sccer mobility

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 current status and structure of the Swiss transport system and sketches possible paths for its evolution towards an energy efficient, climate compatible, environmental friendly and cost effective mobility future.

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 CO_2-emissons as a proxy for the overall sustainability of future mobility. Given the dominant contribution of road transport to these two parameters within the Swiss transport sector, the core of our analysis is focused on this mode. We emphasize on motorized individual transport, which accounts for about two-third of the transport CO_2 emissions, we comment in selected cases on the development of the even faster growing freight transport sector as well. International aviation is however not closely considered – despite its growing importance worldwide – since corresponding policy is a matter of international cooperation, but a closer consideration of this mode will be important in the future.

The document reviews related international strategies for decarbonizing the transport sector and – following the directions of the Swiss Energy Strategy 2050 – develops a systemic framework for decomposing the requested energy and CO_2-output along major drivers of both the demand and supply side. Their development during the past 25 years reveals some interesting dynamics of the mobility system structure. Following recent scenarios for exogenous and endogenous drivers by ARE, BFE, BFS etc., we eventually draw possible trajectories for the time period until about 2050. The CO_2-budget projections of IPCC for keeping global warming within 2°C with a 66% probability are then translated into targets for the Swiss transport sector for the same period. Combining the demand side projections and the transport related CO_2-budget, reveals the need for a massive reduction of specific CO_2-output per travelled distance, essentially to zero within 50 years. We then show that this highly ambitious target can only be achieved with a combination of an evolutionary (short-to-mid-term, efficiency driven) and a disruptive (mid-to-long term, electrification driven) path. The role of synthetic renewable fuels will be supportive along this whole path.

Such a development will require very high investments in energy and other infrastructure that must be designed and implemented effectively. The reduction pace of CO_2 will in any case depend crucially on the CO_2-footprint of the required marginal electricity for transportation, making therefore the assessment of sector coupling within the overall energy system mandatory.

Demand side measures will play a supportive role in enabling a faster CO_2-reduction trajectory. Furthermore, we adress in this context and in a preliminary way possible effects of disruptive developments, such as automated driving, along with the potential for car- and ride-sharing.

To quantitatively illustrate specific CO_2-reduction potentials, we investigate targeted interventions through selected socio-economic and technology side measures in a "what-if" manner, thus identifying areas where priority must be given.

This assessment is then expanded to include total life-cycle-analysis for climate, other environmental and cost effects as a first evaluation of the impacts of the proposed potential improvements of the future mobility system. A major outcome is that electrification of mobility has a high potential to improve the Transport Systems along several dimensions, but attention must be paid to some other criteria as well as to the footprint of the "upstream" processes (invested energy for infrastructure, etc.).

Finally, some considerations for adequate policy measures in order to orchestrate this very ambitious transformation of the mobility sector are discussed. Among them consistent internalization of external costs is of decisive importance. These issues need – in addition to engineering science research – to be addressed more closely in the future through dedicated efforts within the framework of joint activities, in particular with the SCCER CREST.

All told, the present report must be considered as a working paper reflecting the available competencies and current state of knowledge within the SCCER Mobility, and will be further developed thus serving as a "living document" for the elaboration of outreach papers in the future.

1 Scope 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 the living standards of the majority of people in developing countries and emerging economies will lead to a rapid growth of global energy demand according to virtually all projections. This stands in severe conflict particularly with the firmly expressed will 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 Fukushima accident – have formulated a long-term "Energy Strategy 2050" that has set the transformation of the energy system towards the reductions of energy demand and the reduction of CO2 emissions as strategic goals. Provided that this Strategy is approved by the public vote of May 21, 2017 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).

It is widely recognized that both globally and at an individual country level 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 worldwide for more than 50% of the overall CO2 emissions. In principle, therefore the decarbonisation of both sectors must 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 referring to Switzerland, it is worth mentioning that the transportation sector (including international aviation) contributes currently about 1/3 to the final 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 buildings 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 interface insights from engineering/natural as well as social/economic sciences with 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 current status and the future perspective of the Swiss Mobility System. In this way it serves as a platform for reflection and synthesis of views from a variety of disciplines as they are contributed by the different Capacity Areas of the SCCER Mobility among others. Recognizing the need for an efficient integration of such widely distributed knowledge, we envision the establishment of a Learning Laboratory for the Future Transport System in the second period of the SCCER Mobility (2017-2020).

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 first 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.

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 important to also understand the international context of other countries' visions and planning efforts. This section attempts to summarize this context of Swiss and international transportation visions, focusing on first on the ETH Zurich/HSG study Vision Mobilität Schweiz 2050, 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 very broadly compare the common and complementary elements that are present. Given this context, this section will then contrast how the SCCER research program vision is structured, given the analytic 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 may 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.). And 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 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 more narrowly surveyed, but these were selected based more on bibliographic links and prior knowledge. Sustainability remains a dominant goal in the visions surveyed. Sometimes this is explicitly expressed, and sometimes the focus is more or less on specific areas within the 3 sustainability pillars of economy (e.g. adequate, affordable transport capacity), society (e.g. safety, equity, etc.) and environment (emissions and energy use).

Switzerland

The Vision Mobilität Schweiz 2050 study authored by ETH and the University of St. Gallen [Weidmann et al, 2016] takes an approach that develops thematic areas (Themenbereiche) and target concepts (Zielbildthesen), and uses a reference scenario and the effects of transportation trends (Referenzszenario u. 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 results, but does not discuss the numerical methodology used to quantify these results. Overall this study is much more of a comprehensive "vision" than any of the government policies surveyed below.

The Vision Mobilität study uses and cites various official Swiss government planning documents, including the Bundesamt für Raumentwicklung Perspektiven for 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 & modeling than policy planning or vision documents. As with other countries, they 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 Energiestrategie 2050 focuses more on electricity strategy

than overall energy strategy. Transport is chiefly addressed by the assumption that there will be increasing electrification of vehicles, either directly (BEVs, PHEVs) or indirectly (H2 electrolysis).

European Union (European Commission / Joint Research Centre)

Within the EU, the European Commission (EC) department or directorate 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 Report on Transport Scenarios with a 20 and 40 Year Horizon" (2009), and the 2011 Roadmap to a Single European Transport Area. As can be seen from their titles, the EC vision reports explicitly include the components of sustainability. 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 and also goals for system characteristics. The Roadmap also includes a strong emphasis on the goal of furthering European integration. Transport is also affected by the EC Energy Roadmap 2050, but like Switzerland, this is largely an electricity-related policy.

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 UK department focus was not particularly long-term or strategic, but generally divided by mode (road v. rail), with more focus on the elements of infrastructure, investment, etc. The "Single departmental plan 2015 to 2020" (19 Feb 2016) is short-term with very brief vision and objectives, and two sample reports reviewed from 2013 ("Transport – an engine for growth," and "The Strategic Road Network and the Delivery of Sustainable Development") were likewise limited. The first of these two focuses 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 draft publication via the web of Beyond Traffic 2045, for the purpose of soliciting public comment and feedback. The DOT has a separate strategies page that lists various goals and policies, but is rather short-term to be termed a vision. For example, Transportation for a New Generation 2014-18 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 Vision Mobilität study. These include publications by BMW Institut für Mobilitätsforschung, 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 (ITF)

The ITF Transport Outlook 2015 addresses surface, international and urban transport. It covers short term trends and modeling to 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 in general. Policy measures can influence the extent of the growth but not reverse the trend of increasing demand for transportation services.

World Energy Council (WEC)

The WEC's major emphasis is obviously on energy in general, 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 Energy Trilemma, which are used to form an international index ranking, and which also apply to their consideration of transport. The WEC World Energy Scenarios to 2050, where PSI has provided energy sector modeling, also include 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 (IEA)

IEA research is not particularly transport related, but the IEA World Energy Outlook Special Report 2016 on Energy and Air Pollution includes specific discussion of the full transport sector.

World Business Council for Sustainable Development (WBCSD)

The WBCSD's vision for 2050 includes a more than doubling of 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) alternate low-carbon fuels.

Massachusetts Institute of Technology (MIT)

The 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 (ADL)

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 performed 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' performance. These criteria therefore reflect a vision of what makes for good urban transport, 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) with 2) transformative value changes in society (climate protection and sustainability, multi-modality, urban lifestyle, "deceleration", and regionality) and finally 3) mobility-related areas (including reurbanization, 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 the JRC's, is largely reflected in its research areas and portfolio. The DLR's Institute of Transport Research includes research areas on passenger and commercial transport, and 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, 5) mobility applications of information and

Table 1.1 below presents a brief comparison of the relative emphases of some of the vision statements surveyed. 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 rows for groups or governments which were of interest, but where the vision goals are not very broad. 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 is added on the right to indicate such emphasis. While the check marks indicate 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

What conclusions can we draw from this brief survey of strategic transportation planning? Overall, the government plans or strategies are weighted more to 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) values 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 too broad a set of stakeholders to readily synopsize their results. It is however interesting to see, while one is looking "top-down" for transportation strategies, that energy strategies are in contrast much further developed and easier to find. The energy and transport sectors obviously overlap, but energy strategies tend to be dominated by future electricity planning, with relatively little explicit transport content.

Organization / Study	Goals / Criteria													Trends & Means
	Economy				Environment				Society					
	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, how can the SCCER mobility bring its own vision help develop and support the future of the Swiss transport sector? In contrast to the "Vision Mobilität" 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 competence available within SCCER Mobility cover:

Vehicles and drivetrains – Vehicles and 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 – The 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 Mode, Transport demand isdriven by multiple factors including population, income, time constraints, and the services and destinations desired. 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 balance of congestion, travel time and personal stress/aggravation, which affect modal choices at the margin.

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

One particular element that can be mentioned when the transportation problem is divided in this way is that the inertia of the system and the time scales needed to make changes in it vary strongly. The infrastructure is slowest to change, 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 data-based shifts toward smart systems operation.

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 decarbonisation of the energy system), a reduction path for energy-related CO2-emissions for Switzerland can be derived. Finally, with the assumption that the Transport Sector must contribute to this CO2-reduction at the same pace as the overall energy system, one can define target values for decarbonisation of Mobility.

It is important to mention here that for simplicity the CO2-emissions serve as a proxy for the overall environmental burden of a given energy sector. Though this is rather true for the fossil share of the energy carriers portfolio, other parameters must be considered as well for a robust integrated assessment as will be shown later in Chapter 7.

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 realize a large-scale Transformation of the Transportation Sector towards minimal energy demand and CO2-emissions it is imperative to pursue a systemic approach including research effects, policy measures and implementation roadmaps on both the demand and the supply side, as shown in Fig. 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.

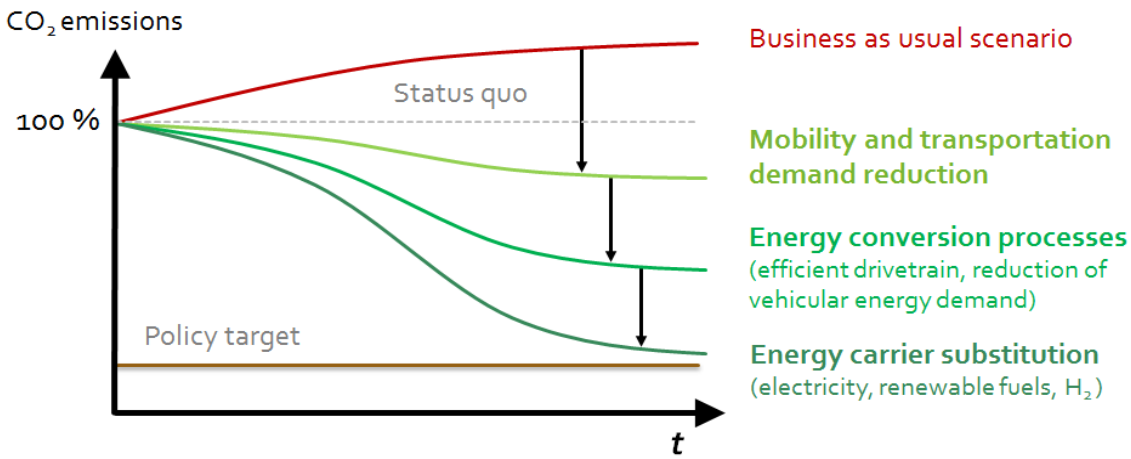


Figure 3.1: A systemic approach towards minimization of CO_2-emissions from Transport (here shown qualitatively) must use synergetic efforts on the demand and supply sides.

The overarching goals of the Swiss Energy Strategy 2050 in terms of minimization of (non-renewable) energy demand and CO_2-output are translated into the envisioned future Mobility Landscape in Switzerland and can be decomposed into several major influencing factors and therefore operationalized by means of a Kaya-type formulation (as introduced in (Kaya & Yokobori, 1998)), here expanded and modified for our specific purpose (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 CO_2-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 first to understand the driving factors for the evolution of energy demand and CO_2-emissions in the transportation sector and second 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 can be aligned 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.

Though the above Kaya-formulation allows decomposing the energy demand and the associated overall CO_2-emissions into individual and specific drivers and interventions one should be careful to acknowledge also its limitations.

One major issue in this context is that in reality many of the individual terms of the above equation are not independent from each other. 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)], that is a direct rebound effect on leads to 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. Exemplarily 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 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 the individual personnel mobility) to each other and help therefore to develop a coherent strategy and vision for a sustainable Future Swiss Mobility.

Chapter 4 deals with the evolution of the CO_2-output and energy demand in the past 25 years to reach its current status, decomposed into major terms of the Kaya-Equation. Subsequently projections in the future are compiled based on different sources (Prognos, ARE, Infras) using the same decomposition but without the effects of specific 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 to 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 CO_2-output Mobility a Reality.

In order to give the reader a flavor of quantitative estimates of what is realistically feasible, CO_2-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 LCA- and economic aspects is then described in *Chapter 7* together with first interesting results.

How this Transformation Path can be actively shaped through policy and innovation measures is then closer but rather in qualitative terms examined in *Chapter 8*.

Furthermore, 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 on Future Sustainable Mobility**.

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 have also clear links to specific topics within the Capacity Areas, along which Research in the SCCER Mobility is conducted.

Exemplarily *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 bases 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 be interfaced with the Joint Activity of all SCCERs on "Scenario and Modeling (JA-S&M)" as well as with the Join Activity between SCCER CREST and SCCER Mobility on socioeconomic Aspects of Mobility.

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

Finally, in *Chapter 10* we conclude on the insights obtained in the framework of the development work for this document and provide an outlook

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 (Kaya & Yokobori, 1998) equation 3.1 in chapter 3. The focus is on direct tailpipe CO_2 emissions – no 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 the infrastructure are neglected leading to the following expression of the direct CO2 emissions of the mobility sector.

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

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

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

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

(A) (B) (C) (D) (E) (F')

The simplified equation (shown above for passenger transportation) decomposes 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 driver on the entire transportation sector, i.e. 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 are influencing 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. The four doughnut charts below provide a rough overview. The two top figures consider the demanded energy of the entire mobility sector (on the left) and the resulting CO2 emissions (on the right), split among passenger and freight transportation, respectively for road and rail. The shares in energy are taken from (Prognos, Infras, & TEP, Analyse des schweizerischen Energieverbrauchs 2000 - 2014 nach Verwendungszwecken, 2015) and are results of a bottom-up modelling. The report lists 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 BAFU.

