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Economic impacts of decarbonizing the Swiss passenger transport sector*

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Abstract

Switzerland committed to achieving net-zero emissions in 2050. This goal is particularly ambitious for the Swiss passenger transport system, which emits more than one third of Swiss CO_2 emissions, and is not yet on a clear emission reduction path. We investigate the economic impact and the emission-saving potential of a decarbonization pathway for the Swiss transport sector based on three edge case scenarios and on a combination of them: (1) improved fuel/engine technology and fostered diffusion of battery electric vehicle, (2) increased capacity use of passenger cars, and (3) enhanced modal shift towards public transport. Our analysis is conducted using a multi-model framework, which interlinks a computational general equilibrium model with two external transportation models. This approach allows us to incorporate a highly disaggregated passenger transport system into the economic analysis. The framework is calibrated to Swiss data to assess the optimal scenario mix in terms of emissions and economic impact. The optimal decarbonization pathway mix slightly increases welfare and lowers CO_2 emissions of passenger transport in 2050 from 6 to 1.7 million tons CO_2 compared to the reference scenario. Despite the sharp reduction in emissions, a decarbonization pathway based on the considered scenarios is insufficient to reach the net-zero emission target.

Keywords: Passenger transport, Decarbonization, Switzerland, Computable general equilibrium model

JEL codes: C68, R40, R42, R48

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¶Modelworks

1 Introduction

By adhering to the Paris Agreement, Switzerland has set the goal of net-zero emission by 2050 in order to limit global warming below 1.5°C. Achieving this goal requires a substantial transformation of the whole Swiss economy and its energy system towards a massive reduction of energy demand and CO_2 emissions. Accounting for 40% of the Swiss CO_2 emissions in 2018, the transport sector plays a prominent role in the transition to a net-zero economy. Contrary to other sectors, the transportation sector is not yet on an emissions reduction path: While CO_2 emissions have been significantly reduced in most other sectors since 1990, they have increased by 3% in the transport sector (BAFU, 2020).[1] It is striking that, despite its great relevance, the political discussion started to shift towards specific measures and transformation paths for the transport sector in Switzerland only recently (see Bundesrat (2021) and BFE (2021)). Also, there has been surprisingly little research about the overall impacts of decarbonization scenarios on the transportation sector and the Swiss economy as a whole. This paper aims at filling this gap by analyzing different decarbonization scenarios for the Swiss passenger transport sector in terms of emission-savings potential and economic impact.

The decarbonization of the passenger transport sector depends, among others, on technological development and behavioral changes, as well as transportation policies. In this study, we focus on "ongoing" decarbonization scenarios, that induce gradual change in the economy over time until 2050.[2] For Switzerland, three ongoing scenarios of how to pursue decarbonization of the Swiss passenger transport system came into focus (see Zimmer et al. (2016)): (1) The technology and battery electric vehicle (BEV) diffusion scenario (TECHS), where increased fuel efficiency, motor vehicle efficiency and transport efficiency towards carbonless and carbon-free technologies, as well as a policy scheme favoring BEVs lead to a future with a majority of BEVs in the car stock, (2) the capacity use scenario (CAPU), where a behavioral change or low-cost governmental policies incentivize car- and ride-sharing, leading to a higher capacity use of passenger cars and (3) the modal shift scenario (SHIFTP), where a policy scheme fosters a modal shift towards public transport. Each scenario contributes differently to a green and sustainable transport system in a "non-transport" industrial country, such as Switzerland.[3] In accordance with the literature and experts, we set the values of the parameters in the scenarios to their upper limit reasonable for Switzerland, making them edge case scenarios. That allows us to perform a "potential analysis" of each scenario, meaning that we can evaluate their economic impact and emission-savings potential, to investigate whether Switzerland can rely on them to

[1]As an example, according to BAFU (2020), the CO_2 emissions of the industry sector decreased by 18% in the same period.

[2]We call them "ongoing" scenarios as they utilize market-based mechanisms, gradual technological improvements and behavioral changes following an "ongoing" approach over time. In contrast, measures such as bans for internal combustion engine vehicles have an abrupt impact.

[3]Switzerland has no strong production sector in the passenger car industry and is dependent on passenger car and fuel imports. The value-added chain of the railway industry (electricity production, rolling stock production), however, is relevant for Switzerland.

achieve net-zero emissions in 2050.

