toward 2050* and many Swiss and German reports taken from the bibliography of the study *Vision Mobilität Schweiz 2050*. These include publications by BMW's Institute for Mobility Research (IFMO), Ernst Basler, Arthur D. Little, mobility.ch, the Frauenhofer Institute, the German Environmental Agency (Umwelt Bundesamt), the German Council for Sustainable Development and the German Center for Air and Space Research (DLR). In general, these strategic plans or visions by businesses, business associations, consultants, academics and regulators were longer-term and more "visionary" than regular government plans. There is (of course) a broader range of stakeholder perspectives, but some are more issue-focused (e.g. on emissions), while governments tend to have a broader perspective. Major vision elements from some of the most interesting reports and/or stakeholders are listed individually below.

### International Transport Forum

The International Transport Forum's (ITF) *Transport Outlook 2015* addresses road, train and ship, international and urban transport. It covers short-term trends and modeling scenarios until 2050, rather than presenting a normative vision of desired system qualities. A very important outcome of this outlook is that a massive increase of pkm and even more of tkm worldwide must be expected of several 100%, mainly driven by emerging economic and non –OECD countries. Policy measures can influence the extent of the growth but not reverse the trend of increasing demand for transportation services. The latest ITF report (2017) emphasizes the need to implement a wide range of policies and measures to in order to limit global warming to 2°C above pre-industrial levels. Technological progress alone will not achieve the CO2 reduction goals agreed in Paris, but will be of utmost importance towards this end.

### World Energy Council

The World Energy Council's (WEC) major emphasis is on the general topic of energy and not on the transport sector in particular. However, the WEC expresses three core dimensions of energy security, energy equity and environmental stability as part of the so-called energy trilemma", which are used to form an international index ranking, and which apply to their definition of transport. The WEC *World Energy Scenarios* to 2050, where PSI has provided energy sector modeling, also includes mobility modeling. Here the "freeway" assumptions are part of the overall "jazz" scenario that is more consumer driven (growth and market forces), and the "Tollway" assumptions are part of the overall "symphony" scenario that is more voter-driven (regulatory policies and market intervention).

### International Energy Agency

The International Energy Agency (IEA) research is not related to transport in particular, but the IEA *World Energy Outlook Special Report 2016: Energy and Air Pollution* (2016) includes specific discussion of the entire transport sector.

### World Business Council for Sustainable Development

The World Business Council for Sustainable Development's (WBCSD) vision for 2050 includes a more than 2-fold increase in passenger and freight transport, a 60-70% reduction in GHG emissions, negligible NOx and particulate emissions, and traffic fatalities "approaching zero." These vision elements are to be achieved by 1) intelligent transportation systems, 2) smart use of vehicles (traffic management and eco-driving), 3) advanced technologies, 4) reduction of GHG intensity in light duty vehicles, 5) decreased carbon intensity in freight, aviation and shipping, and 6) alternative low-carbon fuels.

### Massachusetts Institute of Technology

The Massachusetts Institute of Technology's (MIT) report *On the Road toward 2050* focuses on the potential for reducing vehicle energy use and GHG emissions, using a broad range of means, including advanced drivetrains, size/weight reductions, fuel pathways, technology diffusion, and driver behavior.

### Arthur D. Little

Arthur D. Little (ADL) has published various major transport vision reports, including the older *Zukunft der Mobilität 2020* (2009), and the more recent *The Future of Urban Mobility 2.0* (2014), which was written for the International Association of Public Transport (UITP) as an update of an earlier 2011 study. The urban mobility study uses 19 criteria covering urban transport maturity (11) and performance (8) to rank and compare different cities' performances. Therefore, these criteria reflect a vision of what good urban transport should encompass, including (in a condensed way) public transport cost and share, emissions and road density, cycle path density, urban density, smart card penetration, bike and car sharing, frequency of public transport service, emissions, fatalities, vehicle density and mean travel time. ADL then proposes four key dimensions for planning sustainable urban mobility, with a wide range of strategic and normative metrics (values) for planning.

### Fraunhofer Institute

The Fraunhofer *Vision für nachhaltigen Verkehr in Deutschland* (VIVER, 2011) is a rather qualitative or conceptual vision, rather than a quantitative one. It sees the choice of future transport as a combination of 1) megatrends (demography, income growth, social security, slowing globalization, climate change , decreasing fossil fuel availability and increasing price, and market order through the state); 2) transformative value changes in society (climate protection and sustainability, multi-modality, urban lifestyle, "deceleration", and regionality); and finally 3) mobility-related areas (including re-urbanization, work and leisure, mobility concepts, state regulation, production and markets, and logistics and freight).

### National Center for Aerospace, Energy and Transportation research of the Federal Republic of Germany (DLR)

The DLR's vision, like that of the JRC, is largely reflected in its research areas and portfolio. The DLR's Institute of Transport Research includes research areas on passenger and commercial transport as well as mobility and urban development. More specific research fields include 1) mobility patterns, 2) model forecasting of regional transport demand, 3) technology assessment, 4) the acceptance and potential of electric mobility, and 5) mobility applications of information.

Table 1.1 below presents a brief comparison of the relative emphases of some of the surveyed vision statements. Some comments on the table are appropriate. First, as in the discussion above, it focuses on the goals or criteria for transport system performance, rather broadly aggregated into categories under the overall sustainability areas of economy, environment and society. This table is not a complete synopsis of the literature by any means, and indeed includes some groups or governments, which were of interest, but with very narrow vision goals. Some of the vision statements or reports reflect a much higher emphasis not on the normative goals for system performance, but rather on transport system trends or the means to achieve system change. This is why the "trends and means" column was added on the right to indicate such emphasis. While the check marks indicate that a certain threshold of emphasis has been reached, this is not equal across the different reports, and only the last column has been given multiple checks.

### Concluding remarks

Overall, the government plans or strategies focus more strongly on the short-term or maybe intermediate future, rather than a long-term outlook. They are generally broken down by market sector or mode (i.e. personal v. freight transport, or road v. rail v. air transport), and lean heavily towards infrastructure and investment, but they are not generally integrated, intermodal or particularly (or at least explicitly) value driven. Often these plans are linked to or driven by sustainability concerns and efforts. The academic/business/independent organization studies tend to present more long-term and integrated visions, but they are not official policy, and represent a very broad set of stakeholders so that their results cannot be synopsized easily. However, it is interesting to note, that energy strategies are much further developed and easier to find than transportation strategies. The energy and transport sectors obviously overlap, but energy strategies tend to be dominated by future electricity planning, with relatively little explicit transport content.

|  | Goals / Criteria |  |  |  |  |  |  |  |  |  |  |  |  | Trends & Means |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Economy |  |  |  | Environment |  |  |  | Society |  |  |  |  |  |
| **Organization / Study** | Budgets, finance, cost | Economic growth | Employ-ment | Private mkt & competition-peak prices, ext. costs, etc. | Climate, GHG | Local emissions | Energy, resources, renewable | Other-noise, land use | Quality of service - congestion, travel time, comfort, etc. | Access, equity, privacy, cohesion, acceptance | Accidents, safety, security | Job quality | Inter-national integration or access | Trend analysis, demand forecasts & modeling, technology, fuels, IT, big data, etc., |
| Vision Mobilität Schweiz 2050 | √ |  |  | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| EC TRANSvisions |  | √ | √ |  | √ | √ |  | √ | √ | √ | √ | √ |  |  |
| EC Roadmap to a Single European Transport Area | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |  | √ | √ |
| EC JRC Strategy 2010-2020, JRC website |  |  |  | √ | √ |  | √ | √ |  |  |  |  |  | √ √ |
| UK DfT Transport - an engine for growth | √ | √ | √ | √ |  |  |  |  | √ |  |  |  | √ | √ |
| UK DfT Single departmental plan 2015 to 2020 | √ | √ | √ |  | √ | √ |  | √ | √ |  | √ |  |  |  |
| US DOT Beyond Traffic 2045, Trends and Choices | √ |  |  | √ | √ | √ | √ |  | √ |  | √ |  |  | √ √ |
| US DOT Transportation for an new generation 2014-18 | √ | √ |  | √ | √ | √ | √ | √ | √ | √ | √ |  | √ |  |
| ITF Transport Outlook 2015 |  |  |  |  |  |  |  |  |  |  |  |  |  | √ √ |
| WEC Energy Trilemma and Energy Scenarios 2050 |  |  |  |  | √ | √ | √ | √ |  | √ | √ |  | √ | √ |
| WBCSD website |  | √ |  | √ | √ | √ |  |  |  |  | √ |  |  | √ |
| MIT On the Road toward 2050 |  |  |  |  | √ |  | √ |  |  |  |  |  |  | √ √ |
| ADL Future of Urban Mobility 2.0 | √ |  |  |  | √ | √ |  |  | √ √ |  | √ |  |  | √ |
| Frauenhofer VIVER report |  | √ |  | √ | √ |  | √ | √ |  | √ |  |  | √ | √ √ |
| DLR research portfolio |  |  |  |  | √ | √ | √ |  |  |  |  |  |  | √ √ |
| Dudenhöffer / CAR | √ | √ |  |  | √ |  |  |  | √ |  | √ |  |  | √ |

*Table 2.1 Components of transportation visions surveyed*

Within this Swiss and international planning context and in contrast to the *Vision Mobilität Schweiz 2050* study, which takes thematic areas and target concepts and uses a reference scenario and the effects of transportation trends to develop policy recommendations, the SCCER's academic strengths are the quantitative analysis and technology development for implementation. In particular, the different competencies available within SCCER Mobility include:

**Vehicles and drivetrains:** vehicles, their drivetrain technologies and how their basic technological characteristics (multi-criteria indicators) influence the travelers' decisions on modal choice and intensity of use.

**Energy sources, conversion and storage technologies:** sources of primary transport energy, their conversion to energy vectors (fuels or electricity) and the conversion and storage options to make this energy supply system more flexible influence both transport utility (e.g. vehicle range, or time and availability to refuel/recharge), and also the upstream and downstream LCA burdens from the full energy chain.

**Demand and modal choice**: transport demand is driven by multiple factors including population, income, time constraints, and the desired services and destinations. The modal choice and aggregate modal mix for transport demand also reflect the balance of characteristics that different modes bring to meeting this demand. Routing and scheduling of demand are further elements that affect the degree of traffic congestion, travel time and personal stress/aggravation, which affect modal choices.

The SCCER Mobility has strengths in all these areas for both technological development and analytical quantification of system effects, which generally follow the existing work package structure of the SCCER.

One particular element that can be mentioned when addressing transportation from a systemic perspective is that the different parts of the system evolve and can be affected on different time scales: Changes in infrastructure occur slowly, followed by the rolling stock as annual purchases of evolving technology penetrate the vehicle fleet. People's demand and modal preferences also shift somewhat gradually, but this is modified by the much more rapid market penetration of IT-driven and databased shifts toward smart systems operation. A coherent, targeted yet flexible energy and transport policy must therefore adequately incorporate these quite different time scales when formulating its portfolio of measures over time.

# 3 Swiss energy strategy 2050: Driving factors for the evolution of the Transportation Sector

The Swiss Energy Strategy 2050 sets strategic goals for the reduction of final energy demand and CO2 emissions by mid-century but does not specify strict targets for the individual (sub-) sectors of the overall energy system. Particularly with regard to the CO2 reduction goals, it is useful – in the light of recent insights from climate science – to consider target levels for 2050 based on the global CO2-budget allowed for keeping long-term global warming below 2°C with a probability of 66%. Based on a modest "fairness-rule", demanding equal CO2 emissions for every world citizen within the next 50 years (that is, until full decarbonization of the energy system), a reduction strategy for energy-related CO2 emissions for Switzerland can be devised. Finally, with the assumption that the transport sector must contribute to this CO2 reduction at the same pace as the overall energy system, target values for decarbonization of mobility can be defined.

In this report, we do not consider international aviation despite its crucial future role since both technology development and policy instruments are outside the influence of Switzerland and unfortunately not included in the Kyoto-legislation. Finally, in the following analysis we will focus mainly on the motorized individual mobility (MIV) as it accounts for about 2/3 of the transport-related CO2 emissions in Switzerland but we will refer also to freight transportation in selected cases.

In order to reach a Transportation System with minimal energy demand and CO2 emissions several levers could be addressed: mobility and transportation demand reduction, more efficient energy conversion processes and Energy carrier substitution are typically considered. The figure below illustrates in a qualitative form the different potential reduction associated to broad thematic areas (Figure 3.1).

Reduction of travel demand may involve behavioral as well as pricing and urban planning changes, while on the supply side both efficiency increases along the energy conversion chain and increasing substitution of fossil energy carriers though renewable ones are necessary.

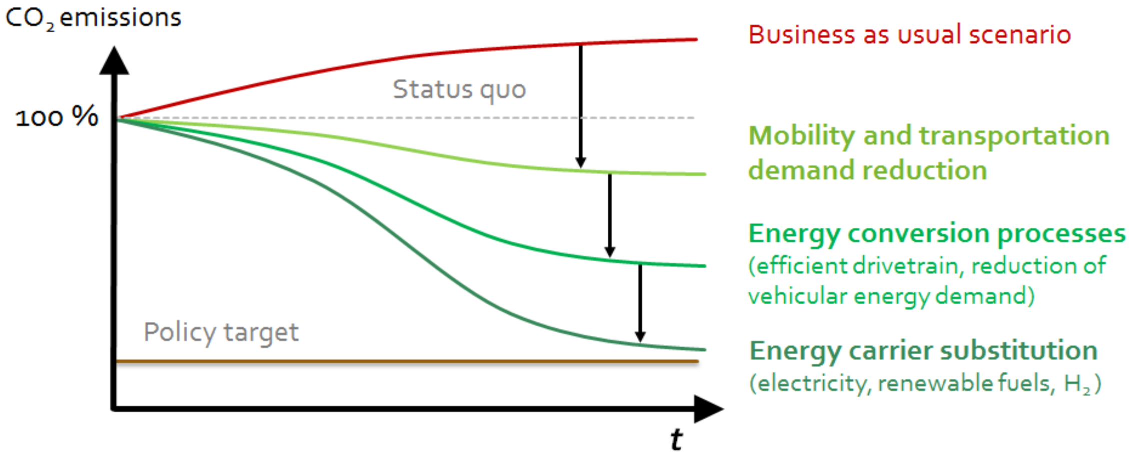

*Figure 3.1: A systemic approach towards minimization of $CO_2$ emissions from transport (here shown qualitatively) must use synergetic efforts on both the demand and supply side.*

In order to perform a more detailed analysis of the factors influencing the CO2 output associated with transportation, the overarching goals of the Swiss Energy Strategy 2050 can be decomposed into several major influencing factors in terms of minimization of (non-renewable) energy demand and CO2 output. These influencing factors can then be operationalized by means of a Kaya-type formulation [(as introduced by Kaya & Yokobori (1998)], expanded and modified for our specific purpose here (exemplarily for individual private transportation).

$$m_{CO2}|_a = (popul) \cdot \frac{GDP}{popul} \cdot \frac{pkm}{GDP} \cdot \frac{vkm}{pkm} \cdot \frac{E_N}{vkm} \cdot \frac{E_{end}}{E_N} \left[ \frac{E_{prim}}{E_{end}} \cdot \frac{m_{CO2}}{E_{prim}} + \frac{E_{invest}}{n \cdot E_{end}} \cdot \frac{m_{CO2}}{E_{invest}} \right]$$

(A) (B) (C) (D) (E) (F) (G) (H ) (I) (J) (K)

n= life-time of Hardware / infrastructure

*Equation 3.1*

The terms (A) – (I) of the Equation refer to the annual operation-related CO2 output while terms (J) and (K) refer to the emissions related to the energy investments in hardware (vehicle, converters etc.) and overall infrastructure.

This equation allows firstly to understand the driving factors for the evolution of energy demand and CO2 emissions in the transportation sector and secondly to link possible interventions for transforming the transportation system towards compatibility with the climate protection goals to specific research fields. In this way, research within the SCCER Mobility is in accord with the overarching strategic goals of the Swiss Energy Strategy 2050.

A closer inspection of the Kaya-equation above leads to the following classification of its individual terms according to whether, and – if yes – how, these can be influenced by research contributions within the SCCER Mobility and the associated "drivers".

(B), (C): exogenous drivers

(D), (E): demography, urban planning, and pricing policies

(F): vehicle technology, legislation

(G): powertrain technology, legislation

(H), (I): energy/electricity infrastructure, technology innovation, and policy

(J), (K): technology innovation, policy/legislation.

Although the above Kaya-formulation allows breaking down energy demand and the associated overall CO2 emissions into individual and specific drivers and interventions, its limitations need to be acknowledged carefully.

For instance, many of the individual terms of the above equation are not independent from one another, which complicates the analysis. The well-documented and highly relevant rebound-effect for example stems from the fact that efficiency gains [along terms (F), (G) and (H)] lead to higher available income and thus to higher demand for transportation services [terms (D), (E)]. This direct rebound-effect is often complimented by the increasing demand for other energy-related services (indirect rebound effect).

Another issue one needs to pay attention to is the fact that several of the terms of the Kaya equation are averages over a distribution, over the population (agents) as well as over space and time. Therefore, when defining and assessing targeted interventions, such distributions must be known in a quantitative sense. For example, the fleet of cars exhibits a wide distribution of engine power, weight, aerodynamic features etc., while on the other hand age, individual income, living circumstances etc. lead to strongly varying demand for transportation services across the Swiss population.

Nevertheless in the following we will use the above equation to elaborate a common thread for linking the manifold aspects of the transportation system (here for simplicity with emphasis on personal mobility) to each other and therefore help to develop a coherent strategy and vision for a sustainable future Swiss mobility.

# 4 Status Quo and perspectives of the Swiss mobility system

This chapter addresses the evolution of the Swiss mobility system up to the current status quo and a future scenario represented in the terms of the above-mentioned Kaya-type equation (Kaya and Yokobori, 1998; Equation 3.1 in Chapter 3). The focus is on direct tailpipe $CO_2$ emissions – not on indirect emissions (related to infrastructure construction and maintenance), emissions in the vehicle life cycle or emissions shifted to the energy sector (e.g. through electrification) are considered in the following analysis. Therefore, the terms (J) and (K) representing the emissions related to infrastructure are neglected leading to the following expression of the direct CO2 emissions of the mobility sector.

$$m_{CO2}|_{a,direct} \quad = \quad (popul) \cdot \frac{GDP}{popul} \quad \cdot \quad \frac{pkm}{GDP} \cdot \frac{vkm}{pkm} \quad \cdot \quad \frac{E_N}{vkm} \cdot \frac{E_{end}}{E_N} \cdot \frac{E_{prim}}{E_{end}} \cdot \frac{m_{CO2}}{E_{prim}}$$

(A) (B) (C) (D) (E) (F) (G) (H ) (I)

Taking the last four terms together results in a simplified equation with five driving terms.

$$m_{CO2}|_{a,direct} \quad = \quad (popul) \cdot \frac{GDP}{popul} \quad \cdot \quad \frac{pkm}{GDP} \cdot \frac{vkm}{pkm} \quad \cdot \quad \frac{m_{CO2}}{vkm}$$

(A) (B) (C) (D) (E) (F’)

The simplified equation (shown above for passenger transportation) dissects the trend in CO2 on an aggregated national level in different driving factors. Those factors can be categorized in three groups, namely socio-economic factors, demand-driving factors and vehicle design (and technology) factors. Term (B) and (C) represent the socio-economic parameter group that is exogenous, i.e. affects the mobility sector as given input and is not a result of it or a quantity within it. In reality, there are some feedback loops between the energy system and the overall economy resulting in dependencies, which are neglected in a Kaya-type representation. The socio-economic parameter group acts as a driver for the entire transportation sector, i.e. it acts identically on passenger and freight or road and rail transportation. The second group of demand-driving factors consists of terms (D) and (E), which describe how we access and use mobility, resulting in a demand of mobility services. Spatial planning, policy measures and social attitudes influence the drivers of those terms. They are different for passenger and freight as well as road and rail transportation. The remaining term (F’) stands for the vehicles chosen to provide the demanded mobility services. It is a fleet average value and purely technological, accounting for the vehicle designs, powertrain configurations and the underlying energy vector (fuel) portfolio.

Before discussing future trends, the status quo – namely the transportation sector of the reference year 2010 – is considered (Figure 4.1). The top panel illustrates the energy demand of the entire mobility sector (left) and the resulting CO2 emissions (right), split (bottom panel) between passenger (left) and freight transportation (right), for road and rail, respectively. The shares in energy are taken from an analysis of Swiss energy consumption from 2000 to 2014 performed by Prognos, Infras and TEP (2015) and are represent results of bottom-up modelling. The report lists the energy demands of different fuel types for various modes of transportation (international and military aviation, waterborne transportation, fuel tourism and non-road/non-transportation, e.g. construction vehicles, are excluded from the modelling). The shares in CO2 shown on the right come from the greenhouse gas statistics of Federal Office for the Environment (Bundesamt für Umwelt, BAFU).

Data from [BFE 2015]: Analyse des Schweizerischen Energieverbrauchs 2000-2014 nach Verwendungszwecken

Data from [BAFU]: Treibhausgasemissionen der Schweiz 1990-2014

data from BFS

data from BFS

*Figure 4.1: Explanatory numbers of the transportation sector in the reference year 2010 represented by road and rail based passenger and freight transportation (4 sectors). Top left: Share of national energy demand of the four sectors including domestic aviation, national ships and 'other' sectors (Source: Swiss Federal Office of Energy, BFE). Top right: CO2 emissions of the respective sectors (Source: BAFU). Bottom left: Comparison of road and rail passenger transportation performance. (Source: Federal Statistical Office, BFS). Bottom right: Comparison of road and rail freight transporation performance (Source: BFS).*

Road transportation dominates energy demand greatly, as road vehicles are responsible for the majority of kilometer performance (distance covered by vehicles within a specified period of time, here 2010), which is seen by the inner rings of the bottom left panel for passenger transportation and bottom right panel for freight transportation. Furthermore, they almost exclusively operate on fossil fuels, which means the vehicle conversion efficiency is lower than for electrically propelled vessels, resulting in a higher demand of end energy for the same kilometer performance. The dominance of fossil hydrocarbons for road based vehicles and electricity (CO2 free in terms of direct emissions) for rail vehicles results in even higher shares for road transportation in CO2 emissions than energy demand (almost 100%). When talking of potential CO2 reduction, road based transportation – passenger and freight – should be of main interest, i.e. relevant points of actions.

