

Pathways to a net zero CO₂ Swiss mobility system

White Paper – March 2021



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Imprint

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SCCER Mobility

The Swiss Competence Center for Energy Research – Efficient Technologies and Systems for Mobility (SCCER Mobility) promotes the generation of knowledge and new technologies for a sustainable mobility system in the Swiss mobility research landscape. Minimal CO₂ emissions, decreased primary energy demand as well as avoiding pollutant emissions characterize such a mobility system. In this sense research carried out within SCCER Mobility promotes the implementation of the Swiss Energy Strategy 2050.

Within the SCCER Mobility network, 25 research groups from ten leading Swiss research institutes collaborate with 28 private companies to develop new solutions and products in the field of mobility, which have a measurable effect on energy efficiency and CO₂ output.

The SCCER Mobility research activities cover a broad thematic range: components for electric mobility, battery systems, new fuel cell concepts, combustion efficiency, renewable fuels and lowering the non-propulsive energy demand of vehicles. In addition, SCCER Mobility investigates systemic aspects of mobility. This includes the holistic examination of mobility systems taking into consideration infrastructure, environmental impacts, spatial planning, spatio-temporal data, technology assessment as well as energy-economic and socio-economic factors.

SCCER Mobility is one of the eight competence centers funded by the Swiss Innovation Agency Innosuisse from 2014–2020. More information can be found at www.sccer-mobility.ch.

Foreword

The global mobility system is very important for the economy and the well-being of society. In parallel, passenger and freight transport exhibit a high demand for space, infrastructure and energy resources, while they may have negative impacts on the environment, specifically through noise and pollutant emissions. Of particular importance however is the contribution of mobility to climate change because the corresponding energy supply is currently dominated by fossil resources. In the case of Switzerland, mobility contributes the largest share of greenhouse gas emissions compared to the other sectors of the economy.

SCCER Mobility was established in 2014 to support the implementation of the Swiss Energy Strategy 2050 through cooperative research between academia and industry and to help train the next generation of scientists in the mobility-energy nexus.

During its seven years of operation, researchers from a wide range of disciplinary backgrounds have advanced the state of knowledge in the field and, together with our industrial partners, contributed significantly to the development and implementation of new products, services, data bases and models. Most importantly, a vivid community has been established that will continue to support the transition of the national mobility and energy system to a sustainable future during the next decades.

Beyond the numerous individual research contributions it has been the ambition of the SCCER Mobility from the very beginning to integrate results of our work into a framework that allows to inform stakeholders, opinion leaders, policy makers and society at large on the current state and the transformation perspectives of our mobility system. This aims at complying with the goals of the Swiss Energy Strategy 2050 and contributing to meeting the targets of the Paris Agreement for climate change mitigation. The SCCER Mobility has thus already published a Vision Development Report and a first White Paper that mainly focused on motorized individual transport at that time.

In this tradition, the present White Paper aims at providing a holistic view of the mobility system, encompassing several sectors, including long-haul transport modes, which can be expected to become much more important in contributing to the overall energy demand and greenhouse gas emissions in the future. Based on this, we examine best ways to address the above mentioned challenges, point out actions that must be taken with priority and derive recommendations for key stakeholders in the area.

This White Paper would not have been possible – as it is also the case with the overall output of the SCCER Mobility – without the generous funding of the Swiss Government through Innosuisse, the support of our industry partners and the strong engagement of our research community including our Management Office, all of which we highly appreciate.

We hope that the present document will prove to be useful to support the transformation of the Swiss mobility and energy system towards sustainability and we are looking forward to a fruitful dialogue with interested stakeholders on the subject.

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Executive Summary

The Paris Agreement on Climate Change as well as the Swiss Energy Strategy 2050 and the strategic intention of the Swiss Federal Council to achieve net zero greenhouse gas (GHG) emissions by 2050 pose grand challenges for both the global and national energy systems.

In Switzerland, mobility accounts for about 40% of the domestic GHG emissions and 48% of the carbon dioxide (CO₂) emissions. Domestic GHG emissions consist of about 99% CO₂, therefore we use CO₂ as lead indicator in this document, but refer to GHG emissions when results of life cycle assessment (LCA) are discussed.

The present White Paper examines pathways to a sustainable future of the mobility sector from a systems point of view. Recognizing the profound importance of transportation for the Swiss economy, the multitude of its environmental impacts beyond climate change and the strategic relevance of energy supply security, we focus primarily on CO₂ emissions as an indicator for sustainability and on the overarching need to reach net zero CO₂ output by the middle of the century. In doing so, we take into account worldwide and in particular European developments as Switzerland is embedded in the international economic, energy and transport environment with regard to technological, market related and increasingly legislative aspects.

Our analysis starts with a description of the current state of affairs of the Swiss mobility sector and the developments during the last 30 years in order to shed light on the major drivers for its evolution. Despite the widespread public perception that mobility-related politics have failed to deliver positive trends in the direction of decarbonization, our data show positive signs of saturation and a gradual decline of CO₂ emissions. Taking into account that the population of the country has increased by 27% and GDP per capita by 23% from 1990 to 2018, we find that technology-related efficiency measures and support for public transportation bear fruit already. This, however, is not the case for the aviation sector, for which the rapid rise in demand has led to an increase of CO₂ emissions by more than 50% within the same period. Overall, despite first encouraging signs, we recognize that these are by far insufficient in view of the strict and ambitious national climate targets.

Therefore, we argue that a massive acceleration of CO₂ reduction efforts must be initiated and maintained over the next decades. In order to assess and prioritize promising steps in this direction we use an analysis framework along the following routes:

- **Avoid** excessive transport demand
- **Shift** to more efficient and environmentally compatible modes
- **Improve** energy conversion efficiency along the full conversion chain from primary to useful energy
- **Replace** fossil energy carriers with new ones exhibiting net zero CO₂ emissions through direct or indirect electrification

Although such a vector of directions is widely recognized, it is necessary to examine limitations, cross-influences among the individual components and the specificity of individual transport sectors. Thus, we attempt to consider such effects and overlay the above strategic thrusts with an examination of passenger and freight, short-, mid- and long-haul modes, surface and road transport as well as aviation and shipping.

We show that the above four routes can be facilitated by policy, pricing, consideration of behavioral aspects and appropriate use of digitalization. Furthermore, a strong commitment for the support of public and – for the urban environment – low-speed modes for passenger transport as well as consistent spatial planning in the long term will be crucial. We also point to the potential rebound effects due to lower costs of more efficient transport means (incl. digital technologies) and argue for a clear strategy to address them. Furthermore, **avoid** and **shift** potentials for long-haul transport are rather limited (with the exception of high-speed rail as a substitute for short- and medium-haul aviation).

Improving energy conversion efficiency (propulsion systems and vehicle design) has ample potentials both for passenger and freight transport and the corresponding low-hanging fruits need to be reaped to the fullest extent possible. However, it is important to notice that commercially dominated transport modes (heavy-duty freight on the road, shipping and aviation) already take advantage of efficiency **improvements**, simply because in their case fuel expenditures constitute a major part of the total cost of ownership (TCO). Also the **improve** trajectory must rely on both technology innovation and policy instruments for guiding consumer and investor decisions.

Ultimately, the **replace** strategy component will be necessary to achieve full decarbonization. Though the other three components will be indispensable to **avoid** exceeding the CO₂ budget in order to limit global warming to 1.5–2°C, only the wide use of non-fossil energy carriers will lead to net zero emissions around 2050.

When examining the individual mobility sectors, it is conceivable that direct electrification with batteries will be more appropriate for short- to mid-range applications, while chemical energy carriers (hydrogen, H₂, and synthetic fuels) will contribute decisively to the decarbonization of mid- to long-range sectors. Though this insight is widely accepted, in this White Paper we present some additional, in part non-intuitive results, namely:

- LCA for cars and trucks indicates that CO₂ emissions depend much stronger on the primary energy used than on the propulsion technology. Furthermore, near zero CO₂ emissions from the mobility sector can only be achieved, if the industrial manufacturing sector is decarbonized in parallel, because the embedded emissions (infrastructure, vehicles, etc.) constitute a major part of the CO₂ output, when the energy carriers are almost CO₂ free.
- Taking into account external costs and technology progress, our analysis shows that TCO of the car fleet will remain about the same as today in the net zero GHG emissions scenario. The share of external to total ownership cost will thereby decrease from the current one third to about 15% in 2050.
- A detailed techno-economic optimization shows that in the long term net zero CO₂ for the passenger car sector can be achieved at the lowest cost with a wide portfolio of energy carriers (electricity, hydrogen and synthetic fuels) and powertrain technologies (battery electric, plug-in hybrids and fuel cells). This is in contrast to emerging policies favoring battery electric vehicles (BEV) almost exclusively.
- Concerning national strategies for the supply of energy carriers for the decarbonization of mobility, we argue that a mix of domestically produced electricity with a portfolio of renewable synthetic fuels, mainly produced abroad, will probably be the most appropriate means for achieving net zero CO₂. The reasons for sourcing such fuels from outside Switzerland are manifold:
 - The additional electricity demand for decarbonizing transport through electrification amounts to about one third of the current electricity demand of the country excluding aviation and it exceeds this current demand when the production of aviation fuels is included.
 - The need for electrification of other energy sectors (industry, buildings and heat) together with the gradual phasing out of nuclear power plants.
 - The fact that there are many potential locations worldwide where synthetic fuels can be produced at massively lower costs using solar and on-/off-shore wind power and transported with existing infrastructure. This is in contrast to the limited and expensive options for transporting large amounts of electricity over long (even intercontinental) distances.

Furthermore, we point to an often overlooked issue, namely the transitional dynamics towards a sustainable mobility system within only a few decades. Since the lifetime of key assets in the transportation sector amounts to several decades, it will be crucial to invest in future technologies early enough in order to **avoid** lock-in effects and minimize stranded assets. In addition, the repurposing and reuse of existing long-lasting infrastructure for new energy carriers will be important in order to keep costs under control. Finally, using new energy carriers with drop-in capabilities to **replace** fossil fuels during the lifetime of vehicles, in particular ships and aircraft, will constitute a relevant part of the effort to minimize cumulative CO₂ emissions over the next decades.

Orchestrating the replacement of fossil energy carriers across different mobility sectors will require massive improvements of the electricity grids when BEVs are considered as well as new transport and distribution networks in cases where hydrogen is employed. Well-coordinated worldwide efforts will be crucial for decarbonizing the upstream processes for producing assets (batteries, vehicles and fuel cells) and energy carriers with an overall benign environmental footprint and at affordable costs.

Enabling the transition to sustainability for the global mobility system will require contributions both by technology innovation and by policy design. While technology innovation will be important across the whole chain of readiness levels, policy design will be a complex endeavor that needs to navigate within a set of requirements, namely:

- Internalization of external costs, with emphasis on environmental impacts and with priority on damages related to climate change.
- Balancing and compensating disadvantages for low-income groups to ensure social acceptance.
- In addition to the development of instruments for influencing consumer behavior (buying and using equipment for short-range passenger transport), emphasis needs to be put on guiding highly important decisions made by investors. Such policy must employ predictable and consistent legislation, because investments towards reshaping the global mobility and energy systems will be required at an unprecedented scale, particularly investments in new infrastructure.
- Concerning national mobility policy, it will be necessary to align regulations and standards with international and particularly European developments.

Overall, our assessment concludes that the transformation of the mobility system towards climate neutrality is a huge challenge. Its successful implementation will require informed decisions, innovative technology and business models, fair pricing and a combination of strategic coherence with tactical flexibility to address unforeseen developments.

1. Introduction

1.1 Past developments, current status and future trends of the Swiss mobility system

Mobility is of paramount importance for the well-being of a modern society, as it allows to efficiently deploy economic activities, exchange goods and move people over short, mid and long distances. In Switzerland the sector employs about 6% of the total work force, while the total turnover of private companies active in road transport alone amounts to about 94 bn. CHF (strasseschweiz 2020). On top of this, substantial revenue comes from public (road and rail) as well as from air transport. Furthermore, Swiss companies are important suppliers for automotive original equipment manufacturers (OEM) worldwide and their annual exports amount to about 12 bn. CHF and provide about 34'000 jobs (swiss CAR 2018). Swiss companies in the field of long-haul transport, in particular shipping, are also among global technology leaders.

Despite these positive effects for society, the current structure of the global mobility system has adverse environmental impacts. Climate change driven by increased emissions of CO₂ and other GHGs can be considered the most serious one with far-reaching and devastating consequences for humankind. The transport sector is a critical player as it contributes about ~20% to global CO₂ emissions (Crippa et al. 2019). Past evolution of the sector worldwide has shown

a surge in passenger mobility over long distances and intensified world trade volumes due to economic development in emerging economies and accelerated globalization. This trend is expected to continue resulting in a substantial rise of CO₂ output, despite policy measures to incentivize public transport and eliminate subsidies for fossil fuels (ITF 2015). These trends are clearly at odds with efforts to combat climate change.

In Switzerland transport weighs in even more as it accounts for roughly 20 Mt CO₂-eq. or 40% of total GHG emissions¹ (FOEN 2020a). Transport on the road takes up the lion share of this with cars currently accounting for 10.9 Mt CO₂-eq., or roughly half of the emissions from transport and 21% of the total (Figure 1). Commercial light-duty vehicles (LDV), heavy-duty vehicles (HDV) and busses account for the remaining GHG emissions on the road. Mainly because cars became more efficient over the years, GHG emissions from the Swiss road transport sector peaked around 16 Mt CO₂-eq. in 2008 and decreased thereafter essentially returning to levels of 1990 (~14 Mt CO₂-eq.).

Along with road transport, GHG emissions from aviation are a major concern in Switzerland. The majority of these emissions stem from international flights, which have increased by 83% since 1990. Currently the sector is responsible

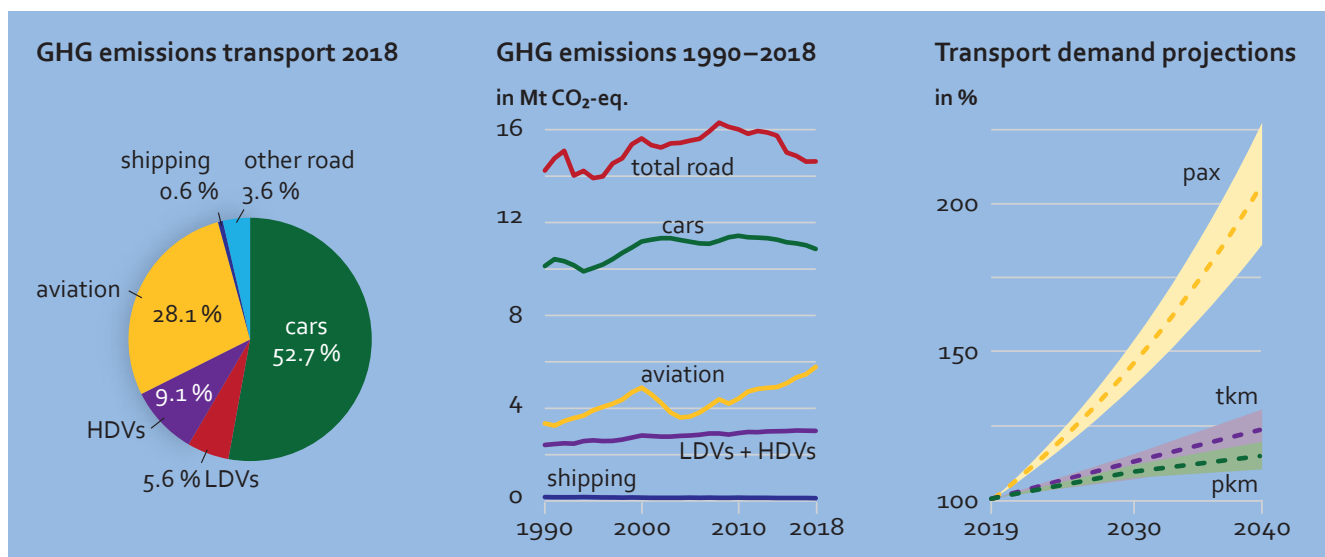


Figure 1. Distribution and evolution of greenhouse gas (GHG) emissions from the transport sector in Switzerland (FOEN 2020a) as well as future demand projections (ARE 2016; Intraplan 2015). Cars (motorized individual transport) contribute more than half of GHG emissions, while demand increase of aviation will become the challenge in the near future. Other road includes emissions from busses, motorcycles, fuel tourism and statistical differences. This category is not shown in the middle panel and accounts for the remaining emissions on the road. LDV stands for light-duty vehicle and HDV for heavy-duty vehicle. In the graph on the right, pax refers to number of passengers transported in aviation, tkm and pkm to surface transport demand (road and rail) for freight and passengers, respectively.

for GHG emissions of 5.8 Mt CO₂-eq., a share of 28% of transport and 11% of total Swiss GHG emissions (FOEN 2020a). In line with this, Switzerland has one of the highest per capita carbon footprints from aviation (640 kg CO₂ per capita per year), even compared to the high European average (345 kg CO₂ per capita per year), while the world average lies around 110 kg CO₂ per capita per year.

