Challenges of decarbonizing the Swiss transport system

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Abstract

Using the energy perspectives of the Swiss federal government and the IPCC 2°C carbon budget, we derive a timeline for the decarbonization of the Swiss mobility sector until 2060. We then apply a Kaya-type decomposition of the operational CO2 emissions to identify the major drivers behind the transformation. While demand-side reductions and vehicular technology improvements provide relief, only the substitution of fossil fuels with renewable energy carriers leads to sustainability. Therefore we analyze the energy demand and ensuing emissions of different electric propulsion technologies, based on vehicle usage profiles from the BFS microcensus 2010. We observed large reduction potentials for battery electric vehicles, yet at the price of a strong increase in the additional electricity demand.

Keywords

Mobility – CO2 reduction – Microcensus – Sustainability – Energy transition – impact electrically propelled vehicles – energy demand of vehicles

1. Context

This paper addresses the evolution of the Swiss transportations system and the available measures to decarbonize the system. Due to its large dependence on fossil energy carriers the mobility sector holds large reduction potentials – but unlocking them is challenging: currently, many different technology and policy options are being discussed, but to what extent they solve the sustainability issues of mobility is unclear, in particular because of their side-effects: for example, electric mobility eliminates tail pipe emissions, but at the expense of a strongly increased electricity demand. Road pricing throttles the demand, but may affect economic productivity. These convoluted feedback mechanisms make it difficult for decision makers to strategize. To help them navigate the complexity, we propose a method to explore the maximum reduction potentials of individual interventions, in the larger, systemic context of mobility.

The content of this paper is based on the SCCER Mobility report "Towards an Energy Efficient and Climate Compatible Future Swiss Transportation System", soon to be released. In this paper, we only consider motorized individual mobility with passenger cars. They account for about 2/3 of the transport-related CO2-emissions in Switzerland (BAFU, 2016).

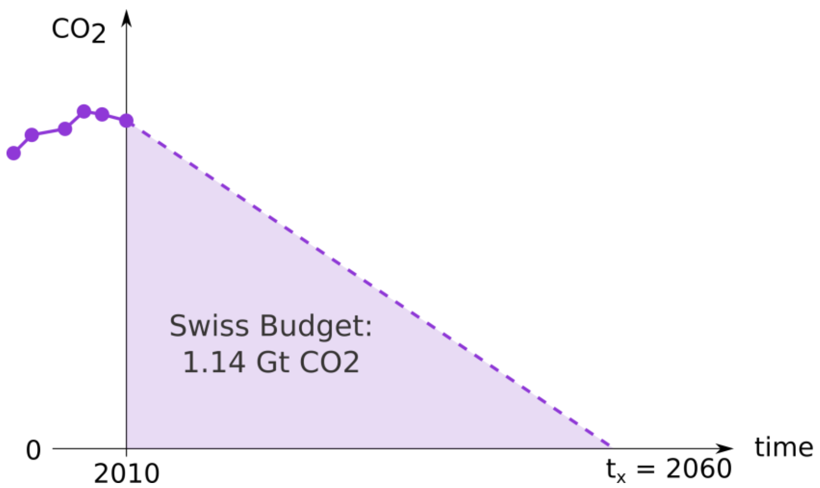
The paper is structured as follows: the introductory Chapter 2 discusses the necessity, timeline and targets of the transformation according to the federal government's energy strategy 2050. Based on that, we set CO2 reduction targets for the Swiss transportation system. Since the energy perspectives assume motorized individual mobility will maintain its dominant role in the future, Chapter 3 looks into the reduction potentials of alternative propulsion technologies. We then compare them to the targets set in Chapter 2.

2. Introduction: evolution of the transportation sector

2.1 Targets for the decarbonization of passenger cars

The "Swiss Energy Strategy 2050" sets strategic goals for the reduction of final energy demand and CO2-emissions by mid-century but does not specify clear targets for the individual (sub-) sectors of the overall energy system. According to climate science there is a global CO2-budget which should not be exceeded to keep long-term global warming below 2˚C with a probability of 66% (IPCC, 2014). In the spirit of democratic fairness, we assume this budget is distributed equally among all world citizens. For Switzerland, with its roughly 8 million inhabitants, this translates to 1.14 Gt. Under a linear reduction path for energy-related CO2-emissions (as illustrated in figure 1), the Swiss budget will last until 2060. If we assume that all sectors must contribute equally, the transportation sector must achieve zero CO2 in 2060, following a linear reduction curve; its slope is proportional to the share of the 2010 emissions (0.324 Mt/y).