Considering transportation performances, the train is capable of supplying a non-negligible share, namely 19% of all passenger kilometers and 40% of ton kilometers. The required vehicle kilometer for this are (basically) negligible compared to the road based values. This can be explained by much higher load capacities of a train compared to a passenger car, light or heavy duty vehicle.

Having an overview of the reference year 2010, the trends of the three groups of driving factors of the introduced simplified Kaya-type equation are illustrated in the figures below normalized to 2010. Demand trends continuing into the future are derived from the ARE transportation perspectives 2040 (ARE, 2016). These are completed by technology trends of the Prognos' *Energy Perspectives 2050* (Prognos, 2012), which are in turn based on the ARE transportation perspectives (ARE, Ergänzungen zu den schweizerischen Verkehrsperspektiven bis 2030, 2012) for the mobility system and Infras for the vehicle technology evolution.

The effect of the socio-economic terms (B) and (C) are identical for all sectors of the mobility system and shown in Figure 4.2. The dark green lines represent the population (B), the brown lines the GDP per capita and the red ones show their product – the group of exogenous socio-economic drivers. The solid lines stand for statistical values coming from federal offices, which show the evolution in the past years. The dashed lines from 2015 are the assumptions of the reference scenario of the ARE 2040 perspectives. The figure shows an increase in both terms of the Kaya-type equation, causing their product to increase by 47% in 2040 with respect to 2010. In contrast to the reference scenario, ARE published two sensitivity scenarios in terms of population and GDP evolution. The effects of those high ("Sensitivität B") and low ("Sensitivität C") scenarios are represented by the shaded areas, spanning a range of possible future trends. The common ground is the strong and steady increase. To complete the figure, the GDP per capita assumption of the energy perspectives 2050 of Prognos and the resulting product with the latest reference population scenario (A-00-2015)[1] (BFS, Szenarien zur Bevölkerungsentwicklung der Schweiz 2015-2045, 2015) are included as dotted lines. They are very similar to the ARE trends assuming a large increase, too. Given the exogenous character of the socio-economic trends, the increase cannot be influenced (or is not desired to decelerate) but has to be compensated by the other terms of the Kaya-type equation, namely specific demand and technology measures (per GDP).

ARE as well as Prognos define those socio-economic trends as common input for their respective reference and alternative scenarios (balance, sprawl, focus for ARE and BAU, POM, NEP for Prognos), i.e. as exogenous input. Policy measures, behavioral change or other inputs are defined differently to derive the alternative scenarios, but all assume in the same evolution of GDP. This decoupling is consistent with the Kaya-type equation and the differences of the scenarios are due to alternatively assumed demand and technology drivers.

Looking at the share of CO2 emissions, the predominant emitter is the road based passenger sector, which is why we concentrate on this sector (despite the anticipated increased share of freight on total transportation related CO2 emissions). The following figures illustrate the assumed trends in demand drivers (D) and (E) of the ARE 2040 and Prognos 2050 perspectives as well as the technology driver (F') of Prognos' 2050 perspectives.

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[1] Prognos 2050 energy perspectives are based on the reference population scenarios of 2010 (A-00-2010), which is significantly lower than the 2015 scenario

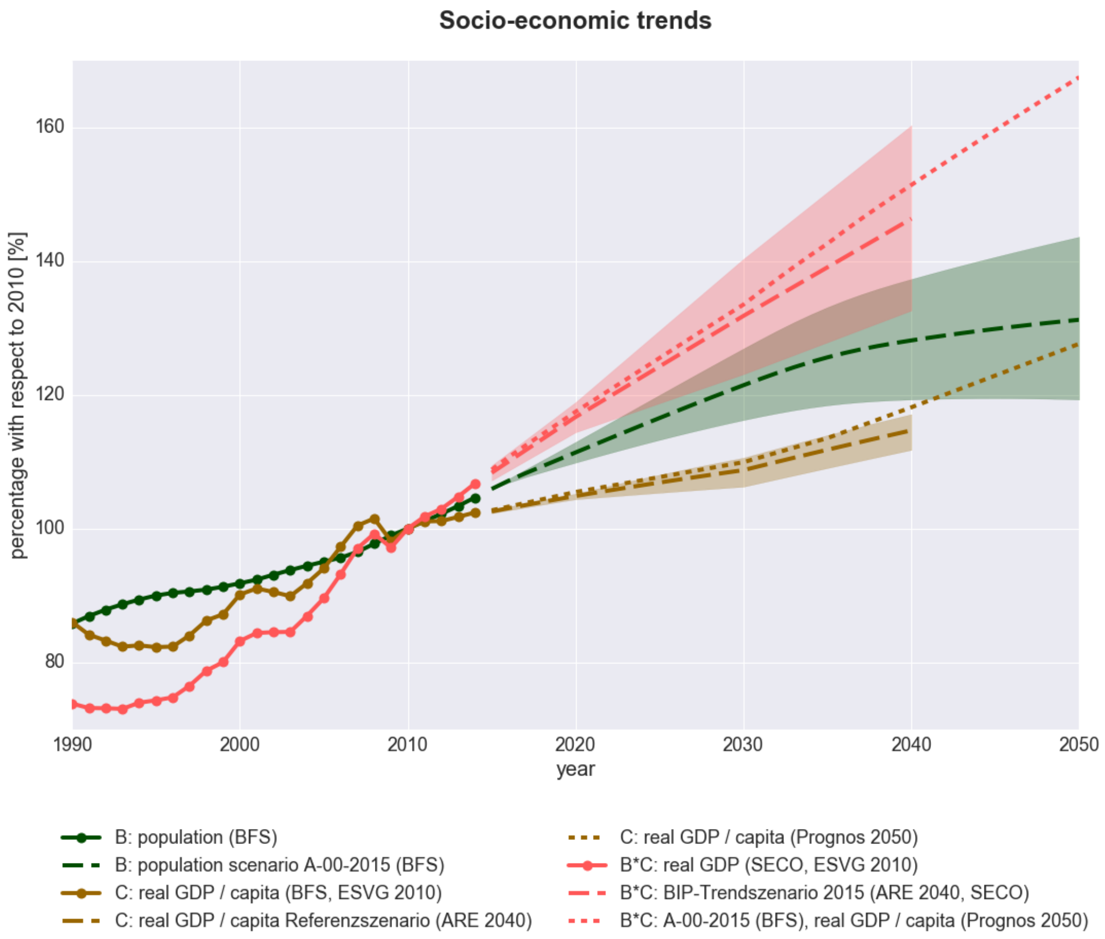

*Figure 4.2: Illustration of socio-economic trends of Switzerland: Population (dark green), GDP per capita (brown) and their multiplication (red). Solid lines: statistics of federal offices. Dashed lines: assumptions of the reference scenario of ARE 2040 perspectives. Shaded areas: possible range considered in the alternative ARE perspectives 'Sensitivität B' (high) and 'Sensitivität C' (low). Dotted lines: respective curves of Prognos energy perspective 2050, adapted to the population scenario A-00-2015 (original scenario of energy perspectives is A-00-2010).*

Focusing first on the demand side, term (D) represents a personal distance per monetary unit. This can be interpreted inversely as cost of mobility services (here for road based passenger transportation) or money available for those services. Mobility pricing, spatial planning, modal shift or developments in ICT act on this term of the equation, changing the current share of available money spent on mobility. The yellow lines in the figure below (Figure 4.3) illustrate the past trend (solid) and the future evolution as assumed by the ARE 2040 perspectives. The shaded area is the range of the alternative scenarios (balance, sprawl, focus) with different underlying assumptions in policy measures and spatial planning. The effective spread in 2040 with reduction between 16 and 22% around the reference of 19% is not significant meaning that based on the ARE computations the effects of those measures are of subordinate impact. The larger deviation between the alternative scenarios is seen in the second term (E). It is the inverse of the vehicle occupancy and shown in purple in the figure below. No changes to the status quo are assumed in the reference scenario, which appears to be a valid assumption based on the trend of the last 20 years. The alternative scenarios differ in their assumptions from a more individualized vehicle usage to a more effective usage of the vehicles (e.g. through ride sharing). Combining both demand drivers D and E results in the green lines, showing an overall decreasing trend of 19% by 2040 with a spread from 10 to 29%. Including the trends of the energy perspectives 2050 of Prognos for the demand drivers completes the figure. The ARE scenarios 2040 agree with the assumptions of the new energy policy scenario of Prognos (dashed-dotted line) and are more optimistic than the reference case business as usual (dotted line) of the energy perspectives.

Section 5.1 further comments on factors influencing the mobility demand and on the plausibility and likelihood of the underlying assumptions of the different ARE scenarios. Additional influencing factors, which were not considered in the array of the shown scenarios but hold potential in changing the demand for mobility, are discussed and assessed in a qualitative manner.

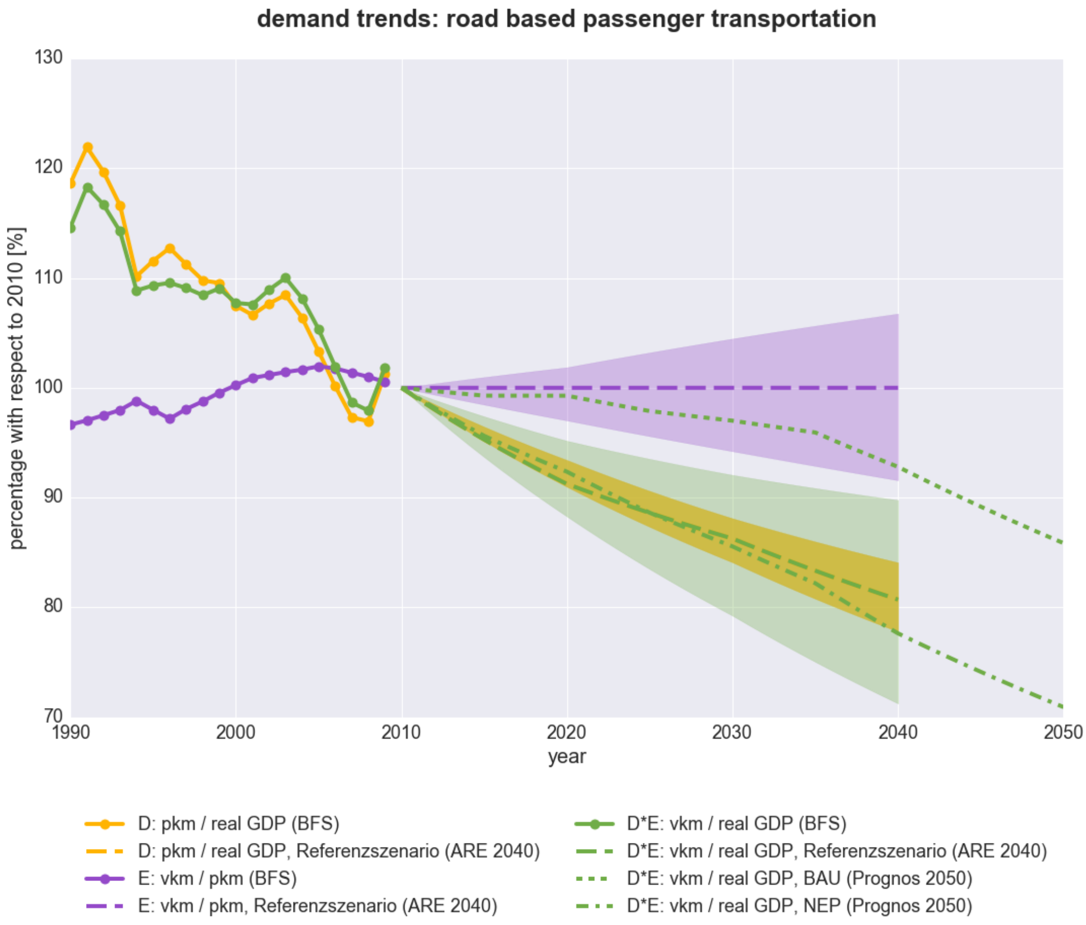

*Figure 4.3: Demand trends for the road based passenger transportation sector: pkm/GDP (yellow), vkm/GDP (purple) and their multiplication (green). Solid lines: Statistics of federal offices. Dashed lines: Assumptions of the reference scenario of ARE 2040 perspectives. Shaded areas: Possible range considered in the alternative ARE perspectives balance, sprawl and focus. Dotted lines: respective curves of Prognos energy perspective 2050 business as usual (BAU) and new energy policy (NEP) scenarios. (only shown for the aggregated demand driver).*

The second driver to counteract the increase of the socio-economic trend is the vehicle technology including its design, powertrain layout and the underlying energy vector, i.e. term (F'). In their energy perspectives, only Prognos provides numbers on how the CO2 emissions per driven distance changes for the Swiss passenger car fleet. The dark red lines of Figure 4.4 result as a product of the two discussed groups of drivers, i.e. trends in socio-economic and demand drivers. They represent the product of the terms (B), (C), (D) and (E), which is a mobility demand expressed in vehicle kilometer. The shaded area indicates the area of possible scenarios (including sensitivity) of ARE 2040 around their reference, represented as dashed line. The dotted and dashed-dotted lines are derived from the energy perspectives of Prognos. The business as usual line coincides with the upper limit of possible ARE 2040 scenarios, while the new energy policy scenario matches the ARE 2040 reference evolution. Together with the vehicle technology trends, which are only available from the Prognos energy perspectives, they build the right-hand side of the Kaya-type equation. Figure 4.4 only shows the evolution in average fleet emission for the NEP scenario (dashed-dotted light blue line), which is more optimistic than the business as usual and shows a smooth continuation of past trends. The line decreases almost linearly until 2040 and predicts a reduction of 70% by 2050 with respect to 2010. This is an assumed reduction from 195 to 59 gCO2 per kilometer. The product of the dark red vehicle kilometer curve and the light blue emission line (both of the new energy policy scenario) results in the dash-dotted black curve representing the right-hand-side of the Kaya-type equation, i.e. the CO2 evolution of passenger car transportation.

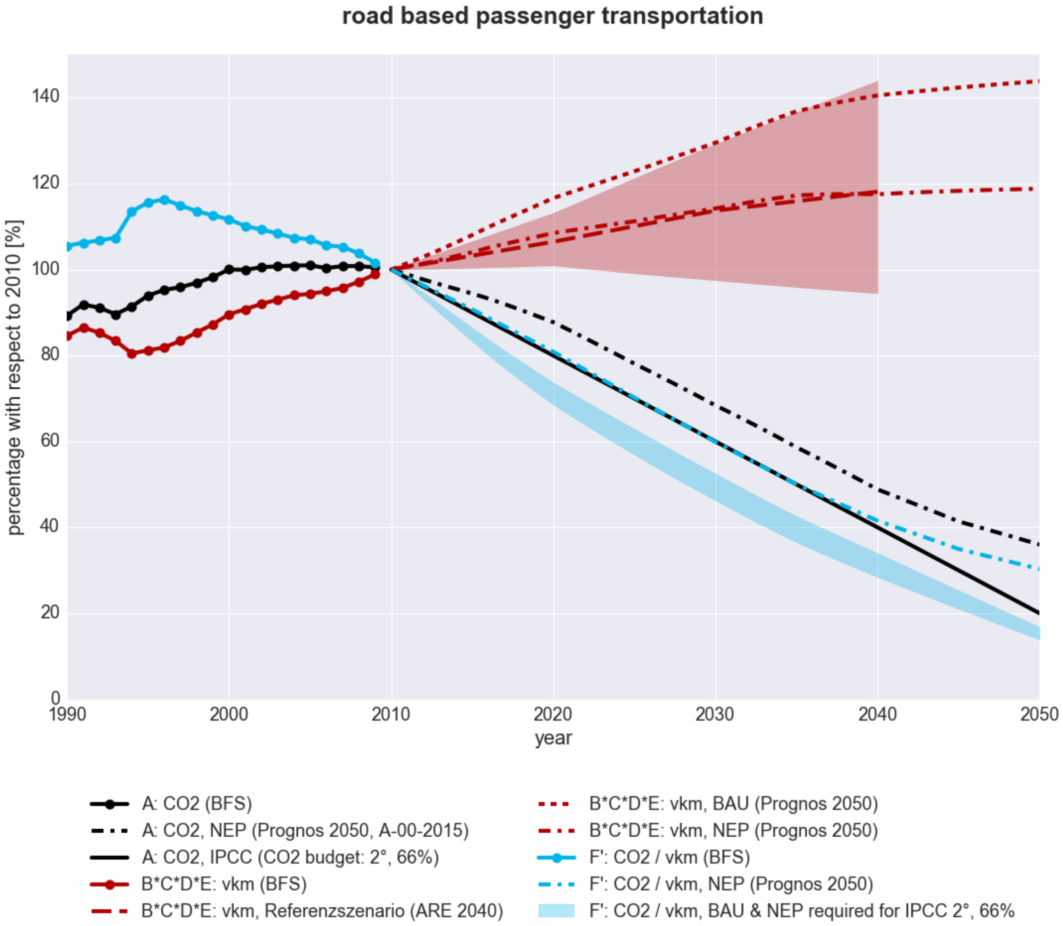

*Figure 4.4: Groups of drivers for direct CO2 emissions of the road based transportation sector: socio-economic driver and demand driver combined in the dark red lines, technology driver in light blue. Their product defines the evolution of the CO2 emissions (black), comparable to the IPCC target (2°, 66% probability). The evolutions are taken from ARE 2040 perspectives and Prognos EP 2050.*

To put the illustrated scenario into context, we need to compare it to a CO2 reduction target. In its latest climate change report (IPCC, 2014), the Intergovernmental Panel on Climate Change (IPCC) recommends that the global CO2 budget from 2011 forward should be 1000 Gt in order to achieve the 2°C target with a 66% probability. Distributing this budget proportionally across the population of 2010 of 6'855.2 million (World Bank, 2011) and of 7.8 million for Switzerland (BFS, mittlere ständige Wohnbevölkerung der Schweiz), results in a 1.14 Gt CO2 budget for Switzerland. Assuming a linear decrease in emissions from its level of 45.14 Mt CO2 in 2010 (BFS, Treibhausgasemissionen der Schweiz 1990-2014, 2016), the budget will be used up by 2060. This means that CO2 emissions should equal zero after the year 2060. Assuming that all sectors of Switzerland (e.g. energy production, transportation, buildings) contribute in the same manner to the IPCC 2° target would require a linear reduction in annual CO2 emissions from the transportation sector, which reaches zero in 2060 (this implies over-proportional reduction in CO2 emissions per capita since the Swiss population is assumed to grow further). The corresponding target line for the CO2 emissions is shown in the figure below as a solid black line (without markers). This trend may be too stringent for the transportation sector and a slower decarbonization compared to other sectors is more likely. This is due to its large dependency on high energy density hydrocarbon fuels and because CO2 reduction in other sectors such as buildings might be easier and faster.

Figure 4.4 shows that not even the future CO2 evolution of Prognos NEP (dashed-dotted black line) reaches the desired reduction target. The scenario results in a 64% reduction by 2050, whereas the target for 2050 is 80%, lower than the reference value of 2010. To close this gap, demand side measures can decrease vehicle kilometers (dark red line) allowing to follow an evolution on the lower end of the illustrated range of scenarios. Nevertheless, to achieve the target of zero emissions after 2060, one driving factor has to reach zero by then, namely CO2 emissions per kilometer, as people will most likely keep using passenger cars as means of transportation. The light blue area indicates the required evolution of CO2 per kilometer for the two Prognos demand scenarios (dotted and dashed-dotted dark red lines) to follow the black target line. In 2050, the average fleet emission has to be 14 to 17% of that of 2010. This is a major reduction and approximately half the value the NEP perspective assumes. Therefore, demand measures are critical in order to reach the planned CO2 emission reduction in particular during the early phase by decelerating the usage of the CO2-budget.

Section 5.2 and 5.3 discuss in more detail which technology development may be expected and the plausibility of the underlying assumptions of the Prognos energy perspectives. We have to be aware that achieving the desired targets in the transportation sector (here road based passenger) does not mean the targets are met in the whole energy sector of Switzerland. Increasing the share of electric vehicles in the fleet leads to the decreasing trends of the light blue line (CO2 per vkm), but at the same time demands additional electricity. Depending on the CO2 intensity of the additionally required electricity production for electromobility, the CO2 reduction path for Switzerland (all sectors) may be by far less drastic even for 100% electrification of passenger cars.

# 5 Future developments on the demand and supply side

## 5.1 Demand side evolution

In this chapter, we focus on passenger mobility demand and on the key driving factors influencing it. We refer to the ARE scenarios (ARE, 2016) presented in Chapter 4 and to the terms of the Kaya decomposition introduced in Chapter 3, (in particular we address the terms D & E containing the variables pkm and vkm). We discuss how their future evolution might influence mobility demand, both in terms of total transport volume (number of trips) and person-kilometers travelled and in terms of modal split.

*Demography* and evolution of *GDP* and *income* (respectively, Term (B) and Term (C) in the Kaya decomposition (Equation 3.1) are key factors influencing mobility demand and can be regarded as exogenous factors. For this reason, all the ARE scenarios make the same hypotheses for their future evolution, even though introducing a spread of high and low sensitivity values (see Chapter 4). Expected growth in the population will produce an increase in total transport volume with respect to 2010. In particular, increased *longevity* will produce a growing population of healthy and mobility demanding users, with significant increase in demand for shopping and leisure purposes. Such a trend will be further enhanced by economic growth (increase in GDP) and increase in average incomes earned by the population. The additional mobility demand generated (both as number of trips and person-kilometers travelled) is expected to be satisfied mainly by cars, provided that systemic development continues in the previous way and if no opposite policy measures are taken.