Less worrisome, the Swiss domestic shipping sector is responsible for only 0.13 Mt CO₂-eq., a share of 2.6% of the total Swiss GHG emissions (FOEN 2020a). However, at an international scale demand for freight transport is expected to triple by 2050 with 75% of goods transported by ship (ITF 2019). Due to its high consumption of imported goods, Switzerland contributes to this increase in freight shipping demand, although the amount is difficult to quantify. Indicatively, shipping contributes 13% to the total GHG emissions of the EU, an amount equal to the one of aviation. Therefore, this mode should not fall under the radar.

Box 1 shows additional relevant numbers related to the evolution of demand for transport services and GHG emissions in the Swiss transport subsectors between 1990 and 2018. It is interesting to see that in this period both the population and GDP per capita of the country have grown substantially, so that specific CO₂-eq. emissions per GDP (including international air transport) have clearly decreased. These encouraging developments demonstrate how incremental technology innovation and policies promoting public and low-speed mobility can be successful. However, projections indicate that demand for both passenger and freight transport, quantified in passenger kilometers (pkm) and ton kilometers (tkm), respectively, will continue to rise until 2040 (ARE 2016). This will inevitably lead to overall increasing emissions. Also alarming is that demand for air travel, assessed in number of passenger transported (pax), is projected to increase by a factor of about two within this time period in Switzerland and even by three in the EU and the European Free Trade Association (EFTA) region and worldwide (Intraplan 2015; ICAO 2018).

1.2 Climate and sustainability targets

The growing demand and GHG emission trends of the mobility sector are clearly at odds with the climate goals endorsed by the Paris Agreement, which was adopted at the United Nations Climate Change Conference (COP21) in 2015. Along with most other nations of the world, Switzerland signed the agreement to increase efforts to limit global warming to less than 2°C above pre-industrial levels and if possible to less than 1.5°C. Assuming a linear decrease from now on, the CO₂ budget for reaching these targets with 66% probability

Box 1. Characteristic data for the Swiss mobility sector from 1990 to 2018 (FOEN 2020a; FOEN 2020b) versus economic development.

- Population: + 27.1%
- GDP: + 56.1%
- GDP per capita: + 23%
- Total transport CO₂-eq.: + 22%
- Road passenger transport CO₂-eq.: + 7%
- Road freight transport CO₂-eq.: + 25%
- Air transport CO₂-eq.: + 73%

Demand

- Road passenger: + 37%
- Road freight: + 47%
- Air transport (passenger): + 189%

Share of transport to total CO₂-eq. emissions

1990: 32% (18 Mt of 55 Mt in total)
2018: 40% (20 Mt of 51 Mt in total)

would require achieving net zero CO₂ emissions around 2070 and 2040, respectively.

Rising emissions and energy demand stemming from transport are also contrary to the Sustainable Development Goals (SDG) of the United Nations Agenda for Sustainable Development (UN 2015). Of the 17 goals and 169 associated indicators, SDGs like good health, clean water, affordable and clean energy, resilient infrastructure, sustainable cities and communities, responsible consumption and production, climate protection, or sustainable use of ecosystems are strongly dependent on the availability of sustainable energy and mobility technologies. Switzerland is formally committed to reaching these sustainability goals (Swiss Confederation 2014).

In line with these commitments, the Swiss Federal Council has recently decided on unprecedented reductions of GHG emissions with the target of reaching net zero emissions by 2050 as well as a strong decrease in the energy demand of the country (Swiss Federal Council 2019).

This White Paper assesses pathways and provides recommendations that can contribute to reaching this ambitious net zero goal. The analysis draws mainly from work done in the framework of the Swiss Competence Center for Energy Research – Efficient Technologies and Systems for Mobility (SCCER Mobility) but it also consulted international literature. The focus is specifically on minimization of CO₂ and other GHG emissions from the transport sector including the associated energy supply and embedded (grey) emissions to the extent possible.

¹ Total Swiss GHG emissions in 2018 amounted to 50.81 Mt CO₂-eq. This includes IPCC sectors 1–6, and international aviation and navigation (FOEN 2020a). Note that GHG emissions in CO₂-eq. include all relevant GHG emissions, but exclude aviation induced cloudiness.

1.3 Framework and strategy

CO₂ currently contributes about 80% to the total Swiss GHG emissions and even 99% of those from transport (FOEN 2020b). While other GHGs like methane (CH₄) and nitrous oxide (N₂O) are also important, it is justifiable to use CO₂ as the lead indicator due to its dominant contribution and its survival over several centuries in the atmosphere. Security of supply and affordable costs in view of socially fair access to energy services and international competitiveness of the export industry should be taken into account as well.

It is evident that drastic measures will be necessary to transform the mobility sector to meet climate and energy challenges of the future. In Switzerland CO₂ emissions and the heavy dependence on imported fossil fuels (59% of imported energy carriers; SFOE 2018) are the main issues to address in the future Swiss transport policy. At the same time, it is central to consider that fundamental changes will likely have profound consequences for the Swiss economy.

The environmental impacts associated with mobility do not only depend on the deployed vehicles and their performance, but also on supplied fuels, materials and component supply chains, which stretch beyond national borders. Furthermore, long-lasting transportation and energy carrier infrastructure must be included in designing a sustainable mobility system. To analyze different solution pathways and in agreement with previous work (SCCER Mobility 2017; EASAC 2019), in this

White Paper we consider a holistic, coherent and long-term oriented portfolio of actions as shown in *Figure 2*.

The necessary decarbonization and transformation of mobility to meet the Swiss policy goals calls for pursuing a strategy of:

- **Avoid** excessive transport demand
- **Shift** to more efficient and environmentally compatible modes
- **Improve** energy conversion efficiency along the full conversion chain from primary to useful energy
- **Replace** fossil energy carriers with new ones exhibiting net zero CO₂ emissions through direct or indirect electrification

Disruptive technology innovation, radically new business models and an appropriate ambitious policy design will also be necessary. Ways to implement the individual elements of this strategy will be examined in the following for all relevant Swiss transportation sectors from the demand and supply side, including technology and infrastructure requirements as well as socioeconomic and integrated assessment aspects. We will conclude this report with a set of recommendations that will be essential for orchestrating the required system transformation towards net zero CO₂ emissions rapidly.

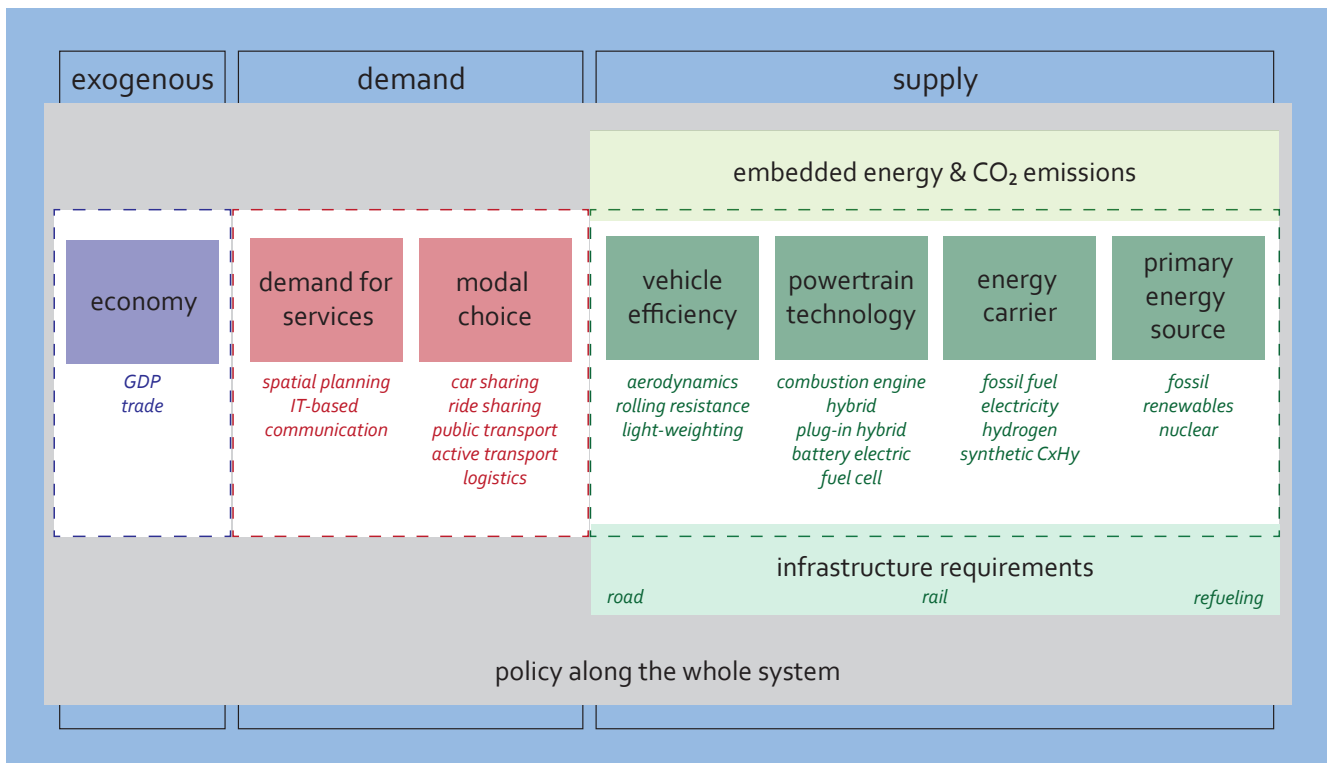


Figure 2. Conceptual illustration of the systemic framework employed in this analysis to assess past developments, identify key drivers and examine pathways for the decarbonization of the mobility system (EASAC 2019).

2. CO₂ reduction potentials of the different transport sectors

2.1 Passenger transport on road and rail

The demand for mobility services is interwoven with the socio-economic conditions in a modern society to such an extent that decoupling it from economic evolution is a highly challenging task. Thus, the reduction potential in the short to mid-term is rather limited.

Under a given demand for mobility services the choice of transport mode is a crucial factor for the resulting GHG emissions. *Figure 3* shows such emissions based on LCA and illustrates how electrified public and low-speed transport (cycling and walking) are by far (up to one order of magnitude) more favorable than motorized individual transport with passenger cars. Concerning the latter, differences among various current powertrain technologies do exist, but lie within a factor of two at the most. The huge difference in GHG emissions between airplanes and (electrified) trains using an almost carbon-free electricity supply is particularly striking.

2.1.1 Options to **avoid** and **shift** motorized individual transport to public and low-speed mobility

Currently, about 50% of all trips in Switzerland rely on motorized individual transport (FSO 2017). **Avoiding** and **shifting** this motorized individual transport to public and low-speed mobility is commonly achieved by employing soft incentives (e.g. advertisements or persuasive applications), providing (virtual) alternatives (e.g. teleconferencing), implementing new policies or financial incentives and penalties, or by improving mobility services and the related infrastructure of public transport and low-speed mobility.

Soft incentives aim at utilizing knowledge about individual attitudes, habits, circumstances and socio-demographic features to nudge travel choices and transport mode decisions in a sustainable direction. Widely known are educative measures such as advertisements, but more recently approaches enabled by information and communications technology (ICT) gained importance, as they allow direct interactions and personalizing incentives based on individually recorded data.

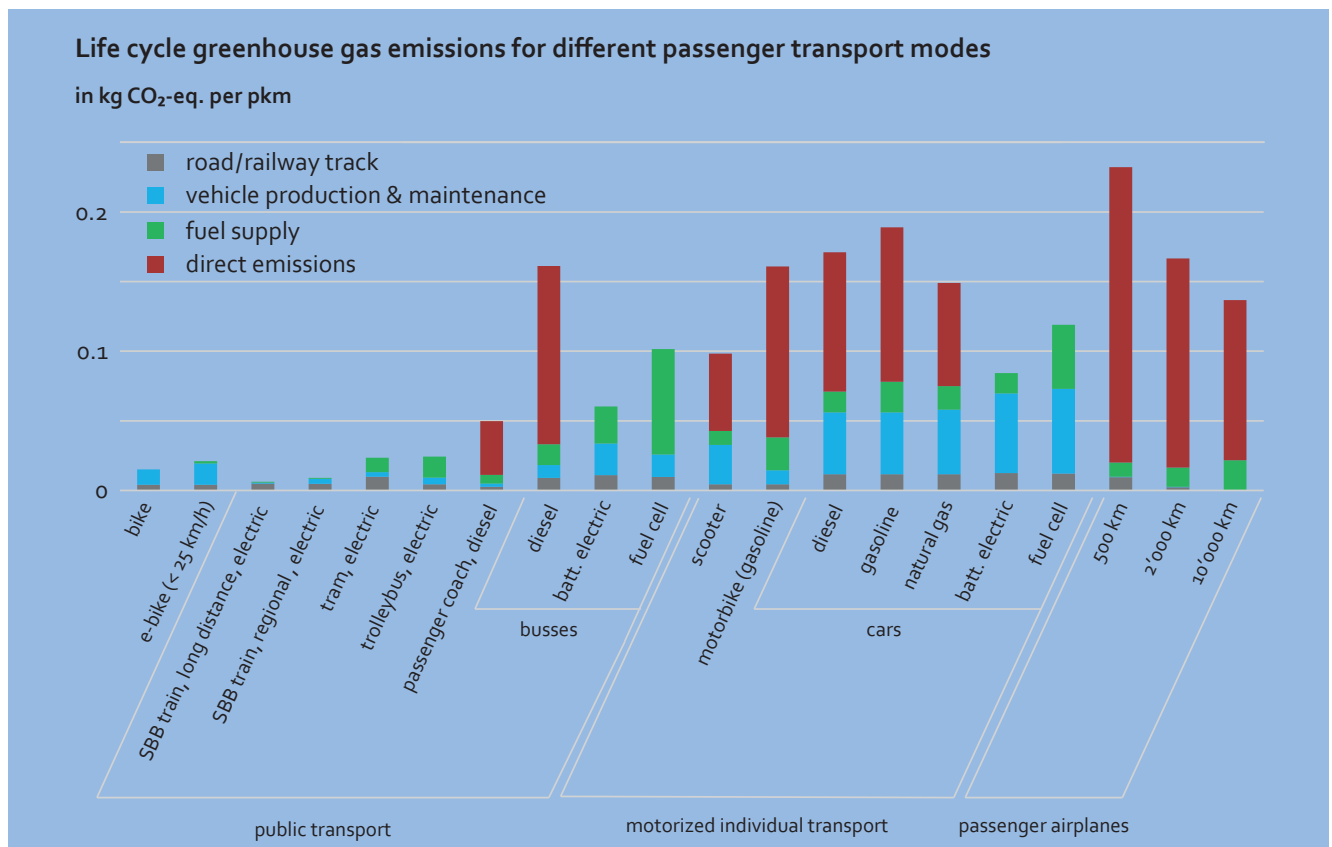


Figure 3. Comparison of current passenger transport modes. Greenhouse gas emissions based on life cycle assessment under the following assumptions: average number of passengers for all vehicles; CH average current electricity consumption mix for battery charging and hydrogen production (Wernet et al. 2016; Cox et al. 2018, 2020a; Sacchi et al. 2020a).