Analyzing the impact of these edge case scenarios requires a framework that combines the overall economy with the transport system in a disaggregated form. To account for that, we develop a multi-model approach, which relies on three different models: (1) a recursive dynamic CGE model for Switzerland capturing the economy as a whole; (2) a cohort model, which we use to compute the survival rate of specific passenger car categories (i.e. cars characterized by a given registration year, fuel type and power), as well as the demand for new passenger cars and (3) a choice model, that classifies the specific passenger car types (i.e. cars characterized by a given fuel type and power) entering the market in a given year. Interlinking the economic model (1) with the two external transport models (2 and 3) allows us to incorporate a highly disaggregated transport system into the economic analysis. Hence, our framework is suitable to compare alternative transport policies and rank them according to their impact on the economy, energy use, and CO_2 emissions. We calibrate our framework to Switzerland to evaluate the economic and emission-savings potential of a decarbonization pathway based on the three edge case scenarios. We first investigate the impact of the edge case scenarios separately. Our results show that, despite having a slightly positive impact on welfare and lowering emissions, none of the edge case scenarios can reach the net-zero target. Under TECHS, boosting BEVs decreases the CO_2 emissions from passenger transport by 45.7% relative to the business-as-usual scenario (BAU) in 2050 to 3.2 million tons. An increase in the capacity use of cars in CAPU reduces the CO_2 emissions from passenger transport by 25.7% to 4.4 million tons. Incentivizing people to rely more on public transport as in SHIFTP results in a decrease by 22.7% to 4.6 million tons CO_2 in 2050. That makes TECHS the most promising edge case scenario in reducing the CO_2 emissions. The reductions of the individual edge case scenarios are, however, not sufficient to achieve the net-zero target. Thus, we use our framework to analyze different combinations of all measures used in the scenarios and to evaluate their optimal mix in terms of reducing emissions. In that case, CO_2 emissions of passenger transport can be decreased substantially by 71.3% relative to BAU in 2050 to 1.7 million tons CO_2, which is, however, not sufficient to reach the net-zero target of Switzerland. Therefore, we conclude that an ongoing decarbonization pathway with realistic assumptions on gradual technological change, policy measures, and behavioral changes can not be relied on to achieve this target. An explanation for that is that a passenger vehicle stays in the market more than ten years on average, and its specific vehicle type can survive up to 28 years. Thus, pursuing the net-zero emissions target might require immediate action having an abrupt impact in the short term. This time pressure prevents Switzerland to successfully follow a smooth decarbonization pathway of the passenger transport system.

1.1 Relation to the literature

Existing CGE models including the transport sector vary significantly in model structure, regional and sector aggregation, and in the representation of transport. In most cases, transport costs are calculated using an external transport model considering one, or perhaps two modes of transport. Different to that and closer to our framework are bottom-up models with specific transport technologies. In these type of modeling structure the transport costs are calculated within the model, as in the MIT-EPPA model developed by Schaefer and Jacoby (2005) and Schaefer and Jacoby (2006). These models have, however, the disadvantage of being highly aggregated (the EPPA model, for example, contains only 11 production sectors).

Another strand of the literature analyzing the transport sector uses spatial network models, which allow to study important issues like congestion, but are not very tractable with regard to transport impacts because of the high-dimensionality of the network (Kim et al., 2004; Venables, 2004; Kim et al., 2011; Bröcker and Korzhenevych, 2013). Moreover, most of them have a highly aggregated transport sector. All the studies mentioned above deal with infrastructure proposals or optimal pricing scenarios (Wickart et al., 2002).

A recent paper by Thalmann and Vielle (2019) also looked at the decarbonization of the transport sector in Switzerland. They use a CGE model to study the impact of different tax strategies regarding transportation fuel on emissions and the economy. The model introduced here differs in two key aspects. First, Thalmann and Vielle (2019) implement the transport system directly in a CGE model, whereas we interlink a CGE model with an external transport bottom-up model for passenger cars. Our approach allows us to disaggregate the transport system into greater detail, which is essential to capture the full impact of transport policies. Second, the model of Thalmann and Vielle (2019) contains 11 sectors, of which five are energy- and three are transport sectors. In contrast to them, we include 78 sectors in our model. This enables us to analyze the impact of transport policies more comprehensively, considering their sectoral effects.