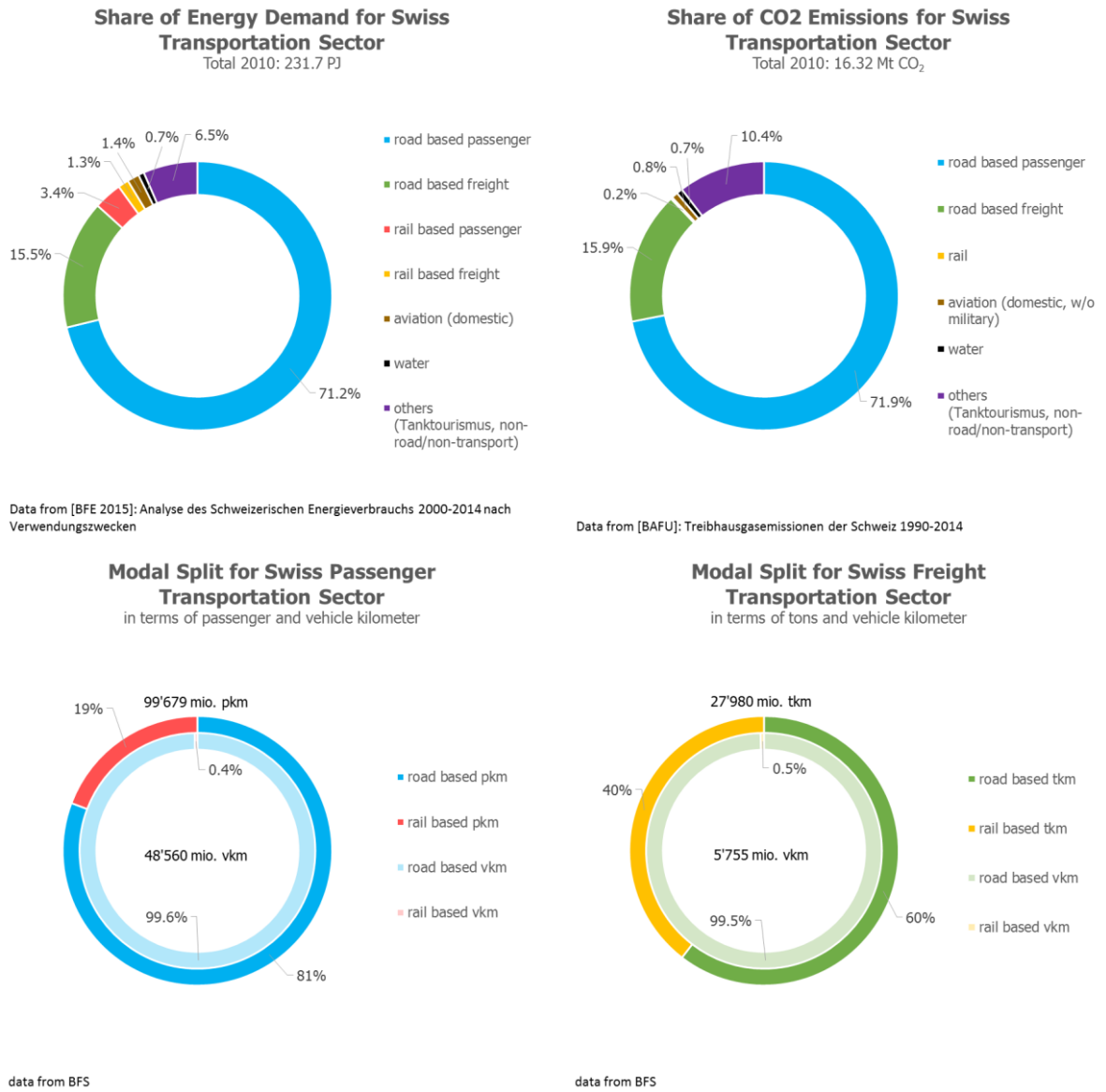


Figure 4.1: Explanatory numbers of the transportation sector in the reference year 2010 represented by road and rail based passenger and freight transportation (4 sectors). Top left: Share of national energy demand of the four sectors including domestic aviation, national ships and 'other' sectors (Source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

The energy demand is highly dominated by road transportation, since road vehicles are responsible for the majority in kilometer performance (distance covered by vehicles within a specified period of time, here 2010), as seen by the inner rings of the bottom left figure for passenger transportation and bottom right figure 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 (CO_2 free in terms of direct emissions) for rail vehicles results in even higher shares for road transportation in CO_2 emissions than energy demand (almost 100%). When talking of potential CO_2 reductions, the 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 ongoing into the future are derived from ARE transportation perspective 2040 (ARE, Perspektiven des Schweizerischen Personen- und Güterverkehrs bis 2040, 2016) and completed by technology trends of the Prognos Energy Perspectives 2050 (Prognos, Die Energieperspektiven für die Schweiz bis 2050, 2012), which is 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 driver. The solid lines stand for statistical values coming from federal offices, which show the evolution in the past years. The dashed lines from 2015 on 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, resulting their product to increases by 47% in 2040 with respect to 2010. Alternatively to the reference scenario, ARE published two sensitivity scenarios in terms of population and GDP evolutions. 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 set differently to derive the alternative scenarios, but all obtain the same evolution in 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 CO_2 emissions, the predominant emitter is the road based passenger sector which is the reason why we concentrate on this sector (despite the anticipated increased share of freight on total transportation related CO_2 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.

[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

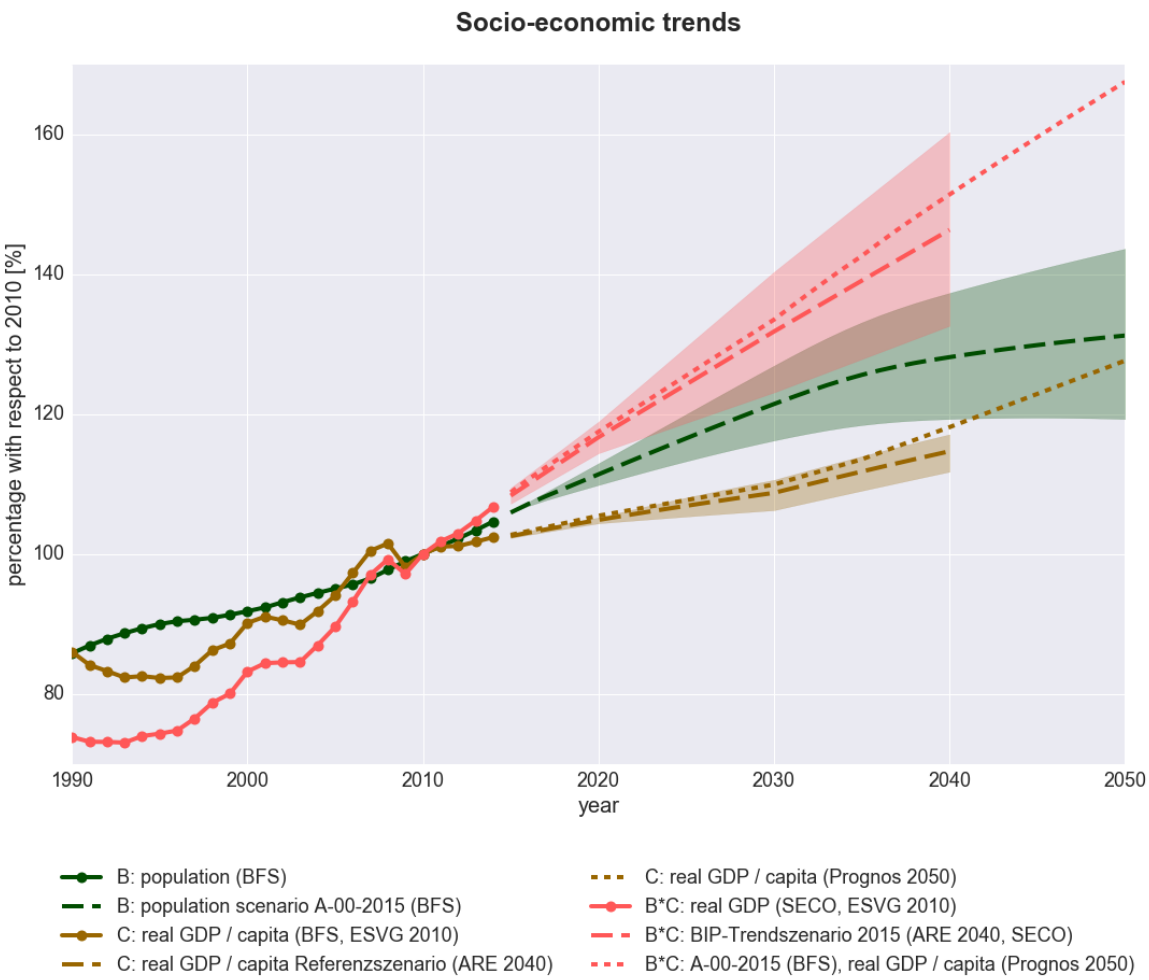


Figure 4.2: Illustration of socio-economic trends of Switzerland: Population (dark green), GDP per capita (brown) and their multiplication (red). Solid lines: Statistics of federal offices. Dashed lines: Assumptions of the reference scenario of ARE 2040 perspectives. Shaded areas: Possible range considered 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, chancing the current share of available money spent on mobility. The orange lines in the figure below illustrate the past trend (solid) and the future evolution 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, small spread around the reference value, 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 overall a 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 influencing factors of 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 generation of the shown scenarios but hold potential in changing the demand for mobility, are discussed and assessed in a qualitative manner.

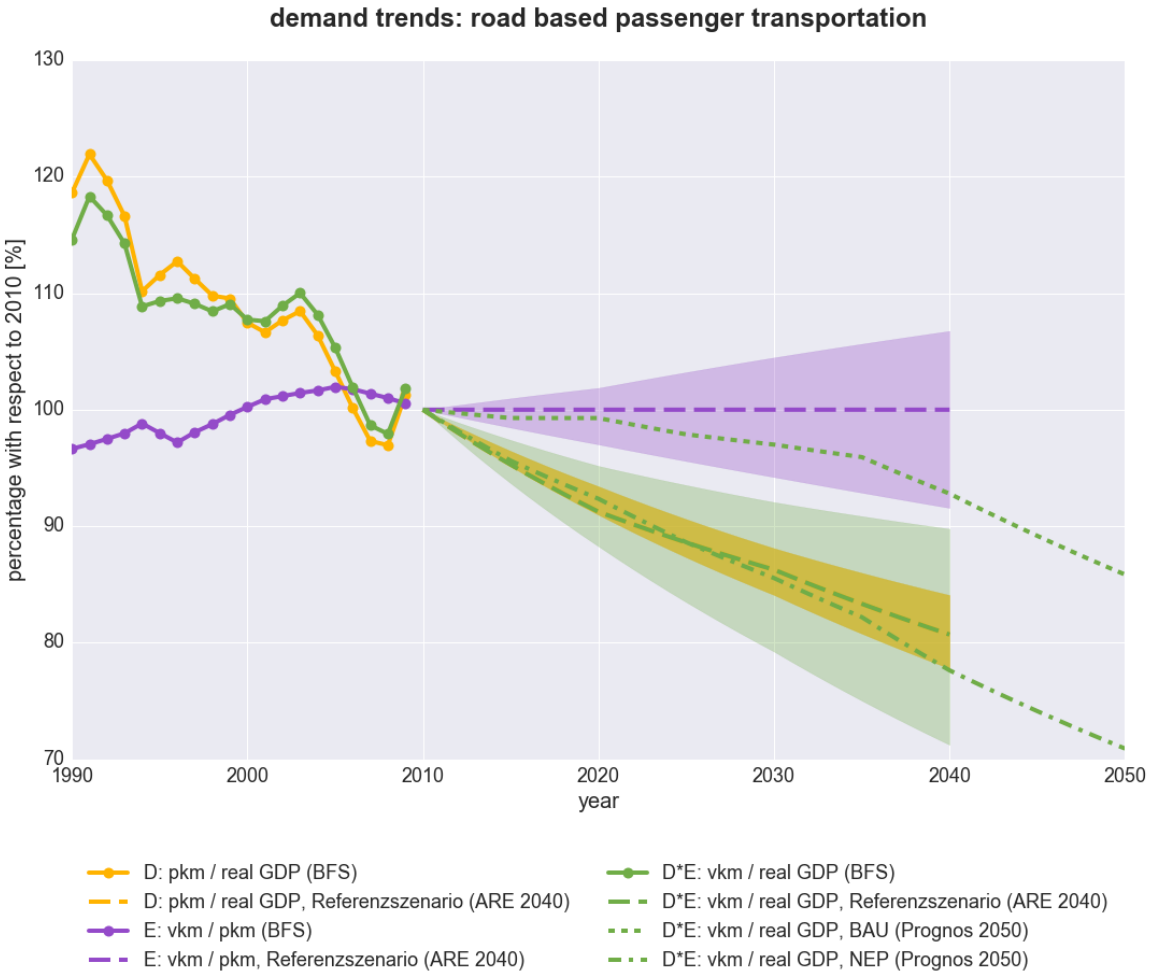


Figure 4.3: Demand trends for the road based passenger transportation sector: pkm/GDP (orange), vkm/GDP (purple) and their multiplication (green). Solid lines: Statistics of federal offices. Dashed lines: Assumptions of the reference scenario of ARE 2040 perspectives. Shaded areas: Possible range considered 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 counter-act 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'). Only Prognos in their energy perspectives provides numbers on how the CO_2 emissions per distance driven 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 gCO_2 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 CO_2 evolution of passenger car transportation.

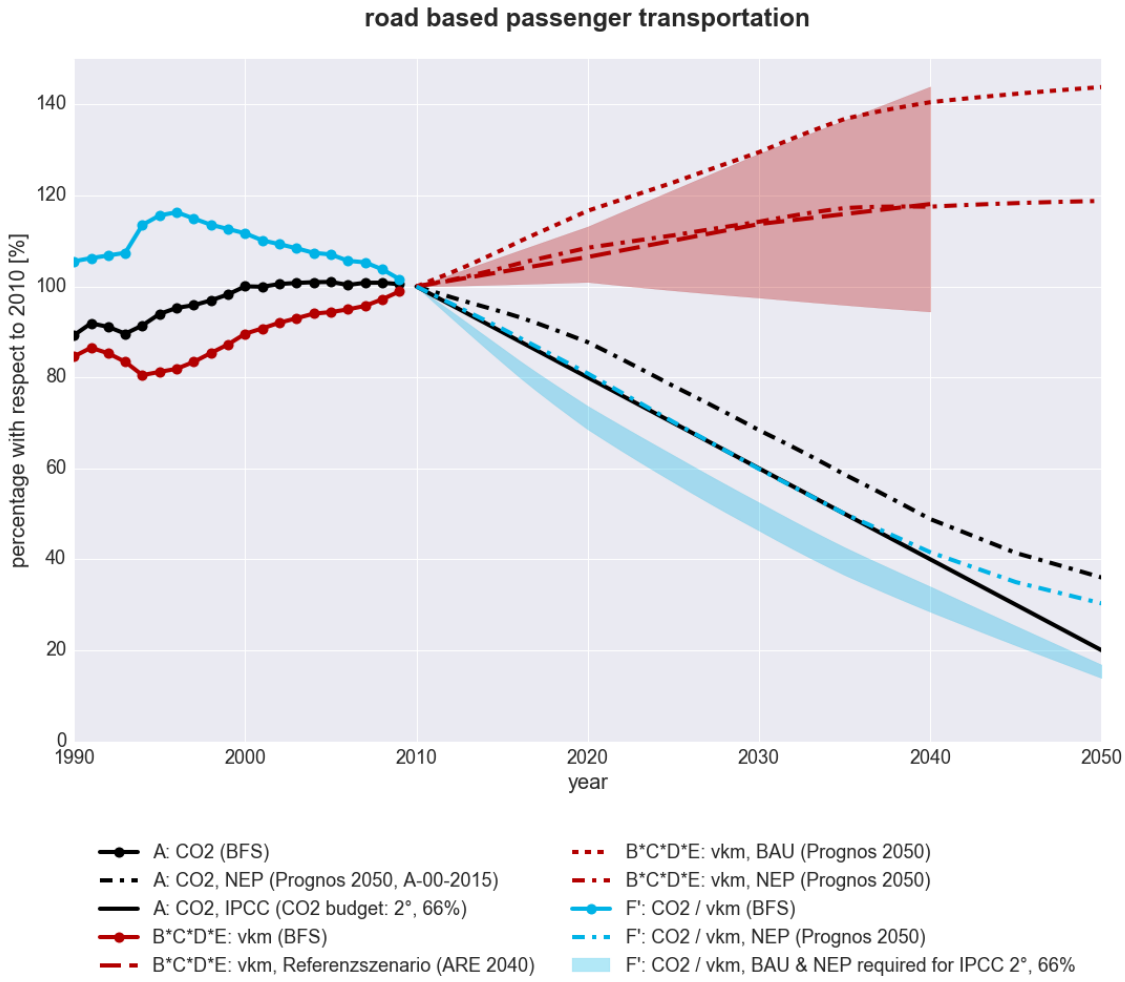


Figure 4.4: Groups of drivers for direct CO_2 emissions of the road based transportation sector: socio-economic driver and demand driver combined in the dark red lines, technology driver in light blue. Their product defines the evolution of the CO_2 emissions (black), comparable to the IPCC target (2°, 66% probability). The evolutions are taken from ARE 2040 perspectives and Prognos EP 2050.