These incentives are particularly useful to provide feedback about exhibited behaviors and to support people by increasing perceived control or reducing planning complexity. Comprehensive studies quantitatively assessing the potential of ICT-enabled soft incentives to change mobility behaviors are rare, but recent studies show high acceptance and potential net savings in CO₂ emissions in the range of 10–15% for people largely relying on individual motorized transport (Anagnostopoulou et al. 2016; Klecha and Gianni 2018; Cellina et al. 2019). For example, *Figure 4* shows the environmental impacts of a gamified app on systematic mobility (e.g. commutes) as investigated in the GoEco! project (Cellina et al. 2019). By playfully challenging app users to try out proposed alternatives (e.g. taking the bicycle instead of the car on a short route), significant CO₂ emission reductions were achieved on regularly traveled routes in more rural areas.

Recently emerging business models have led to novel and improved mobility offers (primarily targeting modal **shift**). Among these are mobility as a service (MaaS), micro-mobility or sharing of non-private vehicles. By simplifying trip planning and excluding financial aspects from the mobility choice process, people use a more diverse mix of mobility options, resulting in decreased CO₂ emissions. The Green Class offer of the Swiss Federal Railways (SBB) commoditizes mobility and frees its demand from individually available mobility options. The resulting flexible use of intermodal mobility in combination with the provision of an electric vehicle (EV) leads to a reduction of CO₂ emissions by approximately 30% (Martin et al. 2019). Policies and financial incentives strongly affect mobility behavior, but also face long implementation periods and (often) large resistance from citizens. The acceptance

of policy changes requires shifts in thinking, which can be mediated by educational measures (soft incentives transparently highlighting alternative mobility options, costs, impacts, etc.). Various studies assessed the CO₂ emission savings due to (individual) policy changes in the range of 2–20% (Lautso 2004; Wolfram et al. 2005).

Fundamental impacts on mobility supply and demand are the result of the way cities and regions evolve, which means that urban planning and policies related to use of space are important instruments. Higher population densities and larger proportions of families lead to lower environmental impacts (Gudipudi et al. 2016). In addition, mobility choices are influenced by the perceived environmental effects on health, safety and comfort. Providing safe and comfortable access to a wide range of mobility options enables a population to optimize mobility behavior towards more sustainable forms of transport. For example, single-purpose infrastructure for electric bicycles that directly connects suburbs to city centers allows large shares of the population to commute to work by bicycle and leads to CO₂ emission reductions of approximately 8% (Bucher et al. 2019).

The examples shown in *Figure 4* highlight that in order to substantially reduce CO₂ emissions by **avoiding** and **shifting** mobility use from motorized individual transport, different strategies, such as persuasive approaches, better accessibility to (inter-modal) transport or policy measures must be combined.

Other options to substantially reduce embedded CO₂ emissions and costs for providing a given amount of mobility services (in pkm) refer to instruments for vehicle sharing.

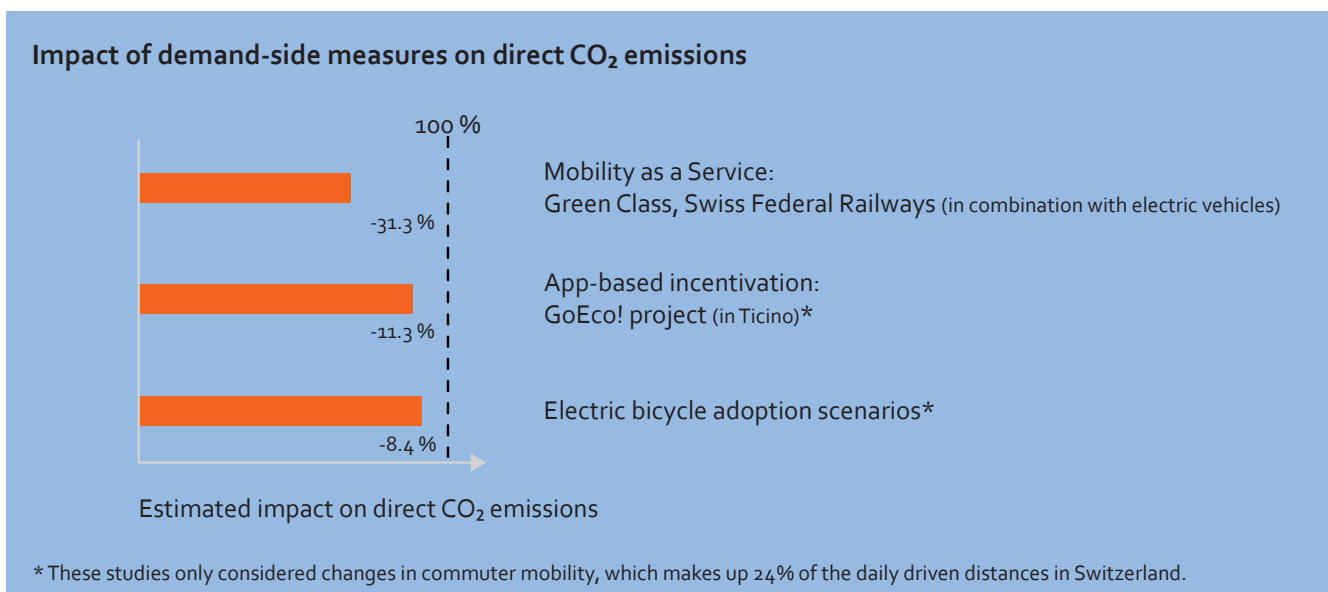


Figure 4. Environmental impacts from different domains, measured as a reduction of CO₂ emissions from passenger mobility respectively commuter mobility. Details are provided in Martin et al. (2019), Cellina et al. (2019) and Bucher et al. (2019).

Recent research results indicate that a business model offering a fleet of electric cars for sharing can satisfy the demand for pkm with 30% less vehicles from a fleet size of about 100 cars and above. Even more importantly, since such shared vehicles can be designed to satisfy varying needs for driving distances per day and therefore be equipped with partially smaller batteries, the total battery capacity of this fleet can be reduced by about 70%. This leads to an overall estimated reduction of total costs and embedded (grey) CO₂ emissions for the vehicle and batteries of around 45%. This demonstrates the clear synergies between vehicle sharing models and electric mobility. The results are based on a regional survey of mobility patterns of the UK but can in principle be considered representative for typical Swiss and, more generally, European conditions (Pareschi 2021).

The pool of vehicles for reaping these significant savings is surprisingly small (100 vehicles, equivalent to roughly 200 people participating) and indicates that access to such a locally concentrated fleet would be easy and fast for typical population densities in European countries. However, important issues in this context refer to the willingness of people to engage in car sharing and corresponding initial incentives as well as to potential rebound effects, since costs for a given driving distance will decrease. Impacts on the competitiveness of private versus public transportation also need to be investigated.

2.1.2 Automotive powertrain technology – status quo, potentials and life cycle assessment

Currently there are three main automotive powertrain technologies available, namely electricity operated BEV, hydrogen operated fuel cell electric vehicles (FCEV) and hydrocarbon operated (hybridized) internal combustion engine (ICE) based vehicles (hybrid electric vehicles, HEV, and internal combustion engine vehicles, ICEV). Plug-in hybrid, plug-in fuel cell or range-extended BEVs are intermediate concepts based on these main technologies.

The end energy consumption of such vehicles is very different, as a two-year field study with a BEV, FCEV, plug-in hybrid electric vehicle (PHEV) with electric and hybrid mode, HEV and a conventional compressed natural gas (CNG) vehicle shows in Figure 5 (Georges et al. 2020). The BEV and PHEV show the lowest end energy demand of 150–200 Wh per km, while the demand of the FCEV is higher by a factor of 1.8–2.2 and the HEV, PHEV-hybrid and CNG by a factor of 2.5–3.0.

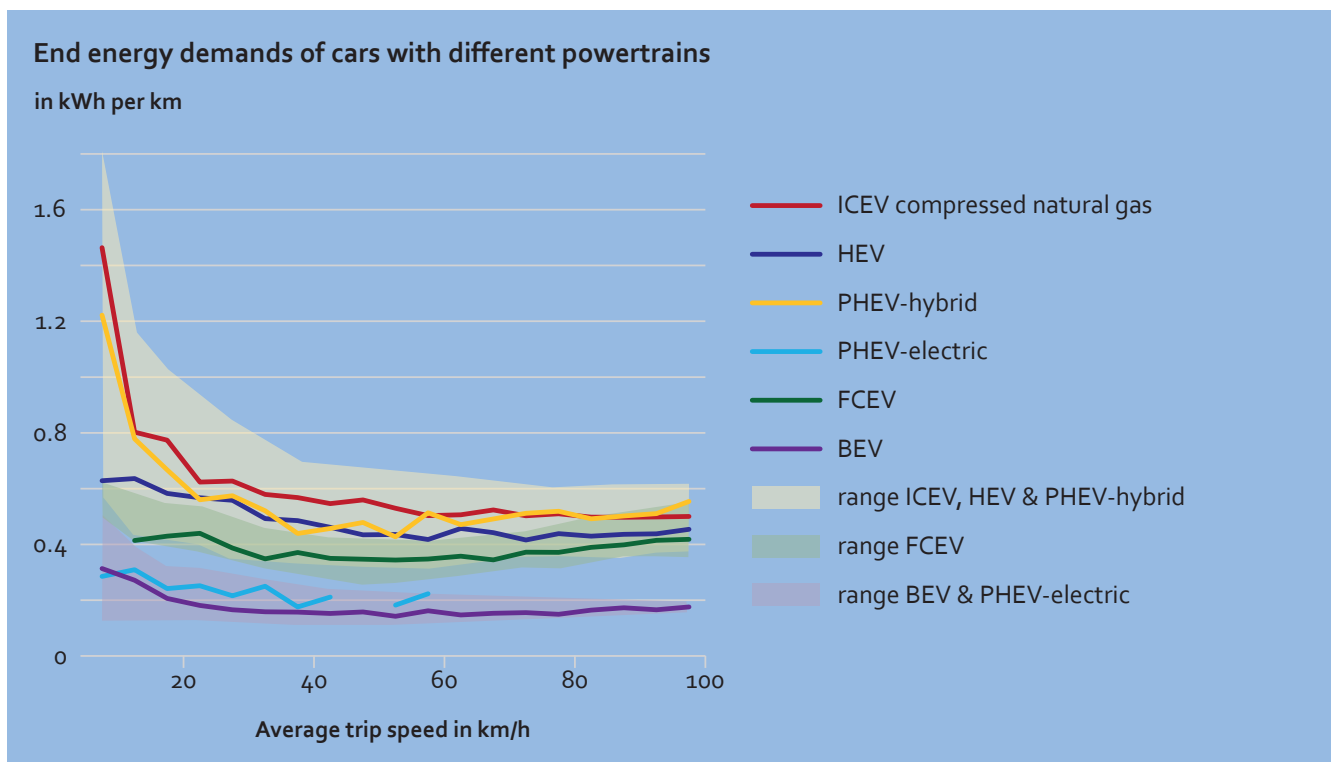


Figure 5. Real-world end energy demand over average trip velocity, including standard deviation for compact vehicles with different powertrain concepts, based on monitored vehicle operation in a two year field study (Georges et al. 2020). ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; FCEV = fuel cell electric vehicle; BEV = battery electric vehicle.

The reduction potentials of the energy demand for the different powertrain concepts are estimated to be considerable but with high uncertainties depending on vehicle size, power range and application type (Zapf et al. 2019). Decreased driving resistance by **improved** air drag, rolling resistance and the reduction of vehicle mass can lower the end energy demand of all powertrains by at least 10% in the short to mid-term (conservative estimate). Furthermore, efficiency **improvements** of 5% each are likely for electric motor/recuperation and **improved** cabin heating for BEVs, 15% for **improvements** in fuel cell powertrains and up to 20% through advanced working processes and combustion systems for HEVs. As a wide range of car models equipped with hybrid powertrains is available on the market and this technology already offers 25–30% savings in fuel consumption compared to conventional ICEVs, it is reasonable to consider HEVs as the state-of-the-art reference for the combustion-based propulsion of cars. Until 2030, the real-world energy demand of the different powertrains will thus decrease between 20–30% compared to the above 2019 values.

Despite the usefulness of trustworthy data on the end energy demand for powertrains, a much more appropriate comparative evaluation can be carried out for adverse environmental impacts based on LCA for the same vehicle category. *Figure 6* refers to the life cycle GHG emissions of cars depending on both the technology and the primary energy used. Several insights can be drawn from this representation. First, ICEVs (in particular HEVs) are roughly on par with BEVs using the EU electricity mix, while FCEVs are not. Second, already with the Swiss electricity consumption mix, FCEVs cause less and BEVs substantially less life cycle GHG emissions than conventional vehicles. Third, when wind is used as the primary energy source, all propulsion technologies² produce about the same amount of GHG emissions. Nevertheless, this level is at about half of that of fossil-fueled HEVs and far from zero. This indicates, fourth, that beyond the CO₂ footprint of power generation and expected improvements of vehicle technologies, a more substantial extent of decarbonization can only be achieved, if the global industrial manufacturing system becomes fossil free as well in order to reduce emissions associated with vehicle production. Furthermore, this analysis shows that an assignment of zero CO₂ emissions to electrified powertrains, as EU and CH legislation currently implies, is by far not justifiable.