Evolution of mobility demand based on the need to travel is grounded in *land use* and in *spatial structure* (Term (D) in the Kaya decomposition), that is in the distribution of cities, communities and rural areas with typical dispersal of economic centers, jobs and housing areas. In the last 2-3 decades, both share of population and of jobs in large and middle centers decreased, while their surrounding areas increased (ARE, 2014). This is leading to an increasing mobility demand due to commuting and a general increase of functional links between cities (large and middle size) and with their surroundings. In parallel, although cities began to implement a more restrictive parking space policy recently, an increasing trend was registered for the length and capacity of the road network – in higher proportions than the growth in public transport networks – as well as for the availability of parking areas (ARE, 2014). Availability of new roads and parking areas reinforces the increase in mobility demand brought about by urban sprawl and, especially, amplifies the present modal split in favor of cars.

Unless integrated spatial and transport policy as well as planning is implemented to strengthen the middle-sized cities ("Mittelzentren") leading to a more decentralized spatial structure in Switzerland, mobility demand based on spatial development can be expected to increase further. The recent revision of the Swiss Federal land planning law establishes key densification principles and goals for Switzerland. Introducing densification principles – as long as they are not compromising the quality of life in cities – has the potential to counter-act the above-described trends in spatial development and, in the medium to long term, produce a reduction in mobility demand. ARE scenarios confirm such considerations: even though the transport volume (number of trips) remains the same in varying land planning hypotheses in all the four scenarios. In the "Balance" scenario, which foresees a stronger application of densification and polycentric spatial development principles, overall person-kilometers travelled show a significant decrease with respect to the reference scenarios.

Possible emerging trends reinforcing such phenomena, only marginally considered in the ARE scenarios, come from younger generations and their values and lifestyles. In contrast to previous generations, who preferred to live in suburban single family homes, where they necessarily needed cars, emerging trends indicate younger generations seem to prefer living in central urban areas, where facilities are easily reachable at walking distance (Policy Frontier Group and U.S. PIRG Education Fund, 2012). Also, younger generations appear to delay the age when they obtain their driving license (OFS and ARE, 2012), instead favoring the use of public transport, which allows them to remain focused on their online social activities, thanks to smartphone and tablet devices (Policy Frontier Group and U.S. PIRG Education Fund, 2012; McDonald, 2015). Currently there is no indication for the overall extent of these phenomena, nor for their persistence over time. In fact, we cannot exclude that even though young generations have different attitudes than their parent generations, some of them will revert to cars once they start their own family. In general, despite the question of whether this different behavior is linked to different attitudes or will change towards a more car-based life with growing age, supporting this less car-dependent lifestyle of these generations might be a key aspect to address when aiming for sustainable mobility.

A key contribution to strengthen such emerging trends could come from the digital revolution and progress in information and communication technologies (ICT). ICT technologies might in fact favor both a reduction in the overall mobility demand (transport volume and person-kilometers travelled) and a shift towards public transport and slow mobility. Daily activities and/or working can be performed online from any place nowadays and at any time of the day or the night. It is still unclear, however, how effective ICTs will be in reducing demand – depending on how life style (in terms of leisure activities and social life) and the working world will change. Besides this, rebound effects might happen, since time saved from everyday mobility duties might be filled up with additional free-time activities, frequently performed by individual motorized transport: depending on individual situations, the balance between saved and additional mobility demand might therefore be negative. Similar considerations are developed in the ARE scenarios: the "Reference", "Sprawl" and "Focus" scenarios account for a slight decrease in trips for commuting purposes, compensated however by an increase in trips for shopping and leisure activities. Only the "Balance" scenario accounts for a higher influence of teleworking and flexible working possibilities on reducing the overall mobility demand.

Diffusion of ICT technologies might also favor a shift towards multi-modal use of the means of transport, and a general reduction in car use. In fact, exploiting ICT technologies and real-time traffic information, public transportation will become more flexible, attractive and competitive: individual mobility services which combine the traditional public transport offer (backbone of the mobility system) with ride-sharing services and slow mobility opportunities will be made available (see Chapter 5.4). Their diffusion might be supported and amplified by a closely-related socio-economic trend, which has gained momentum in parallel, and thanks to, the digital revolution. We refer to the *sharing economy*, which is explicitly discussed in Chapter 5.5. Possibilities to take advantage of advanced and personalized information systems, combined with shared vehicles and offer of mobility services, might profoundly influence modal split with respect to the present situation. Quantitative effects on the modal split due to the diffusion of ICTs and sharing economy are however difficult to predict. ARE scenarios make quite conservative hypotheses regarding such effects as well, basically in terms of slight increases in ride-sharing possibilities and increase in vehicle occupancy rates (higher in "Balance" and "Focus" than in "Reference" and "Sprawl").

A key influence on mobility demand, both in terms of transport volumes, passenger-kilometers and modal split, might also be produced by specific adopted *policy measures*. For example, current trends in climate protection regulations are substantially affecting vehicle powertrain and engine efficiency (Term (F') in the Kaya decomposition). Regulations on $CO_2$ emissions of newly registered vehicles prompt the evolution towards electric vehicles (EV) in particular (Seba, 2014; Prognos, 2012). This will probably reinforce the present modal split (the system will remain car-based). To some extent, EVs diffusion might even stimulate an increase in mobility demand, in terms of person-kilometers travelled. A decrease in fuel costs, together with the perception of being "green" and sustainable, might have stimulated EV users to drive more than in the past, when they were using ICE (internal combustion engine) vehicles (Cellina et al., 2016). On the other hand, reducing the overall transport demand, person-kilometers travelled or changes in the reference modal split might be obtained by coupling the present regulations with additional market instruments and mobility pricing policies. Such market strategies are already in discussion in Switzerland: for example, increasing fuel prices by means of a tax on fuel consumption, and/or increasing the cost of using transport infrastructure by means of congestion pricing schemes for urban areas. Such elements, which are politically and socially ambitious, are explicitly accounted for in the ARE scenarios: the "Balance" and "Focus" scenarios, in particular, consider policy measures aimed at increasing parking rates and internalizing external costs for private motorized transport.

Finally, mobility demand is expected to be deeply affected by technological progress in the field of autonomous, *driverless vehicles* (again, related to Term (F') in the Kaya decomposition). Even though socio-political factors (social acceptance, legal constraints on responsibility in case of accidents) might prevent their future diffusion (Nature, 2015), according to optimistic previsions, first completely autonomous, driverless cars might be available on the market within a decade (Waldrop, 2015; KPMG, 2012). Diffusion of driverless vehicles is frequently referred to as a "disruptive innovation", able to radically change current individual mobility patterns. They would in fact create affordable possibilities for individual transport, requiring neither driver attention nor capability. The possibility to reconsider travelling time as a productive time is expected to create an increase in person-kilometers driven (Plumer, 2013; Wadud et al., 2016): if commuters could continue sleeping while a car drives them to their workplace, or continue working when a car drives them back home, they could live further from their place of work. However, this might also entail an increase of total transport volume, since users without driving license (children, teenager, elderly etc.) might even use cars. Therefore, overall diffusion of autonomous vehicles might reinforce the present car dependence of society. In the ARE scenarios, completely driverless vehicles are not taken into account, due to the complexity of the legal and acceptability issues, which at present are still open and are not expected to be solved by the 2040 time horizon. However, diffusion of partially automated vehicles is considered in all the scenarios, apart for the "Reference" scenario: ARE acknowledges that their diffusion will produce an increase in person-kilometers driven and therefore associates them with an increase in road capacity, more efficient use of the existing road capacity in intercity roads.

## 5.2 Supply side: powertrains and vehicles

Supply-side measures refer mainly to technology development and improvements related to powertrain, vehicles and corresponding infrastructure (roads, rail, fuel, charging capacity, grids etc.). The supply and demand side interact in multiple ways and interface through business models for transportation services. Such business models may benefit from emerging IT/communication technologies (see Section 5.4) and contribute to a smart, lean and more sustainable future transport system.

In this section, we concentrate on non-infrastructure issues and focus on road transport for both freight and individual passengers, as this mode contributes to about 93% of the energy demand and 98 % $CO_2$ emissions of the overall transportation sector (excluding international aviation and "Tankturismus", Figure 4.1). Here we focus on operational CO2 emissions (tank-to-wheel). In this context, it is worth mentioning that significant differences exist between the individual passenger and the freight transport sectors. The former represents a typical consumer goods market, where purchasing and operating decisions exhibit behavior in conflict with economically rational arguments to a certain extent; the latter are in most cases the basis for investment and operation of truck fleets. In addition, fuel consumption plays a much bigger role in freight transport business (amounting to about 1/3 of total ownership costs vs. around a 1/7 share for the average car). On the other hand, there is no specific $CO_2$ price on either sector, which means that climate related external costs are not reflected in the prices of transportation services (BFE, 2014). Thus, the competitive landscape looks quite different between the individual passenger and the commercial freight transportation.

### Individual motorized transport

To estimate impacts on the end-energy demand and CO2 reduction potential of evolutionary and disruptive technologies in the passenger car sector, we considered the current approximate **42 TWh** of fuel energy consumed (dominantly oil products) and about **11 Mio t CO2** emitted by all passenger cars in Switzerland (BFE, 2014 and BAFU, 2015). Furthermore, for simplicity we assumed that the demand for pkm remains unchanged and that current research efforts by academia and industry are maintained in the future. Taking these aspects into account and considering the current technological advances in the field (some of them currently being addressed in SCCER Mobility), first estimates show that (Figure 5.1):

- Combining rather "low-hanging fruits" like improved aerodynamics, reduced rolling resistance and reasonable light-weighting with further internal combustion engine (ICE) efficiency improvements, a reduction in fuel consumption of up to 20% can be achieved
- Large scale development of hybrid powertrains would lead to another 20-25% reduction in fuel consumption down to around 60% of current state of the art
- Finally, a massive switch from diesel/gasoline to natural gas fueled engines reduces $CO_2$ emissions by at least 20%.

All told, passenger cars would then consume around **26 TWh** and emit **5.5 Mio t $CO_2$/year** (for the latter ½ of current emissions). Substituting natural gas with biogas would save another 14% of CO2 emissions, which amounts to **4.7 Mio-t CO2** per year. For this we assumed that the 23 TWh (per year) of sustainable biomass in Switzerland (Steubing et al., 2010) are converted to 15 TWh of bio-methane; 25% of which are assigned to passenger cars, proportional to their current relative share (in diesel and gasoline) within the total fossil energy imports of Switzerland. A further CO2 reduction to **4.3 Mio-t CO2** would be possible, if 50% of the estimated future summer electricity excess (9 TWh according to the Swissgrid scenario Sun2035) would be transformed to synthetic methane in power-to-gas facilities.

Radically new technologies like battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) must compete against this improved potential performance in the future. Assuming now that the same demand is satisfied by BEVs, and estimating an overall efficiency from electricity generation to the wheel of 60% including higher weight and non-propulsive demand, lead to an estimated electric energy demand of **13 TWh** (about ½ of best-practice ICE hybrids] for BEVs and about **31 TWh** for FCEVs (excluding transmission losses). Considering electricity production according to: (a) Swiss consumption mix, (b) combined gas power plants and (c) the EU-mix, the operational $CO_2$ emissions are as follows:

(a) BEV 1.5 Mio t, FCEV: 3.6 Mio t $CO_2$

(b) BEV 4.3 Mio t, FCEV: 10.2 Mio t $CO_2$

(c) BEV 6.5 Mio t, FCEV: 15.4 Mio t $CO_2$

More details on these estimates are given in Chapter 6 referring to the Strategic Guidance Project. It has to be mentioned, that slight differences can be observed among the calculations in this section and in Chapter 7 due to different data sources and sampling years. However, such differences are mostly within a margin smaller than ± 10% when considering the operational energy demand and CO2 emissions alone.

Therefore compared to the current ICE-based powertrain, fuel-cell vehicles are beneficial in terms of climate change mitigation only with the CH-consumer mix or pure renewable power generation, while BEVs maintain a small advantage against best-practice, natural gas-fueled ICE hybrids (ICEH) even if gas combined cycle power generation plants produce the additionally needed electricity. Of course, it should be taken into account that in the decades to come the carbon footprint of electricity generation in both Europe and in the US will decrease substantially. How fast this will happen will affect the comparative advantage of electrified powertrains against IC engines. The life cycle analysis in Chapter 7 will however show that energy investments and CO2 emissions upstream of the "tank" may be quite substantial and need to be taken into consideration in order to project realistic CO2 mitigation scenarios related to the transport sector.

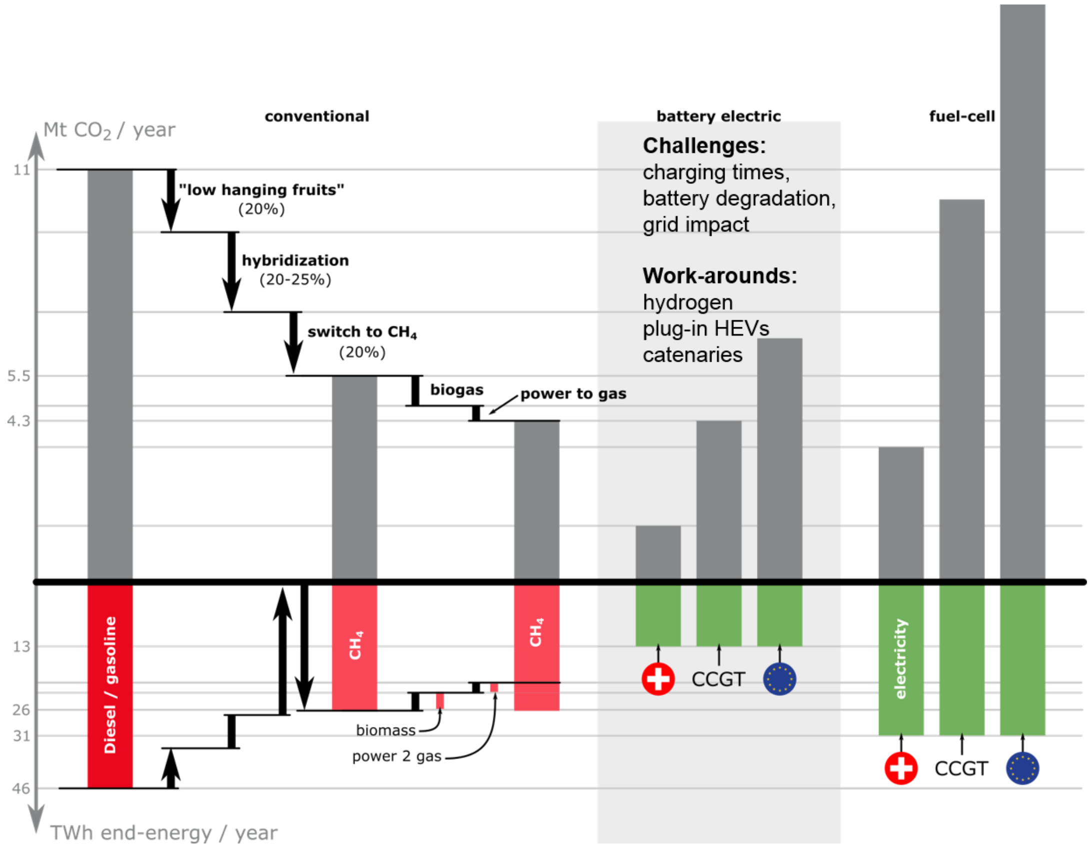

*Fig. 5.1 Impact of the evolutionary transition of drivetrains and energy carriers vs impact of disruptive-electrification driven transition on the final end-energy demand and CO2 emissions of the transport sector.*

**Light-and heavy-duty commercial vehicles**

The same considerations with very similar findings apply to light-duty commercial vehicles, while the situation for long-haul trucks is somewhat different. Here, BEVs continue to outperform internal combustion engine vehicles (ICEV)-though to a lesser extent – in terms of final energy demand and $CO_2$ emissions when renewable electricity is available. However, weight and costs of batteries for the typical daily range appear to constitute a major challenge (for the case of heavy-duty long-range transport may also be prohibitive). Thus, there may be a window of opportunity for fuel cell powertrains in long-range road freight transport if very large amounts of excess renewable electricity is available in the future. An even more pragmatic alternative could be the massive use of natural gas engines, which would replace a large portion of diesel-fueled engines mid-term, thus leading to a $CO_2$ reduction in this sector ranging between 10% (today) and ultimately 20% with high-pressure gas injection (Shell, 2016).

To summarize, intense competition can be expected among different powertrain technologies and the associated energy carriers during the next 2-3 decades. Given the substantial fleet renewal periods of 10-15 years and the even larger lifetime of existing power plants, the transformation of the transportation sector towards sustainability will probably not be accomplished before 2050.

To achieve such targets, ICE powertrain developments will require research efforts in combustion, thermodynamics, after-treatment, advanced controls and sensors as well as adaptive capacity towards fuel flexibility.

Research on BEVs will need to focus on battery performance, where further clear improvements are mandatory in terms of energy density, costs and lifetime aspects under high charging power and depth of discharge. It is worth mentioning, that prices have been dropping recently at 18% annually, energy density has increased and lifetime is on a good track.

Improvements in fuel-cell powertrains are needed mainly with regard to durability and costs, while high-pressure hydrogen tanks seem to be the most promising, though a very expensive option for fuel storage.

For all powertrains technologies, vehicle design and manufacturing must continue to contribute to the reduction of propulsion energy, while design and operation of heating, ventilation and air conditioning (HVAC) and other auxiliary devices will be important for the reduction of non-propulsive energy demand. The latter is particularly relevant for BEVs, to a lesser extent for FCEVs, since its share in the overall required energy is much higher in electrified powertrains than in conventional ones (Georges, 2014).

In conclusion, massive reduction of final energy demand and CO2 emissions makes a holistic implementation of improvements in vehicle and powertrain components imperative. Fierce competition among energy conversion technologies may be expected during the next decades with varying outcomes depending on the sector and on the evolution of the cost and performance of electrified powertrains, which are difficult to predict. Besides cost-to-performance aspects, the evolution of the electricity generation system will be of decisive importance for the final trajectory of the path towards sustainable mobility.

## 5.3 Energy infrastructure requirements and interfaces with the overall energy system

This section considers infrastructure requirements in a qualitative way by examining both energy supply (upstream processes for H2, electricity, biosynthetic fuels) and required transport/distribution networks, charging stations for individual and freight transport. A quantitative assessment is discussed in Chapter 7.

In this section, key questions refer to the technology and investments, which are necessary for replacing or partially substituting the existing fossil hydrocarbon-based fueling infrastructure. Charging infrastructure for BEVs is evolving and costs will probably decrease to competitive levels, however, charging times are still too time-consuming for long-range travel habits of customers. Recently, ultra-fast charging has been advertised as a potential solution. However, there are trade-offs, since battery lifetime may suffer drastically in such cases. In addition, configuration of the electric grid topology is critical to be able to adapt to local power peaks. Plug-in hybrids could counteract this problem if this technology becomes a competitive option, as overnight charging is sufficient and pressure for expensive public infrastructure is rather low. The same applies if home charging equipment becomes widely available within a reasonable time frame.

FCEVs offer some advantages compared to BEVs concerning infrastructure demands. Although initial investments for H2-stations may be quite high, the time for getting energy for a few 100 km driving is comparable to ICE powertrains and therefore the number of necessary charging (refueling) stations is much lower. On the other hand, logistics of H2 transport from generation to consumption location may induce additional costs. Moreover, electricity demand for FCEVs is higher by more than a factor of two compared to BEVs.

With regard to long haul trucks, interesting options for charging on the road (overhead lines) are emerging, which may become an alternative to ultra-heavy batteries, at least along highways and main routes and despite high investment and maintenance costs. However, depending on the actual requirements, an additional battery and/or a hybrid powertrain will probably still be necessary on-board the vehicles to cover all other routes.

Concerning an ambitious trajectory for CO2 emissions reduction of the entire Swiss energy system, it is important to consider the intrinsic coupling and co-evolution of the electricity and transport sectors. Electrified powertrains (for either BEVs or FCEVs) are expected to gain high market shares. Thus, it is crucial to examine the future CO2 footprint of their marginal (additionally needed) energy. While in Chapter 7 estimates of such developments will be presented in more detail, we discuss a few trends and interdependencies in a qualitative way in the following.

Marginal electricity for transportation may be obtained (assuming no new nuclear power plants will be built within the next decades) from the following:

(a) combined-cycle-gas power plants

(b) imports

(c) expansion of renewable energy sources in Switzerland

Option (a) can already be assessed now, as this power generation technology is established and its performance is well known. In addition, its security of supply is reasonable, given the diversified sources of natural gas imports of the country. As said before, under these conditions BEVs would emit about 30% less operational CO2 than the best-in-class gasoline hybrid vehicles and 10 % less than natural gas hybrids.

Option (b) will depend on the future evolution of the European electricity mix. With its current footprint, BEVs are in par with gasoline hybrids. Yet given the explicit need to phase out coal-fired power plants (with a market share of 45 % exemplarily for Germany) as fast as possible and the estimated stagnation of nuclear energy in our neighboring countries, most of the investments in renewable power generation are expected to be directed towards the replacement of fossil electricity. This process will require 20-40 years for its full implementation.

Option (c) requires a significant expansion of renewable electricity generation-capacity in addition to the one needed to replace our nuclear power plants, which are supposed to be gradually phased-out during the next around 20 years. The only conceivable primary source for such additional expansion is solar electricity. Its implementation at such a huge scale will not only require a very long time and extraordinary investment, but also pose big challenges for the electricity grid due to its fluctuating nature. On the other hand, rapid progress of local storage technology may offer interesting options (short-term in batteries, seasonal through electrolysis/hydrogen etc.) The scenario uncertainties and particularly the cost estimates of such disruptive transitions must be investigated in detail within our SCCER and within the framework of Joint Activities with other SCCERs in the next year.

Other non-energy related transportation infrastructure will be very important for the evolution of the mobility system and will influence not only the supply but also the demand side and other environmental and economic performance parameters, potentially leading to new business models and financial schemes for the required high investments (Weidmann et al., 2015).