Figure 1 A qualitative illustration to estimate the time of full decarbonization of the Swiss energy system, in accordance with the 2°C (66% probability) CO2 budget.



It is important to mention here that, for simplicity, the CO2-emissions serve as a proxy for the overall environmental burden of a given energy sector. Of course this is only an approximation.

2.2 Factors driving the CO2 emissions of mobility

The overarching goals of the Swiss Energy Strategy 2050 in terms of minimization of (non-renewable) energy demand and CO2-output can be decomposed into several major influencing factors and therefore operationalized by means of a Kaya-type formulation (as introduced in (Kaya & Yokobori, 1998)). The equation below is expanded and modified for our specific purpose.

$$m_{CO2}|_{a,direct} = \underset{(B)}{(popul)} \cdot \underset{(C)}{\frac{GDP}{popul}} \cdot \underset{(D)}{\frac{pkm}{GDP}} \cdot \underset{(E)}{\frac{vkm}{pkm}} \cdot \underset{(F)}{\frac{m_{CO2}}{vkm}}$$

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

The focus is on direct tailpipe CO_2 emissions – no indirect emissions (related to infrastructure construction and maintenance), emissions in the vehicle life cycle or emissions shifted to the energy sector (e.g. through electrification) are considered in the above equation (refer to the SCCER Mobility report "Towards an Energy Efficient and Climate Compatible Future Swiss Transportation System" for a more extensive representation).

The emissions of mobility are a matter of energy efficiency and demographic growth. Using the Kaya-type we can decomposes the trend in CO2 on an aggregated national level in different driving factors. Those factors can be categorized in three groups, namely socio-economic factors, demand-driving factors and vehicle design (and technology) factors.

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

2.3 Expected evolution and the necessity for a change

To estimate the future evolution of the energy system based on political guidance, the government instructed Prognos AG to produce a report - the Energy Perspectives 2050 (Prognos, Die Energieperspektiven für die Schweiz bis 2050, 2012). It consist of three scenarios between 2010 and 2050, showing different paths. The target scenario NEP (new energy policy) is the most optimistic reduction scenario. The Energy Perspectives 2050 consider the entire energy system, with the mobility sector as one part within it. Transportation demand is based on the ARE transportation perspectives (ARE, Ergänzungen zu den schweizerischen

Verkehrsperspektiven bis 2030, 2012) while Infras was responsible for modelling the vehicle technology evolution.

The NEP scenario can be decomposed in the drivers of the Kaya-type equation and directly compared to the CO2 reduction target[1]. For a leaner illustration, the Kaya-type equation can be further simplified by looking at the transport system consisting of a demand and a supply side. The former represents the requested services, i.e. the need to travel, while the latter provides a portfolio of options how this service can be performed. This view separates the technological and non-technological aspects of the mobility system and can be expressed as follows.