To put the illustrated scenario in context, we need to compare it to a CO_2 reduction target. The IPCC in its latest climate change report (IPCC, 2014) states the global CO_2 budget from 2011 on to be 1000 Gt to achieve the 2° Celsius target with a 66% probability. Distributing it proportionally according to the population of 2010, where the world accounted for 6'855.2 million (World Bank, 2011) and Switzerland for 7.8 million (BFS, mittlere ständige Wohnbevölkerung der Schweiz), results in a CO_2 budget for Switzerland of 1.14 Gt. Assuming a linear decrease in emissions from its level of 45.14 Mt CO_2 in 2010 (BFS, Treibhausgasemissionen der Schweiz 1990-2014, 2016), the budget will be used up in 2060. This means no CO_2 emissions should occur 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 allows to demand a linear reduction in annual CO_2 emissions of the

transportation sector reaching zero in 2060 (this implies over-proportional reduction in CO_2 emissions per capita since the Swiss population is assumed to grow further). The corresponding target line for the CO_2 emissions is shown in the figure below as solid black line (without markers). This trend may be too stringent for the transportation sector and a slower decarbonisation compared to other sectors is more likely, due to its large dependency on high energy density hydrocarbon fuels and because CO_2 reduction in other secotrs such as buildings might be easier and faster.

Figure 4.4 shows that not even the future CO_2 evolution of Prognos NEP (dashed-dotted black line) fulfills the desired reduction target. The scenario results in a 64% reduction in 2050, whereas the target for 2050 is 80% lower than the reference value of 2010. To close this gap, demand side measures can decrease the 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 – which has to be the CO_2 emissions by kilometer since people are most likely to keep using passenger cars as means of transportation. The light blue area indicates the required evolution in CO_2 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 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 CO_2 emission reduction in particular during the early phase by decelerating the usage of the CO_2 budget.

Section 5.2 and 5.3 are discussing 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 Switzerland. Increasing share of electric vehicles in the fleet leads to the decreasing trends of the light blue line (CO_2 per vkm), but at the same time demands additional electricity. Depending on the CO_2 intensity of the electricity production, the CO_2 reduction path for Switzerland (all sectors) may be 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 *incomes* (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 mainly be satisfied by cars, provided that systemic development continues in the previous way and if no policy measures to the opposite 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 gained (ARE 2014). This is leading to increasing mobility demand due to commuting and a general increase of functional links between cities as well as between (large and middle size) cities and with their surroundings. In parallel, although cities begun to implement a more restrictive parking space policy recently, in the past years 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 an integrated spatial and transport policy and planning will strengthen the middle centers leading to a more decentralized spatial structure in Switzerland, mobility demand based on spatial development can be expected to further increase. The recent revision of the Swiss Federal land planning law stated key densification principles and goals for Switzerland. Introducing densification principles – as long as they are not compromising 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 in all the four scenarios the transport volume (number of trips) remains the same on varying hypotheses on land planning, in the "Balance" scenario, which foresees a stronger application of densification and polycentric spatial development principles, overall person-kilometers travelled show a significant decrease 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 they might 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 delay the age when they obtain their driving license (OFS and ARE, 2012), favoring instead 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). There is no evidence, at the moment, on the overall size of these phenomena, nor on their persistence over time. We cannot exclude, in fact, that even though young generations have different attitudes than their parent generation, some of them will revert to cars once they start their own family. In general, however, despite of the question if this different behavior is linked to different attitude or will change towards a more car-based life with growing age, supporting the 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 field). ICT technologies might in fact favour 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 nowadays be performed online from any place 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 higher influence of teleworking and flexible working possibilities on reducing the overall mobility demand.

Diffusion of ICT technologies might also favour 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 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 *policy measures* adopted. 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 in particular prompt the evolution towards electric vehicles (EV) (Seba, 2014; Prognos, 2012). This might 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: decrease in fuel costs, together with the perception of being "green" and sustainable, might stimulate 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, reductions on 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 as the ones already in discussion in Switzerland: for example, thought increasing fuel prices, by means of a tax on fuel consumptions, and/or increasing costs for the use of transport infrastructures, 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 (Mitchell Walldrop, 2015; KPMG and CAR, 2012). Diffusion of driverless vehicles is frequently addressed 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 they could keep sleeping while a car drives them to their workplace, or keep working when a car drives them back home, commuters could live further from their place of work. Also, the total transport volume might increase, since even users without driving license (children, teenager, elderly etc.) might use cars. Overall, then, 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" one: ARE acknowledges that their diffusion will produce an increase in person-kilometers driven and therefore associates them to 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 of course in multiple ways and are interfaced through business models for transportation services. Such business models may benefit from emerging IT/communication technologies (s. Section 5.3) 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 freight and personnel passengers, as this mode contribute to about 93% of the energy demand and 98 % CO_2-emissions of the overall transportation sector (excluding international aviation and "Tankturismus"), see Figure 4.1. We focus here on operational CO2-emissions (tank-to-wheel) whereas in Chapter 7 the analysis will include Life-Cycle Effects. In this context, it is worth mentioning that there exist significant differences between the individual personnel passenger and the freight transport sectors. The former represents a typical consumer goods market, where purchasing and operating decisions exhibit to a certain extent behavior in conflict with economically rational arguments; the latter are is in most cases the basis for investment and operation of truck fleets. In addition, fuel consumption is much stronger in the focus of the 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). Overall, therefore the competitive landscape looks quite different between the individual personnel passenger and the commercial freight transportation.

Turning our attention first to the individual motorized transport it is instructive to attempt to construct a technology envelop for evolutionary development of powertrain and vehicle components. Starting from currently around **42 TWh** fuel energy (dominantly oil products) and about **11 Mio** t CO_2 from all passengers cars

in Switzerland (BFE 2014 and BAFU 2015) and assuming that the demand for pkm remains the same in the future "back of the envelope" estimates show that:

- Combining rather "low-hanging" fruits like improved aerodynamics, reduced rolling resistance and reasonable light-weighting with further IC engines efficiency improvements, up to 20% lower fuel consumption 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 massive switch from diesel/gasoline to Natural Gas Fueled Engines saves 20% CO_2 emissions.

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 the share of sustainably produced biomethane (assumption: 50% of 15 TWh the sustainable biomass of 11 TWh (Steubing et al, 2010), that corresponds to the relative amount of passenger car fuel consumption within the total fossil energy of the Swiss Energy System, would save another 14% of CO_2-emissions leading to 4.7 Mio-t CO_2 per year. A further CO2 reduction down to 4.3 Mio-t CO2 would be possible, if 50% of the estimated future excess electricity in summer (9 TWh according Swissgrid scenario Sun2035) would be transformed in power-to-gas facilities to synthetic methane.

It is against this potential performance that radically new technologies like BEV (battery electric vehicles) and FCEVs (fuel cell electric vehicles) must compete in the future. Similar considerations as above lead to an estimated electric energy demand of 13 TWh (about ½ of best-practice ICE hybrids) for BEVs and about 31 TWh for FCEV`s (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, here however any powertrain improvements (without optimization of the vehicle itself) are considered. It has to be mentioned here, that slight differences can be observed among the calculations in this section and in chapter 7, the reason lying in different data sources and sampling year. Such differences however are contained within ±5% margin.

Therefore, fuel-cell vehicles are beneficial in terms of climate change mitigation only with the CH-Consumer Mix or pure renewable power generation, while BEV`s 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. One has to take into account of course, that in the decades to come the carbon foot-print of electricity generation both in Europe and the US will decrease substantially. How fast this will happen will of course 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.

The same considerations with very similar findings apply to light-duty commercial vehicles, while the situation for long-haul trucks is somewhat different. Here, BEV`s continue to outperform 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 be still prohibitive. A window of opportunity may open here therefore for fuel-cell powertrains in long-range freight transport on the road if very large amounts of excess renewable electricity are available in the future. An even more pragmatic alternative is considered to be the massive penetration of Natural Gas Engines, thus replacing in the mid-term a large portion of Diesel-

fueled engines, thus leading to a CO_2-reduction in this segment of between 10% (today) and ultimately 20% by 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 lift-time of existing power generation power plants the transformation of the transportation sector towards Sustainability will probably not be accomplished before 2050.

Concerning evolutionary developments, ICE powertrains will require research efforts in combustion, thermodynamics, aftertreatment, advanced controls and sensors as well as adaptive capacity towards fuel flexibility.

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

Improvement of fuel-cell powertrains is needed mainly with regard to durability and costs, while high pressure hydrogen tanks seems to be the most promising thought not inexpensive 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 HVAC and other auxiliary devices will be important for the reduction of non-propulsive energy demand. The latter is particularly relevant for Battery Electric Vehicles (for BEV`s, to a lesser extent for FCEV`s), since it is the share to the overall energy required 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 outcome depending on the sector and on barely predictable evolution of costs and performance of electrified powertrains. Besides cost-to-performance aspects, the evolution of the power generation system will be of decisive importance for the final trajectory of the path towards a sustainable mobility.

5.3 Energy infrastructure requirements and interfaces with the overall energy system

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

Key questions here refer to the technology and investments necessary for replacing or partially substituting the existing fossil hydrocarbon-based fueling infrastructure. Charging infrastructure for BEV`s is evolving and costs will probably decrease to competitive levels, however charging times are still way too long for long-range travel habits of customers. Ultra-fast charging is recently advertised as potential solution, however there are trade-offs to consider here, since battery life-time may suffer drastically in such cases. In addition configuration of the electric grid topology in order to be able to adapt to local power peaks is critical. A relief may be created in this context, if plug-in hybrids will become a competitive option, since for these, overnight charging will be sufficient and pressure for expensive public infrastructure will be rather low. The same applies if one assumes that home charging equipment will be broadly available within a reasonable time frame.

FCEV`s offer some advantages compared to BEV`s concerning infrastructure demands. Although initial investments for H2-stations may be quite high, time for getting energy for a few 100km driving is comparable to ICE powertrains and so is the number of necessary charging (refueling) stations is much lower. On the other

hand, logistics of H2 transport from generation to consumption location may become demanding and induce additional costs as well.

With regard to long-haul trucks on the other hand interesting options for charging on the road ("Oberleitung") are emerging and may – despite high investment and maintenance costs - become an alternative to ultra-heavy batteries at least along highways and main routes. Depending on concrete requirements however at least an additional battery and/or a hybrid powertrain will probably still be necessary on-board of the vehicles to cover all other routes.

Concerning an ambitious trajectory for CO2-emissions reduction of the whole Swiss Energy System it is important to consider the necessary coupling and therefore co-evolution of the Electricity and Transport Sectors. When, as expected, electrified powertrains (for either BEV's or FCEV's) are going to capture high market shares and subsequently penetrate into the fleet, it is crucial to examine how the CO2-footprint of the marginal (additionally needed) Energy will look like in the future. While in Chapter 7 estimates of such developments will be presented in more detail we discuss in the following a few trends and interdependencies in a qualitative way.

It is conceivable that marginal electricity for transportation may be obtained (assuming no new nuclear power plants) from:

(a) combined-cycle-gas power plants

(b) Imports

(c) An expansion of renewable energy sources within Switzerland

Option (a) can be assessed already now as the power generation technology is mature and its performance well known. In addition, security of supply is considered to be reasonable, given the diversified sources of natural gas imports of the country. As said before under these conditions BEV's would emit about 30% less operational CO2 than 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, BEV's are in par with gasoline hybrids but 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, a process that will require 2-4 decades for its full implementation.

Option (c) requires a significant expansion of renewable electricity generation-capacity in addition to the one needed for substitution of our nuclear power plants, that 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 require not only 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 Sensibility and particularly cost estimates of such disruptive transitions must be investigated in detail within our SCCER and in the frame of Joint Activities with other SCCERs in the next year.

Other non-energy related transportation infrastructure will be of course very important for the evolution of the mobility system and will influence not only the supply but also the demand side as well as 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 such a case, also 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 with regards to 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* on the one hand and its *real-time regulation and management* on the other hand.

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 continuously become 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 such as current temperature measurements or precipitation rates. Another valuable means for data collection is provided by the wide-spread use of location-enabled devices such as modern smart phones, which are especially relevant with regards to 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 georeferencing 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 spatio-temporal datasets offer unprecedented possibilities for gaining insights into the mechanisms of human mobility, especially when being integrated with context-sensitive information (Miller 2015). Simultaneously, however, 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, however, the gained data represent a necessary 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 by use of intelligent transport systems (ITS), which, based on multi-sensored data, can provide travelers, traffic managers, planners, and policy-makers with real-time traffic information, and therefore reduce traffic congestions, lower the risk of accidents and improve the quality of public transport (UN 2012). These systems are expected to improve from the discussed technological progress in the area of monitoring devices. Without the need for top-down measures, however, travelers themselves will to a greater degree be able to deploy mobility-related location-based services (LBS) via their smart phones which 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.

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

2016b). In view of the fact that there is a potentially preserving digital divide, however, it is important to ensure equal access to such assistive technologies to the entire population. More closely related to motorized traffic is a different form of real-time traffic regulation, namely 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 of mobility-impaired persons to personal car travel (Casner et al. 2016).

To sum up, 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 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.

5.5 Shared mobility and automated vehicles: Potential impact on energy consumption

Shared Mobility

Shared mobility has constantly grown in importance in the last few decades (Shaheen, 2012) and has the potential to disrupt the transportation system as we know it today. There is already a large corpus of literature that deals with shared mobility instances but there are still some evident research gaps. One of the most important is that they have been very often considered as "stand-alone" systems ignoring the whole complexity of the 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 means trying to find optimal combinations of shared mobility solutions, which would provide a substantial reduction of energy consumption without reducing individuals' mobility.