The paper is organized as follows: Section 2 describes the theoretical framework adopted and details the various sub-models. In Section 3 we calibrate the model with data for Switzerland. Section 4 introduces three edge case scenarios and 5 presents the simulation results. Lastly, Section 6 concludes.

2 Theoretical framework

Our framework combines three different models, as outlined in Figure 1: (1) A recursive-dynamic, single-country CGE model for Switzerland calibrated on the energy- and transport-specific input-output table (IOT) for the year 2014 (CGE model); (2) A cohort model that categorizes all available passenger cars according to their category, i.e. registration year, fuel type and power (Cohort model); (3) A choice model, which is used to compute the demand for new passenger cars, that is, cars sold in a specific year, for the different passenger car type, i.e. fuel type and power (Choice Model). The model is solved using two loops. The inner loop is necessary to account for the non-simultaneous solution of the three models ("1"). Specifically, it allows us to incorporate the feedback effects between the demand for passenger cars and its composition derived in the bottom-up models and the economic variables in the CGE model. We use the outer loop to account for time in the model ("2").

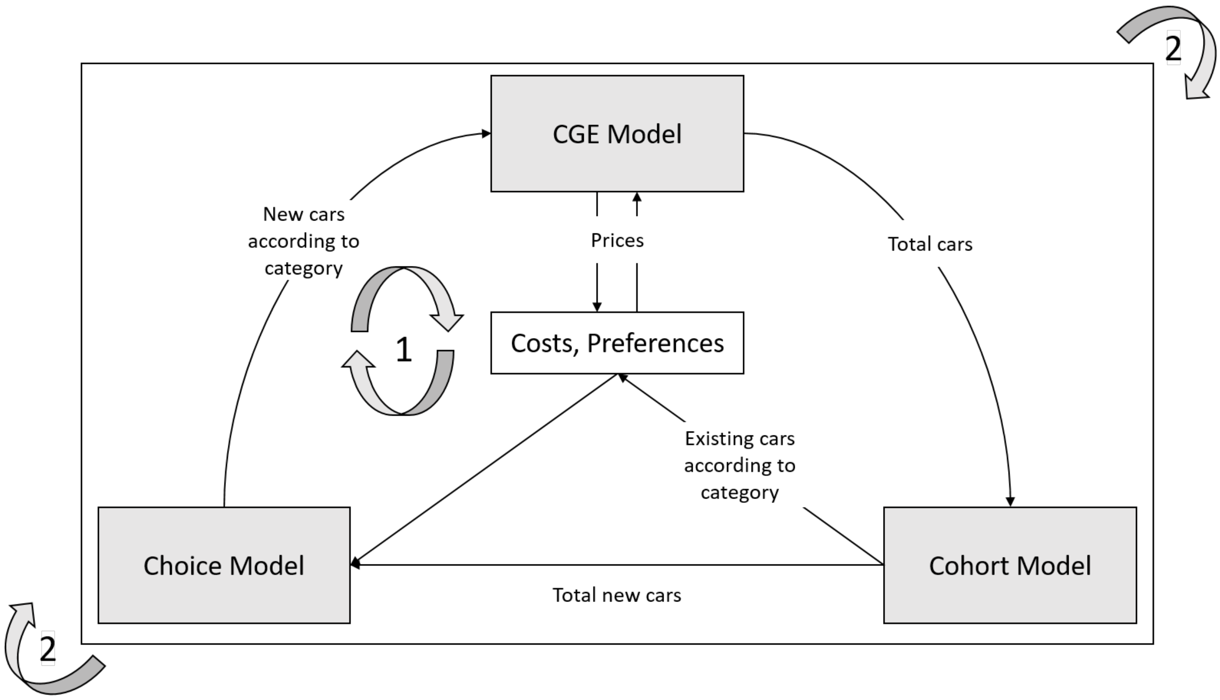


Figure 1 – Framework structure of our model.

The overall functioning of the model is as follows: We first use a regression model including population growth to obtain the total number of passenger cars for the current year. Next, we make an assumption about the number of passenger cars of each type (i.e. fuel type and power) entering the market. This information allows us to solve the CGE model completely and thus to derive the prices that realize in the economy, including the prices for new passenger cars.