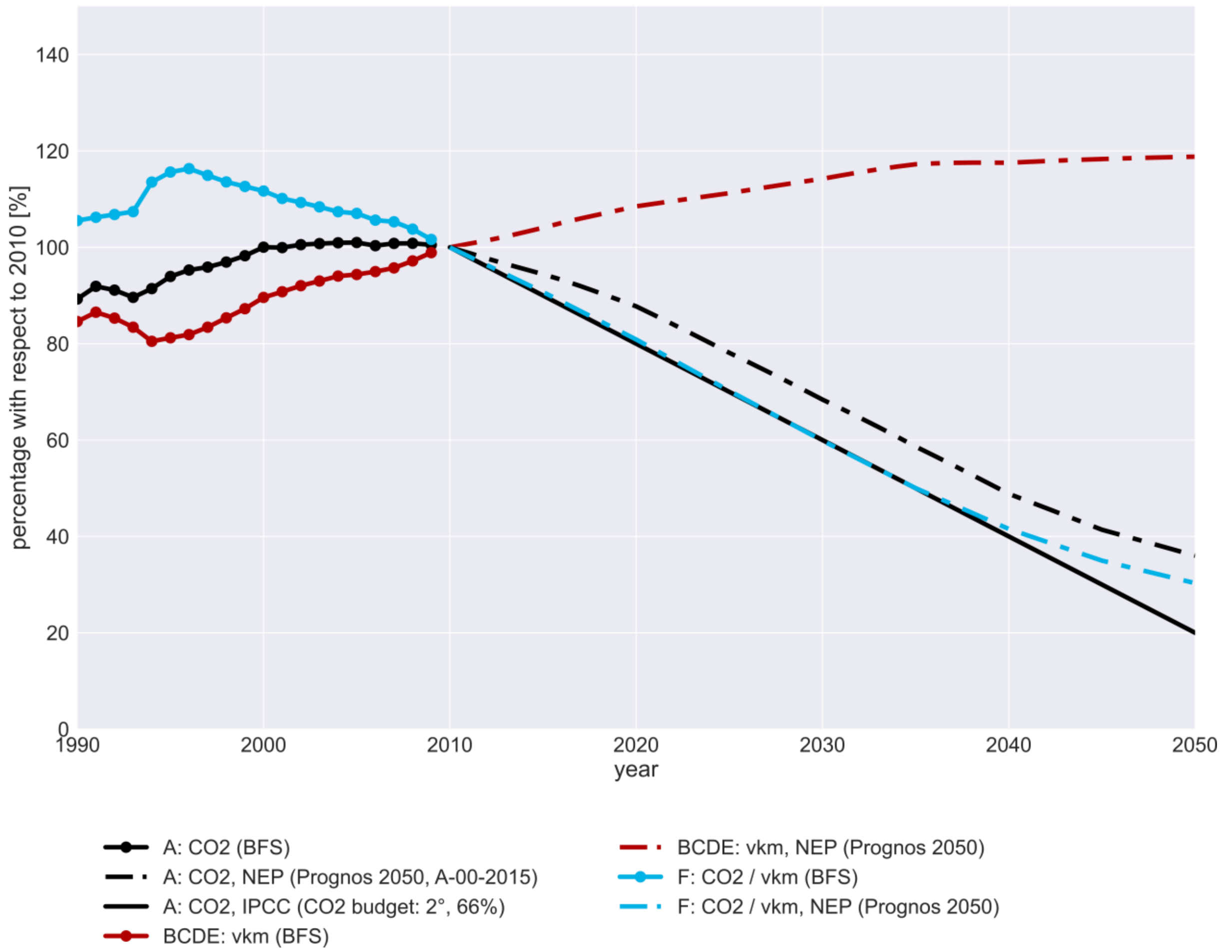
$$\underbrace{m_{CO2}|_{a,direct}}_{(A)} = \underbrace{vkm}_{(BCDE)} \cdot \underbrace{\frac{m_{CO2}}{vkm}}_{(F)}$$

Figure 2 illustrates the trends of terms (A), (BCDE) and (F) for passenger cars and the CO2 reduction target (see section 2.1). Data prior 2010 are taken from the federal office of statistic, while the future data represents the NEP scenario.

To achieve zero emissions, one factor (BCDE or F) must go to zero. Since the demand never goes to zero, the only solution is the supply side, i.e. vehicle design and technological measures. The reduction is thus driven by the technological improvement of the passenger car fleet. Nevertheless, demand measures are important in the transition period (to ensure a linear decrease – see Figure 1); since their aim is a more efficient use of existing infrastructures, they can often be implemented faster (technology options need to diffuse into the fleet, which can take decades). As can be seen in Figure 2, the NEP scenario implies a severe reduction in CO2, but is insufficient to achieve the target (black lines in Figure 2). Additional measures are needed to achieve the 2° C target. Note that Figure 2 only depicts the mobility sector, which is not isolated from the energy system. Changing propulsion technologies decarbonizes the transportation sector, but shifts the burden to the energy provision chain.

[1] Prognos Energy Perspectives 2050 are based on the reference population scenarios of 2010 (A-00-2010), which is significantly lower than the 2015 scenario (A-00-2015). For the representation with the Kaya-type equation, the 2015 scenario was used.

Figure 2 Illustration of the demand and supply side drivers, normalized to 2010. Past evolution based on federal statistics data and future trends based on the NEP scenario of the Energy Perspectives 2050, completed by the CO2 reduction target derived from the IPCC 2°C (66% probability) budget.