To get such insight on possible future scenarios, in which shared mobility systems would be implemented at large scale, the agent-based simulation MATSim is used. MATSim mimics the population of a given region, object of a study, 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. The first stage of the work dealt with the generation and evaluation of some "extreme scenarios" meant to provide insight on the impact of the extremely wide diffusion of a particular shared mode. This allows understanding which kind of trips can realistically be made with which mode, what kind of potential overlap in supply exists, and what kind of cost/benefits can be expected.

The series of simulations performed so far focused on carsharing and bikesharing, and the region around the city of Zurich was taken as study case. For carsharing, 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, looking at actual impact on agents' utility, 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 be used to complement such a carsharing system, a series of simulations where a large bike-sharing system was put into place were conducted. E-bikes are less convenient than car and public transport and the difference grows for longer distances. However, the difference is not very large for short trips especially with respect to public transportation. This means, that there is potential for e-bikes to complement the car-sharing system and capture the demand for shorter trips.

Therefore, the results obtained show that shared e-bikes and carsharing could be usefully combined in order to capture a large part of current travel demand, in particular car travel, in the study region. It seems however, that for medium distances (5-10 km), it could be necessary to integrate an additional option as e-bikes are not very competitive against private cars any more, and carsharing in the suggested form is not yet competitive due to the relatively high effect of the access time in this distance range. Ridesharing could be this additional option, as it would also have a certain, probably similar, access time, but may be cheaper. This requires the exploration of further single-mode extreme scenarios and then of combined scenarios with two of these modes or even all three. The main point is, that finding an equilibrium between a large-scale carsharing and a large scale ride-sharing scheme will not be trivial. It has been shown that a car-sharing system with the selected specifications can substantially reduce the size of a city's car fleet and that it would be possible to totally avoid private car ownership whilst providing a good level of service. However, if ride-sharing would be based on private cars, a large enough fleet of them should still be available. If this would be rather a shared taxi scheme, one would need to find another equilibrium.

The study discussed, was intended to explore the solution space and produce a meaningful basis for the generation of stated preference exercises and therefore, some assumptions were rather coarse (for example car-sharing having the same utility of private cars). The data collected through that survey, will be used to obtain discrete choice models, which will be implemented in the simulation. In the final stage of the project, it will be possible to run new simulations with fully functional representations of car-sharing, bike-sharing and ride-sharing in MATSim. This will provide a plausible insight on how shared mobility modes could be integrated at large scale, capturing a large part of the current travel demand whilst reducing transport-related energy consumption. Whilst minimizing energy consumption is the main focus of this research, in the future, different dimensions could be included. For example, one could extend the scope to life-cycle energy consumption which would also include embodied energy, or generalize the analyses to include 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 the topic addressed exclusively the technological aspects of AVs. Recent developments, however, made clear that the technology will soon be available. The consequences on the transportation system are yet uncertain, but it is reasonable to assume that they potentially will be extremely far reaching. Some researchers pointed already 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, thinking of a large scale AV car-sharing scheme able to satisfy most of the demand currently covered by personal cars, the most evident benefit would be the much smaller total car fleet needed. 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.

A simulation approach, allows investigating the fleet size problem. A fleet of shared AVs, which serves a predefined demand, was simulated. Several simulations were run, assuming that different shares of the current car travel demand were fulfilled with differently sized AV fleets. The demand represents the car travel demand for the greater Zurich region, Switzerland, at high spatial and temporal resolution. This was obtained using MATSim, an activity-based multi-agent transport simulation framework. This demand is used as a static demand in the simulation of AVs. The simulation framework used goes beyond those seen so far in the existing literature in terms of spatial and temporal resolution of the demand. This provides a more solid basis to the ongoing discussion on the fleet size required to serve a certain travel demand with a given level of service. It is found that, for a fixed level of service (expressed by the waiting time), the relationship between trips served and fleet size is non-linear and the ratio increases as the number of trips increases. So there is, as could be expected,

a scale effect, which has the important implication that, for different levels of demand, the fleet is used more or less efficiently.

This first application also allows comparing the scenario results with existing studies on the topic. Compared to earlier studies a much lower peak fleet usage was achieved. The average usage is lower too as the trips served per day per AV and the total usage time of an AV is 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 serve such demand. While here a peak usage of around 70% was achieved, other researchers found values of 97% and higher. The same applies for the average usage. In our study, AVs are used about one third of the day and serve in average 26.9 trips while other studies found a usage rate of two thirds of the 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, 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 to a strong influence of the spatio-temporal 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. Inner cities show an above average high density of demand which results in very high usage numbers of the fleets. The demand used in our study, originating from locations over a very large area (trips are originating from almost anywhere in Switzerland and from some regions outside of it close to the border, and are included in an area of more than 420km x 270km), 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, AV has the potential to replace up to 10 of today's cars if a maximum reaction time of 10 minutes is accepted and the share of the participating population is large enough.

The simulation framework used still has several limitations and future work will address them. The most important one is using a static demand. Transport demand is influenced by new mobility offers and changed mobility costs. The demand in the simulation should be able to adapt to these new offers. 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. This in turn would have demand reducing effects, bringing the system to a new equilibrium. How these effects influence each other, how the new equilibrium looks like and what this means for infrastructure capacity requirements, requires the investigation with simulation frameworks able to explicitly account for such effects.

5.6 Concluding remarks

While evolution of future transportation demand is subject to various drivers that in the absence of strangest policy measures, may lead to increasing or decreasing trends, supply side trends can be predicted concerning the CO_2 reduction potential according to different power train technologies and energy carriers portfolio.

While efficiency increase of vehicles and powertrain up to 50 % can be gradually achieved with hybrid, combustion bases systems, the necessary radical decarbonisation of the transport sector is only feasible with, massive deployment of electrified vehicles on the long term. The footprint of the marginal electricity for transport must be kept however very low despite phasing-out nuclear power plants. Fuel-cell shows thereby logistics advantages for long-range, heavy-duty transport, while battery-electric drives 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 possible break-through in automatic driving technology may lead to strong demand increase and therefore lead to adverse effects on the electricity demand for mobility.

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. It should evaluate the maximum impact potential of various research directions on a systemic level, 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 of the government. The demand side is covered by the survey *Mikrozensus Mobilität und Verkehr 2010* (MZMV 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 for the energy demand computation follow from distributions derived on the MOFIS register, i.e. the database of all matriculated vehicles in Switzerland. It is worth stating that the set of all considered vehicles – the fleet – resembles the actual Swiss fleet, i.e. is composed by 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 bases on vehicle measurements of EMPA (Christian Bach, 2011). The WLTP for light duty vehicles and 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 of 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, there aren't any predictions into the future possible nor are any realistic penetration rates of a technology or social effect covered. Each intervention is carried out independently and to their 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 invariant at today's level, regardless of the additional electricity demand – which is the only cost function. The Swiss consumer mix is the utilized electricity mix and its CO_2 intensity is taken from BFS, 2016.

Motorized vehicles for passenger transportation

Figure 6.1 illustrates results from the strategic guidance project in mass of CO2 reduction for passenger transportation. Each separate numbered lines 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 are affecting the 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 efficiency and thus acts beneficial on term addressing the powertrain conversion efficiently, G of the Kaya-type equation (neglecting increase in vehicle mass). Switching the energy carrier from currently 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 present, since hybrid-electric vehicles only operate on hydrocarbons.

2. **Battery electric vehicles** (Topic A1.1, B1.1, 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 not the entire fleet is substituted by battery electric vehicles, but only where they are applicable. The increased powertrain efficiency (term G) is the main driver for the CO_2 reduction. Additional electric energy is required, which – dependent on the electricity mix and infrastructure losses (grouped term of H and I) – will lower the CO_2 reduction potential. A charging infrastructure allowing to cover 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 one (starting point) and allowing them to charge their battery 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 consist 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 of battery capacity as indicated by the dashed line converges towards the all battery electric vehicle fleet. Additional mitigation stems from substitution of CNG by the finite, national biogas supply (Steubling, Zah, Waeger, & Ludwig, 2010). It is assumed that half of the biogas supply is available to mobility, in analogy to the roughly 50% share mobility currently holds as a consumer of fossil fuel.

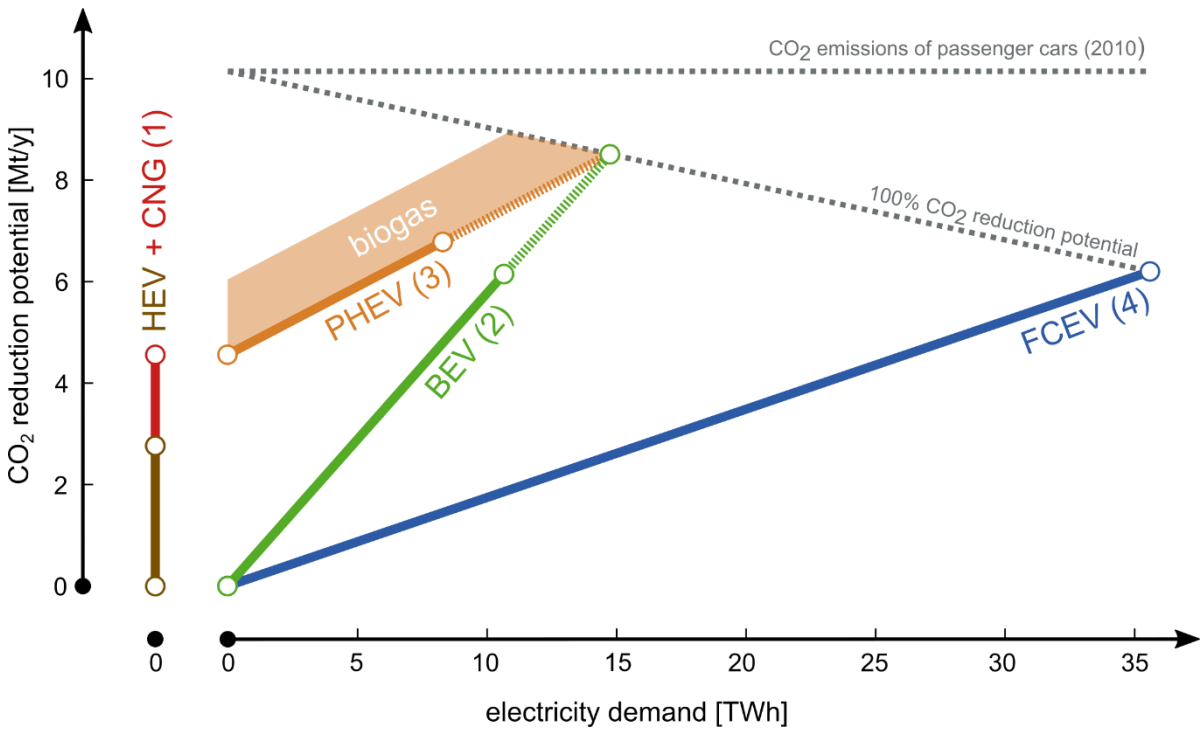


Figure 6.1: CO_2 mitigation potentials and additionally required electricity of different technology "interventions" for passenger transportation studied within the SCCER mobility project "strategic guidance". All numbers are relative to the status-quo as of 2010; only operational CO_2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.

4. **Fuel-cell electric vehicles** (Topic A2.1, A3.3): The substitution of the current ICEV fleet by state-of-the-art fuel cell electric vehicle (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. Neither are changes in the CO_2 intensity of the Swiss consumer mix in time or due to increased demand. In general, there is no temporal dimension given in figure 6.1.

Light duty freight vehicles

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

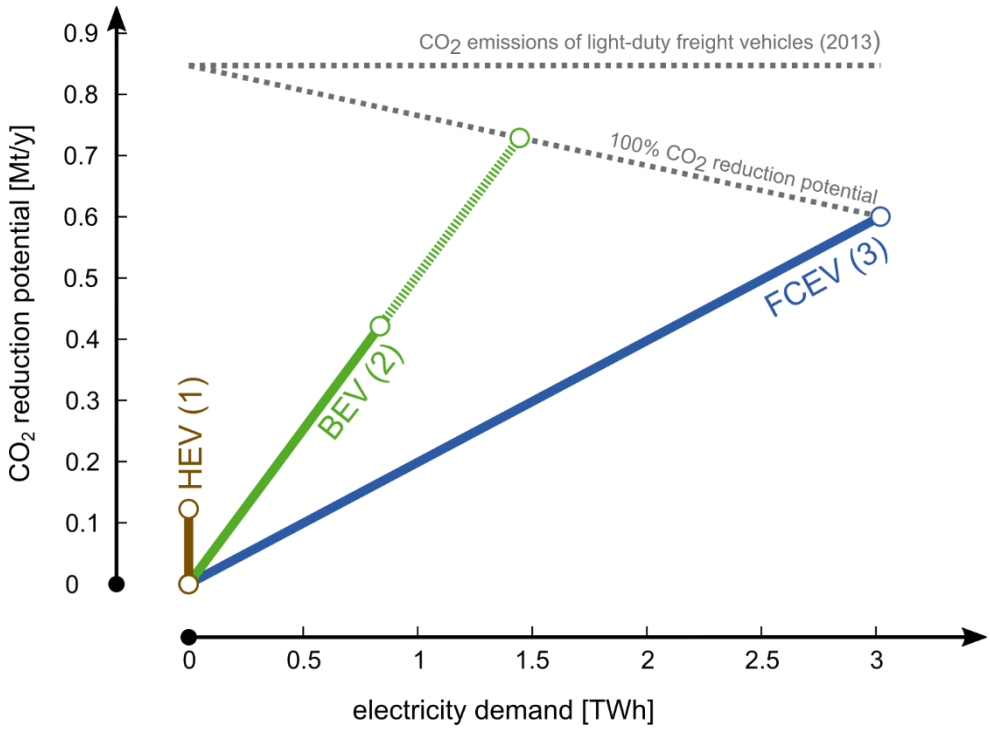


Figure 6.2: CO2 mitigation potentials and additionally required electricity of different "interventions" for light-duty freight transportation. All numbers are relative to the 2013; only operational CO2 is considered; all electricity production is presumed to have the same properties as the current Swiss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

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 not negligible reduction in CO2 emissions. The reason for this trend is the increased fuel conversion efficiency. Compared to the 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 present.

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 provided 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 again the main driver for the CO_2 reduction. A charging infrastructure can help here too to increase the maximum CO_2 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 vehicle, a fuel cell electric vehicle fleet is designed – substituting the fuel carrier to hydrogen and the conversion to electricity to fuel cell stacks. No range anxiety is assumed allowing to alter the entire fleet. Locally, there are no CO_2 emissions, but the reduction potential is limited by the supply of hydrogen with electricity.

Heavy-duty freight transportation

The technology interventions for the heavy-duty freight transportation sector are shown below in figure X3. This sector contains rigid trucks and articulated semi-trailers. There are two interventions carried out, namely battery electric and fuel cell electric vehicles. Hybridization is not considered, since the reduction potential was assumed rather small compared to current conventional powertrain designs. The applied interventions only consider rigid trucks, leaving all semi-trailers of the fleet untouched.