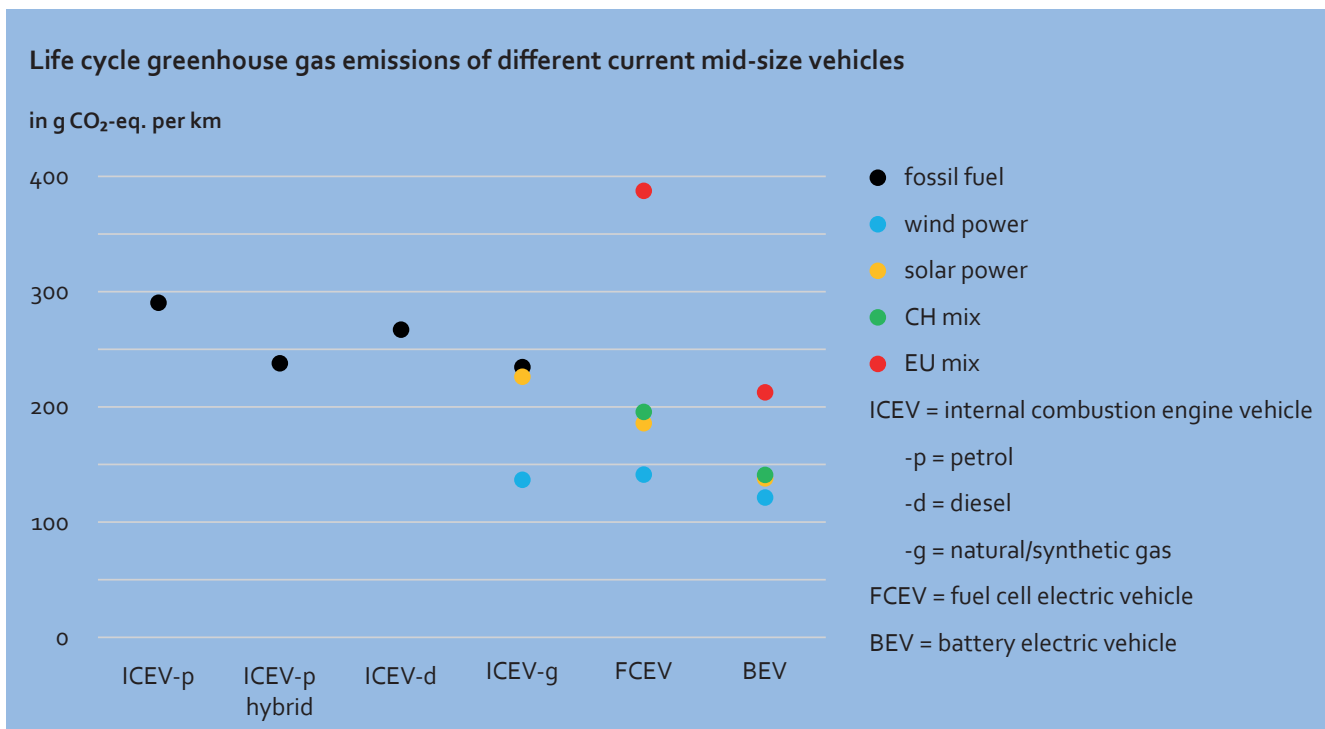


Figure 6. Life cycle greenhouse gas (GHG) emissions of different current medium-size vehicles as a function of GHG content of the electricity used for battery charging, hydrogen production via electrolysis, and synthetic natural gas production (with CO₂ captured from the atmosphere). The location of wind and solar power is Switzerland (Sacchi et al. 2020a).

² Including battery electric, fuel cell, and combustion engines – the latter represented by a gas engine in this comparison. The fuel based on wind as primary energy is in this case synthetic natural gas (SNG), generated through wind power operated water electrolysis – with hydrogen as the output – and subsequent methanation of this hydrogen with CO₂ captured from the atmosphere. Such a fuel is currently not commercially available, but might represent an option for indirect electrification in the future. ICEV using synthetic diesel and gasoline based on the same primary energy would perform similar in terms of life cycle GHG emissions.

Due to anticipated technology developments as well as scenario-based decarbonization of energy and material supply chains the estimates obtained for future cars exhibit much lower life cycle GHG emissions. Thus, for a net zero emission scenario the estimated life cycle GHG emissions of BEVs charged with the corresponding Swiss electricity mix amount to 46 g CO₂-eq. per km, i.e. a reduction by a factor of three compared to the current case. The corresponding result for FCEVs is 48 g CO₂-eq. per km, a reduction by a factor of four. The lowest results were obtained for BEVs charged with electricity from a wood gasification plant with carbon capture and storage (CCS) enabling negative emissions of -147 g CO₂-eq. per km (Sacchi et al. 2020a; Hirschberg et al. 2021). Due to limited primary energy resources for this technology, however, the implementable potential of this option is expected to be quite constrained.

Beyond GHG emissions, other environmental impacts (noise, local air pollution due to nitrogen oxides, NO_x, and particulate matter) are of course also relevant. Conventional powertrain technologies emit such pollutants during operation with a clear perspective towards their practical elimination with current (EURO 6d) and upcoming (EURO 7) legislation for real-world driving conditions, while FCEVs and BEVs exhibit such emissions to a somewhat higher extent than ICEVs during manufacturing. It can be expected that the latter will be drastically decreased with the advancement of more environmentally friendly industrial manufacturing systems.

Finally, the optimal choice of vehicle and powertrain technology will also depend on the customer perspective related to other criteria like costs, convenience, etc.

2.2 Freight transport on land

Land freight transport has the potential to become more environmentally friendly through **improvements** in market demand, modal share, system and vehicle operation, powertrain technology and fuels generated from renewable electricity (direct electrification, hydrogen and synthetic fuels). In general, freight transport intensity could be reduced by decreasing material demand (improving waste management and recycling, reinforcing material substitution and additive manufacturing, boosting digitalization and miniaturization among others) and decoupling its growth from economic growth (increasing local production to reduce shipping distance). Furthermore, **shifting** cargo from road to rail also reduces land freight carbon intensity, since HDVs produce 70–190 g CO₂ per tkm and diesel freight trains produce 25–60 g CO₂ per tkm, while future electric trains will likely emit even less CO₂, if powered by clean electricity (Sims et al. 2014).

Nevertheless, this **shift** requires an expansion of rail infrastructure by e.g. increasing connectivity with strategic terminals and other modes, removing bottlenecks, electrifying lines and improving access to urban and industrial areas.

Regarding road operation, smart driving can lower energy demand and, therefore, reduce emissions. Likewise, collaborative logistics can increase total efficiency and payload rate. Combined transport solutions can reduce congestion on the main roads, also leading to increased energy efficiency and thus reduced emissions. Technologies such as autonomous driving and platooning could reduce road freight energy demand by up to 20% (Tsugawa et al. 2016).

In rail operation, integrated solutions based on ensuring green wave corridors (no interferences with the surrounding traffic) and optimizing speed profiles would **avoid** unplanned stops and successive energy expensive accelerations, thus ensuring energy efficient driving for long, heavy freight trains. This could lead to 12% of system energy savings in Switzerland, which runs one of the world's most dense railway schedules (De Martinis et al. 2018). Furthermore, investment in urban consolidation centers could facilitate a **shift** from road to rail and innovations such as automated braking can also contribute to lowering the energy demand of freight trains.

In the following we focus on mid- and heavy-duty trucks, since short-range LDVs are expected to be electrifiable with batteries due to their quite short daily travelling distance. As with passenger cars (see previous section), **replacing** conventional ICE-based powertrains with battery, fuel cell or hybrid powertrains as well as substituting fossil with renewable fuels are further options for lowering the CO₂ intensity of freight vehicles on the road. Likewise, the freight vehicle's life cycle is relevant to quantify potential GHG emissions reduction. Life cycle assessment of mid-size trucks potentially operated today with different powertrain and fuel combinations, as shown in *Figure 7*, shows that several combinations of powertrain technologies with renewable primary energy (best option: wind-based power generation) lead to significant GHG emissions reduction compared to the incumbent diesel technology of 55% (for ICEVs operated with synthetic methane), 66% (for hydrogen-fueled FCEVs) and almost 75% for BEVs³. Under the assumption of 100% renewable energy and including potential further advancements in technology, trucks operated electrically with overhead catenary lines are projected to have the lowest life cycle emissions, followed by battery electric trucks and fuel cell trucks, while combustion engines have the highest in 2050 (Lozanovski et al. 2020).

The potential for domestic road freight electrification (HDVs) in Switzerland (contributing almost 60% to the total tkm of

³ In this comparison, it should be noted that several fuel and vehicle options are not (yet) commercially available on a large scale, including fuel cell and battery electric trucks as well as synthetic natural gas and hydrogen produced from natural gas reforming with carbon capture and storage.

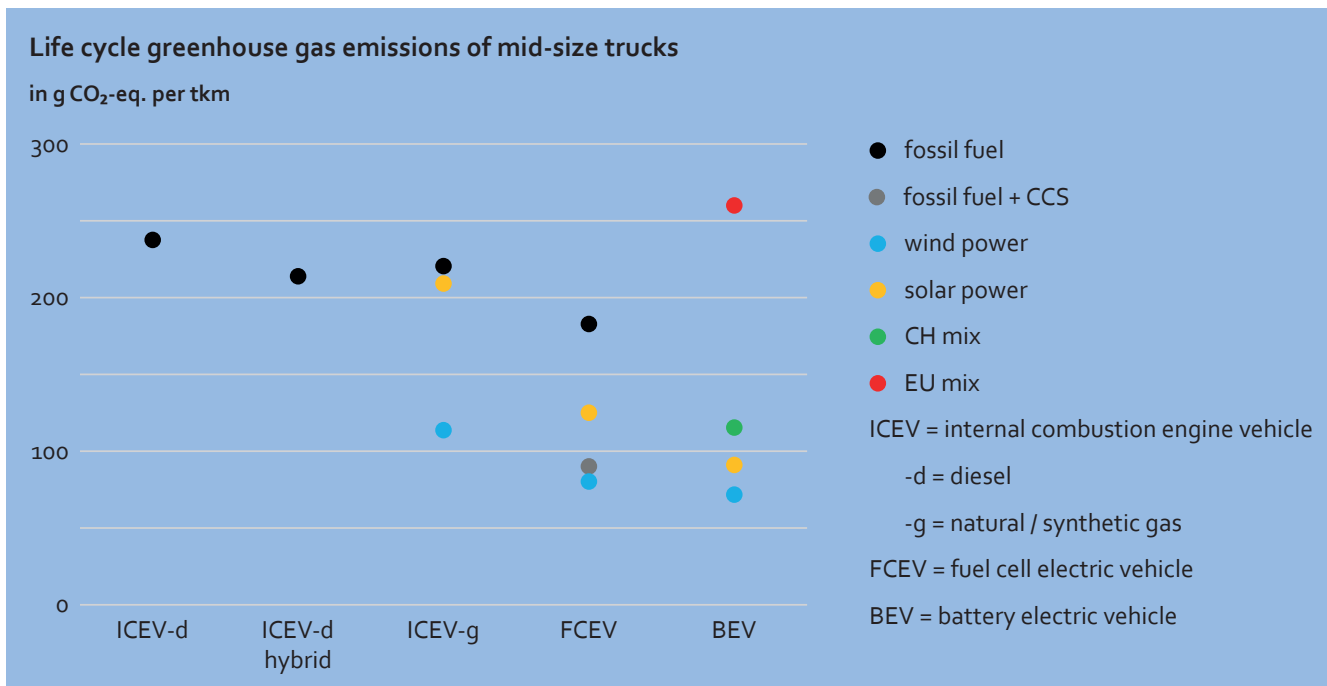


Figure 7. Life cycle greenhouse gas emissions of mid-size trucks per tkm (Sacchi et al. 2020b). + CCS refers to steam methane reforming of natural gas with carbon capture and storage. Synthetic natural gas is generated by using CO₂ from the atmosphere. Location of wind and solar power is Switzerland.

heavy-duty trucks moving on Swiss roads) is high due to the short distance the majority of these trucks carry out daily. It is technically possible to transform the sector and substitute a majority of ICE trucks for BEV trucks under favorable circumstances. In economic terms this transformation could be a challenge, if BEV TCO does not improve and break even with that of (diesel) ICEVs. Also here, an appropriate policy that aims at internalizing external costs will be crucial to create a level field for fair competition among technologies. In particular, the further development of the LSVA instrument (Leistungsabhängige Schwerverkehrsabgabe, in English performance-related heavy vehicle charge) needs to be optimized accordingly.

As shown in Figure 8, our analysis (Mancera Sugañes 2021) indicates that night charging of domestic trucks can mitigate 0.2–0.4 Mt CO₂ of the current 1 Mt CO₂ (tank to wheel) total for this category (on an end energy basis) for current and future anticipated battery energy storage capacities (at cell level). Including daily charging at delivery locations can increase this to 0.6–0.8 Mt CO₂, albeit only with expensive infrastructure. This might require some upgrade of the electricity grid depending on the case. Differently, for widespread FCEV truck penetration, a production, distribution and storage system for CO₂ neutral H₂ needs to be developed and implemented. Finally, for widespread e-highways with overhead catenary lines, Swiss highways would require significant investment along their main axes.

Though deploying such technologies for freight transport is promising for reaching emission goals, it will increase the demand for electricity drastically. A full conversion of today’s Swiss HDV fleet to battery electric powertrains would increase the electricity demand of the country by 5% (3 TWh per year), for fuel cells these numbers increase by a factor of ~2.5 and the mitigation potential is strongly dependent on the supply of renewable electricity. In a related study (Çabukoglu et al. 2019) it has been shown that FCEVs would be capable of electrifying more than 80% of the total tkm of the HDV fleet of Switzerland given H₂ refueling twice daily. Nevertheless, it is possible that the future Swiss HDV fleet will be a combination of different technologies depending on the operational needs of freight carriers (i.e. daily range, type of shipment, etc.). The penetration rate of new technologies will depend on infrastructure availability (charging and battery swapping stations, H₂ fueling stations or electrified highways), purchasing price of new vehicles, customer acceptance as well as new business cases such as last-mile electrification, both in Switzerland and in the surrounding countries.

2.3 Non-road long-haul transport: aviation and shipping

Different actions are needed to decarbonize the aviation and shipping sectors. This is because they differ from road transport in four key aspects:

(1) Energy density: airplanes and ships have higher requirements in energy density of the energy carrier. Therefore, they are considered hard to decarbonize. While battery electric propulsion is feasible for cars and LDVs and H₂ fuel cells for HDVs, both are not appropriate for ocean-going ships and long-haul airplanes. Only battery electric, short-distance ferries have proven to be feasible so far (ABB 2020a).

(2) Longer lifetimes: the average lifetime of aircraft and vessels is ~30 years (Dray 2013; Held et al. 2020) compared to ~15–20 years for cars (Oguchi and Fuse 2015). New aircraft and ships that join the fleet shortly after 2020 are likely to still be in service in 2050, while there will have been two generations of cars until then. Hence, committed (locked-in) emissions are higher for shipping and aviation and decisions that are made now have long-lasting impacts. Thus, a target of zero CO₂ emissions in 2050 is more challenging to achieve for these two sectors. Delayed action is likely to entail costly retrofits, if climate targets are to be met.

(3) Regulation: road transport is regulated via legal emission limits at the EU level. For aviation and shipping, there are no such emission limits. Only domestic aviation is currently part of the EU Emissions Trading Scheme (ETS), to which the Swiss ETS is linked since 1 January 2020 (EC 2020; FOEN 2020c). Initially, it was planned that the EU ETS would also include international aviation, however, the stop-the-clock regulation deferred this inclusion until 31 December 2023. Hence, currently the EU ETS only applies to flights between airports located in the European Economic Area (EEA) (EC 2020). Furthermore, a lot of emission allowances are allocated to airlines free of charge. The European Green Deal plans to reduce the number of these free allowances (EC 2019).

Nevertheless, there is no binding international legislation to curb emissions from international aviation or shipping.

(4) Radiative Forcing (changes to Earth’s radiative equilibrium that cause climate change or global warming): aviation is different from all other modes of transportation as its emissions are released at high altitudes. Given certain atmospheric conditions particle emissions in the exhaust gas of an airplane can act as condensation nuclei depending on water vapor both in the aircraft exhaust and in the surroundings. This can induce contrails, cloud formation or aviation induced cloudiness (AIC). According to current research, only ~40 % of all aviation-derived radiative forcing can be attributed to CO₂, the rest stems from AIC (~55 %) and NO_x (~5 %) (Kärcher 2018).