2.4 How to achieve the target?

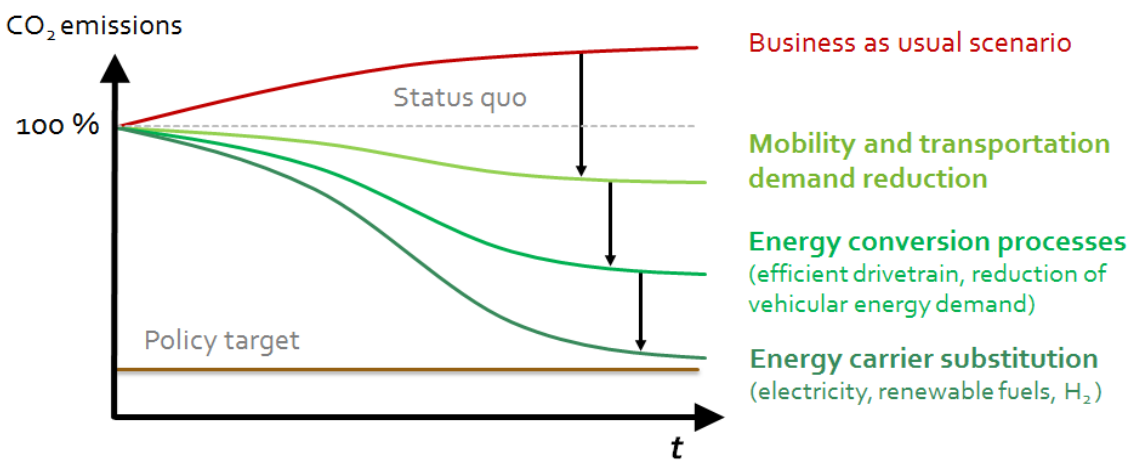
As discussed in section 2.3, the actions of the NEP are insufficient to achieve the CO2 targets set forth in section 2.1. To reach the policy target, three different levers exist, which can be identified in the Kaya-type equation (see Figure 3):

1. Reducing the demand for mobility: there are essentially two routes: efficiency and sufficiency. Sufficiency aims at reducing the demand for mobility, e.g. through subsidies, pricing or urban planning. Efficiency aims at improving the usage of the existing infrastructures, e.g. by incentivizing users to use less CO2-intensive modes

where possible or share rides. Since much of this is a matter of informing customers, novel communication technologies may enable rapid deployment.

2. Minimizing vehicular energy demand: independently of powertrain technology, there are a host of optimization potentials in the way vehicles are built, ranging from aerodynamics over tires to the heating and air conditioning system. These also work with existing, conventional propulsion systems and can be deployed at the speed that new vehicles diffuse into the fleet.
3. Energy carrier substitution: since oil is the root of passenger car's sustainability issues, substituting it by other energy vectors can effectively set emissions to zero. However, this implies different powertrain technologies, as well as the installation of new energy infrastructures (such as hydrogen fuel stations and electric charging poles). Because of the latter, deployment may take decades.

Figure 3 A qualitative systemic approach towards minimization of CO2-emissions from transport must use synergetic efforts on the demand and supply sides



3. Simulation of Demand and Supply

3.1 Methodology

The used model is an energetic model, consisting of a demand and a supply (vehicle) part, linked to the energy system by standardized energy carriers, e.g. gasoline, diesel, CNG, etc. It describes the end-energy demand and ensuing operational CO_2 emissions (not of an LCA) of the road-based Swiss transportation system and is based on statistical data of the government. The demand for private transportation is covered by the survey *Mikrozensus Mobilität und Verkehr 2010* (MZMV 2010). This survey contains a representative set of vehicle usage profiles and information about the used vehicles. The missing vehicle specifications for the energy demand computation follow from distributions derived from the MOFIS register, i.e. the database of all matriculated vehicles in Switzerland. It is worth stating that the set of all considered vehicles – the fleet – resembles the actual Swiss fleet, i.e. is composed by individual and not categorized vehicles. The conversion of traction energy to end energy demand (fuel energy) of the individual vehicles is carried out by using standardized driving cycles and a linear conversion model, the so called Willans-line. This model originates from the physical description of energy converters, and bases on vehicle measurements of EMPA (Christian Bach, 2011).

The model we apply is still under development, but it can already be used to evaluate some example interventions, which will be discussed below. The term "intervention" implies a one-at-a-time modification of the transportation system at the reference state – the status-quo – as it is defined by the MZMV data of 2010 (latest release). At this stage, no predictions into the future are possible nor are any realistic diffusion rates of a technology or social effect covered. Each intervention is carried out independently and to their maximum application, resulting in a maximum reduction potential. Rebound effects are not part of the model and thus not considered in the results. The electricity production mix is presumed invariant at today's level, regardless of the additional electricity demand – which is the only cost function. The utilized electricity mix is assumed to be the Swiss consumer mix of 2010, set to 111.3 gCO2 per kWh (Steubling, Zah, Waeger, & Ludwig, 2010).