Examples of such infrastructure that can significantly influence the future mobility system are among others: a European high-speed train system, integrated logistics hubs and dedicated infrastructure for autonomous, interconnected cars, if the technology will make headways in the near future. In this case, cyber-risk/security are additional issues of concern.

## 5.4 Game changing technologies

Throughout its historical development, human mobility has been deeply interwoven with technological advances, some of which, such as the invention of the automobile, have profoundly changed our ways of traveling (Taaffe et al., 1996). Currently, a comparable game changing effect is often attributed to the rapid progress of information and communication technologies (ICT), also concerning the potential for supporting smarter and more sustainable forms of future transport (UN, 2012). With this background, this section aims to identify ICT trends of prospective relevance for the future of sustainable mobility. In our opinion, there are two distinct but mutually connected areas where ICT-driven applications can particularly support future sustainable forms of mobility and transportation, namely *ubiquitous monitoring of mobility behavior* and its *real-time regulation and management*.

The potential for improved monitoring is closely related to the current technological developments in the field of geosensor networks. Recently, these small-scale computing platforms have become continuously less expensive, smaller in size, and easier to use, which increased the feasibility of creating widespread, extensive geosensor networks (Nittel, 2009). Providing a backbone for future smart cities, these wireless interconnected devices enable real-time collection and integration of various data, e.g., describing current weather conditions or flow densities on transportation networks (Tubaishat et al., 2009). Thus, there is potential to monitor individual and collective mobility behavior at a much finer and more comprehensive level, and integrate this information with simultaneously collected contextual data like current temperature measurements or precipitation rates. Another valuable means for data collection is provided by the widespread use of location-enabled devices such as modern smart phones, which are especially relevant concerning recording the movement of individual persons (Yuan & Raubal, 2016). Such data are often freely available as a novel form of user-generated content, generally subsumed under the umbrella term of volunteered geographic information (VGI), which can be either contributed actively, e.g. by explicitly geo-referencing selected media, or passively, e.g. by automatically collecting data from the phone's various sensors (Goodchild 2007). Providing a basis for the development of novel methods for big-data-driven mobility analysis and modeling, these semantically rich spatiotemporal datasets offer unprecedented possibilities for gaining insights into the mechanisms of human mobility, especially when being integrated with context-sensitive information (Miller, 2015). However, at the same time it is critical to protect the individual user's privacy by means of privacy-preserving mechanisms (Freudiger et al., 2012).

Apart from mobility modeling and analysis, these type of data represent a prerequisite for a real-time regulation and management of transportation systems (Tubaishat et al., 2009). One possible way to increase their efficiency and safety is to use intelligent transport systems (ITS), which, based on multi-sensor data, can provide travelers, traffic managers, planners, and policy-makers with real-time traffic information, and thus reduce traffic congestions, lower the risk of accidents and improve the quality of public transport (UN 2012). However, without the need for top-down measures, travelers themselves will be able to deploy mobility-related location-based services (LBS) via their smartphones to a greater degree. These services will be able to provide highly personalized situation- and context-dependent mobility decision support (Raubal, 2010), e.g. in the form of multi-modal route planning (e.g., Bucher et al. 2016a) or by providing assistance towards improving the sustainability of one's personal mobility behavior (e.g., Rudel et al. 2014). An example for such approaches is the GoEco App[2], which aims at investigating if and how information feedback and social interactions (social comparison and peer pressure) can be effective in fostering long-term changes in personal mobility behavior towards choosing more sustainable travel options (Rudel et al., 2014; Bucher et al., 2016b). However, in view of the fact that there is a potentially preserving digital divide, it is important to ensure equal access to such assistive technologies for the entire population. Closely related to motorized traffic is the current trend towards car automation and autonomous driving. Today's automobiles already partly take over their drivers' responsibilities with automation levels ranging from providing purely informational assistance to assuming or seizing complete control of the vehicle. The potential effects of these technological developments on sustainable mobility include more efficient traffic flows, increased safety levels and an improved access to individual car travel for mobility-impaired persons (Casner et al., 2016).

In summary, the possibilities for the collection of large, highly detailed datasets on mobility behavior as well as its contextual and personal determinants can be expected to increase drastically in the future, and thus build a foundation for thoroughly understanding human transport as well as for regulating and managing mobility. Although there is a risk of unintended rebound effects, such as increased levels of traffic as a direct result of more efficient transportation systems, these trends have immense potential for strengthening sustainable forms of mobility.

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[2] http://goeco-project.ch/index.php/en/

## 5.5 Shared mobility and automated vehicles: potential impact on energy consumption

In the following the potential and possible scenarios for implementing shared mobility and automated vehicles at a large scale was analyzed using MATSim, an activity-based multi-agent transport simulation framework (Horni et al., 2016). MATSim mimics a virtual population based on census data of particular study region by means of individual agents which perform daily plans (a series of activities), and get positive utility from activity performing and negative utility from travel. In both cases, the greater Zurich region, Switzerland, was used as a study case to model demand at high spatial and temporal resolution.

### Shared Mobility

The importance of shared mobility has grown constantly in the last few decades (Shaheen, 2012) and has the potential to disrupt the transportation system, as we know it today. Literature dealing with shared mobility is already quite extensive, but there are still some evident research gaps. The most glaring gap is that shared mobility has been considered as a "stand-alone" system frequently, ignoring the whole complexity of its interactions with other (shared) modes. Therefore, it is not yet possible to estimate how large-scale, integrated systems of shared mobility will impact the transportation system. Addressing this gap entails trying to find optimal combinations of shared mobility solutions, which would provide a substantial reduction of energy consumption without reducing individual mobility needs.

The first stage of the MATSim simulation project dealt with the generation and evaluation of some "extreme scenarios" meant to provide insights about the impact of the extremely wide diffusion of a particular shared mode. This allows understanding which kind of trips can be made realistically with which mode, what kind of potential overlap exists in supply, and what kind of cost/benefits can be expected.

The series of simulations performed so far focused on car and bike sharing. For car sharing, it was found that about one fourth of the current fleet size would be necessary to substitute all privately owned cars and provide a reasonable level of service for the users (within five minutes of waiting time). However, when only considering the actual utility of such a system, it appears that access time is critical, and for shorter trips, the personal car is still the most appealing option. To test if shared e-bikes could complement such a car sharing system, simulations with a large bike-sharing system were conducted. E-bikes appear to be less convenient than car and public transport and the difference grows for longer distances. However, for short distances, e-bikes have a real potential to complement the car-sharing system.

Therefore, the results obtained show that shared e-bikes and car sharing could be combined suitably to cover a large part of current travel demand, in particular car travel in the study region. However, it seems that for medium distances (5-10 km), it could be necessary to integrate an additional option as e-bikes do not compete well with private cars in this case and car sharing in the suggested form is not yet competitive due to the relatively high effect of the access time in this distance range. Ridesharing could represent this additional option, as it would also have a certain, probably similar, access time and may in fact be cheaper. This requires the exploration of further extreme scenarios with only single mobility options and combining scenarios with two of these modes or even all three. Finding an equilibrium between a large-scale car sharing and a large-scale ride-sharing scheme will not be trivial. A car sharing system with the selected specifications can substantially reduce the size of a city's car fleet and it would be possible to avoid private car ownership completely whilst providing a good level of service. However, if ride sharing would be based on private cars, a large enough fleet should still be available. Another equilibrium would have to be found if this were to be a shared taxi scheme.

These simulation results provide first information about how shared mobility solutions could be combined and implemented with the overarching goal of reducing energy consumption, but without sacrificing individual mobility needs. This creates a foundation to assess which policies could potentially support the transition to a more sustainable and less energy intensive transportation system. In the next phases of this project, discrete choice models will be implemented in the simulation so that it will ultimately be possible to run new simulations with fully functional representations of car sharing, bike sharing and ride sharing. This will further illustrate how shared mobility modes could be integrated at large scale, covering a large part of the current travel demand whilst reducing transport-related energy consumption. Besides minimizing energy consumption, different dimensions could be included in the simulations, such as embodied energy (the energy required to produce goods or services) or broader environmental and social benefits.

**Automated Vehicles**

The idea of an automated vehicle (AV) is already several decades old. For a long time, research on this topic addressed the technological aspects of AVs exclusively. Recent developments, however, made clear that the technology will soon be available. The consequences for the transportation system are still uncertain, but it is reasonable to assume that they could be extremely far reaching. Some researchers already pointed to the fact that to effectively harvest all the possible benefits of AVs, a "car-sharing"-like scheme should be preferred to an ownership based model. Specifically, a large-scale AV car-sharing scheme able to satisfy most of the demand currently covered by personal cars, would require a much smaller total car fleet, an obvious benefit in terms of invested energy and public parking, but not necessarily for operational energy. Moreover, it would enable a more efficient use of the vehicles in terms of productive time with a cascade of positive outcomes, for instance reduced parking requirements and thus freeing up large areas of high value urban space.

To explore how the introduction of AVs could reduce the overall required vehicle fleet size, several simulations were run, assuming that different shares of the current car travel demand were fulfilled with differently sized AV fleets. Demand was defined as a static value (i.e. demand cannot adapt to the available transport supply and traffic situations) and it is resolved at smaller spatial (meter coordinates) and temporal scales (1 s intervals) than demand simulations found in current literature (e.g. Burns et al., 2013; Fagnant et al., 2014; Spieser et al., 2014; Zhang et al., 2015). Furthermore, demand originates from locations over a very large area from almost anywhere in Switzerland and from some regions outside close to the border (an area of 420km x 270km). This provides a more solid basis for the ongoing discussion of the fleet size required to serve a certain travel demand with a given level of service. We found that, for a fixed level of service (in terms of the waiting time), the relationship between trips served and fleet size is non-linear and the ratio decreases as the number of trips increases. This resulting scaling effect implies that the fleet is used in a more or less efficient way depending on the level of demand.

In comparison to earlier studies (Fagnant et al., 2014; ITF, 2015), a much lower peak fleet usage was achieved. The average usage was also lower as the trips served per day per AV and the total usage time of an AV was lower. Further details on the results are provided focusing on a scenario in which 10% of the original car travel demand is translated into demand for AVs and where the AV fleet size is 10 times smaller than the number of cars originally used to satisfy this demand. While a peak usage of around 70% was achieved here, other studies (Fagnant et al., 2014; ITF, 2015) found values of 97% and higher. The same applies for the average usage. In our study, AVs were used about one third of the day and served an average of 26.9 trips while other studies found a usage rate of two thirds of a day and an average of 35.87 trips per day.

While some of these effects can be explained by the larger scenario area and the lower population shares used in our cases, at least some of this difference is also attributed to the more detailed demand. This is supported by the fact that still only 10% of the existing car fleet is sufficient to serve the current car travel demand, which also hints at a strong influence of the spatiotemporal characteristics of the demand on the possible substitution rate. Indeed, it is argued that, these differences are mainly due to the inner city character of other studies (Fagnant et al., 2014; ITF, 2015). Inner cities show an above average high density of demand, which results in very high usage numbers of fleets. The demand used in our study shows what should be considered if a more open scheme would be applied. Indeed, looking at the number of met requests versus trip distances, hints at the fact that a limitation of the service area has strong influence on the average fleet usage and the level of service achievable.

It is interesting, however, that even for this large area, AVs have the potential to replace up to 10 of today's cars if a maximum waiting time of 10 minutes is accepted and the share of the participating population is large enough.

The used simulation framework still has several limitations and future work will address them. The greatest limitation is applying a static demand. Transport demand is influenced by new mobility offers and changing mobility costs. Ideally, demand should be able to adapt to these new offers in the simulation. AVs might induce more demand because they make traveling more comfortable and less expensive. This might also induce mode changes from public transport and slow modes to AVs. Such demand changes might bring the transport infrastructure to its limits and increase travel times with AVs. In turn, this would have reducing effects, bringing the system to a new equilibrium. How these effects influence each other, what the new equilibrium entails and what this means for infrastructure capacity requirements, prompts an investigation with simulation frameworks able to account for such effects explicitly.

## 5.6 Concluding remarks

While evolution of future transportation demand is subject to various drivers that may lead to increasing or decreasing trends in the absence of stringent policy measures, supply side trends concerning the CO2 reduction potential can be predicted according to different powertrain technologies and energy carriers portfolio.

While efficiency increase of vehicles and powertrains of up to 50 % can be achieved gradually with hybrid, combustion based systems; the necessary radical decarbonization of the transport sector is only feasible with a massive deployment of electrified vehicles on the long term. However, the footprint of the marginal electricity for transport must be kept very low, particularly due to the phasing-out of nuclear power plants. Thereby, fuel cells show have logistical advantages for long-range, heavy-duty transport, while battery-electric vehicles are expected to dominate short-to-mid range, light-duty mobility due to their superior energy chain conversion efficiency.

Positive effects towards multi-modality can be expected from digital technologies on the demand side, while a possible breakthrough in automatic driving technology may lead to strong demand increase, subsequently leading to adverse effects on the energy demand for mobility, despite positive first-order effects of new options for car- and in particular ride-sharing.

# 6 Examples of interventions investigated within the Strategic Guidance Project

The Strategic Guidance Project aims to put specific research focuses of individual groups in the SCCER Mobility in context with the Swiss transportation system. Thus, it attempts to evaluate the maximum impact potential of various research directions in a systematic way, i.e. the impact on the individual terms of the Kaya-type equation of Chapter 3.

The model used within the Strategic Guidance Project is an energetic model, consisting of a demand and a supply (vehicle) part, linked to the energy system by standardized energy carriers, e.g. gasoline, diesel, LPG, etc. It describes the end-energy demand and ensuing operational $CO_2$ emissions (not of an LCA) of the road-based Swiss transportation system and is based on statistical data from the government. The demand side is covered by the survey *Mikrozensus Mobilität und Verkehr 2010* (MZMV, 2010) for private transportation and by the surveys *Erhebung leichte Nutzfahrzeuge* (LWE) and *Gütertransporterhebung* (GTE) for light and heavy-duty good transportation, respectively. Those surveys contain a representative set of vehicle usage profiles (including good type and payload for freight) and information about the used vehicle. The missing vehicle specifications needed for the energy demand computation are based on the distributions derived from the MOFIS register, the database of all registered vehicles in Switzerland. It is worth stating that the set of all considered vehicles – the fleet – resembles the actual Swiss fleet, i.e. it is composed of individual and not categorized vehicles. The conversion of traction energy to end energy demand (fuel energy) of the individual vehicles is carried out by using standardized driving cycles and a linear conversion model, the so-called Willans line. This model originates from the physical description of energy converters and it is based on vehicle measurements done at EMPA (Bach, 2011). The Worldwide harmonized Light vehicles Test Procedure (WLTP) and World Harmonized Vehicle Cycle (WHVC) for heavy duty vehicles are used as driving cycles.

The model we apply within the Strategic Guidance Project is still under development, but can already be used to evaluate some example interventions, which will be discussed below. The term "intervention" implies a one-at-a-time modification of the transportation system from the reference state – the status quo – as it is defined by the MZMV data of 2010 (latest release) for passenger transportation and LWE and GTE data of 2013 for freight transportation. At this stage, predictions into the future are not possible and any realistic penetration rates of a technology or the resulting social effect are not evaluated. Each intervention is carried out independently and to its maximum application resulting in a maximum reduction potential. Rebound effects are not part of the model and thus not considered in the results. The electricity production mix is presumed to be invariant from today's level, regardless of the additional electricity demand – which is the only cost function.

### Motorized vehicles for passenger transportation

Figure 6.1 illustrates results from the Strategic Guidance Project on mass of CO2 reduction for passenger transportation. Each separate numbered line stands for an intervention, which can be related to a modification of a term of the Kaya-type equation in Chapter 3. All shown interventions affect vehicle technology and/or the used fuel carrier. To clarify, the calculations are carried out with the model described above and are only linked to the Kaya equation to illustrate the method descripted in Chapter 3.

1. **Hybridization and fuel switch** (Topic A2.2): Hybridization of the entire passenger car fleet increases powertrain conversion efficiency and thus acts beneficial on term G of the Kaya-type equation (neglecting increase in vehicle mass). Switching the energy carrier from gasoline and diesel to CNG (affecting grouped term of H and I) could increase the maximum reduction potential to roughly 4.5 megatons of CO2. No additional electricity demand is needed, since hybrid-electric vehicles only operate on hydrocarbons.
2. **Battery electric vehicles** (Topic A1.1, B1.1, and A3.3): Starting from the current Swiss fleet, battery electric cars are introduced where they are capable of providing the demanded mobility service

(according to MZMV 2010). Current battery technology is deemed able of providing 100 km autonomy range (neglecting change in vehicle mass, including cabin heating). It is important to understand that in this intervention battery electric vehicles are only employed where applicable and do not substitute the entire fleet. Increased powertrain efficiency (term G) is the main driver for CO2 reduction. Additional electric energy is required, which – dependent on the electricity mix and infrastructure losses (grouped term of H and I) – will lower the CO2 reduction potential. A charging infrastructure, which allows covering a larger daily distance without modifying the vehicle (same battery size) can shift the maximum reduction potential further along the dashed line towards the 100 percent limit.

3. **Plug-in hybrid electric vehicles (Topic A1, A2.2, A3.3)**: By increasing the battery capacity of the HEV fleet of Intervention 1 (see above) and allowing battery charging at the electricity grid, an additional degree of freedom is introduced, namely the choice of energy carrier with effect on terms H and I of the Kaya equation (Equation 3.1). It is assumed, that the entire fleet consists of plug-in hybrid electric vehicles with an all-electric range of 40 km (state of the art) and the increase in vehicle mass is neglected. Further increase in battery capacity as indicated by the dashed line converges towards the all-battery electric vehicle fleet. Additional mitigation stems from substituting compressed natural gas (CNG) by the finite, national biogas supply (Steubling et al., 2010). It is assumed that half of the biogas supply is available to mobility, analogous to the approximate 50% share, which mobility currently holds as a consumer of fossil fuel.
4. **Fuel-cell electric vehicles** (Topic A2.1, A3.3): Substituting the current ICEV fleet by state-of-the-art fuel cell electric vehicles (or technology) can provide the demanded mobility services (no concerns about range) with no local $CO_2$ emissions. Nevertheless, a large amount of additional electricity is required to produce hydrogen, which lowers the maximum $CO_2$ reduction potential. The vehicle powertrain efficiency increased compared to conventional ICEV (lower G term). The illustrated CO2 reduction potential is computed based on the hydrogen production with electrolysis using the current Swiss consumer mix. Further $CO_2$ reduction (based on existing vehicle technology) can only occur by reducing the $CO_2$ intensity of the electricity mix or a less energy intense hydrogen supply (grouped term H and I).

The results resemble maximum reduction potentials based on the current transportation sector (status quo). Renewable energy storage, e.g. power-to-gas, are not considered. Likewise, changes in $CO_2$ intensity of the Swiss consumer mix in time or due to increased demand are not taken into account. In general, temporal dimension are not given in Figure 6.1.

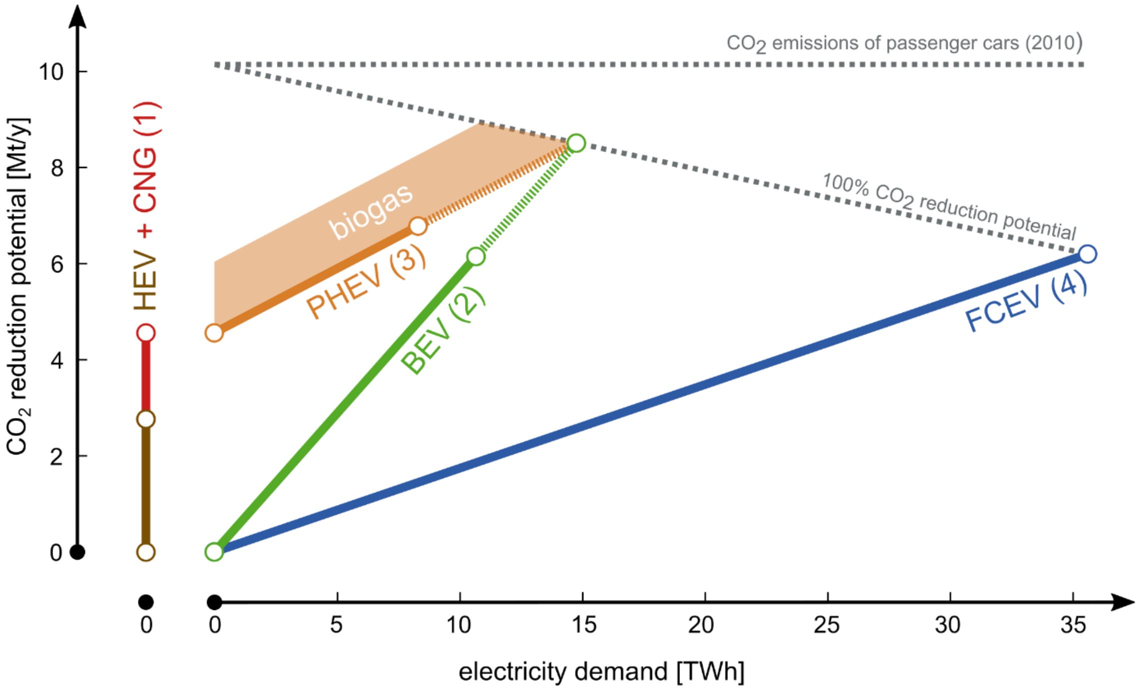


*Figure 6.1: CO2 mitigation potentials and additional required electricity for the different technology "interventions" for passenger transportation studied within the SCCER Mobility project "strategic guidance". All numbers are relative to the status quo as of 2010; only operational CO2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.*

### Light duty freight vehicles

Technological intervention can also be evaluated for freight transportation sector. Figure 6.2 shows results for the light-duty sector and Figure 6.3 for the heavy-duty sector, respectively. Those interventions rely on slightly different assumptions than the previously discussed interventions on passenger vehicles, accounting for changes in vehicle mass and using constant component conversion efficiencies.