In summary, the challenge of decarbonizing shipping and particularly aviation is higher than for any other mode of transportation. Hence, it is likely that there will be remaining emissions from these two sectors in 2050, which will have to be compensated by other sectors or drastic measures will have to be taken in order to achieve net zero emissions.

2.3.1 Aviation

Although different incentives and policy measures can help lower the demand for air travel, it is absolutely inconceivable that demand will ever be close to zero. Thus technological solutions are required to decrease emissions. These include technology and operational **improvements**, sustainable aviation fuels (SAF) and mode **shift**.

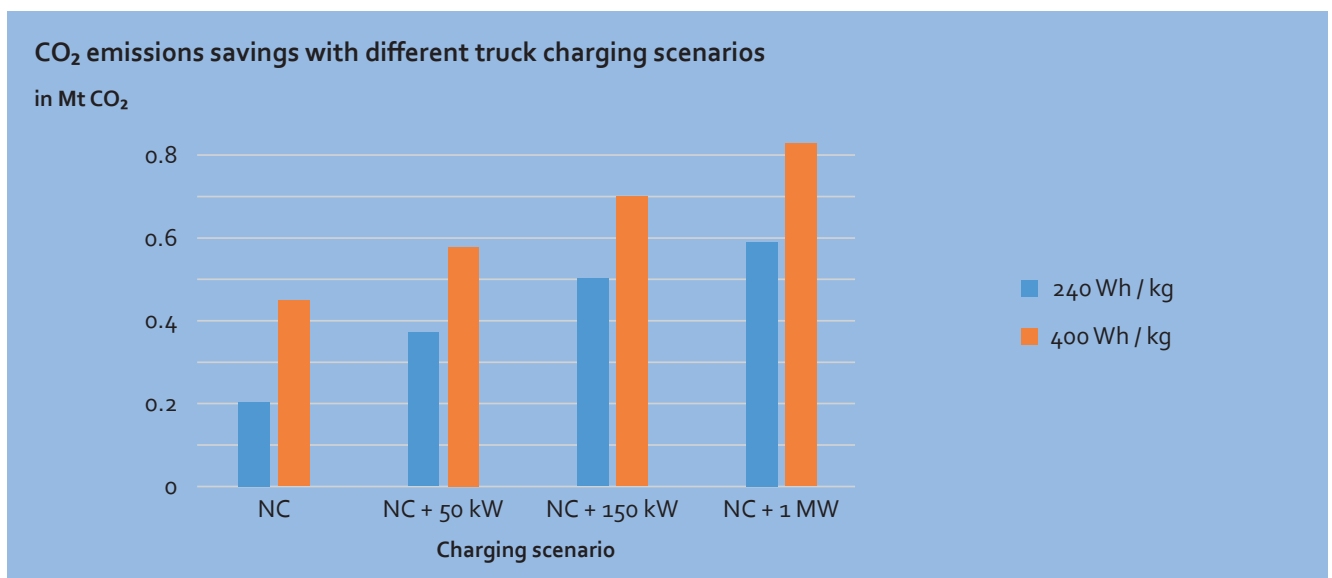


Figure 8. CO₂ emission reduction potential for the current fleet of domestic heavy-duty battery electric trucks in Switzerland (tank to wheel). NC stands for night charging, where trucks can fully recharge their battery after a day of work. NC + X kW stands for night charging plus charging at a power station of X kW for 30 minutes during their daily loading/unloading operations (Mancera Sugrañes 2021).

Technological **improvements**, e.g. by ultra-high bypass or geared turbofan engines are likely to reduce CO₂ emissions on the order of 10–20% by 2035. Revolutionary technologies like open rotor engines, new airframe designs or alternative propulsion concepts like hybrid, H₂ fuel cell or battery electric engines (the latter most likely only being feasible for short flights), could curb emissions more significantly by 2050. For a detailed overview on technology options, refer to the International Air Transport Association (IATA 2019, 2020). These are, however, subject to high development risks and so far, neither Airbus nor Boeing have taken any serious steps towards these more ambitious technologies.

As *Figure 9* shows, a range of possible increase of worldwide fuel demand for aviation can be estimated (Seymour et al. 2020) based on projected growth in flying performance (demand for pkm) and technology **improvements** with regard to efficiency of the aircraft and its propulsion system. Starting from a value of about 300 bn. liters per year in 2018, a frozen technology for the aircraft fleet would lead to about

1'100 bn. liters per year in 2050, while a plausible range of implementation of new technologies could yield a jet fuel demand in 2050 of 625 bn. liters annually (+38%, -23%).

Since it is conceivable that direct full electrification will not be feasible for mid- and long-haul flights (which dominate the CO₂ emissions of aviation) even in three decades from now, SAFs (or hydrogen) must **replace** fossil kerosene in order to achieve full decarbonization of the sector. As costs of such chemical energy carriers are expected to be very high for quite some time, increasing efficiency will have a substantial influence on investments and the need for rapid development of fuels at the required scale. Of course the evolution of both the demand for aviation services and technology progress will also heavily depend on future policies for this mobility sector. Among these, a CO₂ price that increases gradually yet rapidly and predictably will be crucial for stimulating innovation and helping achieve cost parity among fossil fuels and renewable SAFs. It can be anticipated that this CO₂ price will be among the highest of all sectors, reflecting the huge challenge for decarbonizing aviation.

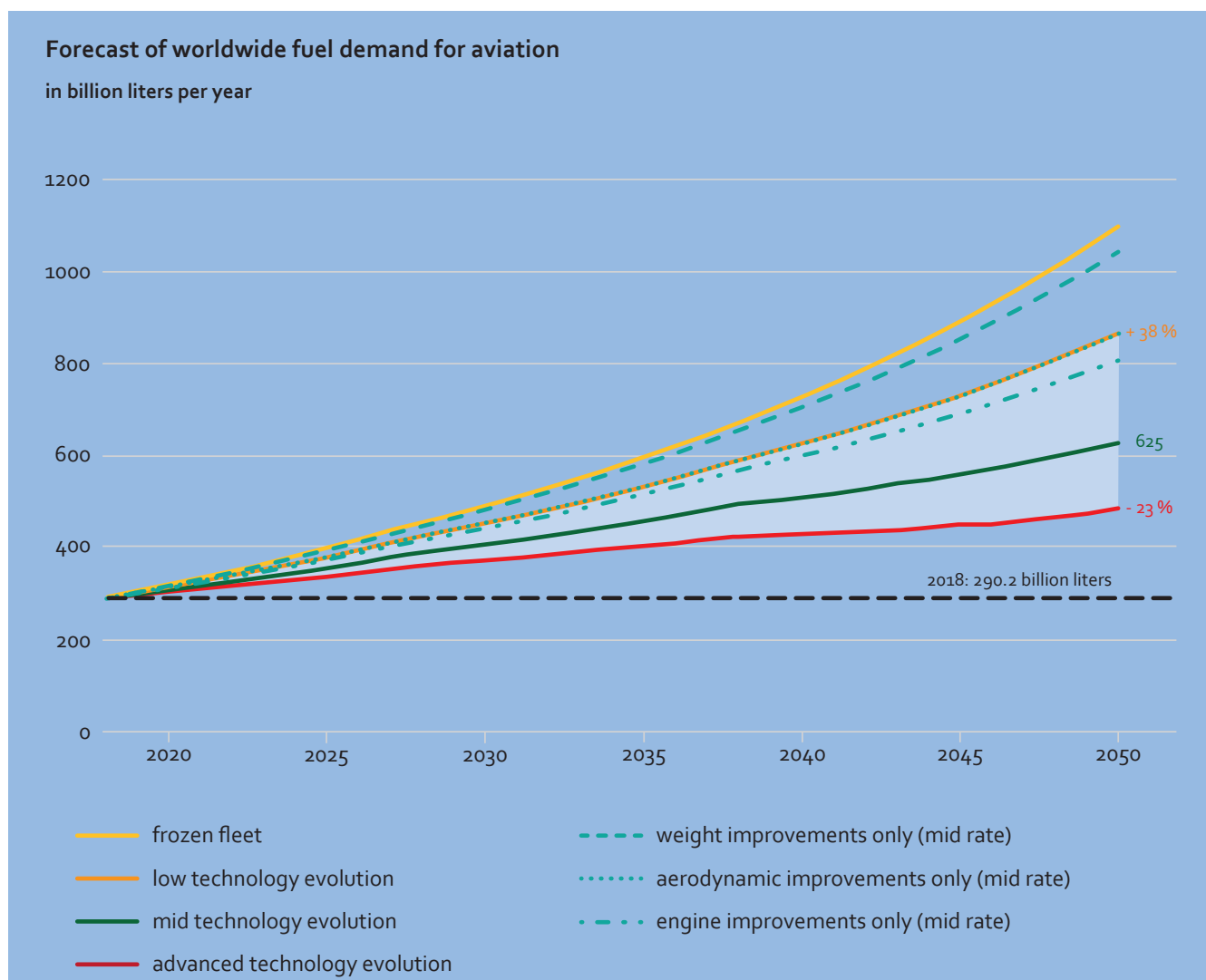


Figure 9. Forecast of worldwide fuel demand for aviation depending on the implementation of different efficiency improvement technologies (Seymour et al., 2020).

Operational measures include **improved** air traffic management like the Single European Sky (SES) initiative, which would allow for more direct flight paths due to merging of the current ~40 flight control zones to one single European zone. The SES aims for an emission reduction of 10% (ATAG 2010). According to a recent study (McKinsey & Company 2020), hydrogen could be an efficient alternative for the propulsion of commuter short- (later medium-) range aircraft in the mid-term. This could lead to additional non-CO₂ GHG benefits compared to synthetic fuels, in particular, if fuel cells **replaced** gas turbines in the long term. While infrastructure and aircraft investments will be needed to this end, industry experts project a feasibility within the next 10 to 15 years at considerable but potentially affordable additional costs per passenger. However, for mid- and especially long-range aviation, gas turbine combustion of renewable SAFs will probably continue to dominate in the long run. An important advantage of appropriately designed SAFs is their inherent drop-in capability that allows using existing infrastructure, propulsion technology and aircraft design. This is highly relevant, as the lifetime of commercial aircraft is currently 20 to 30 years.

SAFs can be produced from biomass (biofuels), via Fischer-Tropsch synthesis from electricity and captured CO₂ (e-fuels) or via thermochemical processes from concentrated solar power and captured CO₂ (solar fuels). CO₂ reduction potentials are on the order of 50–80% for biofuels, while e- and solar fuels could reduce emissions by more than 90% (IATA 2016). Although SAFs could also reduce particle emissions by 50% (Schripp et al. 2018), it is uncertain to what extent this will influence AIC (Kärcher and Voigt 2017; Caiazza et al. 2017; Burkhardt et al. 2018), the major driver for radiative forcing from the sector. Furthermore, SAFs are currently ~3–10 times more expensive than fossil jet fuel (Rojas et al. 2019). These unfavorable market conditions are likely to **improve** due to technology **improvements** and cheaper renewable electricity production. However, the current cost gap cannot be closed by technology alone. If SAFs are to be deployed on larger scales, governments will have to set the regulatory framework to support their market entry. Among many different policy designs, the planned flight tax (Swiss Parliament 2019) could e.g. be used to subsidize SAF use (Zurich Airport 2020).

Furthermore, the simplification of accounting methods in SAF supply (Pechstein et al. 2020), as well as research and development support for bio-, e- and solar fuel production technologies would further decrease market barriers. SAF production has to be powered by renewable electricity to ensure a

reduction in CO₂ emissions. Providing Switzerland's current demand of jet fuel from domestic SAF production facilities would entail an additional electricity demand of ~50 TWh per year⁴ compared to the current electricity demand of the whole country of 58 TWh per year (SFOE 2018).

Interestingly, 19% of Switzerland's emissions from aviation are produced by flights shorter than 1'000 km (own calculation⁵ based on Seymour et al. 2020). These emissions can be drastically reduced by a **mode shift** to high-speed rail (Sims et al. 2014). While high-speed trains have an energy demand of ~0.20 kWh per pkm, the energy demand of an aircraft for short flights amounts to ~0.45 kWh per pkm⁶. Assuming future jet fuel can be produced from renewable electricity (via Fischer-Tropsch synthesis), the electricity demand for one pkm would approximately be five times higher for an aircraft than for high-speed train (note: this holds true only for short flight distances). Therefore, enlarging and improving the existing rail network is crucial and should be encouraged by infrastructure investments, not only domestically, but in cooperation with the neighboring countries of Switzerland.

Current international efforts to reduce emissions from international aviation are weak, and only include carbon neutral growth from 2021 onwards (ICAO 2019, CORSIA). Under this scheme, the difference between the forecast emissions and sustained 2020 emissions can simply be offset by reducing emissions in other sectors.

2.3.2 Shipping

Compared to aviation, there are a variety of potential CO₂ reduction measures for shipping. These include changes to the hull (5–18% CO₂ reduction⁷, e.g. economy of scales), **improved** operations (4–24%, e.g. slow steaming), **improved** power and propulsion systems (1–8%, e.g. waste heat recovery), alternative energy sources (4–12%, e.g. on-shore power supply) and alternative fuels (20% for liquefied natural gas, LNG, and 70% for biofuels). Besides biofuels and synthetic methane, also carbon-free fuels are under discussion for ocean-going ships. Foremost, these include ammonia and hydrogen, with current technology readiness levels of 5–9 depending on the production method (Geertsma and Krijgsman 2019; Royal Society 2020). For smaller container ships and ferries operated over shorter distances, battery electric propulsion has proven to be a feasible decarbonization option as well (ABB 2020a). For Switzerland's inland waterway shipping on Swiss lakes and at the Port of Switzerland in Basel,

⁴ Calculation is based on an e-jet fuel production efficiency of 47%, excl. the energy demand for carbon capture (Pareschi et al. 2019).

⁵ 63% of all flights, 25% of all flight kilometers and 19% of all CO₂ emissions stem from flights departing from Switzerland with a distance of less than or equal to 1'000 km.

⁶ The value for high-speed rail assumes a capacity utilization of ~0.25 (Janic 2016). The value for aircraft is based on an A320 configured with 150 seats at a capacity utilization of 0.7, for a flight of 1'000 km. The calculation is based on the framework of Seymour et al. (2020).

⁷ Median CO₂ reduction potential values in brackets taken from Figure 2 of Bouman et al. (2017).

where 6–7 million tons of freight are traded per year (Port of Switzerland 2020), battery electric propulsion might be a feasible option. However, the bulk of emissions from global shipping stems from other vessel types, foremost large container ships, bulkers and oil tankers. Among the ships entering ports within the EEA in 2018, only the fleet of RoRo (roll on/roll off) and RoPax (RoRo passenger combi carrier) vessels show a considerable number of ships with a maximum trip distance of less than 1'000 km⁸ (Stolz et al. 2020). International shipping that serves the import and export needs for freight transport of the Swiss economy is not attributed to Swiss emissions according to the Paris Agreement (territorial principle). As an indication of the amount of such hidden footprints one must mention that the entire CO₂ emissions of the EU shipping economy are roughly equal to those from aviation, each corresponding to about 13% of the total European transport emissions.