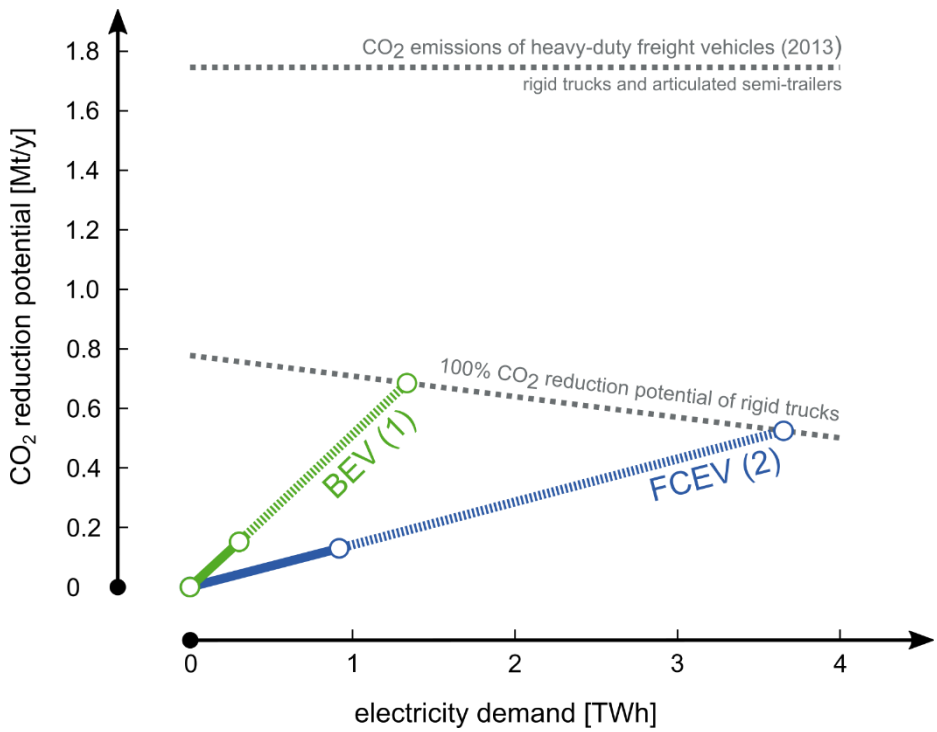


Figure 6.3: CO_2 mitigation potentials and additionally required electricity of different "interventions" for rigid trucks accounting to heavy-duty freight transportation. All numbers are relative to the 2013; only operational CO_2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.

1. Battery electric heavy-duty vehicles (Topic A1.1, B1.1, A3.3): Based on existing battery electric truck designs (EFORCE ONE AG) and allowing for maximum legislative vehicle weight of 40 tons, the reduction potential is shown in figure 6.3. The higher conversion efficiency (term G) acts beneficial on the reduction potential. Available range and reduced payload capacity limit are hindering factors. Improvements in battery technology, fast charging or battery swapping are options to further increase the reduction potential 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 reduce the payload capacity limitation, due to limited range and the electricity intense provision of hydrogen the reduction potential is in the same order as the battery electric option. A good infrastructure allowing for fast refueling can increase the reduction potential significantly.

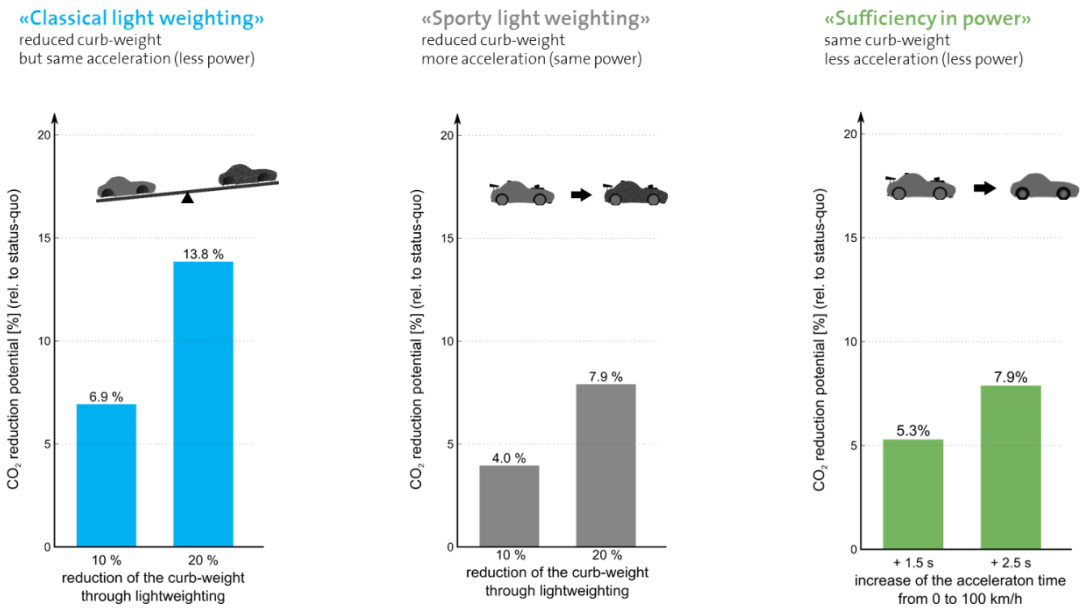


Figure 6.4: Share of CO2 mitigation potentials of change in vehicle curb weight an/or rated propulsion power of passenger cars. All numbers are relative to the status-quo as of 2010; only operational CO2 of passenger cars is considered.

Influence of vehicle weight and engine power

All shown interventions refer to the vehicle powertrain, which is not the only possibility for CO2 reduction measures. Another option are light weighting 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 two optimistic weight reductions levels of 10 and 20 percent proposed by the researchers active in the field (Capacity Area A3.1). An alternative approach could be the "sporty light weighting" represented by the middle 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, however less than in the first case. The third set of bars on the right are 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 0 to 100 kph. Although it is a technical modification on the vehicles acting on term G of the Kaya-type equation, this intervention is purely limited by people acceptance. Therefor it can be classified as a social – in contrast to a technical – intervention. 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.

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 get people to travel less with passenger cars. The two following interventions are addressing two kinds of such a shift of 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 travels 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 kilometers for bicycle and 10 kilometers for e-bikes. The criteria for feasibility considers that from leaving home until returning (trip) no single distance (stage) between point of interests, 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 6.6.

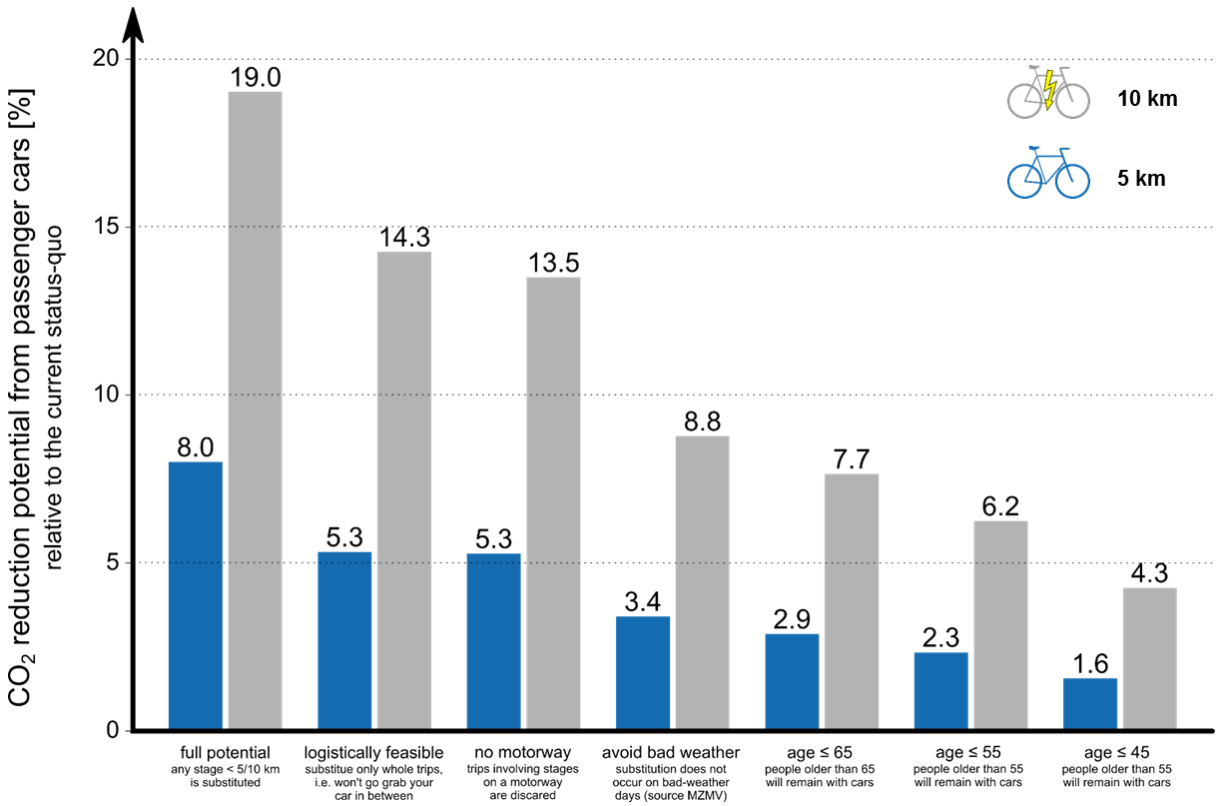


Figure 6.5: Share of CO2 mitigation potentials of substituting passenger car stages with bicycles and e-bikes. The set limiting stage lengths are 5 and 10 kilometers. All numbers are relative to the status-quo as of 2010; only operational CO2 of passenger cars is considered.

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 of Switzerland (Zurich, Bern, Basel, Geneva, 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 as 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.

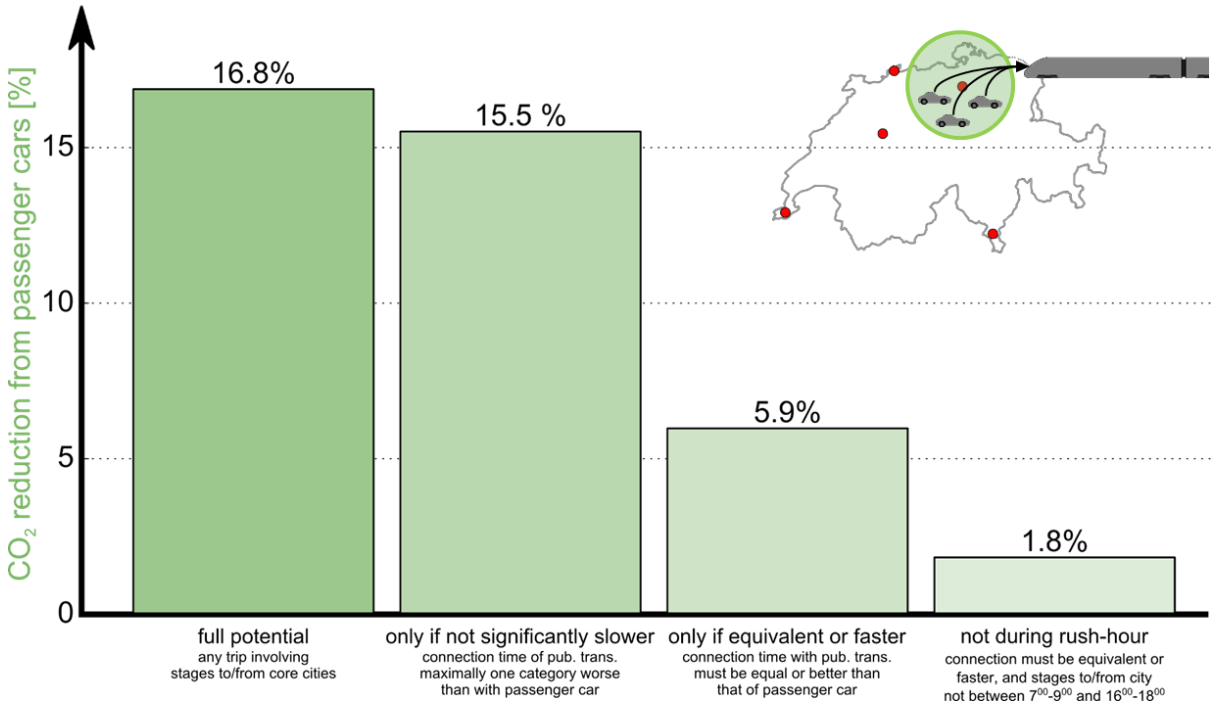


Figure 6.6: Share of CO2 mitigation potentials of substituting commuting trips to the five core cities performed with passenger cars by train. All numbers are relative to the status-quo as of 2010; only operational CO2 of passenger cars is considered.

Concluding remarks

The above considerations show that a combination of demand, modal choice and supply –side (technology) measures can lead to substantial energy demand and CO2 emissions in transportation. We have discussed here however, "first-order" interventions, not pursuing further subsequent "second-order" effects and policy measures enabling implementation of such interventions. In addition, we have so far explored only operational C02 emissions and energy demand, 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.

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 include for example Life Cycle Assessment (LCA), Cost Assessment (CA) and Risk Assessment (RA). Multi-criteria Decision Analysis (MCDA) is applied on 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. The 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. This allows to analyze 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 the state-of-the-art assessments. This does not apply yet to the other mobility modes such as public or goods transport, which will be correspondingly upgraded 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, to the extent possible logically independent, consistent and manageable (i.e. representative but not exhaustive). While in the context of Energiewende 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, 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 at least to some extent conflicting objectives. 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, essential for many individual users. The criteria used in the multi-criteria decision analysis are listed in Table 7.1.

Environmental	**Economy**	**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.

Evaluation of indicators is based on a variety of methods, some of them mentioned above. This has been fully operationalized for current and future passenger cars. In the next section examples of 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

Figure 7.1 Left 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. Figure 7.1 Right shows the total passenger kilometers travelled by each mode in Switzerland in 2014. As is clear in this 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 perform the best of all. As cars are by far the dominant mode of passenger transport, and also have very large potential for future improvement, they are the focus of the rest of this chapter.

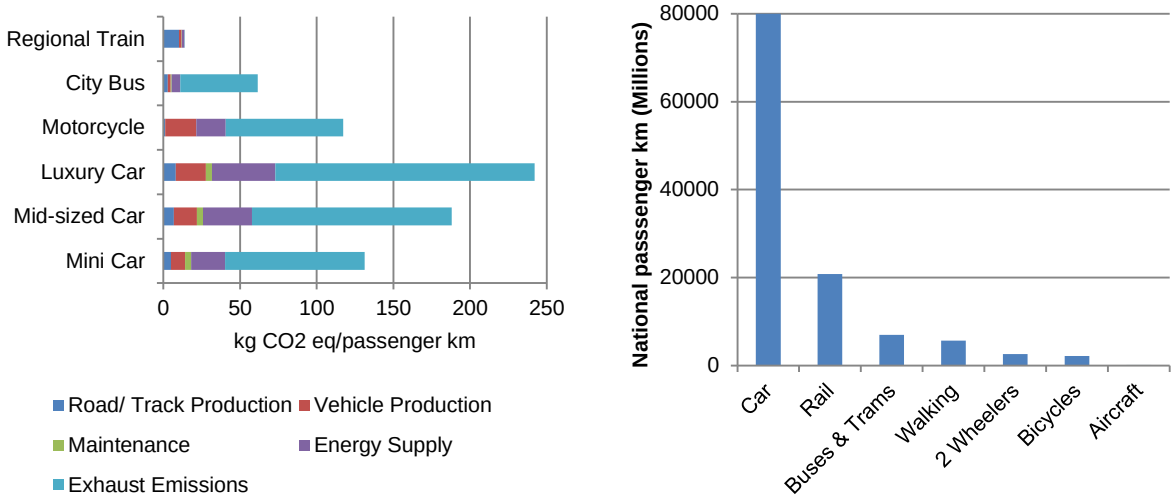


Figure 7.1. Life cycle global warming emissions per passenger kilometer and 2014 Swiss national passenger klometers travelled for common passenger transport modes. Cars are assumed to have 1.6 passengers (Swiss average) and drive according to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) 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. City buses are assumed to be 25% filled 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. The cars and motorcycle 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 climate change impacts and total costs of mid-sized passenger cars in Switzerland for production years 2012 and 2050 and different powertrains and energy chains per vehicle kilometer. On the left side, this figure breaks the GHG emissions down into contributions from direct tailpipe emissions (shown in blue), indirect emissions that occur in Switzerland, such as emissions from road production or fuel production (shown in red), and emissions that are due to Swiss passenger cars but do not occur in Switzerland, such as the emissions from producing lithium ion batteries in China (shown in green). 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, with CO_2 eq/vkm emissions from cars produced in 2050 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 greenhouse gas 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 7.1 the total costs of these vehicles are compared for the 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.