1. **Hybridization** of light duty freight vehicles (Topic A2.2): Even accounting for the increase in vehicle mass due to additional components, the hybridization of the entire light-duty freight vehicle fleet leads to a significant reduction in CO2 emissions. The reason for this trend is the increased fuel conversion efficiency. Compared to passenger cars, this potential is lower due to the lower rated power to mass ratio of freight vehicles. This results in less part-load operation, leading to a higher average conversion efficiency than passenger cars. Again, no additional electricity demand is produced.
2. **Battery electric** light-duty freight vehicles (Topic A1, B1.1, A3.3): Battery electric delivery vans are introduced with an autonomy range (including cabin heating) of 150 km. Only if they can provide the demanded service according to LWE 2013, accounting for payload limitations and vehicle mass change due to the alternative powertrain, a battery electric vehicle is a valuable alternative. Not all vehicles of the fleet can be substituted. The increased powertrain efficiency (term G) is the main driver for the CO2 reduction. A charging infrastructure can facilitate an increase in the maximum CO2 reduction potential (along the dashed line).
3. **Fuel-cell electric** light-duty freight vehicles (Topic A2.1, A3.3): In analogy to the fleet of hybrid electric vehicles, a fuel cell electric vehicle fleet is designed – substituting the fuel carrier with hydrogen and the conversion to electricity with fuel cell stacks. No range anxiety is assumed, which allows altering the entire fleet. Locally, there are no CO2 emissions, but the reduction potential is limited by the supply of hydrogen with electricity.

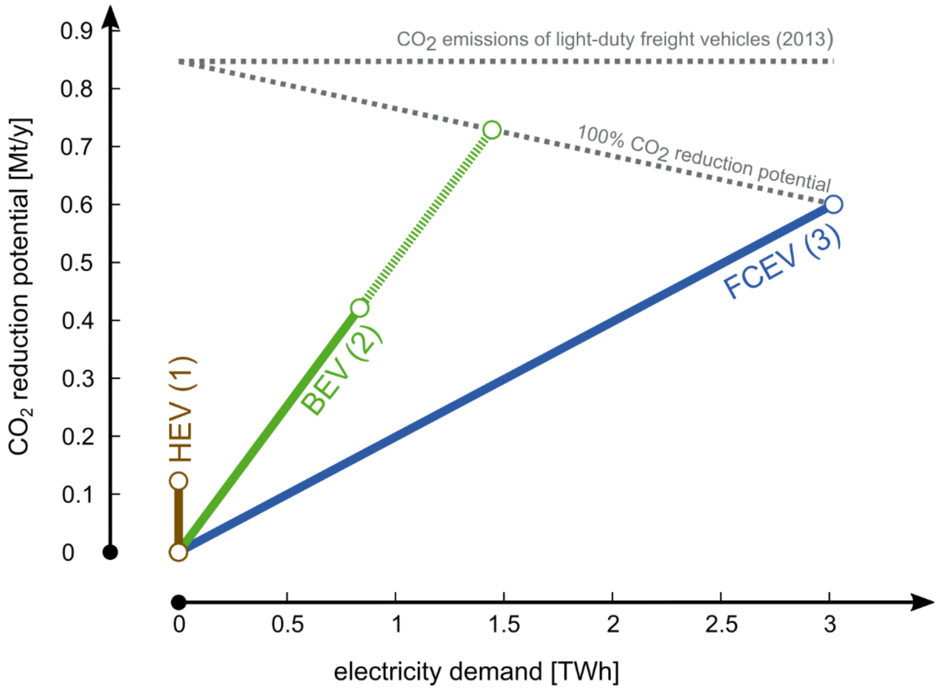


*Figure 6.2: CO2 mitigation potentials and additional required electricity for the different "interventions" for light-duty freight transportation. All numbers are relative to the year 2013; only operational CO2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.*

### Heavy-duty freight transportation

The technology interventions for the heavy-duty freight transportation sector are shown below in Figure 6.3. This sector contains rigid trucks and articulated semi-trailers. Two interventions are carried out, namely battery electric and fuel cell electric vehicles. Hybridization is not considered, since the reduction potential was assumed to be rather small compared to current conventional powertrain designs. The applied interventions only consider rigid trucks, leaving all semi-trailers of the fleet untouched.

1. **Battery electric** heavy-duty vehicles (Topic A1.1, B1.1, and A3.3): Based on existing battery electric truck designs (EFORCE ONE AG) and allowing for a maximum legislative vehicle weight of 40 tons, the reduction potential is shown in Figure 6.3. The higher conversion efficiency (term G) has a positive effect on the reduction potential. Available range and reduced payload capacity limit are hindering factors. Improving battery technology, fast charging or battery swapping are options to increase the reduction potential further along the dashed line.
2. **Fuel-cell electric** heavy-duty vehicles (Topic A2.1, A3.3): Starting from the all-electric design of 1, the hypothetical fuel cell option requires a smaller battery and supplies the charge by fuel cell stacks converting hydrogen. The system is designed to carry the same energy after conversion, i.e. at the wheel. Although the superior energy density reduces the payload capacity limitation, due to limited range and the electricity intense provision of hydrogen, the reduction potential is on the same order as the battery electric option. A good infrastructure allowing for fast refueling can increase the reduction potential significantly.

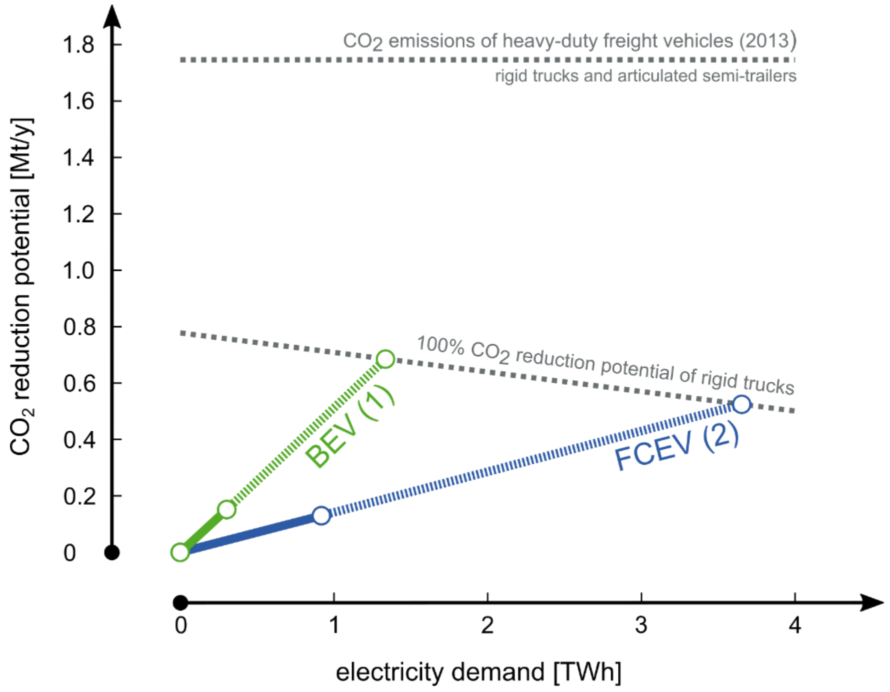


*Figure 6.3: CO2 mitigation potentials and additional required electricity for different "interventions" for rigid trucks accounting to heavy-duty freight transportation. All numbers are relative to the year 2013; only operational CO2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.*

### Influence of vehicle weight and engine power

All shown interventions refer to the vehicle powertrain, which is not the only possibility to reduce CO2 emissions. Another option are lightweight materials, investigated in Capacity Area A3.1 of the SCCER Mobility. The application of those technologies can occur based on different choices, resulting in quite different CO2 reduction potentials. Figure 6.4 shows the results of two light weighting interventions. The absolute numbers must be treated carefully since they are derived with a preliminary energy conversion model. The left bars show the results of a "classical light weighting" approach, where the curb weight of the car is reduced and combined with a downsizing of the engine, keeping the vehicle acceleration constant. The shown numbers correspond to two optimistic weight reduction levels of 10 and 20% proposed by the researchers, who are active in the field (Capacity Area A3.1). An alternative approach could be "sporty light weighting" represented by the center figure. There, no engine downsizing occurs, resulting in a higher acceleration. The reduced weight acting on term F of the Kaya-type equation shows a stronger impact than the increase of term G due to more part load operation, leading to an overall reduction potential of CO2 emissions, less than in the first case, however. The right panel shows the results of an intervention on rated vehicle power. No light weighting is applied, but the engine size is reduced to meet a given increase in acceleration time from zero to 100 kph. Although it is a technical modification on the vehicles acting on term G of the Kaya-type equation, this intervention is limited purely by people's acceptance. Therefore, it can be classified as a social invention, in contrast to a technical one. A change in individual behavior is implied, resulting in the selection of a differently designed car. As shown, substantial CO2 reduction can be achieved by this "sufficiency" measure.

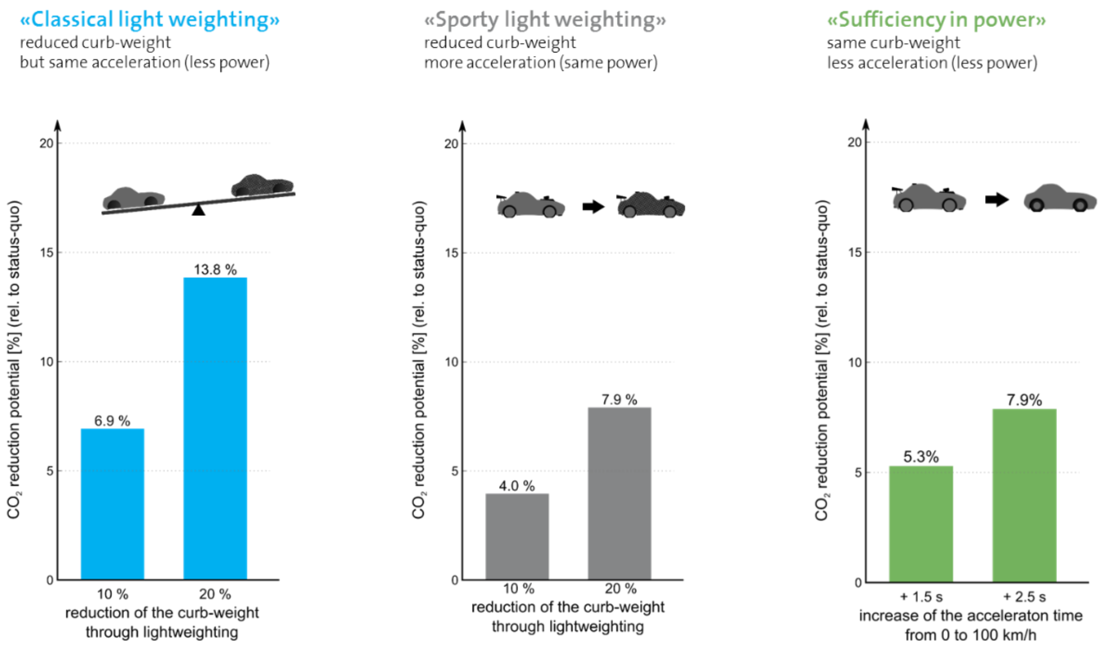


*Figure 6.4: Share of CO2 mitigation potentials of change in vehicle curb weight and/or rated propulsion power of passenger cars. All numbers are relative to the status quo as of 2010; only operational CO2 of passenger cars is considered.*

**Modal shift – two examples**

An often-discussed topic implying a behavioral change is the shift of the modal split towards a higher use of public transport, i.e. promoting rail transportation to encourage people to travel with passenger cars less frequently. The two following interventions address two kinds of such shifts in mobility services (vehicle kilometer) provided by passenger cars to other means of transportation. First, the reduction potential of non-motorized mobility is investigated by substituting short travel distances with bicycles and e-bikes. The full reduction potential is achieved by substituting all travelled distances shorter than the maximum stage length, chosen to be 5 km for bicycle and 10 km for e-bikes. The criteria for feasibility considers that from leaving home until returning (trip) no single distance (stage) between points of interest, e.g. home, work, shopping center, etc. may exceed the set limits. Additional hurdles further reduce the CO2 emission reduction potential as illustrated in Figure 6.5.

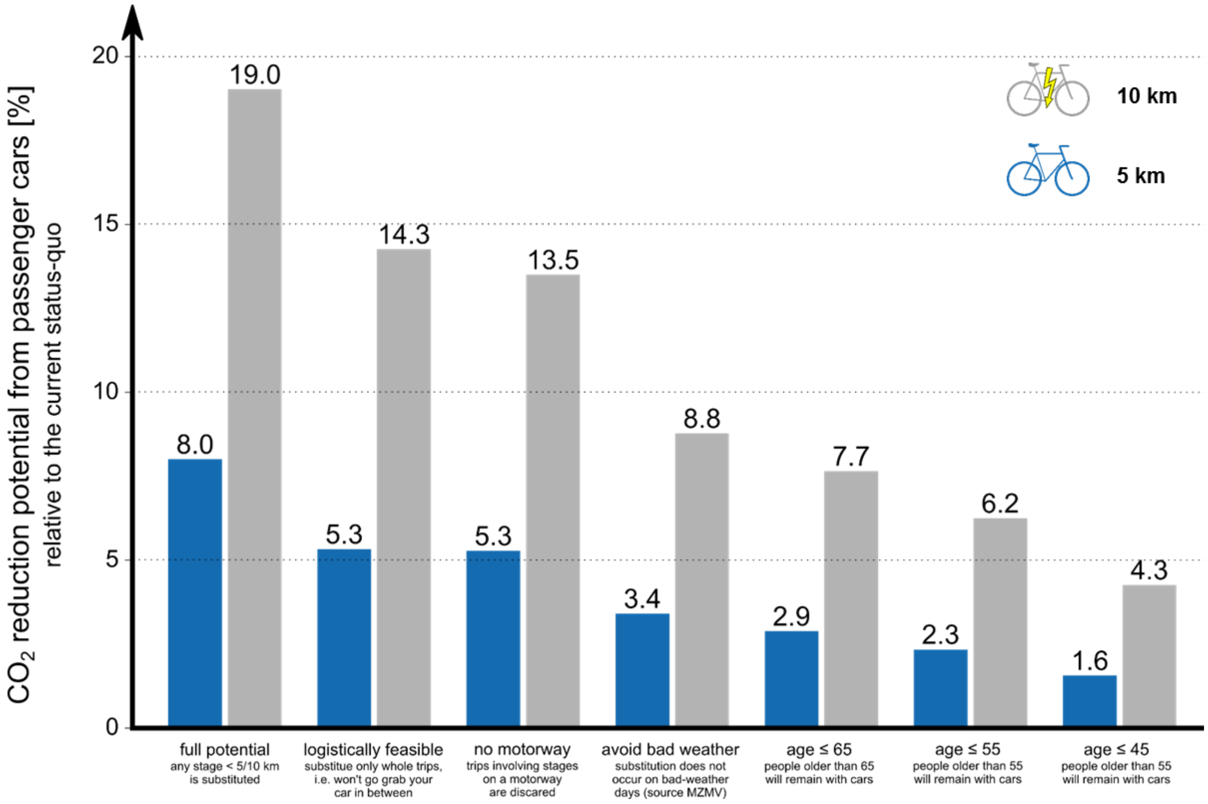


*Figure 6.5: Share of CO2 mitigation potentials from substituting passenger car stages with bicycles and e-bikes. The set limiting stage lengths are 5 and 10 km. All numbers are relative to the status quo as of 2010; only operational CO2 of passenger cars are considered.*

The second already mentioned alternative are trains. They are high capacity vehicles pooling people with similar travel destinations. The focus of the following intervention is on commuting people to one of the five core cities in Switzerland (Zurich, Bern, Basel, Geneva, and Lugano). The public transport infrastructure within those cities are assumed to be well established and capable of providing equivalent mobility services as a passenger car would. The commuting part of the trip is considered the reason why people prefer passenger cars. If all those people would shift to train, the full CO2 reduction potential is around 17 percent of the status quo passenger car emissions (as shown in Figure 6.6). This translates into additional necessary infrastructure (rolling material etc.). Additional hurdles like travelling time and comfort reduce the maximum reduction potential.

**Concluding remarks**

The above considerations show that a combination of demand, modal choice and supply –side (technology) measures can lead to a substantial reduction in energy demand and CO2 emissions in transportation. However, in this context we have discussed "first-order" interventions, not pursuing further subsequent "second-order" effects and policy measures enabling implementation of such interventions. In addition, we have only explored operational CO2 emissions and energy demand thus far, not taking into account effects of invested ("grey") energy and CO2 for hardware/ infrastructure. The following chapters will expand the discussion to consider such additional effects as well.

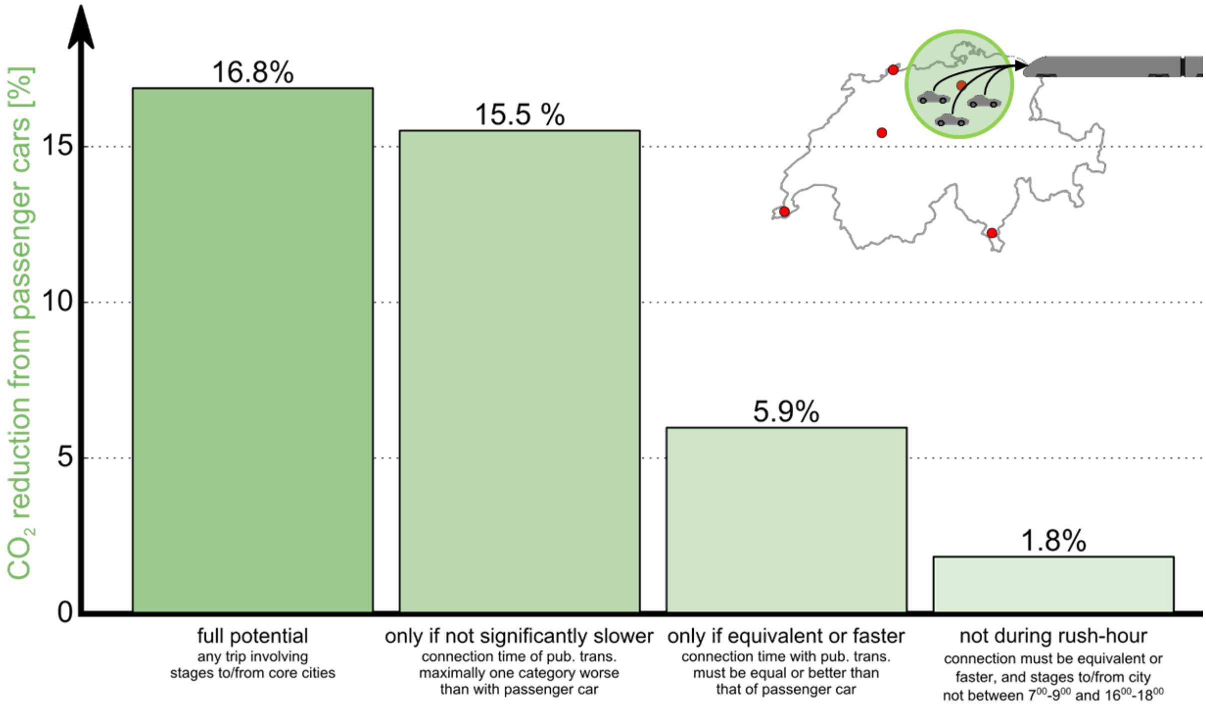


*Figure 6.6: Share of CO2 mitigation potentials from substituting commuting trips to the five core cities performed with passenger cars by train. All numbers are relative to the status quo as of 2010; only operational CO2 of passenger cars is considered.*

# 7 Integrated Assessment of Technology and Mobility Systems

This chapter provides examples of approaches and results used in the integrated assessment of current and future mobility. When addressing future mobility, prospective technological advancements are explicitly considered and modeled. The approaches employed for technology evaluation for example include life cycle impact assessment (LCIA), cost assessment (CA) and risk assessment (RA). Multi-criteria decision analysis (MCDA) is applied at the level of individual technologies as well as to car fleet options with different extents of penetration of advanced technologies, such as electric battery cars and fuel cell cars. First results from the application of the new bottom-up energy systems model with detailed representation of energy and mobility technologies and high time resolution are presented in the following. This allows analyzing in detail the complex interactions and dependencies between energy supply and mobility as one of the core end use sectors. While all the major modes of mobility are represented in the model at this stage, the representation of car technologies reflects state-of-the-art assessments. However, this does not apply to the other mobility modes such as public or goods transport, which will be integrated correspondingly in the second phase of SCCER Mobility.

The basic component of the assessment is a set of criteria and the associated indicators. These should be quantifiable, technology-specific, balanced, logically independent as much as possible, consistent and manageable (i.e. representative but not exhaustive). Concerning the energy transition and in view of its explicit goals, the most central criteria are climate protection (i.e. reduction of greenhouse gas emissions), reduction of the use of non-renewable energy resources and implicitly also the economic affordability. However, a much broader set of criteria needs to be established when addressing sustainability. This calls for covering the three pillars of sustainability, i.e. environment, economy and social aspects, which from the practical point of view represent conflicting objectives at least to some extent. Furthermore, one needs to keep in mind that also issues such as security of supply are of high importance along with specific performance characteristics such as range of vehicles, which are essential for many individual users. The criteria used in the multi-criteria decision analysis are listed in Table 7.1.

| Environmental | Economic | Social |
|---|---|---|
| Greenhouse gas (GHG) emissions | Purchase cost | Average mortality |
| Primary energy use (non-renewable) | Operating cost | Expected severe accident mortality |
| Use of metal and mineral resources | Total internal cost | Maximum fatalities from a severe accident |
| Impacts on ecosystems | | Security of energy supply |
| | | Vehicle driving range |
| | | Charging/fueling time |

*Table 7.1 Summary of indicators used for multi-criteria decision analysis.*

The evaluation of indicators is based on a variety of the above-mentioned methods. This has been fully operationalized for current and future passenger cars. In the next section, examples for the use of sets of indicators will be provided. For the purpose of comparative evaluation of the various modes of transportation, modifications and extensions of the current sets will be necessary. The full implementations will be pursued in the next phase of SCCER Mobility.