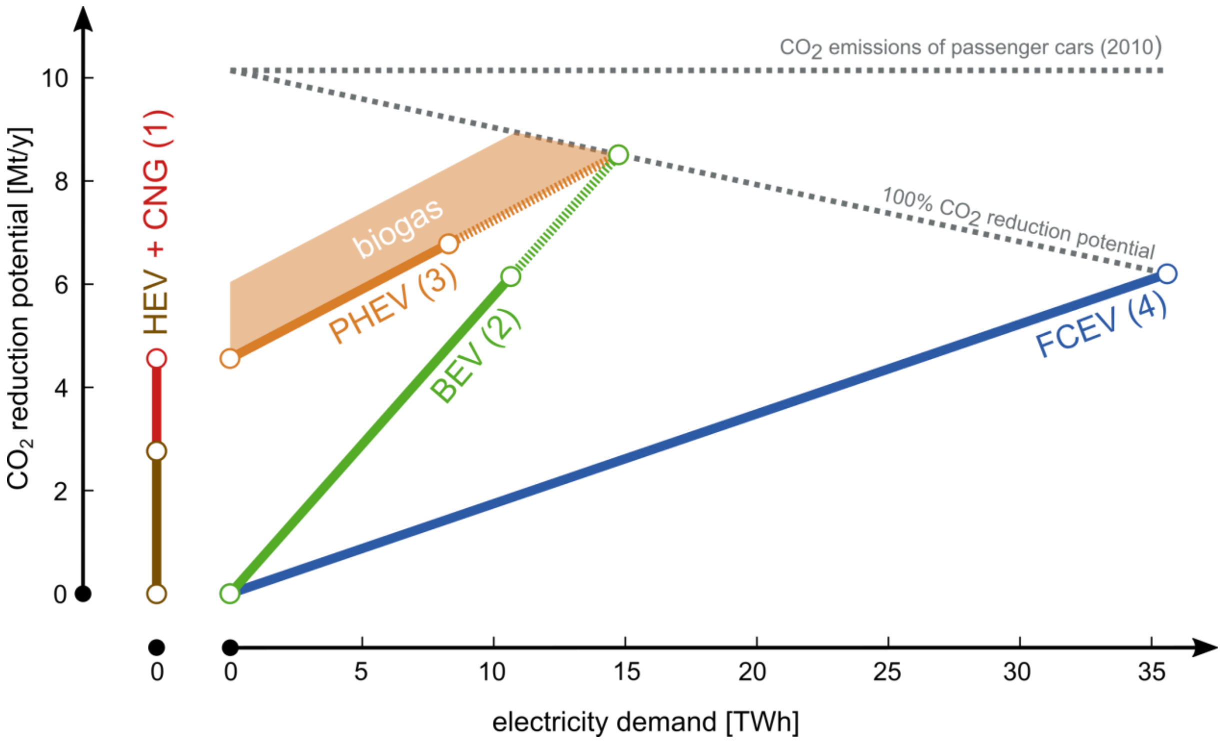
3.2 Results

Figure 4 illustrates results in mass of CO2 reduction for passenger car transportation. Each separate numbered line stands for an intervention, which can be related to a modification of the supply term of the Kaya-type equation. All shown interventions are affecting the vehicle technology and/or the used fuel carrier.