Beyond the actual shipping activity in Swiss waters, Switzerland is home to an innovative marine industry, mainly in the field of marine propulsion systems and alternative energy

carriers. ABB provides e.g. system components like battery racks and shore-side electricity systems (ABB 2020a) and has recently signed a memorandum of understanding together with Hydrogène de France to “jointly manufacture megawatt-scale fuel cell systems capable of powering ocean-going vessels” (ABB 2020b). WinGD supplies two-stroke marine engines, like its dual fuel engines that can be operated with LNG (WinGD 2018), while ABB is leading worldwide on turbo-charging technology for marine applications. Moreover, other small and medium-size enterprises provide propulsion system components to the shipping industry and Switzerland-based companies like Climeworks and Synhelion may enable the production of future synthetic fuels like LNG or jet fuel. Thus, the impact of innovative technological solutions developed in Switzerland goes way beyond domestic borders and highlights its important role in research and development towards decarbonizing international shipping.

3. CO₂ mitigation through sector coupling

3.1 Embedding mobility in the future energy system

The decarbonization of the mobility system within the next ~30 years requires a multistep transformation process that will differ among the individual transport sectors. Though, it is very difficult to predict these steps, some paths can already be sketched. Beyond the already mentioned indispensable developments towards containing demand for transportation services to a reasonable level and consequential exploitation of efficiency potentials with regard to mode choice, vehicle and powertrain design (EASAC 2019), a massive **shift** from fossil to renewable energy carriers will ultimately be necessary.

With the exception of some rather limited potentials of bio-fuels from renewable biomass and the long-term perspective of using high-temperature solar thermochemical processes to produce synthetic renewable fuels, the main avenue for decarbonizing the transport sector will be its direct and indirect electrification. Direct electrification means that BEVs will **replace** ICEVs and dominate the market in the transport sector. Based on recent developments it is conceivable that this will happen to a large extent in the subsector on the road as well as in the (peri-) urban transport of freight with LDVs.

However, as the distance to be covered increases or as the transport service becomes more heavy-duty (in tkm or pkm per mission), the volumetric and gravimetric energy density of the energy carrier becomes crucial. This will probably result in a distribution of renewable energy carriers and propulsion technologies in the mobility sector depending on the mission and trip length as shown conceptually in *Figure 10*.

Mid- and long-haul transport around 2050 will probably be covered by energy carriers like hydrogen (road freight, small- to medium-size ships and interurban busses) and synthetic hydrocarbons or ammonia (ocean-going shipping, aviation, heavy construction machinery, etc.). Such fuels must therefore be produced mainly by electricity from renewable sources leading to what is known as sector coupling. This concept describes both the electrification of end-use energy sectors and the multiple interfaces between the electricity and the chemical fuels sectors through (re-) conversion, storage and distribution processes. This is illustrated schematically in *Figure 11*.

⁸ We assume that the longest trip distance of all trips performed by a ship in one year determines the energy requirements on board, and hence the feasibility of direct electrification.

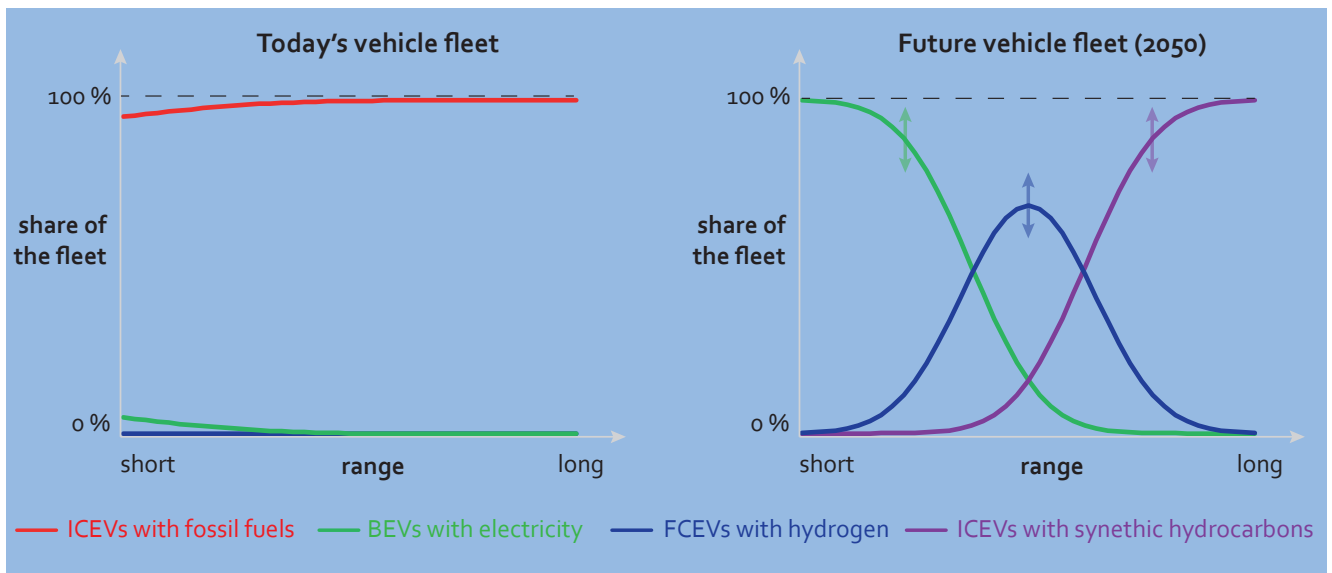


Figure 10. Conceptual illustration of possible market shares around 2050 of various energy carriers and powertrains depending on the length of the mission. ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle.

For short-haul, light-duty applications (cars, delivery trucks and short-range ferries), direct electrification should be preferred as the efficiency of the whole conversion chain from primary to propulsion energy is in principle much higher than when using intermediate conversion to chemical energy carriers. However, direct application of batteries in long-haul transport will most probably not be achievable in the foreseeable future, so that there will be a competition between H₂ and synthetic hydrocarbons to supply this transport sector. From the point of view of thermodynamic efficiency, H₂

offers advantages compared to hydrocarbons and it does not require recycled carbon (CO₂). However, synthetic hydrocarbons would profit from the existence of ready-to-use transportation and distribution infrastructure, which does not yet exist for hydrogen. When discussing efficiencies, it is important to notice that since in the future the renewable electricity upstream of the whole energy conversion chain will be delivered by wind and solar energy to the greatest extent possible, of which the annual yields (full load hours) may vary substantially across geographic locations, the important investment

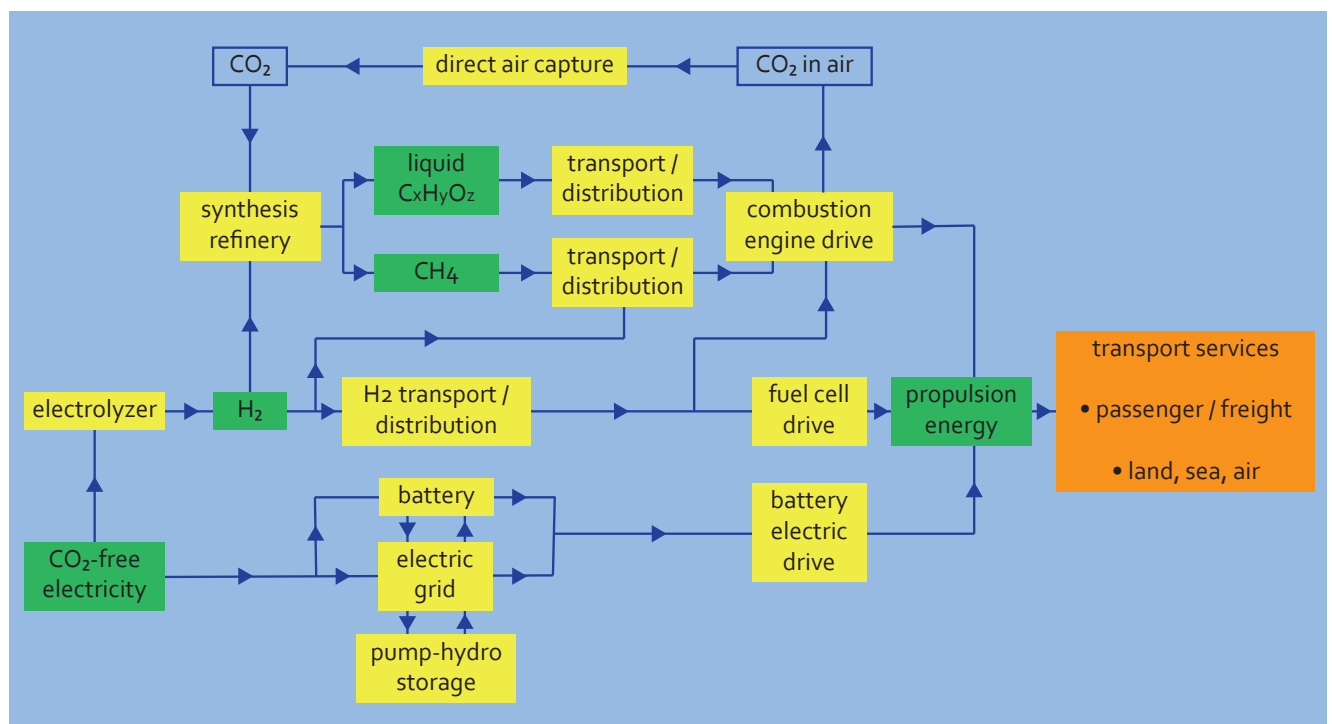


Figure 11. Schematic illustration of sector coupling for delivering transport/mobility services through direct (batteries) or indirect (H₂, synthetic fuels) electrification. C_xH_yO_z refers to a synthetic hydrocarbon.

cost factor will be the necessary capacity of such power generation at optimal locations (see below *Section 3.2*). Obviously, costs will be crucial for the related market shares but the requirement for commercialization of emerging technologies (electrolyzers, methanation plants, green refineries, etc.) will pose big challenges to the energy industry in any case. Synthetic renewable fuels are currently about three to five times more expensive than (pre-tax) fossil fuels (Concawe 2020). Though technology and overall business innovation is expected to lower these costs substantially, it is likely that their competitiveness versus fossil fuels will only be achieved if CO₂ is priced well above ~100 € per ton in the mid- to long term.

Direct and indirect electrification of the Swiss transportation sector will inevitably increase the electricity demand massively (*Box 2*). For comparison, total net Swiss electricity demand is ~60 TWh per year. The potential supply of the aviation sector with synthetic fuels alone would almost double total electricity demand. To reach climate goals this electricity should come from renewable sources, which would require a massive buildup of generation capacity and transport, storage and distribution infrastructure. These back-of-the-envelope estimates are based on current demand for mobility services (or assuming that future demand increase will be roughly compensated by efficiency **improvements**) and current conversion efficiencies from primary to final (tank) energy. For the aviation sector, the assumption of constant fuel demand in the future is overly optimistic but the actual evolution will substantially depend on climate policy, in particular on CO₂ prices in this sector.

Box 2. Estimates of electricity demand for direct and indirect electrification of the Swiss transport sector.

- Passenger cars: ~10–19 TWh (BEV–FCEV)
- LDVs/busses: ~3–4 TWh (BEV–FCEV)
- HDVs: ~2.5–5 TWh (BEV–FCEV)
- Aviation fuel ~50 TWh (SAFs)

3.2 Installed power generation capacity for Swiss transport electrification

According to the rough estimates shown in *Box 2*, future electricity demand for the Swiss transport sector could amount to at least 70 TWh in total. As *Box 3* shows, the necessary installed electricity capacity will increase substantially, depending on the location of its production. It is therefore conceivable that BEVs would be supplied by Swiss electricity but FCEVs and ICEVs would require imports of renewable fuels generated abroad.

Box 3. Necessary installed power generation capacity for 70 TWh annual electricity.

- Solar energy in CH: 1'000 full load hours (70 GW)
- Solar energy in best locations: 2'200 full load hours (32 GW)
- Wind energy in best locations: 4'600 full load hours (15 GW)

3.3 Transitional dynamics

Envisioning an optimal decarbonized final state of affairs around 2050 is one thing, exploring the steps along the path towards this final stage is another. As shown in *Box 4*, virtually all transport sector-related assets have lifetimes on the order of several decades, which is at least comparable to (or even exceeds) the time for the net zero CO₂ transformation. Therefore, wrong investment decisions will result in unintended lock-in effects (Küng 2020) or stranded assets as well as very high costs, if policy is tightened in the middle of the transitional period.

It is important to consider that due to industry inertia (established processes, long lead times for commercialization, etc.) and consumer behavior, long-term optimal investments will probably not be realized early enough. An example from the passenger car sector: it is conceivable that until around 2035 lock-in effects will have already spent half of the CO₂ budget of the sector, while newly purchased vehicles after 2019 will exhaust the whole budget, unless they are all equipped with hybrid powertrains. It is therefore important to reap cheap efficiency improvements (low-hanging fruit) during the transitional period as well as introduce disruptive technologies and processes as early as possible (Küng et al. 2019).

Box 4. Lifetimes of mobility-related assets.

- Cars: 15–20 years
- Trucks: 15–20 years
- Ships, aircraft: 20–30 years
- Roads, railway tracks: >50 years
- Refineries, distribution grids: >50 years
- Power generation plants: 20–50 years
- Electrolyzers: ~15 years

4. Integrated assessment of mobility technologies in a system context

As seen in the previous chapter, the mobility and energy systems are closely linked. While decarbonization of the transport sector is the overall goal, it is essential to assess the performance of current and future mobility options taking into consideration the systemic context and the mobility sector's interdependencies with the broader energy system and competing objectives. Technology assessment provides specific technical, economic and environmental performance characteristics of mobility options as inputs to the integrated scenario analysis in order to evaluate their decarbonization potential and certain trade-offs that may be considered. For this, the LCA methodology (ISO 2006; see *Chapter 2* for selected results) is used along with internal and external cost assessment, risk assessment, multi-criteria decision analysis (MCDA) and energy economic systems modelling. Integrated model-based scenario results are derived from the Swiss TIMES Energy system Model (STEM), which employs a cost optimization approach and generates possible future trajectories of the entire Swiss energy system under specific assumptions about the developments of technologies, socioeconomics and policies (Panos and Kannan 2018).

The above assessment dimensions are discussed in the following mainly for passenger cars, but the same methodology has been used for other transport sectors.

4.1 External and total costs

The estimation of external costs of mobility covers environmental (climate change, regional pollution, land use and noise) and non-environmental (accidents) impacts on the level of individual technologies. On the fleet level, congestion costs are also accounted for. The estimates of external costs of regional pollution are based on the semi-regionalized impact pathway approach (Heck 2014), enabling to account for the dependence of impacts on the location of emissions.

Moderately high monetary values were assumed for damages due to global warming as well as for value of year of life lost when quantifying mortality caused by pollution. In the current case for BEVs and FCEVs, the Swiss electricity consumption mix is used for charging BEVs as well as for producing hydrogen for FCEVs. The corresponding mix in the future case corresponds to net zero emission scenario also referred to as extremely ambitious climate scenario (EACP). *Table 1* shows estimates of external environmental costs for selected current (state of the art in 2019) and future (2050) cars.

Table 1. External costs for selected current and future lower medium-size cars (Hirschberg et al. 2021).