## 7.1 Evaluation of mobility technology options

The left panel of Figure 7.1 shows a comparison of the life cycle climate change impacts per passenger kilometer for common transportation modes in Switzerland. These values represent current Swiss operating conditions, fuel types and occupancy rates. The right panel of Figure 7.1 shows the total passenger kilometers travelled by each mode in Switzerland in 2014. As clearly seen in the figure, the size of the car has a strong impact on the greenhouse gas emissions, with smaller cars performing much better. Motorcycles are found to be a good compromise between transport freedom and efficiency and have the lowest climate change emissions of all private transport modes, though carpooling has similar impacts per passenger kilometer. Public transport by bus and train is clearly more climate efficient than all private transportation modes, and electric powered trains achieve the best performance among all. As cars are by far the dominant mode of passenger transport and have very large potential for future improvement, they are the focus of the rest of this chapter.

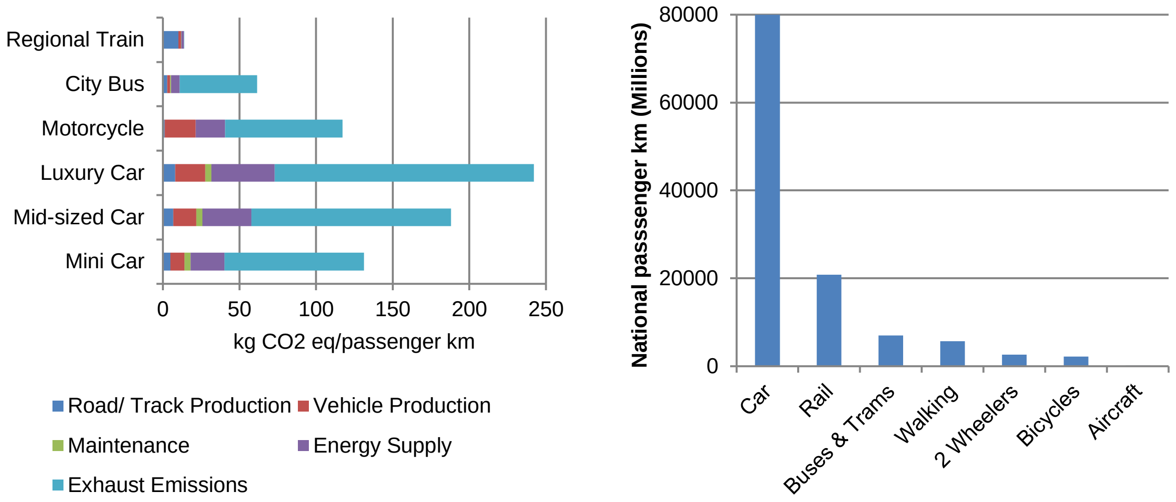


*Figure 7.1. Life cycle global warming emissions per passenger kilometer in 2014 Swiss national passenger kilometers travelled for common passenger transport modes. Cars are assumed to have 1.6 passengers (Swiss average) and drive according to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) for average driving. Motorcycles are 4-11 kW assumed to have one passenger, and drive according to Worldwide Harmonized Motorcycle Emissions Certification/Test Procedure (WMTC) for rural and urban driving. Fuel tanks of city buses are assumed to be 25 % full and operate according to the World Harmonized Vehicle Cycle for Urban Driving. Regional trains are powered by electricity and have Swiss national average occupancy rates. Cars and motorcycles are powered by gasoline, the city bus by diesel and the train by Swiss consumption mix electricity. (Sources: Bauer et al., 2015; Cox and Mutel, 2015; Ecoinvent, 2016; Hofer, 2014; Swiss Federal Office of Statistics, 2016)*

Figure 7.2 shows the lifecycle impacts on climate change and total costs of mid-sized passenger cars in Switzerland for production years 2012 and 2050 for different powertrains and energy chains per vehicle kilometer. On the left side, this figure breaks down greenhouse gas (GHG) emissions into different contributions including direct tailpipe emissions (shown in blue). Indirect emissions produced in Switzerland, such as those from road production or fuel production (shown in red), and emissions that are caused by producing Swiss passenger cars abroad, such as the emissions from producing lithium ion batteries in China (shown in green), are also displayed. This figure demonstrates the importance of considering life cycle greenhouse gas emissions as opposed to only direct emissions when designing national climate targets. The figure also compares the performance of similar mid-sized cars, with construction years 2012 and 2050. All car powertrain and energy chain combinations are expected to improve significantly in the future, e.g. CO2 eq/vkm emissions from cars produced in 2050 are expected to be only 60-80% of those for similar vehicles in 2012. While all vehicles are expected to improve in the coming decades, the most important GHG reduction potential comes from switching from conventional combustion engines to fuel cell and battery electric vehicles powered by low carbon energy sources. The interplay between the transport and energy sectors are further examined in Section 7.2

On the right side of Figure 7.2, the total costs of these vehicles are compared for the specified categories. *Vehicle*, representing the purchase cost of the vehicle shown in blue; *Energy*, representing the energy costs of operating the vehicle shown in red; and *Tax*, representing the energy taxes based on the 2012 energy tax on gasoline in Switzerland, shown in green. It should be noted that the same energy tax as presently levied on Swiss gasoline sales was added for all energy carriers. While costs for alternative drive train vehicles are currently not competitive with conventional vehicles, all vehicle types are expected to be much more competitive by 2050.

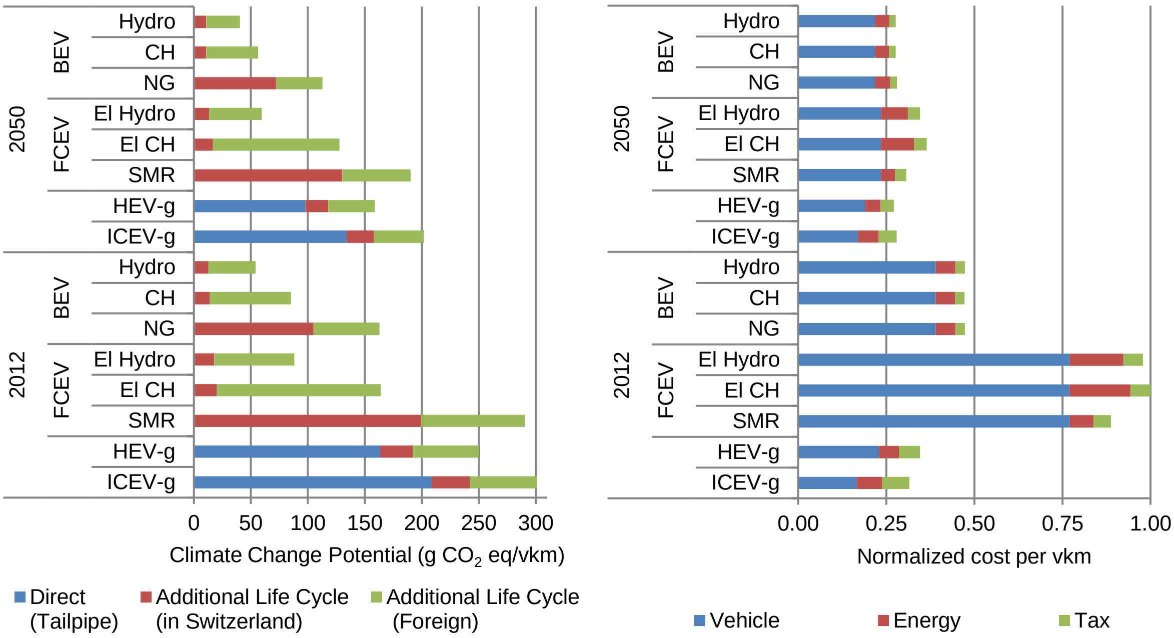


*Figure 7.2. Life cycle greenhouse gas emissions and total costs per vehicle kilometer from mid-sized passenger cars in Switzerland, production years 2012 and 2050. ICEV-g =gasoline internal combustion engine vehicle, HEV-g = gasoline hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle. Hydro = hydroelectricity, CH = Swiss electricity consumption mix, NG = natural gas combined cycle electricity, El = electrolysis, SMR = steam reforming of methane. Gasoline is assumed to represent conventional petroleum refined in Switzerland. Steam reforming of methane is assumed to occur in Switzerland. Swiss electricity mix represents the Swiss electricity consumption mix including imports. Natural gas combined cycle represents electricity from a natural gas combined cycle power plant theoretically built in Switzerland. (Sources: Bauer et al., 2015; Hirschberg et al., 2016; Miotti, Hofer, and Bauer, 2015; Simons and Bauer, 2015; Simons et al., 2011.)*

Figure 7.3 shows normalized LCIA results for the selected set of midsize vehicles for four more impact categories. Results of each impact category have been normalized to the largest total impact of each category. Moreover, the figure illustrates the results of the LCIA for generating electricity and hydrogen for both current and future technologies. The results demonstrate – in contrast to current common practice – the need for analyzing environmental indicators beyond greenhouse gas emissions in order to identify potentially problematic environmental issues during life cycles.

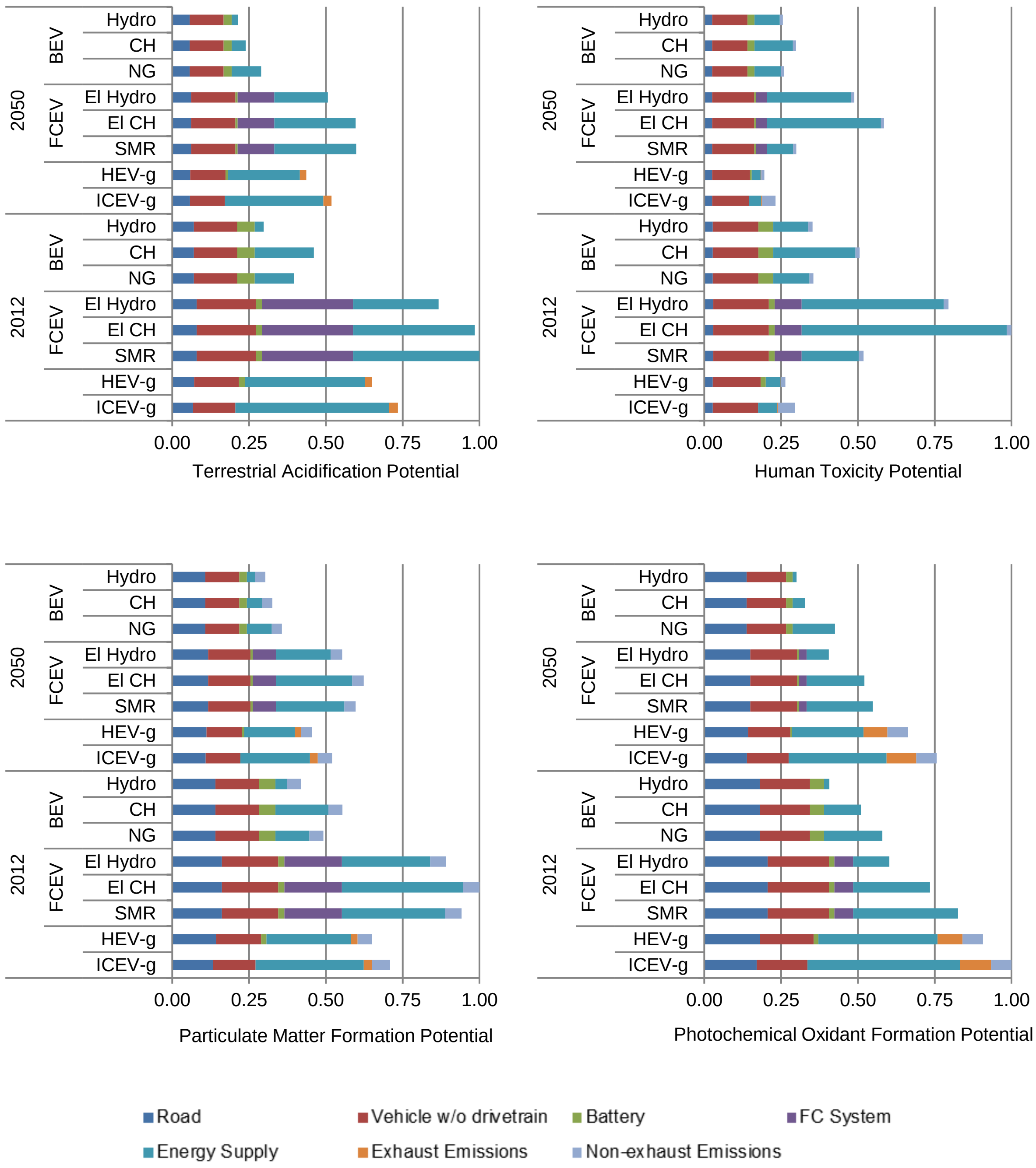
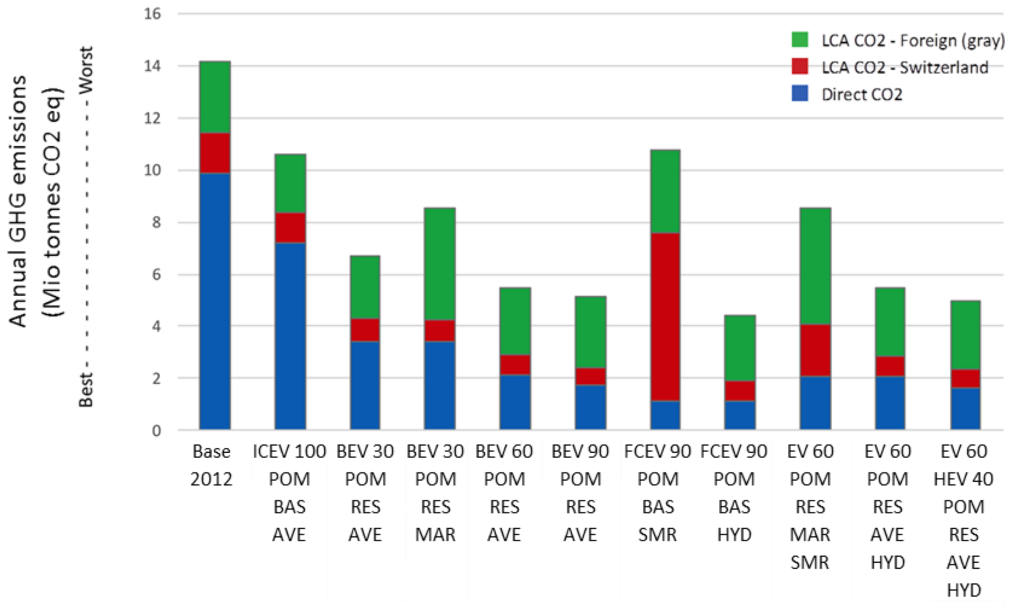


*Figure 7.3. Normalized life cycle impact assessment results per vehicle kilometer from mid-sized passenger cars in Switzerland, production years 2012 and 2050. ICEV-g =gasoline internal combustion engine vehicle, HEV-g = gasoline hybrid electric vehicle, FCEV = fuel cell electric vehicle, BEV = battery electric vehicle. Hydro = hydroelectricity, CH = Swiss electricity mix, NG = natural gas combined cycle electricity, El = electrolysis, SMR = steam reforming of methane. (Sources: Bauer et al., 2015; Hirschberg et al., 2016; Miotti, Hofer, and Bauer, 2015; Simons and Bauer, 2015; Simons et al., 2011.)*

As shown in the following equation (see also Chapter 3), total GHG emissions of the transport fleet are calculated considering not only the tailpipe emissions of the vehicles, but also all GHG emissions along the entire energy and infrastructure chains as well:

$$m_{CO2}|_a = (popul) \cdot \frac{GDP}{popul} \cdot \frac{pkm}{GDP} \cdot \frac{vkm}{pkm} \cdot \frac{E_N}{vkm} \cdot \frac{E_{end}}{E_N} \left[ \frac{E_{prim}}{E_{end}} \cdot \frac{m_{CO2}}{E_{prim}} + \frac{E_{invest}}{n \cdot E_{end}} \cdot \frac{m_{CO2}}{E_{invest}} \right]$$

This calculation has been carried out for the Swiss passenger car fleet in 2012[3] and for different scenarios in 2050. Some of the results are shown in Figure 7.4. The fleet is modelled using nearly 3000 vehicle classes, drivetrains and fuels. The numbers on the x-axis indicate the relative share of each drivetrain type in each future fleet scenario. Scenarios range from 100% internal combustion vehicles (ICEV) to mixed fleets with varying shares of battery electric (BEV), fuel cell electric (FCEV), and hybrid electric (HEV) vehicles. The energy system for each scenario is also indicated on the x-axis. For all scenarios shown here, the electricity sector demand is fixed according to the Political Measures (POM) scenario of the Swiss Federal Office for Energy, while the electricity supply scenario either can be gas dependent (BAS) or focused on renewables (RES). Furthermore, the electricity mix for charging BEV can be set as either the average mix of electricity generation or as the marginal electricity mix. Hydrogen for fueling FCEV is produced by either steam methane reforming or electrolysis with hydropower. These complex scenarios are further described in Hirschberg et al. (2016). The total GHG emissions for each scenario are shown in three parts in Figure 7.4, representing the direct tailpipe emissions, the additional life cycle emissions that are produced in Switzerland, and finally the life cycle emissions that are produced outside of Switzerland. While the first two have political priority within the Swiss energy debate, GHG effects are global and all three components must be considered when comparing scenarios. Compared to the base year, 2012, the total life cycle GHG emissions caused by Swiss passenger cars in 2050 are estimated to be 25%-65% lower, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system.



**Drivetrains**

ICEV - Internal Combustion Engine Vehicles
BEV - Battery Electric Vehicles
FCEV - Fuel Cell Electric Vehicles
EV - ½ BEV, ½ FCEV
HEV - Hybrid Electric Vehicles

**Electricity**

POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

**Hydrogen**

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

*Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.*

*Figure 7.4. Annual fleet GHG emissions for base year 2012 and 2050 scenarios.*

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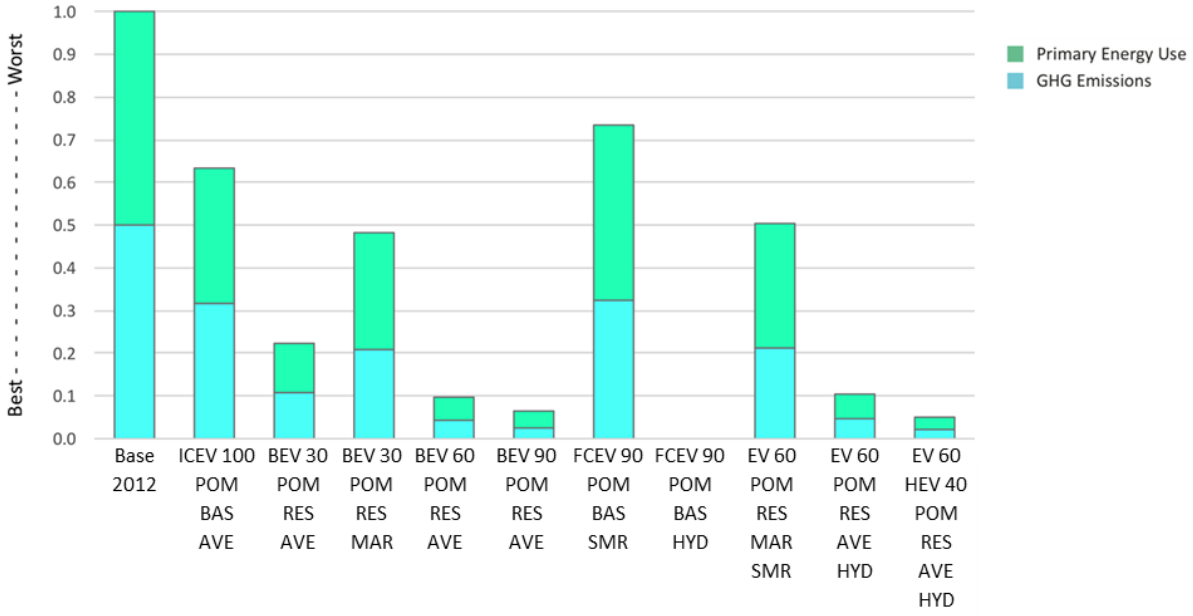
[3] It is noted that the greenhouse gas emissions for the base year 2012 are slightly underestimated here. This has two reasons. Firstly, the 2012 fleet is modelled to contain only cars with construction year 2012 and does not consider older models. This is accounted for in the 2050 scenarios. Secondly, the used MATSim data did not allow separating different annual distances for different car vehicle sizes. In reality, smaller vehicles tend to have lower annual travelled distances than larger vehicles. Both of these factors contribute to an underestimation of the 2012 fleet's total emissions by approximately 10%.

In addition to considering only GHG emissions, Figure 7. shows the multi-criteria decision analysis (MCDA) results for two equally weighted criteria, i.e. use of non-renewable energy and GHG-emissions. Figure 7.6 shows the evaluation for a much wider set of environmental, economic, social, security of supply and utility criteria.