1. **Hybridization and fuel switch:**
   Hybridization of the entire passenger car fleet increases powertrain conversion efficiency (neglecting increase in vehicle mass). Switching the energy carrier from gasoline and diesel to CNG could increase the maximum reduction potential to roughly 4.5 Mt of CO_2. No additional electricity demand is required, since hybrid-electric vehicles only operate on hydrocarbons.
2. **Battery electric vehicles:**
   Starting from the current Swiss fleet, battery electric cars are introduced where they are capable of providing the demanded mobility service (according to MZMV 2010). Current battery technology is deemed able of providing 100 km autonomy range (neglecting change in vehicle mass, but including cabin heating). It is important to understand that in this intervention not the entire fleet can be substituted by battery electric vehicles, but only where they are applicable. The increased powertrain efficiency is the main driver for the CO_2 reduction. Additional electric energy is required, which dependent on the electricity mix and infrastructure losses will lower the CO_2 reduction potential. A charging infrastructure allowing to cover a larger daily distance without modifying the vehicle (same battery size) can shift the maximum reduction potential further along the dashed line towards the 100 percent limit.
3. **Plug-in Hybrid Electric vehicles:**
   By increasing the battery capacity of the HEV fleet of intervention 1 (starting point) and allowing them to charge their battery at the electricity grid, an additional degree of freedom is introduced, namely the choice of energy. It is assumed, that the entire fleet consists of plug-in hybrid electric vehicles with an all-electric range of 40 km (state of the art) and the increase in vehicle mass is neglected. Further increase of battery capacity as indicated by the dashed line converges towards the all battery electric vehicle fleet. Additional mitigation derives from substitution of CNG with the finite, national biogas supply (Steubling, Zah, Waeger, & Ludwig, 2010). It is assumed that half of the biogas supply is available to mobility, in analogy to the roughly 50% share mobility currently holds as a consumer of fossil fuels.
4. **Fuel-cell electric vehicles:**
   The substitution of the current ICEV fleet by state-of-the-art fuel cell electric vehicles (or technology) can provide the demanded mobility services (no concerns about range) with no local CO_2 emissions. Nevertheless, a large amount of additional electricity is required to produce hydrogen, which lowers the maximum CO_2 reduction potential. The vehicle powertrain efficiency increases compared to conventional ICEV. The illustrated CO_2 reduction potential is computed based on the hydrogen production with electrolysis using the current Swiss consumer mix. Further CO_2 reduction (based on

existing vehicle technology) can only occur by reducing the CO2 intensity of the electricity mix or by adopting a less energy intensive hydrogen supply.

Figure 4 CO2 mitigation potentials and additionally required electricity of different technology "interventions" for passenger transportation. All numbers are relative to the status-quo as of 2010; only operational CO2 is considered; all electricity production is presumed to have the same properties as the current Swiss consumer mix.



The results resemble maximum reduction potentials based on the current transportation sector (status-quo). Renewable energy storage, e.g. power-to-gas, are not considered. Neither are changes in the CO2 intensity of the Swiss consumer mix in time or due to increased demand. In general, there is no temporal dimension given.

We can see that state-of-the art technologies are already capable of reducing CO2 emissions. However, we have discussed “first-order” interventions, not pursuing further subsequent “second-order” effects, acceptance and policy measures enabling implementation of such interventions. In addition, we have so far explored only operational CO2 emissions and energy demand, not taking into account effects of invested (“grey”) energy and CO2 for hardware/ infrastructure.

4. Conclusions and outlook

To summarize, we translated the IPCC 2°C to a complete decarbonization of mobility in 2060. The NEP scenario, as by the federal government's energy perspectives 2050, does not achieve this target. Therefore, we explored hybridization and electrification using batteries and fuel cells as technological reduction paths. As seen in Figure 4, in 2010, an almost 90% reduction would be achievable through full electrification of the entire fleet (which is not yet possible due to insufficient range with current battery technologies – see section 3). This would be enough to be on track in the year 2050 according to our target. Next to technological improvements in battery and vehicle technology (to achieve the necessary autonomy range), this requires new energy infrastructures – and the CO2 intensity of the Swiss consumer mix must be kept constant at today's levels. However, we are talking about a net additional energy demand of roughly 14 TWh – which corresponds to almost ¼ of the total current Swiss electricity demand. The challenge for the energy provision sector is thus enormous, especially if considering that nuclear is to be phased out over the same period.

In this paper, we tried to give an impression of how our methodology combines the energy demand of vehicles with demand data and the energy provision sector, in the hope of prompting a discussion on the results and general approach. There are many aspects we could not discuss in detail; the most important being, that interventions can of course be combined. We are in the process of submitting a detailed journal publication, to which we refer the reader (2-3 months after the conference…).

As next steps, we are extending the analysis to road freight, where the challenges of electrification are even greater, due to the heavy weights and much more intense usage. In passenger transportation, we are extending our energy demand model to account for real-world conditions, which generally lead to a higher energy demand than under norm conditions due to e.g. weather influences and sub-optimal maintenance. Based on this, we model the interaction with the energy provision sector in greater detail, including bottlenecks in the electric grid, electricity imports and the need for additional generation capacity (resp. how existing assets are being operated differently).

5. Acknowledgment

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