Current (2019)	ICEV petrol (EURO 6)	ICEV diesel (EURO 6)	Hybrid petrol	Hybrid diesel	PHEV petrol	PHEV diesel	BEV	FCEV
CHF cents/vkm	13.4	12.3	10.8	10.6	11.9	11.3	10.2	11.9
Future (2050)	ICEV bioethanol	ICEV biodiesel	Hybrid bioethanol	Hybrid biodiesel	PHEV bioethanol	PHEV biodiesel	BEV	FCEV
CHF cents/vkm	4.1	4.7	3.9	4.4	4.3	4.6	5.0	4.7

ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle

It is interesting to notice that both for current (considering HEVs as reference powertrains for ICEVs) and future vehicles, the external costs for the different propulsion technologies are very close to each other within a range of no more than $\pm 15\%$. It is also useful to compare current values from Table 1 with the estimates of the Swiss Federal Office for Spatial Development (ARE) for the year 2015 (Bieler et al. 2019). The latter estimate an average of total external costs for the current fleet of passenger cars of 7.7 CHF cents per pkm. Given that in Switzerland one vehicle kilometer (vkm) corresponds to about 1.6 pkm for cars, the comparison for current technologies shows reasonable agreement despite the different methodologies used.

Clearly, the future environmental costs can be reduced by more than a factor of two compared to the current technologies due to technology improvements, use of alternative fuels and implementation of very stringent climate policies. It should be noted that the current car fleet still includes older cars with low environmental standards. Non-exhaust emissions from brakes, tires and road abrasion will become more important in relative terms in the future given reductions in exhaust emissions. They will remain an issue for land transport also in the far future because they are relevant for

electric vehicles (electric cars, electric trains, electric busses, electric trucks, etc.).

Figure 12 shows the aggregated total (internal and external) costs of three mobility scenarios representing climate policies with moderate, ambitious and extremely ambitious climate goals (see Section 4.3).

The internal costs (ownership costs) increase in future scenarios compared to the current fleet, with highest costs for the net zero emissions scenario. The opposite is true for the external costs, leading to the total costs being at about the same level in all cases, if we take the higher range of climate change costs as the reference. Apart from climate impacts and regional pollution, car accidents, congestion and noise contribute substantially to the external costs. Overall as shown in Figure 12, external costs of the current fleet make up about one third of the total costs, while for the EACP scenario they contribute about 15% of the total costs.

Concerning other modes of passenger transport, the ARE estimates external costs of 6.2 CHF cents per pkm for public road transport, 3.2 CHF cents per pkm for rail and 2.6 CHF cents per pkm for aviation (Bieler et al. 2019). Obviously, these

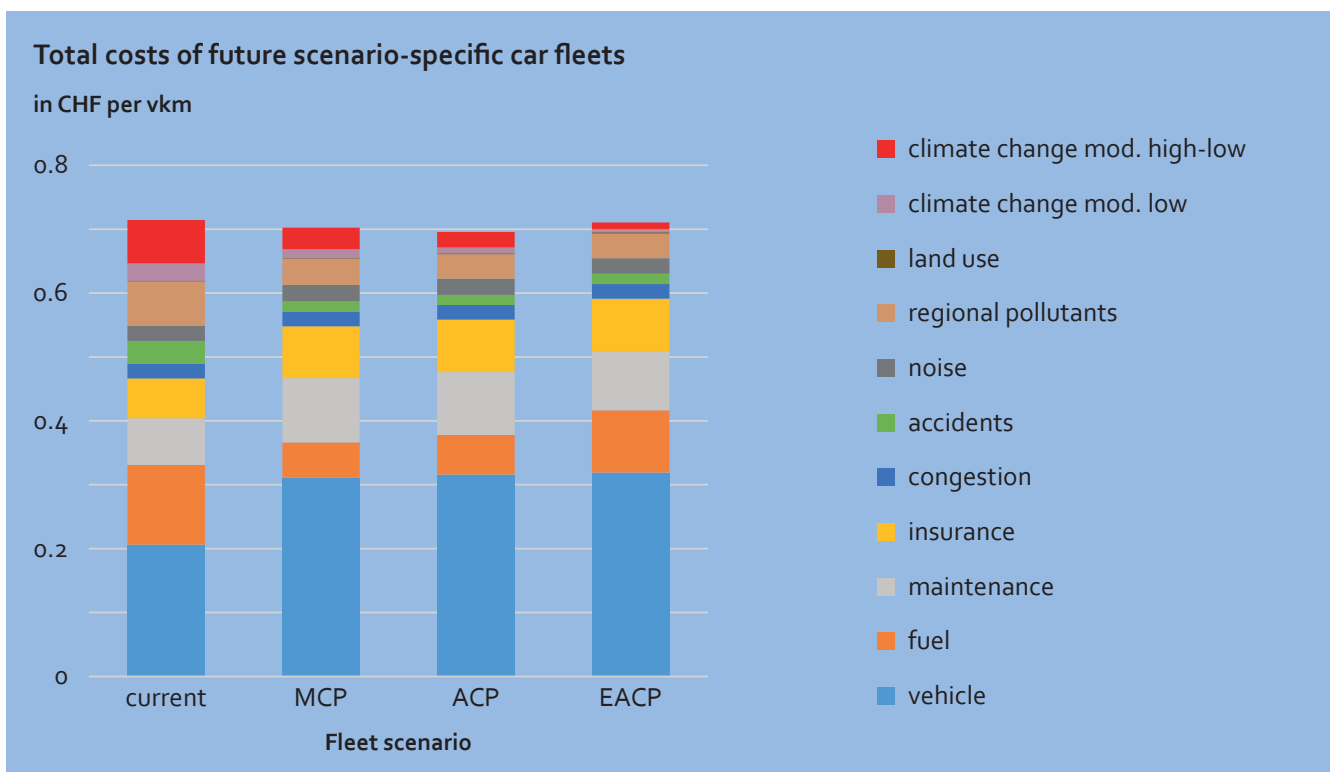


Figure 12. Total costs of future scenario-specific car fleets in CHF per vkm today and in the year 2050 (Hirschberg et al. 2021). MCP = moderate climate scenario; ACP = ambitious climate scenario; EACP = extremely ambitious climate scenario. Regional pollutants include NO_x, sulfur dioxide, particulate matter, etc. Climate change impacts are subject to high uncertainties with large range of values for these external costs. Here we use moderate values both for lower and higher range: climate change mod. low (moderately low) refers to the lower range; climate change mod. high-low (moderately high to low) is the difference between high and low.

estimates are subject to some uncertainties and especially the climate change externality will be very important in the future.

Indicatively for road freight, the ARE study approximates externalities of about 9.7 CHF cents per tkm (of which 3.1 CHF cents per tkm are internalized via LSVA to finally yield 6.6 CHF cents per tkm net) as opposed to 4 CHF cents per tkm for rail freight transport (Bieler et al. 2019). Further data will be necessary in the future in order to assess future propulsion systems for road freight transport (BEVs, FCEVs, HDVs with catenary systems, ICEVs with synthetic fuels, etc.).

4.2 Trade-off sustainability analysis of cars

MCDA has been used for carrying out sustainability assessments of the various mobility options on the level of individual technologies as well as for alternative composition of the whole system. The approach allows to combine the estimated performance indicators of the options with varying preference profiles with respect to three dimensions of sustainability. Building on earlier work (Hirschberg et al. 2016), nine representative indicators (four environmental, two economic and three social) were quantified for 41 current and 56 future car options. The options represent distinct combinations of powertrains, fuels and electricity inputs. For the future case the supply chains correspond to the analyzed scenarios reflecting the alternative climate policies. MCDA was also performed for the scenario-specific car fleets.

All scenarios perform better than the current fleet. The net zero emissions scenario is superior to the other for six out of eight indicators. As expected this includes superiority with regard to reduction of GHG emissions and consumption of non-renewable energy, which are the main goals of the Swiss energy strategy. However, the net zero emissions scenario has the highest costs and highest metal depletion. The ambitious climate scenario is the most balanced from a sustainability point of view and thus can be seen as a trade-off candidate (Hirschberg et al. 2021). However, this scenario would not meet the net zero CO₂ target for 2050 as set by the Swiss Federal Council.

4.3 Systems analysis

The trends described below are based on the STEM analysis for the future evolution of the whole energy system and refer in particular to most ambitious EACP scenario, prescribing net zero CO₂ emissions from the Swiss energy system in 2050. It must be noted though, that even in the EACP scenario for 2050 the GHG emissions on LCA basis (incl. non-domestic emissions) will be reduced by about 85% and not by 100%.

The STEM-based analysis for a techno-economic optimization indicates a continuously increasing electrification of powertrains for cars during the next three decades, which will involve BEVs, FCEVs, PHEVs and HEVs in varying degrees. Hybrid technologies represent a transition technology towards mainly BEVs and to some extent FCEVs, and reach a deployment peak in 2030–2040 according to this analysis.

To reach almost complete decarbonization of the transport sector, the STEM results for this scenario show that in 2050 the passenger car fleet will be composed by almost 50% BEVs, around 30% PHEVs, about one sixth FCEVs as well as a marginal share of HEVs and ICEVs. This is displayed in *Figure 13*, which also indicates that electricity would contribute almost 50%, hydrogen more than 20% and synthetic and biofuels together about 30% to the composition of the energy carrier mix. Of course, these numbers may vary somewhat depending on the future evolution of technology performance, costs and other boundary conditions. The main message from this analysis is that even in a scenario of full decarbonization around 2050, a broad variety of both propulsion technologies and energy carriers is to be expected in the motorized individual mobility sector. Interestingly enough this is in striking disagreement with current national and European policy strategy that appears to focus almost exclusively on the promotion of BEVs. Furthermore, *Figure 13* shows that even if the domestic CO₂ emissions from passenger cars were zero in 2050, about 3 Mt CO₂-eq. would still be produced by upstream processes outside of the country.

Another interesting insight from *Figure 13* is that despite an anticipated increase of car numbers by more than 25% from 2019 to 2050 in Switzerland, the final energy demand for the sector will be around 30% of today's. This is obviously a result of the much higher efficiency of partially or completely electrified powertrains versus incumbent (mostly even non-hybrid) technologies (Hirschberg et al. 2021; Kannan 2021 et al.).

For medium- and heavy-duty road transport (mainly trucks and busses) the shares of BEVs and PHEVs are anticipated to be lower than for passenger cars, because the energy density of current and possible battery technologies in the foreseeable future are not sufficient to cover the majority of the much longer daily trips (see also *Figure 8* and Çabukoglu et al. 2018).

Therefore, H₂-fueled FCEVs on one hand and ICEVs operated with synthetic or biofuels on the other are expected to make up a substantial share of the fleet. Nevertheless, battery electric powertrains will probably capture a significant market in urban freight transport (in particular LDVs) and busses operating in urban environments.

The above analysis yields an electricity demand for Switzerland in order to electrify passenger and freight transport

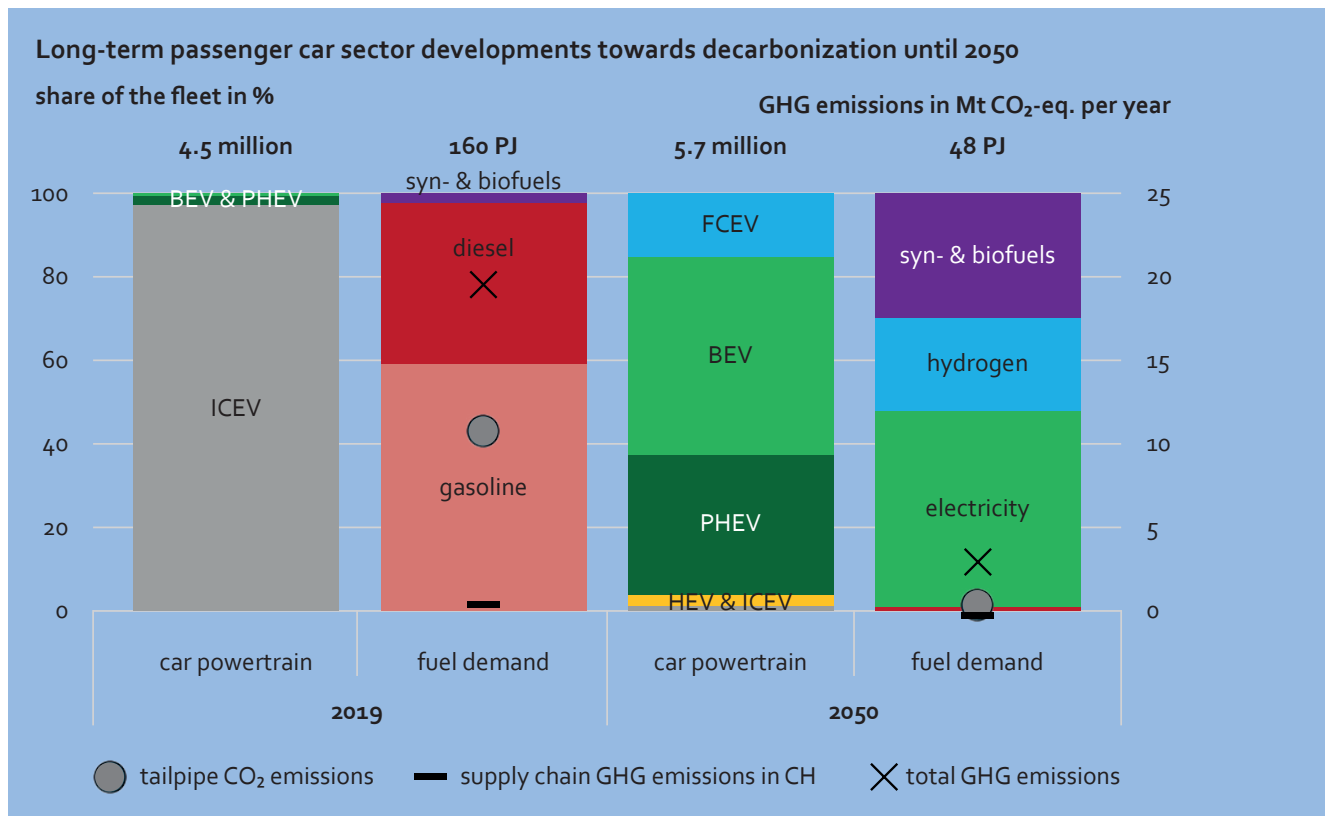


Figure 13. Long-term transport sector developments towards net zero greenhouse gas (GHG) emissions until 2050 (Hirschberg et al. 2021; Kannan 2021 et al.) according to the extremely ambitious climate scenario. BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; ICEV = internal combustion engine vehicle; FCEV = fuel cell electric vehicle; HEV = hybrid electric vehicle.

on the road in 2050 of about 21 TWh, 14 TWh for direct electrification and 7 TWh for the production of H₂ for FCEVs (see also *Box 2* with a back-of-the-envelope estimated range of electricity demand for road transport of 16–28 TWh).

It is important to notice, however, that such estimates do not take into account the aviation sector, which (as indicated in *Box 2*) is anticipated to require at least 50 TWh electricity for the production of either H₂ or SAFs and therefore to dominate future electricity demand for the decarbonization of the transport sector.

Furthermore, the role of chemical energy carriers, being it H₂, bio- or synthetic fuels, is a field of continuous debate, as the evolution of performance and costs of new technologies is subject to uncertainties. The STEM analysis discussed here indicates a growing importance of H₂ during the next decades and particularly around 2040 and beyond. This appears to be in agreement with the recently launched European Hydrogen Strategy, which will be embedded in the EU New Green Deal. Although a major part of the required hydrogen is expected to be produced by clean electrolysis (and later on presumably also by solar chemical processes), alternative pathways do exist for H₂ production, among them production from natural gas together with CCS, called blue hydrogen.

Finally, while imports of oil products to Switzerland become almost eliminated by 2050, imports of biofuels increase in the mid- and long term and complement the domestic biofuel production. In 2030, the share of biofuel corresponds to a blending quota of circa 10%. After 2030, biofuels gain importance as combustible fuel in sectors other than transport as well, which intensifies competition for this energy carrier in a decarbonized energy system.