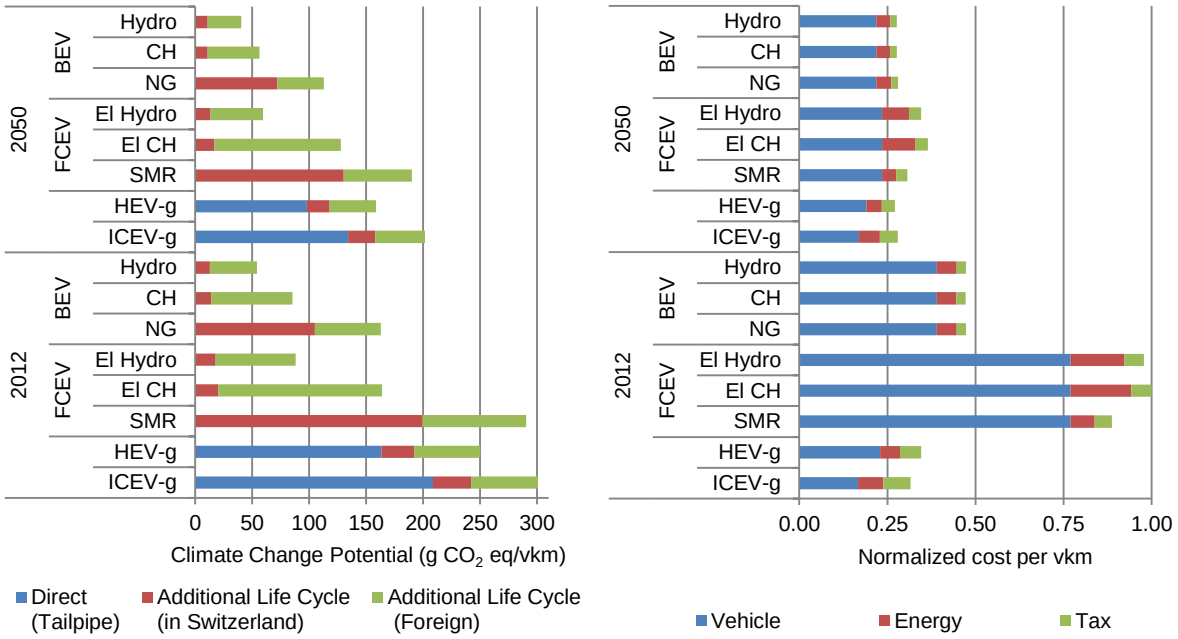


Figure 7.2. Life cycle greenhouse gas emissions and total costs per vehicle kilometer from mid-sized passenger cars in Switzerland, production years 2012 and 2050. ICEV-g =Gasoline Internal Combustion Engine Vehicle, HEV-g = Gasoline Hybrid Electric Vehicle, FCEV = Fuel Cell Electric Vehicle, BEV = Battery Electric Vehicle. Hydro = Hydroelectricity, CH = Swiss electricity consumption mix, NG = Natural Gas combined cycle electricity, El = Electrolysis, SMR = Steam Reforming of Methane. Gasoline assumed to represent conventional petroleum refined in Switzerland. Steam reforming of methane 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 further impact categories. Results for each impact category have been normalized to the largest total impact in each category. The sensitivity of the four damage category LCIA results concerning electricity and hydrogen generation pathways for both current and future technologies are illustrated. The results also demonstrate – in contrast to current common practice – the need of analyzing environmental indicators beyond greenhouse gas emissions in order to identify potentially problematic environmental issues along the life cycles.

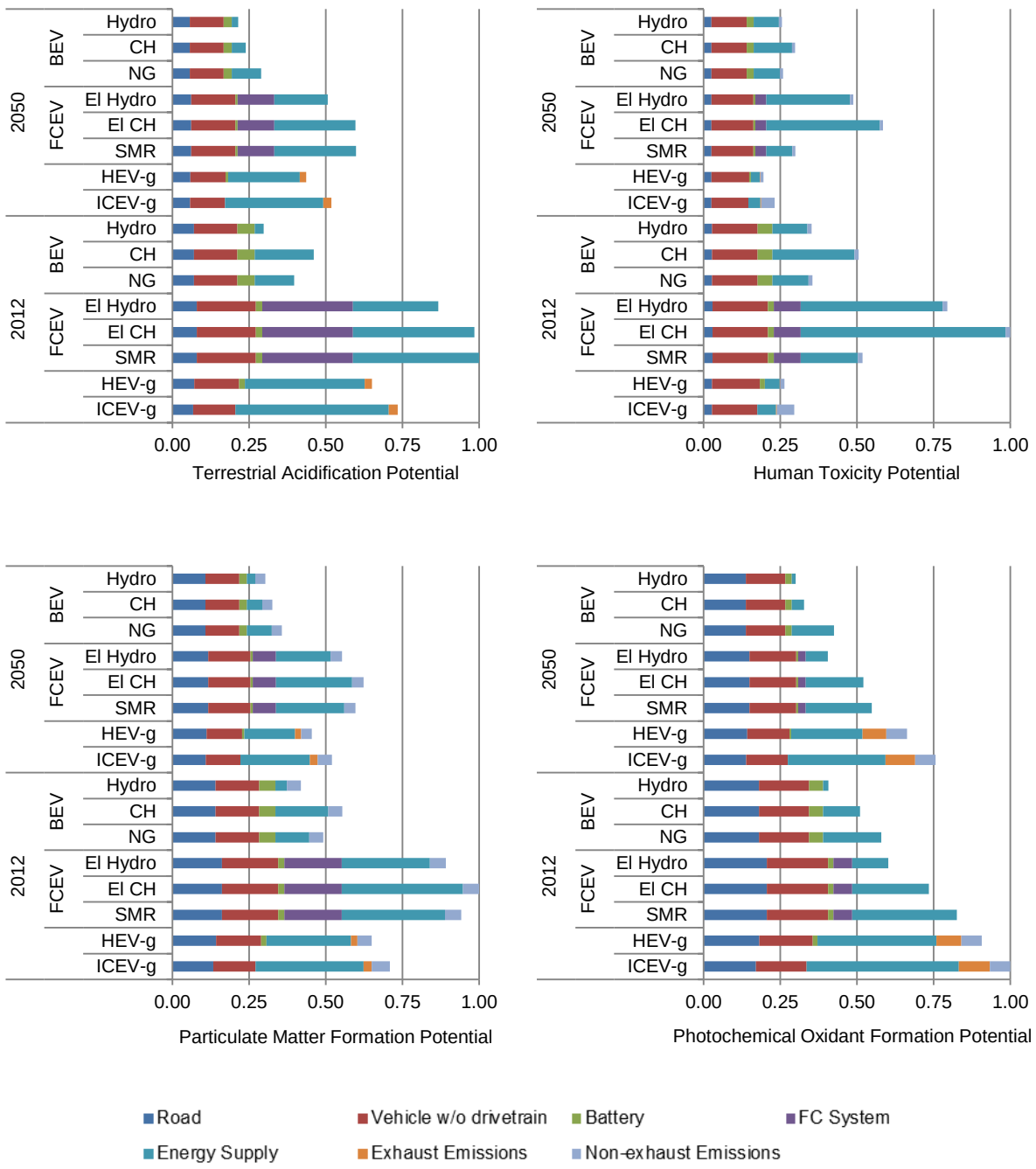


Figure 7.3. Normalized life cycle impact assessment results per vehicle kilometer from mid-sized passenger cars in Switzerland, production years 2012 and 2050. ICEV-g =Gasoline Internal Combustion Engine Vehicle, HEV-g = Gasoline Hybrid Electric Vehicle, FCEV = Fuel Cell Electric Vehicle, BEV = Battery 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.)

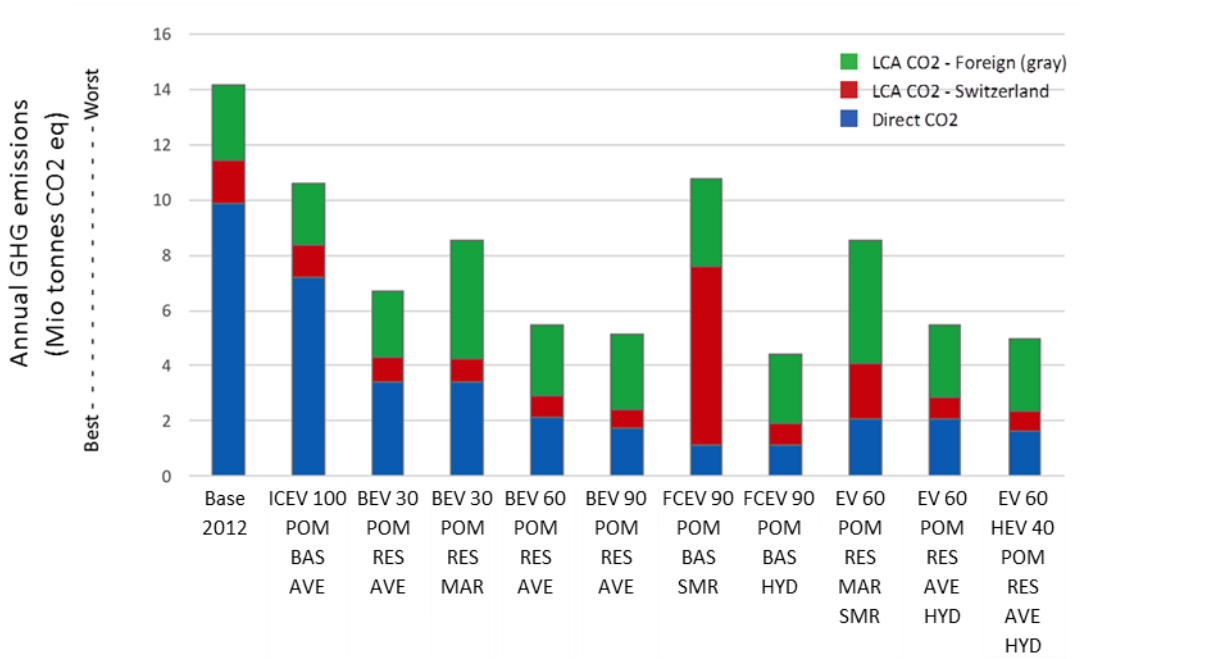
As shown in the following equation:

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

the total GHG emissions of the transport fleet are calculated considering not only the tailpipe emissions of the vehicles, but also all greenhouse gas emissions in the whole energy and infrastructure chains as well. This calculation has been carried out for the Swiss passenger car fleet in 2012[3] and, for different scenarios, 2050. Some of the results are shown in Figure 7.4. The fleet is modelled using nearly 3000 vehicle classes, drivetrains and fuels. The relative share of each drivetrain type in each future fleet scenario is indicated by the number in the x-axis labels. 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 in the x-axis label. For all scenarios shown here, the electricity sector demand is according to the Political Measures (POM) scenario of the Swiss Federal Office for Energy, while the electricity supply scenario can be either gas dependent (BAS) or renewables focused (RES). Furthermore, the electricity mix for charging BEV can be either the average electricity generation mix, or the marginal electricity mix. Hydrogen production for 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 occur in Switzerland, and finally the life cycle emissions that occur 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 reduced by 25%-65%, depending on the penetration rate of advanced powertrain vehicles and the development of the energy system.

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.

[3] It is noted that the greenhouse gas emissions for the base year, 2012 are slightly underestimated here. This is for 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 MATSim data used did not allow the separation of different annual distances to different car vehicle sizes. In reality, smaller vehicles tend to have lower annual distances travelled than larger vehicles. Both of these factors contribute to an underestimation of the 2012 fleet total emissions by approximately 10%.



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

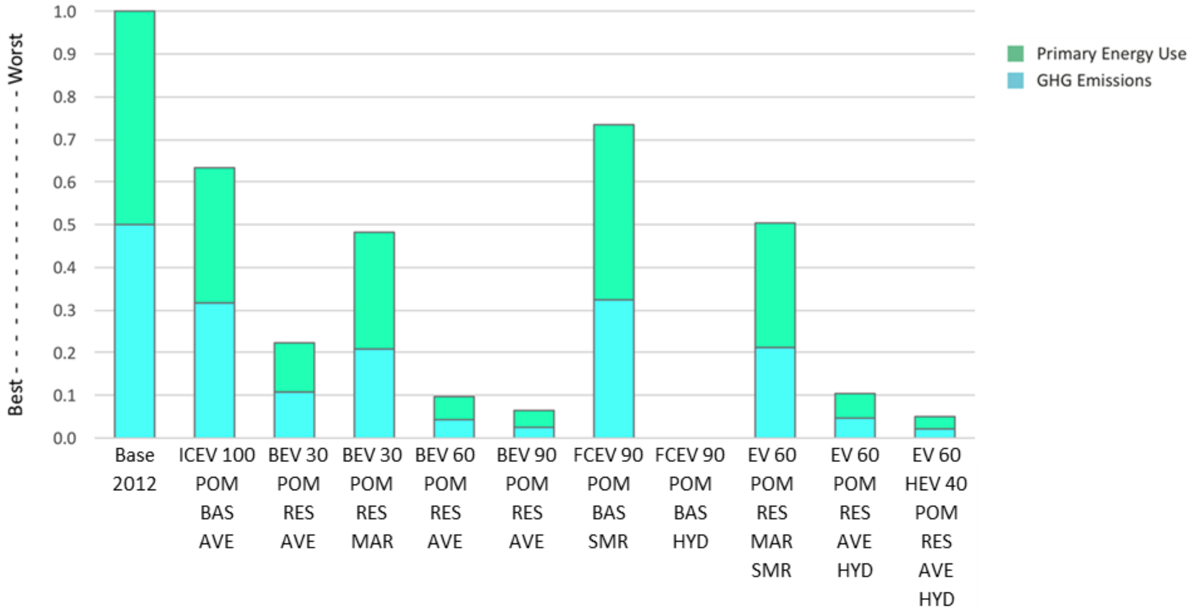
POM - Demand is SFOE "Political Measures"
BAS - Supply is gas-dependent strategy
RES - Supply is renewables strategy
AVE - Charging is average generation mix
MAR - Charging is marginal generation mix

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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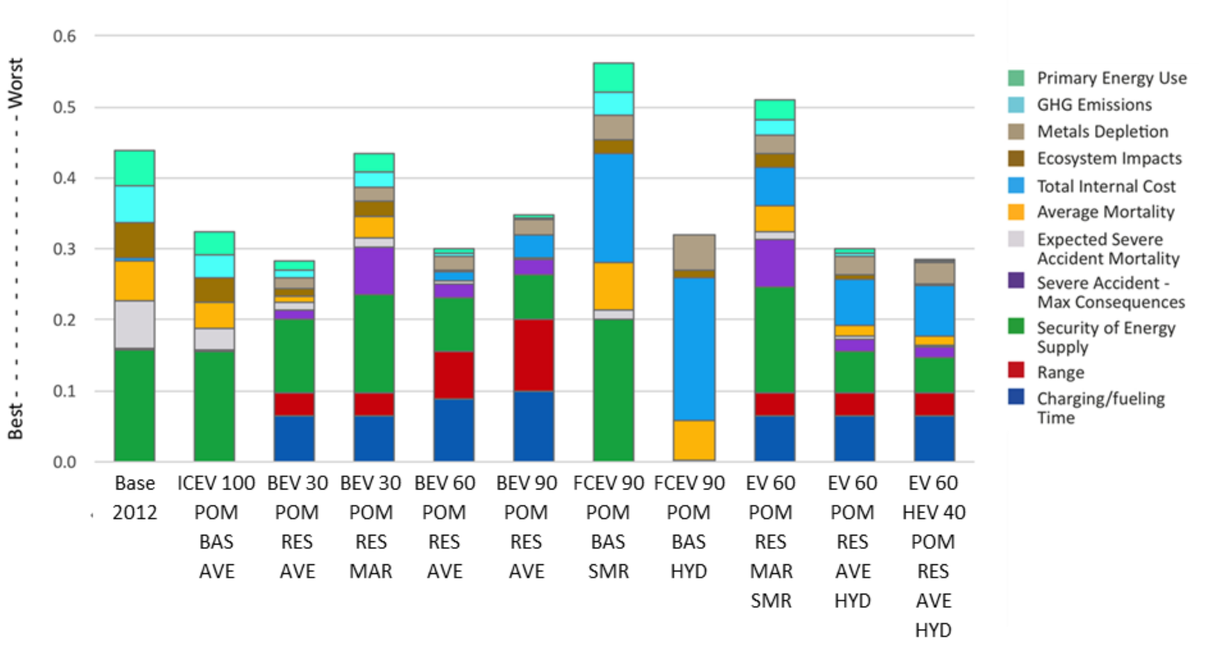
SMR - Steam Methane Reforming
HYD - Electrolysis using Swiss Hydropower

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).