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MAR - Charging is marginal generation mix

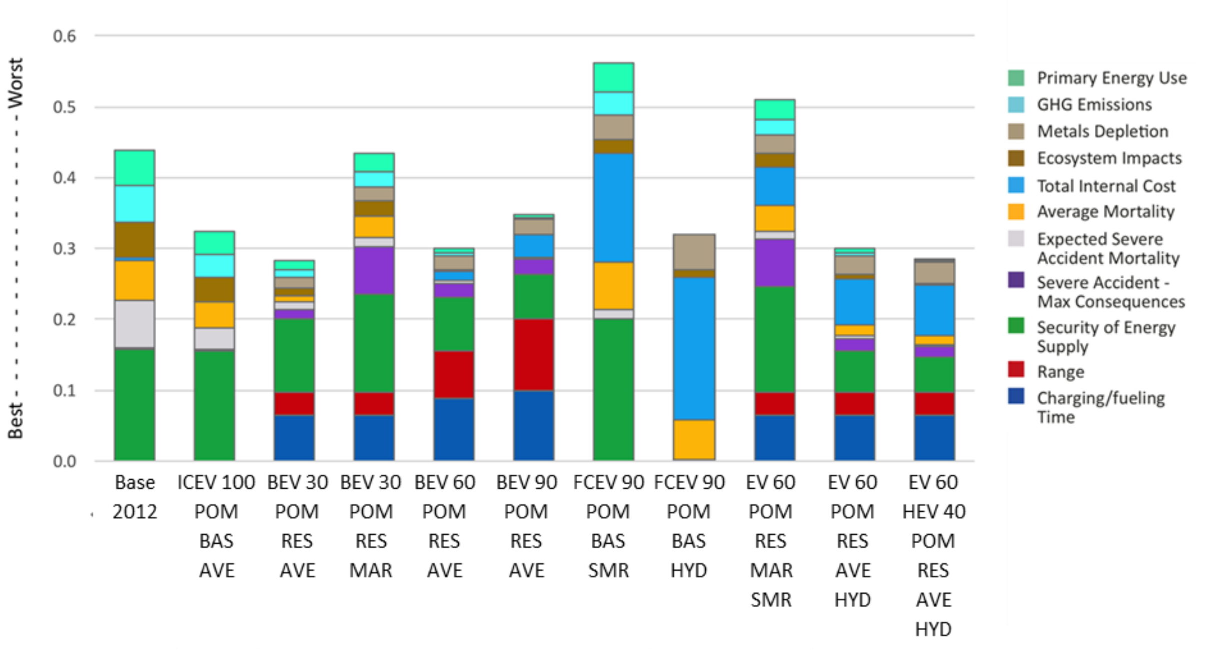
**Hydrogen**

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

*Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.*

*Figure 7.5. Car fleet multi-criteria decision analysis (MCDA) Ranks - 50/50 primary non-renewable energy & GHGs. (Source: Hirschberg et al., 2016).*

The first case above demonstrates the much-improved fleet performance for future scenarios with regard to the two core goals of the Swiss energy transition. The broader evaluation exhibits a more differentiated picture and indicates some challenges for the advanced mobility with respect to sustainability goals. As can be seen in Figure 7.6, there is no single fleet option that performs well in all areas of sustainability. Fleets with high shares of conventional combustion vehicles perform well in terms of driver utility and cost, but perform poorly in terms of environmental impacts and security of supply. Battery electric vehicles typically result in lower greenhouse gas emissions and primary energy use, but have downsides in terms of driver utility and, depending on the electricity source, security of energy supply. Fuel cell vehicles have the potential to greatly reduce greenhouse gas emissions and non-renewable energy consumption when charged with hydrogen from hydroelectricity, but perform quite poorly when hydrogen is supplied by steam methane reforming. Fuel cells also have drawbacks in terms of internal costs. Interested readers are encouraged to examine the entire report for more detailed descriptions of the scenario results, different sustainability weighting profiles, and complete numerical results (Hirschberg et al., 2016).



**Drivetrains**

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MAR - Charging is marginal generation mix

**Hydrogen**

SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

*Numbers are % fleet penetration in 2050. Balance of fleet is internal combustion vehicles.*

*Figure 7.6. Car fleet multi-criteria decision analysis (MCDA) ranked with equal waiting of sustainability criteria (Source: Hirschberg et al., 2016).*

## 7.2 Long term mobility transition scenarios - whole energy systemic approach

In Swiss TIMES (The Integrated MARKAL-EFOM System) energy system model (STEM) (Kannan and Turton, 2014), the entire energy system of Switzerland is modelled from primary energy supply to all end-use demands. It is a technology rich, bottom-up cost-optimization energy model and represents a broad suite of energy technologies/infrastructure and energy commodities. The model has a time horizon of 2010-2100 and gives an hourly representation of weekdays and weekends during three seasons. The transport sector has two types of demands, namely personal and freight transports in vehicle kilometer (*vkm*) and ton kilometer (t-km). A wide range of existing and future vehicle technologies (e.g. cars, buses, and trucks) and fuel supply options are implemented. The detailed car technologies with multiple drivetrains and fuels (see section 7.1 ) are already included in STEM; a similar level of technology detail will be introduced for other transportation modes in the second phase of our SCCER. Two types of electric vehicles, namely pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are modelled. For cars, an average driving pattern is also implemented based on micro-census data. A novel feature of STEM is its hourly time resolution, so that electricity demand for e-mobility becomes endogenous and based on marginal cost. We analyzed a set of scenarios to meet transportation demands taken from the Swiss Energy Strategy 2050 (SES). A full description of STEM and its inputs data/assumptions is documented in Kannan and Turton (2014).

We apply *what-if* type scenario analysis to identify a number of key technology transitions in the long-term development of the Swiss car fleet that are important for realizing various energy policy goals (Kannan and Turton, 2016). The *Base* scenario incorporates several existing policies, including the phase out of nuclear generation and option for new gas power plant (without carbon capture and storage, CCS); while in the low-carbon (*LC60*) scenario additionally assumes a 60% total CO2 emissions reduction pathway following the *New*

*Energy Policy* scenario of the SES. We also explored scenarios, in which we excluded investments in new centralized gas power plants (*Base-NoCent* & *LC60-NoCent*) and sensitivities to international energy prices. In all the above scenarios, net electricity import is disabled.

In the *Base* scenario, gasoline- and diesel hybrid cars become cost-effective, which can be realized with continuing price signals (along with efficiency gains resulting from implementation of vehicle standards of EU legislation). The deployment of hybrid cars results in a 40% reduction in car fleet energy demand by 2050 compared to 2010 (Figure 7.7). The average tailpipe CO2 emissions of the entire car fleet decline from 208 g-CO2/km in 2010 to 98 g-CO2/km by 2050, a reduction by 55%.

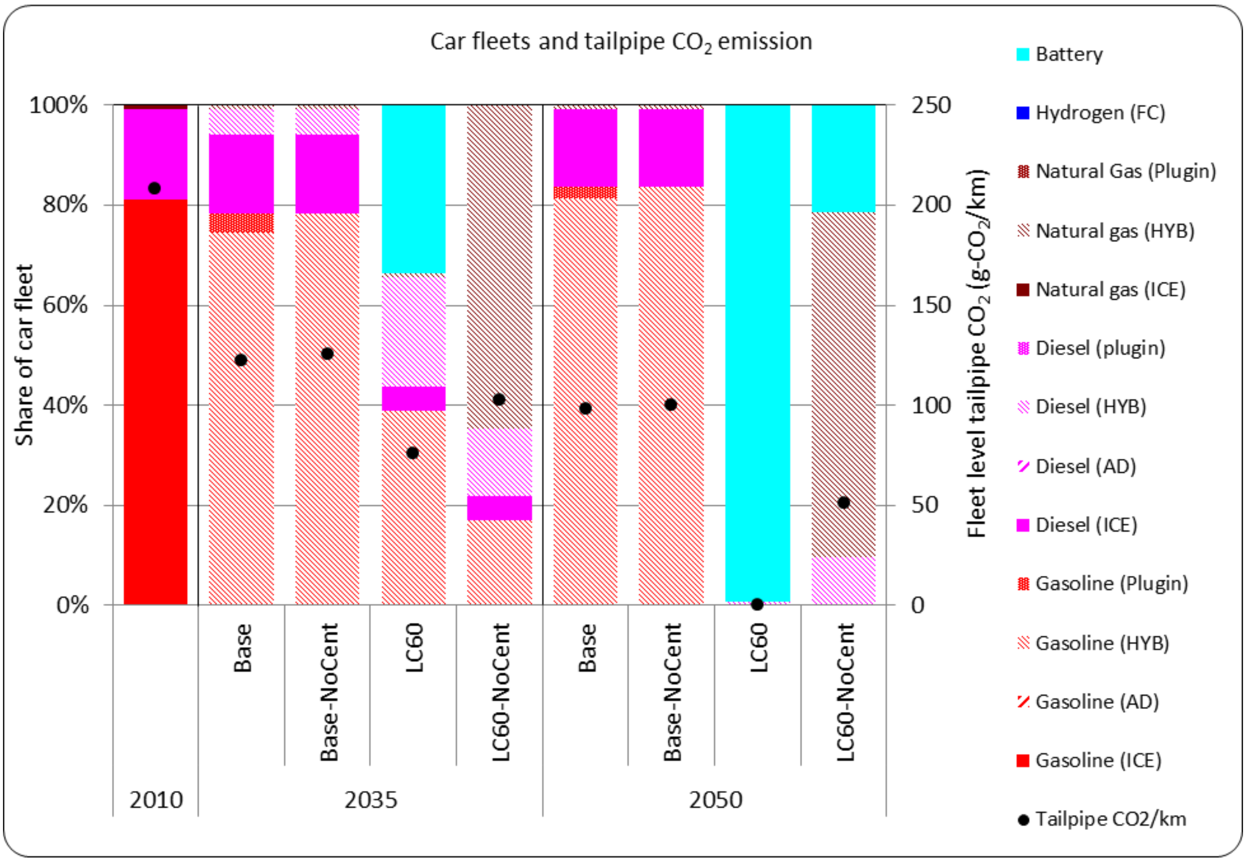

*Figure 7.7. Vehicle types in car fleet and tailpipe CO2/km emission for different scenarios in 2035 and 2050 compared to today's data*

In the *LC60* scenario, BEVs penetrate the market starting in 2035, which results in earlier decarbonization of the car fleet. By 2050, all cars are BEVs. The energy demand of car fleet in 2050 declines by 72% (vs. 40% in *Base*) in comparison to the 2010 level (Figure 7.8). Electric mobility has fully decarbonized the car fleet, but emissions in the electricity sector are greatly increased due to gas based electricity generation (Figure 7.9) —that is, e-mobility 'shifts' some of the CO2 emissions to the electricity sector as renewable energy sources are potentially fully exploited and no net import of electricity is enabled in the current scenario in accordance with historical trends. Nevertheless, there is a net reduction in CO2 emissions (Figure 7.10). Increasing electrification results in continuous growth of electricity demand. Under the condition of phasing out nuclear generation, there is need for additional domestic capacity in both the short and long term (or alternatively, sufficient imported electricity).

Centralized gas plants are meant to support the deployment of BEVs by providing off-peak electricity during weekends. However, the long-term transition of the car fleet towards different electric drivetrain technologies depends on the source of electricity supply. There are clear linkages between the availability of centralized gas-based electricity generation and the choice to utilize natural gas in cars (*LC60-NoCent*). This indicates that the cost effectiveness of electric cars also depends on policy decisions in the electricity sector. Given that the car fleet accounts for more than half of the total transport energy use and CO2 emissions in 2010, future vehicle technology and fuel choice play a crucial role for the overall development of the Swiss energy system.

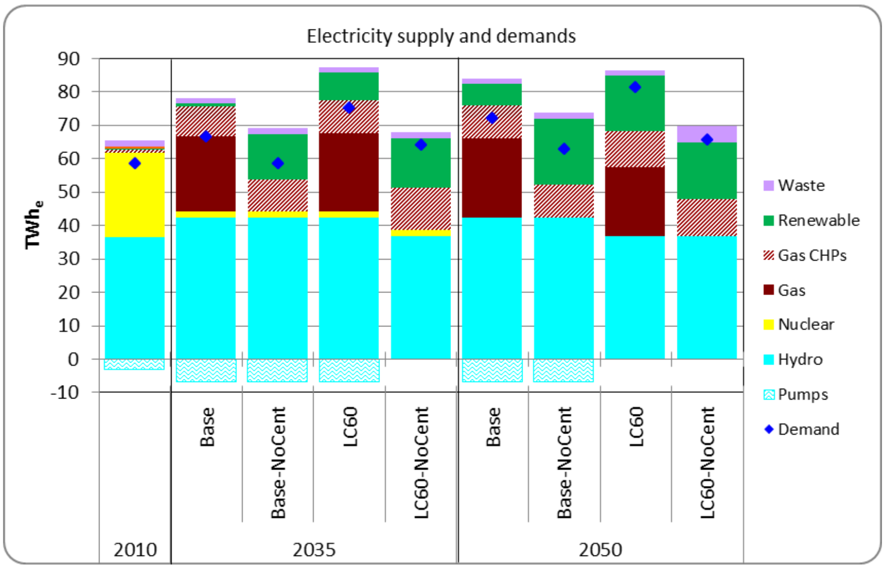

*Figure 7.8. Electricity supply and demand. Demand represents the end-user electricity demand excluding losses. Electricity consumption of pumped storage is shown as "Pumps". CHPs (combined heat and power) include both centralized and distributed stations.*

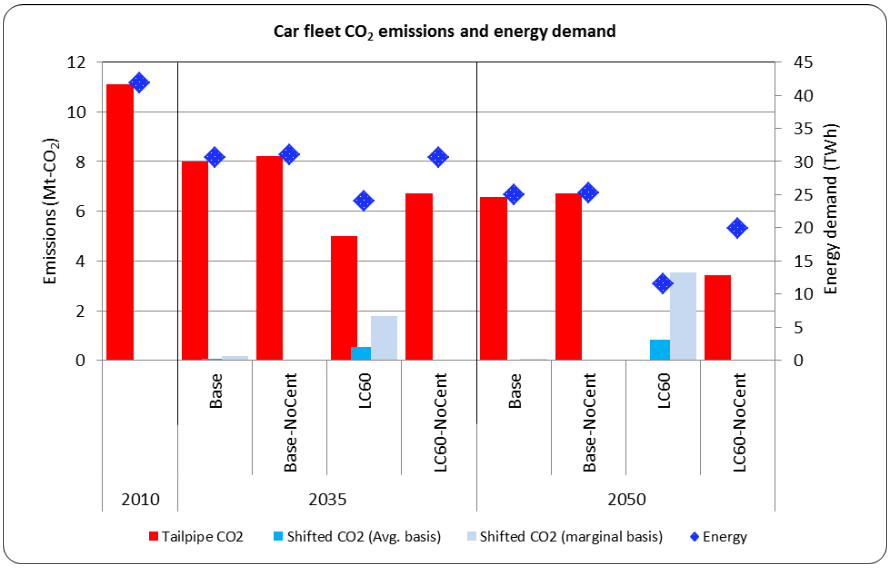

*Figure 7.9. CO2 emissions and energy demand of the car fleet. The shifted CO2 emission is estimated based on electricity used in car fleet and the average /marginal emission factor of electricity supply.*

International energy prices are also a key uncertainty affecting the future configuration of the car fleet. Low energy prices do not push e-mobility, nor do they trigger a major shift from conventional technologies. Under low fossil fuel prices, the absence of e-mobility implies a 20% lower electricity demand in 2050 compared to the *Base* scenario and, therefore, it reduces challenges to the electricity sector compared to the development under higher fossil fuel prices. However, this scenario raises additional challenges to meet any climate change mitigation policy goals (and would continue to be dependent on imported fossil fuels), and thus likely requires additional policy intervention to support new technologies (gas, electric vehicles, etc.). On the other hand, higher energy prices induce accelerated deployment of electric mobility (and indirectly support climate change mitigation). However, higher energy prices naturally imply higher energy system costs, which raise economic and social challenges. In either fuel price case, policy intervention to lower barriers to employ suitable technologies and support conditions for investing in mobility and electricity infrastructure would benefit deployment of advanced transport technology or might even be essential to achieve this.

Compared to the *Base* scenario, the additional (undiscounted) costs of the *LC60* scenario is about **CHF 8.8 billion** in 2050 (or **16%** higher than the *Base* scenario). The additional cost in the transport sector, mostly vehicle costs, is about **CHF 5 billion**. Given the reduced consumption of conventional fuels in the *LC60* scenario, fuel costs and taxes decline by about **CHF 4 and 2 billion**, respectively. A large share of this cost reduction occurs in the transport sector. Additional costs in the electricity sector are about **CHF 2.9 billion** because of deployment of capital-intensive renewables. However, it must be considered that electric cars cannot be excluded from taxation for road infrastructure in the long term, for which expenditures are on the order of several billions per year.

The cost optimal framework of STEM uses energy systemic approach to modeling and quantification of scenarios. At this stage the STEM model does not deal systematically with market barriers and behavioral aspects. In order to examine the penetration of specific vehicles/market segments, other complementary modeling approaches such as agent based modeling or market diffusion/adaptation theory employed in EBP (2016) could be employed. However, even this limited set of analyzed scenarios yields important insights into the development of the Swiss car fleet and its influence on the overall energy system. Additional scenarios focusing on the role of hydrogen fuel cells and CCS technologies are being explored.

# 8 Supporting the transformation process

## 8.1 Introduction

Today's energy and mobility system is a result of past trends elaborated in Chapter 4, influenced and shaped by exogenous and internal trends as described in Chapter 3. Assuming that no major guiding intervention will take place, the Swiss mobility system of the future will be a result of ongoing developments as illustrated in Chapter 5.1 and partially in 5.2 for the demand and supply side.

In contrast to this assumption of a trend-based, more or less adaptive and path-dependent development the idea of system, 'transformation' describes a process of a more fundamental systemic change. A transformation process might be initiated by different catalysts, such as technological or social innovation (e.g. game changers as described in Chapter 5.4), or by political decisions resulting in a new system with a transformed status in various fields. The establishment of the auto-mobility regime during the first half of the 20th century is an impressive example in this context as the technological innovation of the car did not only fundamentally change mobility, but it also changed economic structure, settlement patterns, lifestyle, etc. on a global scale.

The political decision in favor of the Swiss energy transition and its related activities in economy, R&D as well as on the political and social level, reaches a dimension of fundamental change resulting in a system transformation. In order to understand system transformation in a holistic way and to derive recommendations about how to support the process of change, two main premises are important:

I. Trends need to be analyzed within an overall systemic context. The impact and role of trends in the transformation process need to be considered in order to understand drivers and their dynamics shaping the future system.

II. In parallel, there is a need for a future vision of the intended state of the system after a successful transformation. As a systemic transformation like the Swiss energy transition requires a goal-oriented and guided process, joint objectives need to be defined as part of this vision.

Between these two conceptions of future systems – "energy transition" and "business as usual" – there is a gap, which has to be bridged in order to reach the intended goals. Fields of action need to be identified, measures need to be developed and implemented by political (and economic) strategies and decisions. As continuous monitoring and adaptation is essential in any process of change, it is important to define main decision principles as action guiding heuristics approaches (see also Chapter 9).

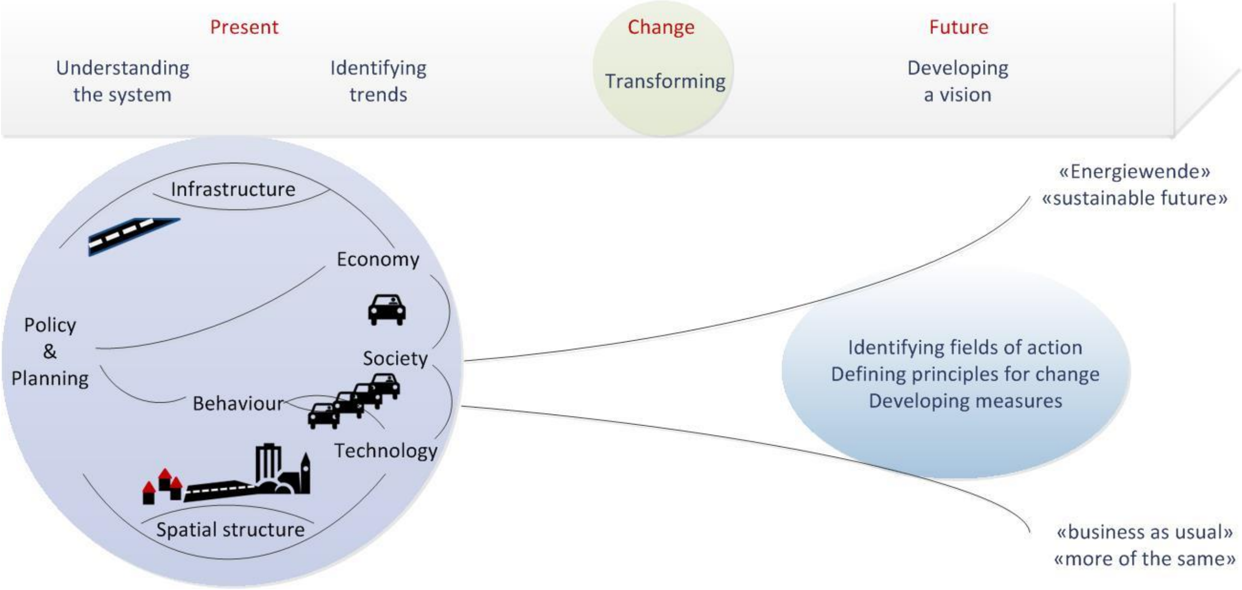

*Figure 8.1: System transformation versus path-dependent trend-based future scenario*

## 8.2 Transformation of the Swiss mobility system

In order to understand system transformation and to identify the potential for systemic change with the most promising fields for actions, a model is necessary as a base for the analysis. Based on this understanding, a model explaining system transformation on a multilevel perspective from Geels (2002; 2007; 2007; Geels and Schot, 2007; Figure 8.2) has been adapted to analyze the Swiss case.

The original model suggested by Geels describes how technological (or social) niche-innovations can influence a certain socio-technical regime, which is at the same time embedded in - and thus affected by - trends of a given socio-technical landscape. The model focuses on the diffusion of innovation with transforming potential on a theoretical base. In order to use it for practical oriented analysis, it has been adapted as an approach for SCCER Mobility. Three levels of the system have been defined to analyze trends and transformation potential for each level: **I. the micro-level** of individuals with their mobility (related) behavior, **II. the meso-level** of organizations (political and planning institutions, economy, institutions of research and education, etc.) as well as related decision makers actively influencing the transformation process and **III. the macro-level** covering the whole of the system and including different (mega-) trends in the fields of technology, economy, society, culture, spatial structure, infrastructure etc. which are affecting the mobility system.