5. Transport policy aspects

Policies to **improve** the energy efficiency and promote decarbonization of the passenger vehicle fleet in Switzerland can be grouped into monetary (CO₂ taxes and vehicle registration taxes) and non-monetary measures (emission and fuel economy standards and energy labels). The first group aims to change vehicle purchase and use decisions through taxes or subsidies, while the second group includes information measures to help consumers in their choices and policies like emission and fuel economy standards that describe energy efficiency or CO₂ emission levels of new products.

5.1 Policy measures for motorized individual transport

Ideally monetary instruments should contribute to the internalization of external costs (see *Section 4.1*), but unfortunately current legislation is incoherent and varying from case to case.

CO₂ taxes: In Switzerland, the CO₂ tax has been introduced in several sectors, but not in the transport sector. This tax is a straightforward way to include environmental damages from energy consumption in the energy price. This tax can motivate people to limit energy use through behavior change and encourage them to buy energy efficient vehicles. In addition, the revenues can be redistributed to the population according to specific criteria, if necessary.

Filippini and Heimsch (2016) show that introducing such tax would generate important energy and CO₂ savings. The majority of these savings would come from long-term changes due to the adoption of energy efficient cars. Regional and household distribution effects of an environmental tax or subsidies are an important dimension of this type of policy measure. The Swiss context suggests that a CO₂ tax on gasoline would affect rural drivers more than urban drivers (Filippini and Heimsch 2016). Through proper redistribution mechanisms of the tax revenues, however, it is possible to mitigate the geographical disparities in the impact of the tax.

Registration taxes and bonus-malus policies: In some cases, introducing or modifying a CO₂ tax can be politically unfeasible. Furthermore, it is possible that a subgroup of consumers underestimates energy costs (and thus taxes on vehicle fuel) when comparing different vehicles. In those instances, taxes or subsidies promoting energy efficient vehicles are justifiable from an economic point of view (Allcott et al. 2014). An example of these measures in Switzerland are cantonal vehicle registration taxes (yearly taxes on car ownership) coupled with bonus-malus policies based on energy labels or CO₂ emissions per km. Efficient vehicles benefit from a

discount on the regular registration tax (bonus), while inefficient vehicles have to pay an additional charge (malus).

Evidence from the current registration tax system suggests that penalties for energy inefficient vehicles have a modest effect on inducing consumers to buy more efficient cars (Alberini and Bareit 2019). Two important factors contributed to this result. First, non-retroactive bonus-malus measures affecting only new vehicles can simply delay the **replacement** of older, less efficient cars (Alberini et al. 2018). Second, only a fraction of the Swiss population is aware of the presence of these monetary incentives for efficient cars and widespread information about the bonus-malus is essential for incentivizing the purchase of energy efficient vehicles (Cerruti et al. 2019).

Energy labels: The vehicle energy label provides a letter rating (from A to G) of the energy efficiency of a car compared to vehicles of similar weight. This offers a simpler way to compare the energy efficiency of cars of the same class than the raw fuel consumption rate. Research on the effect of energy efficiency rating for passenger vehicles showed that individuals value the rating and they are willing to pay more for cars with higher energy efficiency rating, even when the actual **improvement** in absolute energy consumption is small (Alberini et al. 2016). Energy labels can also be used to convey information about energy costs of a vehicle. In Switzerland most buyers do not perform an investment calculation of future energy costs when buying an appliance, thus justifying the adoption of displaying future energy costs on the label (Blasch et al. 2019). However, this might not necessarily apply to vehicle purchases. Research in the US context shows that displaying information on annual and lifetime fuel costs to prospective consumers had little effect on their choices (Allcott and Knittel 2019).

5.2 Policy measures for freight and long-haul transport

In contrast to motorized individual transport, where consumers decide on the purchase and operation of cars based on limited financial literacy on the subject and driven to a large extent by non-monetary considerations (cars as status symbols, value of exclusive ownership vs. optimal utilization of resources, etc.), both surface freight and long-haul (aviation and shipping) transport are purely commercial activities. Here trucks, ships and airplanes are investment goods and there is empirical evidence that decision making is driven to a large extent by financial and utility function trade-offs. Corresponding investment decisions are also typically long-term since the fleet assets are long-living and demand for transport services depends on long-lasting developments of global trade and other international sectors (tourism, globalization and internalization of business).

In these sectors both regulatory standards related to energy efficiency and CO₂ emissions (driving product development in industry) and internalization of external costs (influencing TCO) are powerful and imperative tools and must be designed appropriately.

5.3 Overall policy recommendations

Future transport policy must:

- Be targeted at the specifics of the individual sectors and decision makers
- Be driven by the overall philosophy of internalizing (carefully assessed) external costs
- Combine regulatory standards with monetary steering instruments
- Take care of distributional effects on low-income population groups
- Carefully balance strategic coherence and predictability with tactical flexibility
- Promote technology and business model innovation
- Be aligned with international policy instruments
- Take into account policy instruments in other energy sectors (electricity, industrial manufacturing)

6. Research and development needs and innovation paths

In order to direct the transport system towards sustainability and reach net zero GHG emissions by 2050, there are several topics that require further research and development (R&D) as well as innovation. Aligned with the strategy **avoid**, **shift**, **improve** and **replace** introduced in Chapter 1, R&D and innovation should focus on the following:

Avoid and shift

To **avoid** increasing demand for transport and promote a **shift** to modes with lower environmental impacts, users need to fundamentally change their mobility behavior. Further insights on a social, technical and economic level are required to foster such change. Rising technologies, especially digitalization and autonomous mobility, have the potential to make the entire mobility system more customized and efficient. Smart tools and tracking apps can encourage and motivate consumers to make more sustainable travel choices, but also target other groups (e.g. policy and decision makers, stakeholders from industry) and thus need different levels of scope, depth, complexity and type of interfaces adjusted to the needs and capabilities of the users. However, little is known regarding people's willingness to utilize digital technologies (more specifically there is a lack of long-term studies) as well as the degree to which these can really affect mobility demand.

Changing mobility behavior will also have economic consequences so that consumer behavior must be better integrated into techno-economic system models as well as include social aspects (e.g. social impacts of high fuel and electricity prices) in interdisciplinary assessments. The extent to which attitude and behavioral changes can contribute to **avoiding** excessive mobility and **shifting** the remaining demand to more sustainable transport modes must be systematically investigated in targeted living labs and other appropriate experimental settings at local and regional levels.

Customized and efficient mobility options require large-scale development and implementation of low-carbon mobility solutions enabled through MaaS. If fully powered by renewable energy, such services can be sustainable and fulfill individual mobility needs. This includes the development of smart trip, traffic planning and operation platforms.

This customization can be further enhanced by a widespread penetration of autonomous mobility and systems supported by digitalization and MaaS solutions. To ensure that this also happens in an efficient and sustainable way, further analyses employing interdisciplinary and integrated methods are needed. This should address environmental, economic and

social impacts, new risk challenges including hypothetical accidents and cyber attacks as well as human behavior with regard to technology acceptance and potential rebound effects. Furthermore, the development of tailored scenarios for a gradual integration of autonomous vehicles into the Swiss mobility system is needed.

The combination of autonomous driving and MaaS is expected to substantially reduce costs for mobility services, so that research on assessing rebound effects and appropriate measures (incl. policy instruments) to minimize their extent will be very important in the future. In addition, the potential of a **shift** of competitiveness in favor of individual motorized versus public transport has to be investigated and counteracted because other resources (in particular land) are limited and must have a price tag as well.

Improve

Reducing tank- and battery-to-wheel energy consumption by lowering vehicle mass, rolling resistance, air drag and auxiliary consumption (mainly air conditioning and cabin heating) as well as efficiency **improvements** on the powertrain side to ultimately lower the primary energy demand for all powertrain and vehicle energy technologies are a high priority.

To reduce the tank-to-wheel energy demand of combustion-based powertrain concepts, such systems need to **avoid** low and low part load operation of the ICE by hybridization, allowing also to recuperate brake energy or employ measures like fully variable valve drains. Furthermore, the high-load efficiencies have to be **improved** by preventing limiting events like unwanted self-ignition. Appropriate molecular structure of renewable synthetic fuels could be helpful in this context. The tank-to-wheel efficiency target for combustion based passenger car powertrains in 2030 is >45% (vs. 40% today); in 2050 >55% at full load. In addition, full hybridization must become the reference technology for ICEVs to eliminate the low-efficiency operation at low load.

Necessary improvements for BEVs refer primarily to gravimetric energy density increase for long-range applications. For FCEVs, efficiency increase at high loads and cost reduction are important targets.

Plug-in hybrid electric powertrain concepts, utilizing combustion (or fuel cell) based energy converter and electric motors allow to combine electric short-range and chemical energy based long-range operation and therefore exploit the potential for low energy consumption under real-world driving conditions. However, the system design today is not made for achieving the lowest possible energy consumption, but to achieve the highest possible utility factor in certification, which unfortunately are not the same. Plug-in hybrid electric powertrains need **improved** designs with lower overall

power and higher energy management intelligence. In addition, measures are necessary to motivate users to plug in the vehicles as often as possible, using opportunity charging when renewable electricity supply is available.

Furthermore, there is a need for a scientific update of the fast evolving development of battery production emissions as well as chemical energy technologies in the upstream processes. Future assessment methods should not only include the entire life cycle but they should also differentiate between different operational profiles as for example short- and long-distance as well as low- and high-load applications for summer and winter operation, also including their impact on the energy system as a whole.

Focus also needs to be put on integrating functions (energy storage, electrical conductivity, lights and sensors) directly into the vehicle structure, making it multifunctional, while monitoring the overall LCA impact of the vehicle during its manufacturing and lifetime. Novel manufacturing technologies for thermoplastic composites already exist, however costs are still very high compared to more traditional metallic materials. Therefore, only low cost carbon fiber materials, simple processing routes and function integration, combined with policy incentives will promote the integration of light materials into vehicle bodies.

Replace

Replacing fossil fuels with renewable or even net zero CO₂ energy carriers can be achieved through direct (BEVs) or indirect electrification (FCEVs or ICEVs with synthetic fuels). To optimally integrate BEVs powered by electricity into the fleet, further R&D is needed for battery technology. Increasing the power and energy density of battery cells to decrease battery weight, thus reducing total car weight and energy demand must be a priority. Charging power can be increased by reducing internal losses of batteries and better thermal management. Furthermore, standardized battery characterization over their lifetime using statistical, operation derived data will allow for a better estimation of the remaining value of batteries. Likewise, advanced physical-based models combined with machine learning and big data will help to optimize lifetime battery operation. Research and innovation also need to focus on next generation batteries, new battery chemistries, reuse and recycling as well as wide bandgap electronics for power electronic components to increase efficiency of chargers, motor controllers and auxiliaries.

In order for BEVs to be climate neutral, their electricity supply must also be decarbonized and their charging optimally integrated into the electric distribution grid. This can be supported by using smart charging strategies, which require an analysis of people's mobility patterns and determining optimal charging behavior. Methods and components for sector

coupling between mobility and electric power supply including digitalization to coordinate vehicle to grid (V2G) operation of BEVs and determining the impacts of V2G on the life cycle of batteries will be essential. Investigations on the optimal distribution of charging infrastructure with special focus on charging infrastructure in large parking structures (parking houses and multi-family homes) and cloud-connected bidirectional charging infrastructure will also promote the replacement of fossil fuels by renewable electricity in the transport sector.

Indirect electrification with hydrogen fuel cells or combustion-based powertrains run on synthetic fuels also requires a decarbonized power supply system necessitating large investments in electricity generation capacities in appropriate locations worldwide (e.g. solar energy in deserts or off-shore wind energy). For fuel cells to become widely adopted, the cost of hydrogen systems has to be reduced through substitution of noble metal catalysts by non-noble metals. Additionally, the durability of fuel cell technology for heavy-duty applications (trucks and trains) needs further **improvement**. For hydrogen and particularly for synthetic fuels, energy system-oriented assessment of ecologic impacts needs to be further developed. Furthermore, large-scale refueling infrastructure are currently lacking.

Regarding long-haul transport, R&D should prioritize the development of zero-carbon energy propulsion systems for aviation and maritime transport applications. In this context, synthetic fuels play a major role. Today, several synthetic fuels (compressed and liquefied biogenically or catalytically produced methane, Fischer Tropsch-diesel, methanol, dimethylene ether and different polyoxymethylene dimethylethers) are competing. More fundamental research is needed to **improve** the efficiency and selectivity of the synthetic fuel production. Due to the higher costs of synthetic compared to fossil fuels, solutions for their economic integration need to be developed. In particular, specific policies for internalizing external costs associated with the use of fossil fuels must be put in place. Together with technology innovation and learning curves from rapid upscaling, such policies will be indispensable for achieving cost parity of net zero CO₂ energy carriers with fossil fuels well before 2050.

Overarching needs

Overarching the strategy of **avoid, shift, improve and re-place**, questions remain regarding the overall mobility system. For example, how to design a sustainable and resilient mobility sector. To answer this there is a need for further development and applications of the modeling framework for holistic assessment of mobility on technology and overall system levels. This will enable systematic consideration of trade-offs in view of different stakeholder perspectives as well as assessment of the potential contributions and impacts of innovative mobility systems (e.g. underground ultra high-speed trains, underground goods transport). Furthermore, security of supply, availability and reliability of low-carbon electricity, critical material flows, recycling, price volatility and resulting social impacts require in-depth investigations leading to overall system optimization. For Switzerland there is a need to develop perspectives on the Swiss mobility system in a European context and, on an even larger scale, analyze the macroeconomic impacts of radical transformation of mobility systems and based on this propose new transport sector policy instruments and market designs. This is especially important since the disruptive innovations needed will require very large investments in new technologies, processes and infrastructure. Mobilizing the appropriate financial resources will be an endeavor of unprecedented scale and must rely on robust decisions of key technology, industrial and financial stakeholders. This makes globally harmonized, coherent and long-term oriented policies and standards imperative.

Abbreviations

Aviation induced cloudiness	AIC
Battery electric vehicle	BEV
Carbon dioxide	CO ₂
Carbon capture and storage	CCS
Compressed natural gas	CNG
Electric vehicle	EV
Emissions Trading Scheme	ETS
European Economic Area	EEA
Extremely ambitious climate scenario	EACP
Fuel cell electric vehicle	FCEV
Greenhouse gas	GHG
Heavy-duty vehicle	HDV
Hydrogen	H ₂
Hybrid electric vehicle	HEV
Information and communications technology	ICT
Internal combustion engine	ICE
Internal combustion engine vehicle	ICEV
Leistungsabhängige Schwerverkehrsabgabe (performance-related heavy vehicle charge)	LSVA
Life cycle assessment	LCA
Light-duty vehicle	LDV
Liquefied natural gas	LNG
Methane	CH ₄
Mobility as a service	MaaS
Multi-criteria decision analysis	MCDA
Nitrogen oxides	NO _x
Nitrous oxide	N ₂ O
Original equipment manufacturers	OEM
Passenger kilometer	pkm
Passenger transported	pax
Plug-in hybrid electric vehicle	PHEV
Research and development	R&D
Single European Sky	SES
Sustainable aviation fuels	SAF
Sustainable development goal	SDG
Swiss Competence Center for Energy Research – Efficient Technologies and Systems for Mobility	SCCER Mobility
Swiss Federal Office for Spatial Development	ARE
Swiss Federal Railways	SBB
Swiss TIMES Energy system Model	STEM
Ton kilometer	tkm
Total cost of ownership	TCO
Vehicle kilometer	vkm
Vehicle to grid	V2G

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