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

Figure 7.6. Car Fleet Multi-Criteria Decision Analysis (MCDA) Ranks with equal waiting of sustainability criteria (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 "Energiewende". 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 lack 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 sourced from steam methane reforming. Fuel cells are also found to 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).

7.2 Long term mobility transition scenarios - Whole energy systemic approach

In Swiss TIMES energy system model (STEM), the whole energy system of Switzerland is modelled from primary energy supply to all end-use demands. The model belongs to the family of technology rich, bottom-up cost-optimization energy models and represents a broad suite of energy technologies/infrastructure and energy commodities. The model has a time horizon of 2010-2100 with an hourly representation of weekdays and weekends in three seasons. The transport sector has two types of demands, *viz*. 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 Phase II. 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, with which electricity demand for e-mobility become endogenous based on marginal cost. We analyzed a set of scenarios to meet transportation demands taken from the 2050 Swiss Energy Strategy (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 CCS); while in the low-carbon (*LC60*) scenario additionally a 60% total CO_2 emissions reduction pathway following the New Energy Policy scenario of the SES is assumed. 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.). The average tailpipe CO_2 emissions of the entire car fleet decline from 208 g-CO_2/km in 2010 to 98 g-CO_2/km by 2050.

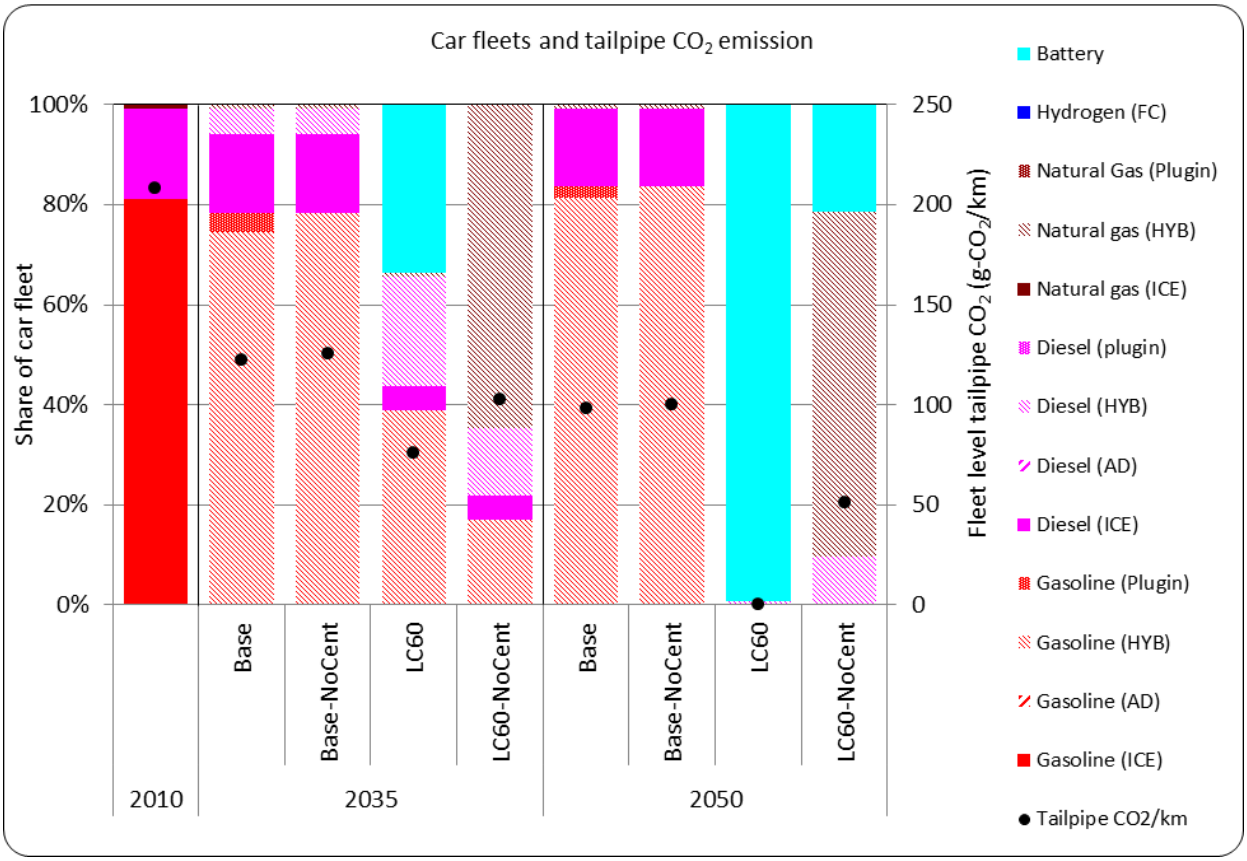

Figure 7.8. Vehicle types in car fleet and Tailpipe CO2/km emission for different scenarios in 2035 and 2050 against today's data

In *LC60* scenario, BEVs penetrate from 2035 which results in earlier decarbonisation of the car fleet. By 2050 all cars are BEV. The energy demand for car fleet in 2050 declines by 72% (vs. 40% in *Base*) from the 2010 level (Figure 7.). 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.) —that is, e-mobility 'shifts' some of the CO_2 emissions to the electricity sector as renewable potentially is 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 CO_2 emissions (Figure 7.). The increasing electrification is resulting in continuous growth in electricity demands. Under the condition of phase out of nuclear generation, there is need for additional domestic capacity in both the short and long term (or sufficient imported electricity, which is not enabled).

The centralized gas plants support the deployment of BEV by providing off-peak electricity during weekends. However, the long-term transition of the car fleet towards different electric drives 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 a half of the total transport energy use and CO_2 emissions in 2010, future vehicle technology and fuel choice play a crucial role for the overall development of the Swiss energy system.

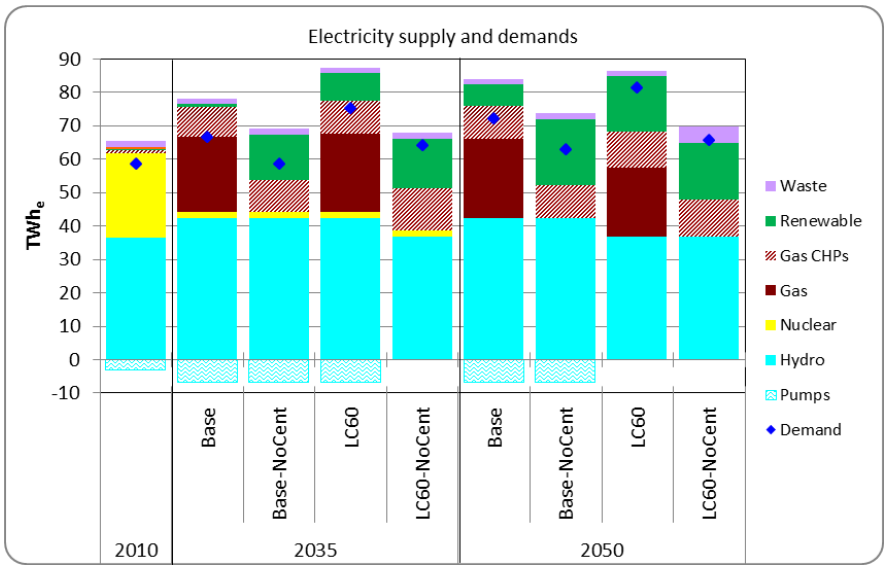

Figure 7.9. Electricity supply and demand. Demand represents the end-user electricity demand excluding losses. Electricity consumption of pumped storage is shown as "Pumps". CHPs include both centralized and distributed.

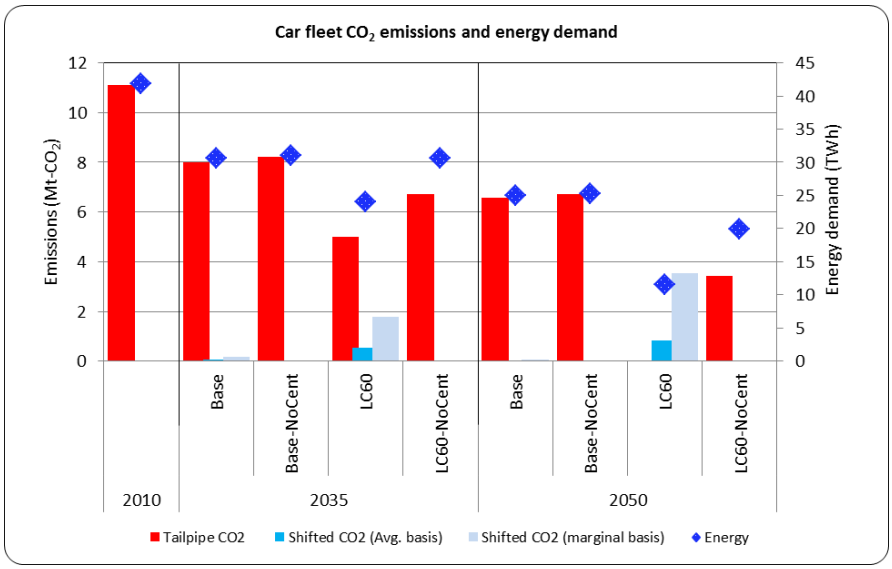

Figure 7.10. CO_2 emissions and energy demand from car fleet. The shifted CO_2 emission is estimated based on electricity used in car fleet and the average /marginal emission factor of electricity supply.

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 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 reduces challenges to the electricity sector compared to the development under higher fossil fuel prices. However, such a scenario raises additional challenges to meet any climate change mitigation policy goals (and would continue to dependent on imported fossil fuels), and thus likely requires additional policy intervention to support new technologies (gas, electric vehicles, etc.). On the other hand, high energy prices induce accelerated deployment of electric mobility (and indirectly support climate change mitigation). However, high 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 the uptake of suitable technologies and support the conditions for investing in mobility- and electricity infrastructure would benefit deployment of advanced transport technology or might even be essential therefore.

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. It must however be considered here that on the long term electric cars cannot be excluded from taxation for road infrastructure, expenditures for which are on the order of several billions per year

The limited set of scenarios analyses sheds important insights into the development of the Swiss car fleet; and its influence on the whole energy system. Additional scenarios focusing on role of hydrogen fuel cell and CCS technologies are being explored

8 Supporting the transformation process

8.1 Introduction

Todays' energy and mobility system is a result of past trends shown 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 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 political decisions resulting in a new system with 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 was not only fundamentally changing mobility, but also the economic structure, settlement patterns, lifestyle etc. on a global scale.

The political decision for the Swiss 'Energiewende' with related activities in economy, R&D as well as on the political and social level reaches a dimension of fundamental change resulting in system transformation. In order to understand system transformation in a holistic way and to derive recommendations 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 with 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 "*Energiewende"* requires a goal-oriented, guided process joint objectives need to be defined as part of this vision.

Between these two conceptions of future systems – 'Energiewende' 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 here, 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, see also Chapter 9.

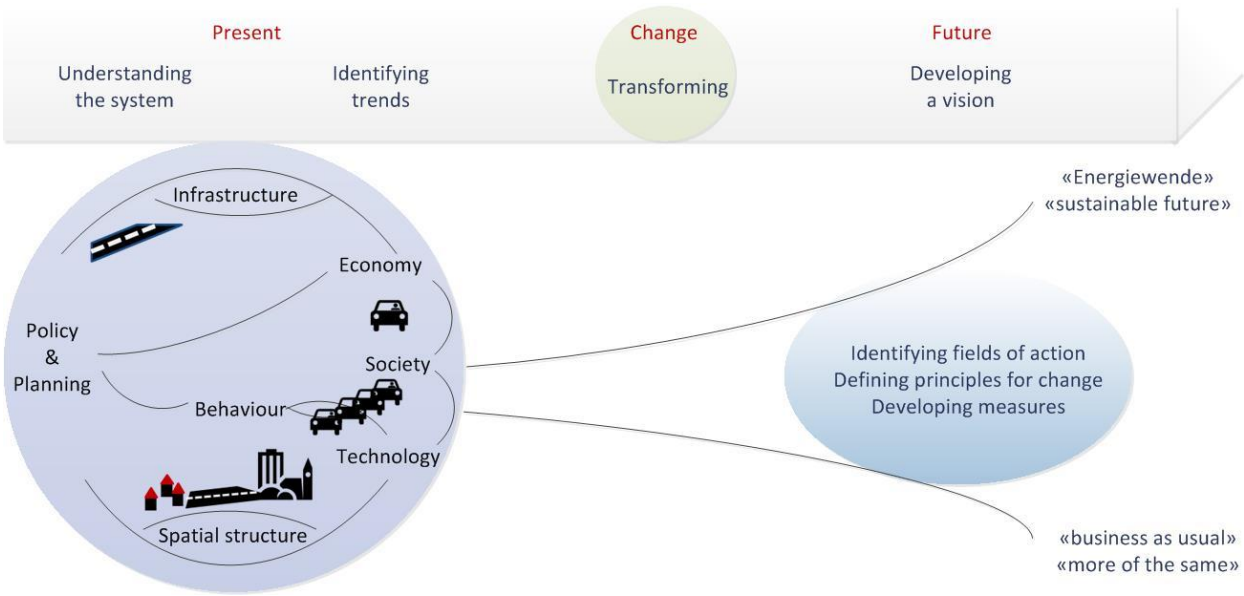

Figure 8.1: System transformation versus path-dependent trend-based future scenario

8.2 Transformation as a fundamental change 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 basis 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) has been adapted as a framework 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 and in order to use it for practical oriented analysis and it has been adapted as an approach for SCCER. 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 to understand 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** describing the role of organizations in the transformation process. The role of stakeholders will be crucial here; thus this stakeholders have to be included in order to shape the 'Energiewende'. 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 successfully shape the transformation process; a change will happen anyway – 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 come along with the opportunity of guiding the development in a certain direction – if right actions are taken. Especially changes of the economy and 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 virtual one, which would decrease mobility demand. Although corresponding technologies already exist this hasn't happen so far, which points to the fact that the need for cultural change in this context has been underestimated. With new generations of digital natives and industries strongly based on virtualized cooperation as global cultural trends of the working world can be expected to change. Policy together with employers and stakeholders in economy and society 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 coming up with the future trends in combination with the specific Swiss strengths and weaknesses; both aspects (challenges/opportunities and strengths/weaknesses) are derived from trend analysis in different fields of the macro-level such as mobility itself, environment, demographic and socio-cultural development, economy and spatial development as well as technology.