First results of the analysis allow understanding the Swiss status quo with its potential for transformation.

On the **micro-level** a model of individual mobility behavior change has been developed, which considers behavior change as a mid to long-term process needing tailored and multiple interventions to be supported. A first conclusion for this level is that new mobility services and technologies for energy and emission reduction need to be accompanied by supporting measures going beyond the pure market introduction and purchase subsidies.

The **meso-level** describes the role of organizations in the transformation process. The role of stakeholders will be crucial, thus these have to be included in order to shape the energy transition. Decision makers in policy, in the transportation sector and in the economy have the power to set incentives in order to develop the transport system and the working environment towards more flexibility concerning mobility needs. A broad agreement, which is based on a strong joint vision of policy, economy and society concerning the needs and benefits of this kind of development, is necessary in order to shape the transformation process successfully. A change will happen anyway and if not actively addressed in a possibly unintended direction.

On the **macro-level**, trends, which are expected to affect the development of Swiss mobility and energy demand in the future, have been identified. They will be relevant for the transformation process as they result in the opportunity of guiding the development in a certain direction if right actions are taken. Especially changes of the economy and the working environment – partially based on technological change – have a great potential in this context. New ways of organizing work (mobile work, digitalization, etc.) provide opportunities for replacing physical mobility with a virtual one, which would decrease mobility demand. Although corresponding technologies already exist this has not happened so far, which implies that the need for cultural change has been underestimated in this context. With new generations of digital natives and industries strongly based on virtualized cooperation, global cultural trends in the working world can be expected to change. Policy together with employers and other economic and societal stakeholders have the potential to support the social innovation process in this field.

The Swiss potential for transformation can be estimated by considering challenges and opportunities arising with these future trends in combination with the specific Swiss strengths and weaknesses. Both aspects (challenges/opportunities and strengths/weaknesses) are derived from trend analyses in different fields of the macro-level such as mobility itself, the environment, demographic and socio-cultural development, the economy, spatial development as well as technology.

The high quality of public transport, emission legislation, and political strategies like energy transition initiatives such as "the 1 t CO2/2000 Watt society" as well as the high potential for shared mobility are examples of Swiss strengths. Related to this, opportunities arise from trends like sharing economy, digital revolution, new vehicle and material technologies (which are still in a niche) and political/legislative strategies towards a decrease of energy consumption and GHG emissions on a global scale emerge as well.

Other characteristics of the Swiss system can be considered as weaknesses when it comes to transformation. High standards for traveling and the mobility system are strengths on one side, but they come with inefficiencies (use of energy, low occupancy of cars, infrastructure constructed for traffic-peaks, etc.) and serve as a barrier for change, as need for action is less obvious or is expected to decrease the level of quality. Fragmented political and administrative structures as well as urban sprawl are barriers as well. Threats arise from ongoing socioeconomic developments. Growth of the economy, population, income and real estate prices lead to an increased mobility demand. This is further pushed by social trends like elderlies spending their leisure time more actively, a growing group, and economic structural change with increasing spatial specialization of jobs leading to longer commuting distances

Based on this analysis main action fields can be identified to support the system transformation:

1. **Efficiency increases** and technological innovation based on sustainable energy sources and new technologies
2. **Avoidance of rebound effects** considering energy-, time- and cost-efficiency
3. **Integrated spatial and transport planning** aiming for quality of life in cities and agglomerations in order to avoid the 'need' to travel
4. **Shift towards quality of the economy and working world** to meet sustainability requirements, which might lead to a more digital and flexible working behavior.

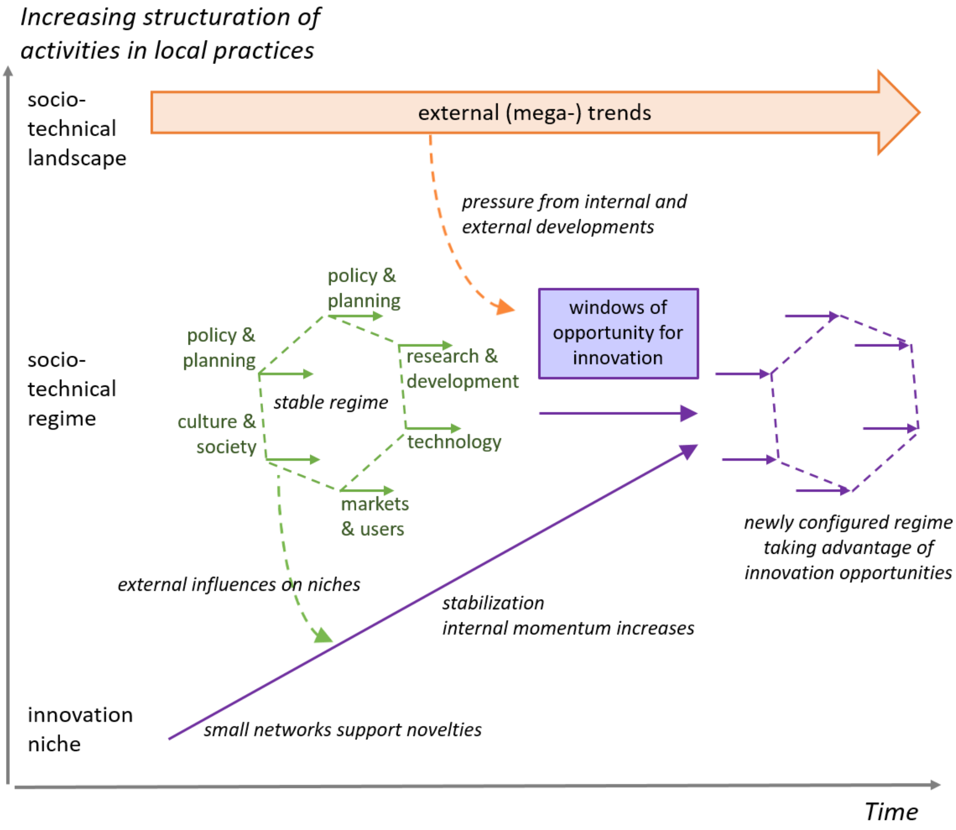

*Figure 8.2: Model for systemic transformation from a multilevel-perspective (adapted from Geels, 2007)*

## 8.3 Examples of concrete policy directions / measures to achieve this transformation

Following the theoretical framework mentioned earlier, we discuss now some concrete, mainly policy-related measures that help to achieve the strategic goals of the Swiss Energy Strategy 2050 with regard to the mobility sector. The list of measures is not exhaustive nor does the numbering necessarily correspond to a concrete ranking in terms of importance. The examples below serve rather as parts of a policy portfolio that should have consistency and allow for assessment/monitoring and adaptability to continuously changing boundary conditions and unforeseen developments.

1. Fair prices through internalization of external costs of all kinds for all transport modes are required to the extent possible and according to up-to-date knowledge. According to recent studies, annual external costs of the Swiss transport sector amounted to roughly **9.4** billion CHF or about 1.5 % of Swiss GDP in the year 2010 (Ecoplan, Infras 2014). Motorized individual passenger transport accounts for **5.5** billion CHF and freight transport on the road for **1.0** billion CHF of external costs, while rail and public road transport contribute with **920** Mio CHF (about the same as aviation).

   Interestingly enough, specific external costs are not that different among modes, amounting for example to about **5.3** Rp/pkm for passenger cars, **4.8** Rp/pkm for buses and clearly less; namely **2.3** Rp/pkm for trains, while for bicycles net external costs are about **4** Rp/pkm. For freight transport, external costs for the road are around **2.5** Rp/tkm on average and thus at about the same level as rail freight [the performance-related heavy vehicle charge (LSVA) plays an important role here as it compensates for about **4.5** Rp/tkm for heavy-duty freight transport on the road]. On the other hand, light-duty road freight transport has external costs of **53** Rp/tkm due to low transported freight volume and usually operating in and around environmentally sensitive urban settings.

   It is worth mentioning here that the total annual external costs of **6.7** billion CHF allotted to road transport currently exceed the estimated annual road transport (pre-tax) fuel costs of about **4** billion CHF by about 50%. Therefore, their internalization would have a significant effect on the overall marginal costs of road transport and thus considerably affect the demand for transportation services.
2. To achieve fair prices, steering measures by internationalizing external costs are much more efficient than subsidies, as a recent study for the whole energy sector in Switzerland has also shown (Böhringer et al., 2017). Although subsidies also guide demand towards a required shift to specific modes (for example from car to rail), they tend to expand overall demand, whereas the internationalization of external costs dampens this demand considerably.
3. A successful policy for internalizing external costs must be in accord with international policies (at least in the European level), otherwise public acceptance will be limited and economic competitiveness of key industries may suffer.
4. At least equally important is, however, a set of policy instruments that yields consistent price signals over all energy sectors. Taking CO2 prices as an example, it is on one hand reasonable for Switzerland to adopt the European legislation for specific CO2 emissions for cars as this supports the automotive industry in deploying appropriate technologies across all relevant markets rapidly. On the other hand declaring that the electric powertrain is CO2-free, despite the (currently and in the foreseeable future) substantial CO2 footprint of marginal electricity, sends wrong signals to the markets, thus increasing specific CO2 mitigation costs of the overall energy system against the optimal path.
5. Although, as mentioned above economic theory and practice have proven that steering measures are superior to subsidies in terms of cost/benefit trade-offs, people do consistently prefer the latter to the former. A lack of understanding of life cycle costs of given investment decisions and rather high discounting attitudes for the future pose several challenges for public acceptance of the right policy instruments. Herein, the role of scientific expertise and proper communication tailored to the specific

audience is crucial for improving mobility/energy related “financial” literacy of society and key stakeholders in particular.

6. In addition, a well-orchestrated policy strategy with regard to life time and depreciation schemes of important assets, specifically including large scale infrastructure, is of outmost importance for maximizing reduction of $CO_2$ and other pollutant emissions from transportation with affordable costs. Long-lasting infrastructure (urban/spatial structures, roads, power plants, etc.) must be addressed early enough to avoid lock-in effects. For appliances such as vehicles, higher natural replacement rates are in place and, therefore, technology improvements can penetrate into the fleet, so that policy can follow evolutionary paths here.

It is worth mentioning that several of the above mentioned policy issues lead to highly interesting and relevant questions for socioeconomic research. Evidence-based policy recommendations can be expected to be the outcome of research projects within the SCCER Mobility in the next few years and, in particular, in the framework of the Join Activity between SCCER Mobility and SCCER CREST

# 9 Navigating uncharted waters – the Learning Lab for Future Sustainable Mobility

In accordance with the approach discussed in Chapter 3, it is obvious that the future evolution of the Swiss mobility system will be a multi-facetted process with several underlying developments and multiple cross-sectoral interactions. Scenario work as already in place within Capacity Area B2 (see Chapter 7) will exemplarily address patterns of potential future development and thus help define them as "best" and "worst" cases, at least to our best possible knowledge.

Experience has shown that unexpected shocks (geopolitics, disruptive technological innovations, macroeconomic instabilities and radically new business models) may shape the future trajectory so that the energy and mobility system will react in unpredictable ways. As technology, policy and other important boundary conditions evolve, it is thus mandatory to explore the internal dynamics and potential responses of the whole system continuously. This leads straight to the need to create a **Learning Lab for Future Sustainable Mobility** that will provide a link between "top-down" strategy and "bottom-up" developments. The lab's work will be based on a systems dynamics approach (if possible accompanied by agent-based models) and will use powerful simulation capabilities to help understand how targeted interventions or even random inputs propagate though the system and may lead to favorable or unfavorable outcomes, in particular in view of the Swiss Energy Strategy 2050. We expect that the Learning Lab, which can be seen as a major expansion of the Strategic Guidance Project, will seek synergies within and outside our SCCER, will help to make our roadmap(s) more flexible and adaptive to new developments as well.

The strength of a system dynamics approach lies in the ability to explore the response of the transportation system to external influences through a set of equations describing the relationships between its key elements. However, the challenge is that some of these relationships are not known a priori quantitatively and the associated models require validation. This is particularly true with regard to socioeconomic interactions including aspects of human behavior. In this case, agent-based-models (expanding for example the work carried out within the SCCER Mobility under the MATSim umbrella) are worth considering as a way to specify some of the above-mentioned interactions. Nevertheless even such "bottom-up" models need some "calibration", which can in principle be provided by a combination of data-mining techniques (if such data exist or can be obtained) and targeted experiments within a living lab.

In the following, we would like to illustrate qualitatively how the system dynamic description of a part of the mobility system would work. We examined for example, how the influence of a game changing technology like automated driving would affect the expected evolution of energy-demand and CO2 emissions of the motorized individual transport sector.

The effect of one element or factor on another are shown by arrows with a plus (+) or minus (-) sign. The plus sign indicates a positive causal link (e.g., urban sprawl increases demand for travel); while the minus sign indicates the opposite (e.g., high cost of transportation reduces travel demand). As Figure 9.1 illustrates, the outcome concerning energy demand and CO2 emissions depends on several interactions among the elements of the system, which create a sequence of escalating or stabilizing feedback loops. Based on our current understanding of some of these interactions the result is barely predictable, yet this representation helps to formulate appropriate research questions in order to address such uncertainties.

Although the current and future development of computational capabilities allow the simulation of increasingly complex systems, it is important that the Learning Lab pursues a balanced modelling approach: simplicity must be preferred over sophistication, if the latter implies additional uncertainties. The model structure will be kept transparent and "cause-and-effect" relationships will be formulated in an aggregated manner. With this instrument, we will not pretend to be able to predict the future, but instead it will be used as an exploratory tool for probing into the rich interactions among the system elements that can lead to quite different trajectories in the future. We can expect from such insights that additional, highly interesting research questions will emerge.

To accomplish its purpose the Learning Lab will have adequate computational and visualization resources installed in a dedicated room to facilitate interactions within the SCCER community but also with students, industry, opinion leaders and policy makers.

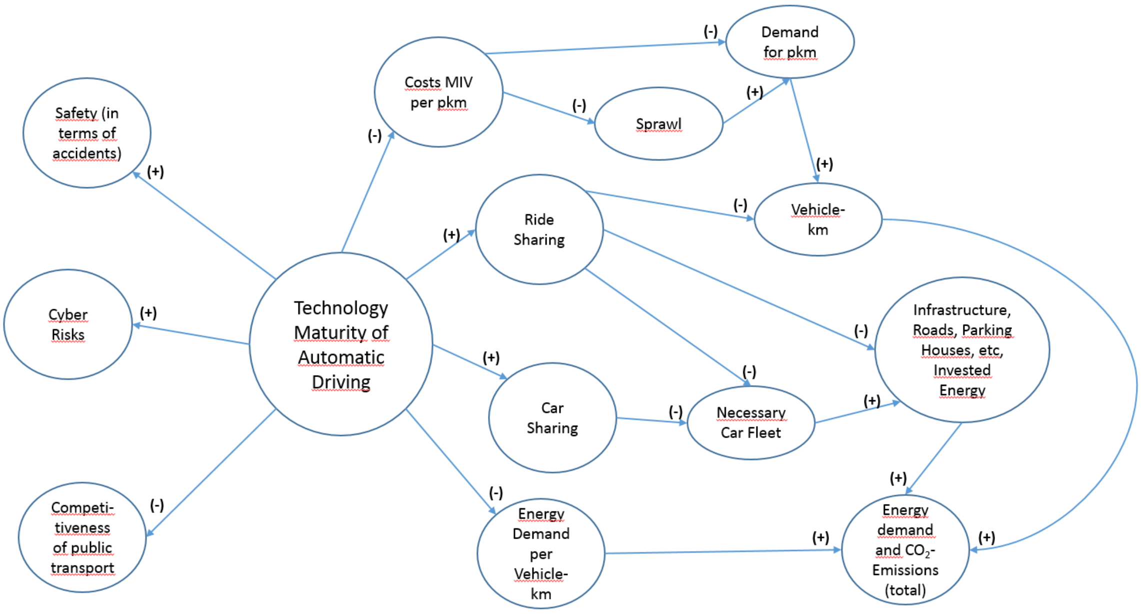

*Figure 9.1: Example of a system dynamic representation of the mobility system regarding possible disruptive effects of automatic driving.*

# 10 Conclusions and Outlook

The major challenges for the future Swiss transport system include its contribution to climate change mitigation, reduction of energy demand, diversification of its energy carrier portfolio, increasing the security of the energy supply and further minimization of pollutants under the requirements of affordable cost and wide social access to transportation services. In this respect, we have primarily used CO2 emissions and energy demand as a performance indicator of future mobility since the goals of the Swiss Energy Strategy 2050 emphasize these two aspects and the desired reductions are expressed in quantitative terms. As a review of international strategies indicates, this is in agreement with worldwide efforts in this direction.

In the present document, we have used a systemic approach in order to analyze the status of the Swiss transport sector and to examine possible paths it may take in the future to fulfill the above-mentioned requirements. This includes a close examination of the demand and the supply side and this will be expanded in the future to address multiple interactions resulting from policy measures and associated emerging (new) business models.

For this purpose, we have used the evolution of the annual CO2 output from the dominating individual personal (individual) transportation sector as a key indicator of progress towards reaching the goals of the Swiss Energy Strategy 2050. In Chapter 3, we have dissected this evolution into the effects of major exogenous and endogenous drivers to investigate corresponding CO2 reduction potentials. In Chapter 4, an analysis of the status of the Swiss transport sector and the development trends of the mentioned drivers over the last 25 years provides first insights into the underlying dynamics that shape changes in CO2 emissions. A close inspection of predicted trends for the future demand for person-km on the road according to the newest ARE scenario demonstrates that a drastic reduction of specific CO2 emissions per vehicle-km is mandatory on the supply side, if the CO2-budget for a containment of global warming within 2°C is to be reached. However, this is not enough. Additional reductions are needed from the demand side either by a considerable reduction of vkm or by using smaller lighter vehicles or by a shift towards more energy efficient modes.

In Chapter 5, additional effects considering socioeconomic and technological development are discussed to provide a possible direction for the future evolution of the transportation system. While such trends can only be addressed in a qualitative way on the demand side, clear statements can be made for the reduction potential of energy demand and CO2 emissions on the supply side. In particular, based on research performed within the SCCER Mobility framework we found that substantial reduction potential for operational CO2 emissions does indeed exist. With an anticipated evolution and systematic implementation of foreseeable technology development, including a shift to natural gas and synthetic renewable fuels, more than 50% of CO2 emissions per vehicle can be realized within the next 10 to 20 years, and with no major challenges to the electricity structure. In addition to the introduction of synthetic fuels, massive decarbonization beyond this level will require a substantial penetration of electric mobility into the market. Under favorable conditions, battery electric vehicles are expected to dominate the short-to-medium range vehicle market on the long term, while it is conceivable that some heavy-duty, long-range applications may profit from fuel cell technology. Despite the quite low overall energy-conversion-chain efficiency of fuel cells, the need for seasonal storage of excess renewable electricity could pave the way for H2 as part of the energy carrier portfolio in the future transport sector. In general, we consider the decarbonization challenge to be significant for long-distance road transport and in particular for marine and aircraft applications.

What remains extremely difficult to assess are the potentially disruptive effects of game-changing developments such as digital technologies in general and automated driving for freight and individual motorized mobility in particular. Research performed within the SCCER Mobility indicates the advances in ICT could support multimodal mobility positively (real time, tailored information) and new sharing services combining AV could greatly reduce the fleet size providing the same service. On the other hand, it cannot be excluded that comfort issues and the low cost induced by such disruptive technology developments may increase demand for transportation services significantly. This will put public rail versus road transport in a competitive disadvantage and therefore largely compensate first-order positive effects. This constitutes a major research question for the years to come and must be addressed accordingly.

Overall, estimates of the necessary electricity demand for a massive electrification of the individual transportation clearly show that power generation, the electric grid and storage solutions will pose big challenges as shown in Chapter 6. Moreover, as mentioned before the CO2 footprint of the future electricity system – at least at the European level – will prove to be crucial for the pace at which the decarbonization of the transport sector can be implemented.

In Chapter 7, we have expanded the analysis of future mobility trends in several ways. Firstly, life cycle assessment results show that upstream CO2 emissions and invested energy for hardware and infrastructure can be quite important in case electric mobility acquires large market shares. This would provide a lower threshold in the achievable decarbonization level of the transportation sector, even if the operational CO2 output of mobility were close to zero. Secondly, as mentioned above increasing electrification levels lead to a strong coupling between the electricity and transport sectors as the CO2 footprint of the marginal electricity demand needed for mobility plays a crucial role in accordance with the findings of Chapter 6. Finally, although electric mobility is expected to provide clear benefits with respect to climate compatibility over current fossil fuel based technology in the long term, there are other criteria (for example related to human toxicity index) for which no advantages are observed.

Chapter 8 finally dealt with ways to organize the necessary transformation process of today's mobility system towards sustainability. Based on a theoretical framework with regard to innovation processes, required measures are structured into a hierarchy (individuals, organization, state, and institutions) and policy measures are proposed for guiding the mentioned transition in an effective and efficient way. Among other instruments on both the demand and the supply side, a policy framework for the internalization of external costs is considered crucial for this purpose.

When developing scenarios and projections on the future of the transport sector, several important issues lead to uncertainty. Most important among them are game-changing technologies, which may be difficult to anticipate, the very long life times and costs of infrastructure, the future development of international energy prices and the complex aspects of individual and group (social) behavior in decision-making processes. In addition to promoting technology-related research, the SCCER-Mobility dedicates itself to work at multiple interfaces through the Joint Activities in the second phase of the SCCERs. In particular, together with the SCCER CREST, it will tackle socioeconomic aspects and questions of future mobility. A major topic of interest in this context will be the rebound effect in the transportation sector, which tends to counteract increase in efficiency through higher demand and therefore diminishes the positive effects of technology progress. Finally, in order to promote integration of results and disciplinary views into a framework for cross-communication, outreach and strategy development, we are dedicated to strengthening integrated assessment activities in CA B2 and, in addition, to establishing a Learning Lab for the future transportation system.

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