As Swiss strengths, especially the high quality of public transport, emission legislation, political strategies like "Energiewende" itself and initiatives as the 1 t CO_2/ 2000 Watt society as well as a high potential for shared mobility can be mentioned. 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.

Other characteristics of the Swiss system can be considered as weaknesses when it comes to transformation. High standard of 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 economy, population, income and real estate prices lead to increased mobility demand, which is further pushed by social trends like more actively spent leisure time of the growing group of the elderlies 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, which unconditionally needs to be linked to **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 and **4. Shift towards quality of the economy and working world** to meet sustainability requirements, which might lead to a more digital and flexible working.

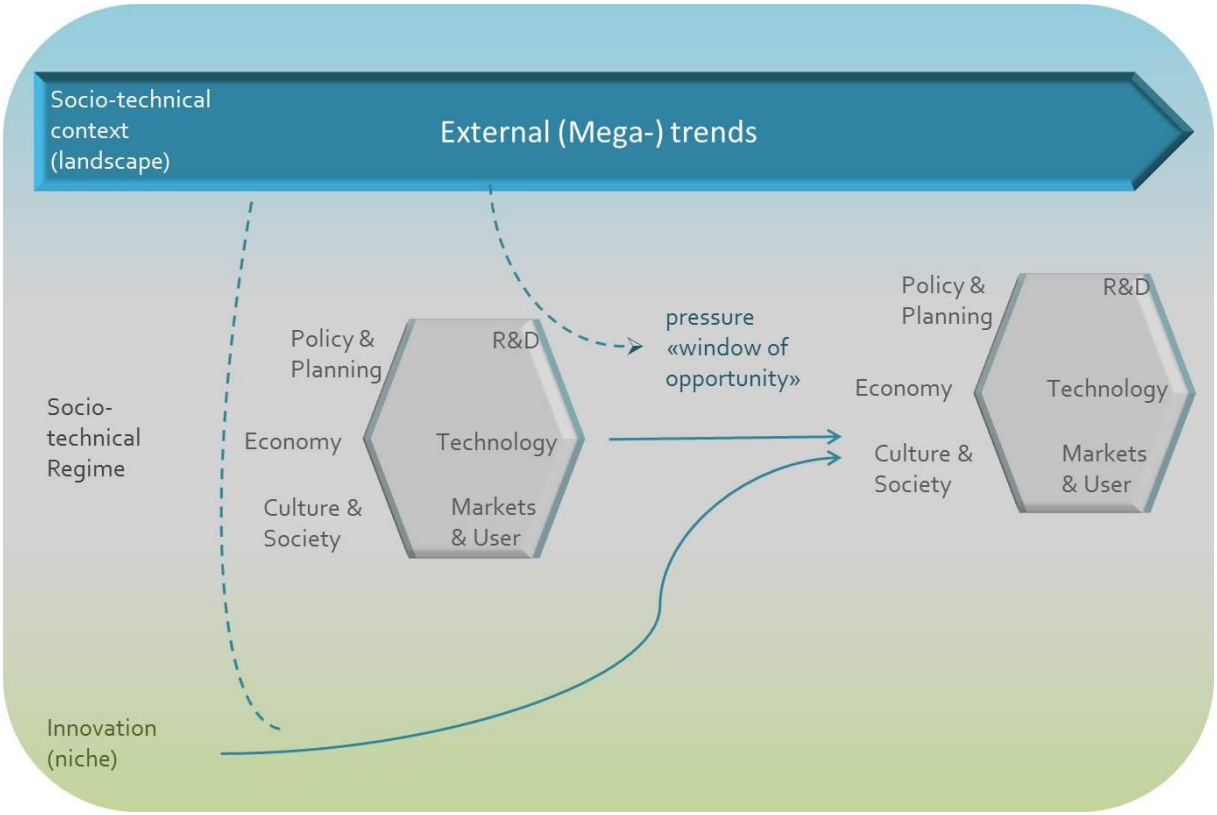

Figure 8.2: Model for systemic transformation on a multilevel-perspective (Geels 2007, adapted)

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

Following the theoretical framework mentioned earlier we discuss in the following some concrete, mainly policy-related measures, that help to achieve the strategic goals of the Energy 2050 with regard to the Mobility Sector. The list of measures is not exhaustive nor does the numbering correspond necessarily 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, to the extent possible according to up to date knowledge. According to recent studies, annual external costs of the Swiss transport sector amount to roughly **9.4** billion CHF or about 1.5 % of Swiss GDP in year 2010, (Ecoplan, Infras 2014). Motorized individual passenger transport accounts for **5.5** billion CHF and freight transport on the road to **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; **2.3** Rp/pkm for trains, while for bicycles net external costs costa are about **4** Rp/pkm. For freight transport external costs for the road are with **2.5** Rp/tkm on average at about the same level as rail freight (the LSVA playing and 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 driving usually in and around environmentally sensitive urban settings.

   It is worth mentioning here that the total annual external costs of the road transport of **6.7** billion CHF exceed the estimated annual road transport (pre-tax) fuel costs of currently about **4** billion CHF by about 50%. Their internalization would therefore have a significant effect on the overall marginal costs of road transport and thus affect considerably the demand for transportation services.

2. To realize fair prices, steering measures (" Lenkungsmassnahmen") through internationalization of external costs are much more efficient than subsidies as also a recent study for the whole energy sector in Switzerland has 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 external costs internationalization dampens this demand considerably.

3. A successful policy for internalizing external costs must care for coordination 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 however is a set of policy instruments that yields consistent price signals over all energy sectors. Taking CO_2-prices as an example, it is on one hand reasonable for Switzerland to adopt the European Legislation for specific CO_2 emissions for cars as this helps automotive industry to deploy fast appropriate technologies across all relevant markets. On the other hand declaring electric powertrain as CO_2-free despite the (currently and in the foreseeable future) substantial CO_2-footprint of marginal electricity sends wrong signals to the markets, increasing therefore the specific mitigation costs for CO_2 of the overall energy system against the optimal path.

5. Although economic theory and practice have proven that steering measures ("Lenkungsmassnahmen") are superior to subsidies in terms of the cost/benefit trade-off, humans do consistently prefer the latter against the former. Lack of appreciation for Life-cycle costs of given investment decisions and rather high discounting attitudes for the future pose severs challenges for

public acceptance of the right policy instruments. Here the role of scientific expertise and –tailored to the specific audience- proper communication are crucial for improving mobility/energy related "financial" literacy of the society and key stakeholders in particular.

6. In addition a well orchestrate policy strategy with regard to the life-time and depreciation schemes for important assets, specifically including large scale infrastructure, is of outmost importance for maximizing reduction of CO_2 and other pollutant emissions from transportation. Long-living infrastructure (urban/spatial structures, roads, power plants, etc.) must be addressed early enough to avoid lock-in effects, while for appliances such as vehicles one can rely on higher natural replacement rates and therefore technology improvements penetration into the fleet; therefore 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 in the next few years out of research projects within the SCCER –Mobility and in particular in the frame of the Join Activity between our SCCER and SCCER CREST

9 Navigating uncharted waters – the Learning Lab on 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-interactions. Scenario work as already in place within Capacity Area B2 (see Chapter 8) will address exemplarily patterns of potential future development and thus help bracket it within "best" and "worst" cases, at least to the extent they can be conceived today.

Past experience has shown however that unexpected shocks (geopolitics, disruptive technology innovations, macroeconomic instabilities, radically new business models) may shape the future trajectory that the Energy and Mobility System will follow in unpredictable ways. As technology, policy and other important boundary conditions evolve, it is therefore mandatory to continuously explore the internal dynamics and potential responses of the whole system. This leads straight to the need to create a **Learning Lab on Future Sustainable Mobility** that will provide a link between "Top-Down" strategy and "Bottom-up" developments. The Lab's work will be based on the Systems Dynamics Approach 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 but will seek synergies within and outside our SCCER – will help also to make our Roadmap(s) more flexible and adaptive to new developments.

The strength of the 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. The challenge is however that some of these relationships are not a priori known quantitatively and the associated models require validation. This is particularly true with regard to socioeconomic interactions including aspects of human behaviour. Here it appears worth considering Agent-Based-Models (expanding for example the work carried out within the SCCER Mobility under the MATSim umbrella) 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.

Here we would like to qualitatively illustrate how the system dynamic description of a part of the Mobility System would work, for example with regard to the influence of a game changing technology like the Automated driving on the expected evolution of the energy-demand and the CO_2-emissions of the Motorized Individual Transport Sector.

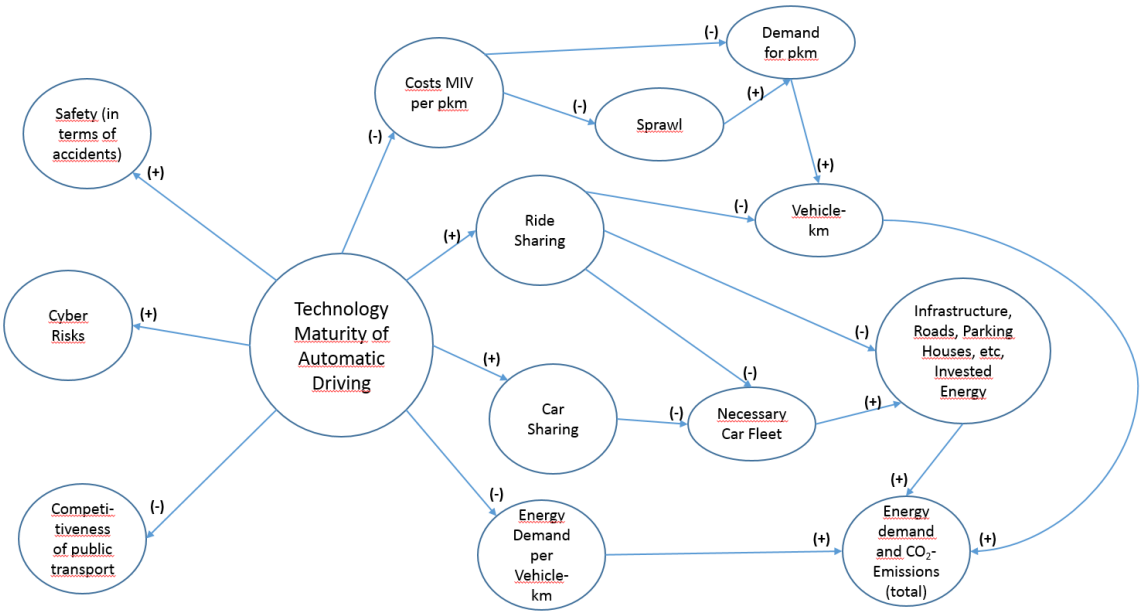

Figure 9.1: Example of a System Dynamic representation of the Mobility System regarding possible disruptive effects of automatic driving.

The effect of one element or factor on another are shown by arrows with a (+) or (-) sign. Positive indicates a positive causal link (e.g. urban sprawl increases demand for travel), while negative indicates the reverse (e.g. high cost of transportation reduces travel demand). As Figure 9.1 illustrates, the final outcome concerning energy demand and CO2-emissions depends on several interactions among the Elements of the System, that create a sequence of escalating or stabilizing feedback loops. Based on our current understanding of some of these interactions the result is barely predictable, but 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 exploratory tool for probing into the rich interactions among the system elements that can lead to quite different trajectories in the future.

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.

10 Conclusions and Outlook

The major challenges for the Future Swiss Transport System include its contribution to climate change mitigation, reduction of energy demand and diversify the energy carrier portfolio, increasing the security of the energy supply and further minimization of pollutants under the requirements of affordable costs and social access to transportation services. In this respect here we have used primarily CO2-emissions and energy demand as performance indicator of Future Mobility since the goals of the Swiss energy strategy 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 current 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 will be expended in the future to address their multiple interactions as a result of 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 personnel transportation sector as an indicator of progress towards reaching the Swiss Energy Strategy goals. Chapter 3 we have decomposed this evolution into the effects of major exogenous and endogenous drivers to investigate corresponding CO2-reduction potentials. An analysis of the current status of the Swiss Transport Sector and the development trends of the mentioned drivers over the last 25 years in Chapter 4 provides a first insights into the underlying dynamics that shape final outcome 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 and its fair share for the transportation transport, is to be respected.

In Chapter 5 additional effects considering socioeconomic and technology development are discussed to provide a possible envelope envelope of the future evolution of the Transportation System. While on the demand side such trends can only be addressed in a qualitative way, on the supply side clear statements can be made for the reduction potential of energy demand and CO2-emissions. What remains extremely difficult to assess also are the potentially disruptive effects of such game-changing developments as digital technologies in general and Automated Driving for freight and individual motorized mobility in particular.

Chapter 6 illustrates, on the basis of selected interventions in the modal choice and on the technology side ,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. Massive decarbonisation beyond this level will require – in addition to the introduction of synthetic fuels – a substantial penetration of electric mobility in the market. Battery electric vehicles are expected to dominate the short-to-medium range vehicle market in this scenario, while it is conceivable that some heavy-duty, long-range applications may well profit from fuel cell technology. Despite the quite low overall energy-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.

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

In Chapter 7 we have expanded on the analysis of future mobility trends in several ways. First, Life-Cycle-Analysis 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, thus providing a lower threshold in the

achievable decarbonisation level of the Transportation Sector, even if the operational CO_2-output of mobility were close to zero. Second, increasing electrification levels lead to a strong coupling between the electricity and transport sectors with the CO_2-footprint of the marginal electricity demand needed for mobility playing a crucial role in accordance with the findings in Chapter 6. Finally, although in the long term electric mobility is expected to provide clear benefits with respect to climate compatibility over current fossil-fuels-based technology, there are other criteria (for example related to human toxicity index) for which no advantages are observed.

Chapter 8 finally deals with ways to organize the necessary Transformation Process of today's mobility System to Sustainability. On the basis of a theoretical framework with regard to innovation processes, measures to be taken are structured at different levels (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 are sources of uncertainty. Most important, among them are game-changing technologies that may be difficult to anticipate, the very long lifetimes and costs of infrastructure, and the complex aspects of individual and group (social) behavior in decision-making processes. In addition to promoting technology-related research, the SCCER-Mobility is therefore dedicated to work on multiple Interfaces through the Joint Activities on the Second Phase of the SCCERs, in particular together with the SCCER CREST on socioeconomic aspects of Future Mobility. 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 the Integrated Assessment Activities and establishing in addition a Learning Lab on the Future Transportation System.

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