The total number of passenger cars obtained from the regression model then serves as an input for the cohort model, where we use an age-function for passenger cars to compute the stock of surviving cars that were already in the market in the previous year. Subtracting the surviving cars from the total number of passenger cars allows us to calculate the total demand for new passenger cars.

The demand for new passenger cars together with the prices obtained from the CGE model enter then the choice model, which allows to derive the number of new passenger cars according to fuel type and power. Next, we check whether the output of the choice model coincide with the initial assumption on passenger cars type entering the market in the CGE model. If not, we re-calibrate the CGE model accordingly and execute the first loop again. This inner loop is repeated until the model converges, i.e. the difference in the number of new cars for each type is less than ten cars. Once convergence is achieved, we update the stock of passenger cars using the regression model, and move to the outer loop, where the model is re-calibrated for the next time period. We use the savings/investments of the consumers from the previous year to calculate the new capital stock. Moreover, we update the values for the working force and use the projected autonomous energy efficiency increase to re-calibrate the energy demand and use. After these adjustments, we move back to the inner loop and solve the CGE model for the next year. In what follows, we describe in greater detail the three models of our framework.

2.1 CGE model

The first building block of our framework is a CGE model for Switzerland, which follows an Arrow-Debreu type of framework and captures the behavior of supply, demand and prices in the whole economy, allowing for several interacting agents and markets. Moreover, the model depicts the interaction with the rest of the world through import and export. The driving factors for an equilibrium are the following three assumptions on the behavior of the producers and consumers, together with the requirement of non-negative prices: First, each consumer maximizes utility taking prices as given and under the assumption of a balanced budget. Second, producers maximize their profits (or minimize their costs), given their production technology. Third, supply at least covers demand in each market.

2.1.1 Consumers and Government

Consumers in our model are a representative household and the government. They maximize welfare in the form of a hierarchical CES utility function as shown in Figure 2.

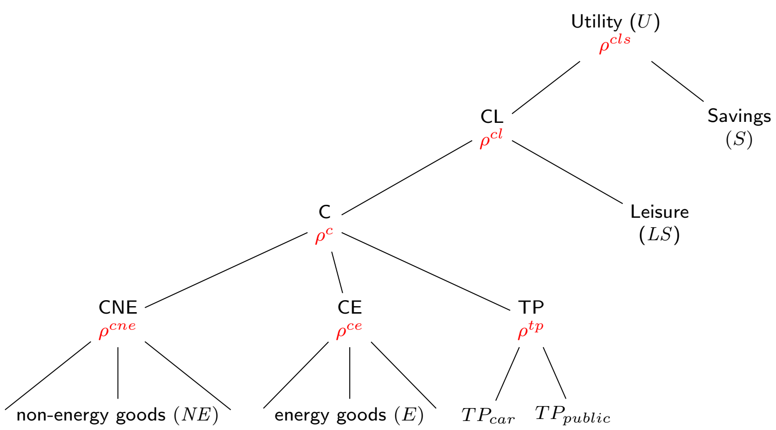


Figure 2 – Utility function with substitution parameters (ρ) for each nest.

For each nest of the utility function, the elasticity of substitution captures the responsiveness of demand for the good in each nest to relative price changes.[4] At the lowest level of the hierarchy, the consumer decides on the composition of a bundle of non-energy CNE, energy goods NE and private transport TP. The parameters ρ^{cne}, ρ^{ne} and ρ^{tp} capture the substitution parameters within the various energy, non-energy and transport goods, respectively.[5] These three bundles build a composite consumption good C, according to the substitution parameter ρ^c that, at the next level, is combined with leisure LS. At the top level, the composite of consumption and leisure is combined with savings S, providing overall welfare. The parameters ρ^{cl} and ρ^{cls} capture the substitution between consumption and leisure, and between the consumption-leisure bundle and savings, respectively. The utility function of the government does not contain leisure and savings. Moreover, the saving share of the government is fixed.

Assumption 2.1 (Utility function)**.** *The utility function of consumers is given by*

$$U = \left\{ \theta^{cls} \left[\left(\theta^{cl} C^{\rho^{cl}} + (1-\theta^{cl}) LS^{\rho^{cl}} \right)^{\frac{1}{\rho^{cl}}} \right]^{\rho^{cls}} + (1-\theta^{cls}) S^{\rho^{cls}} \right\}^{\frac{1}{\rho^{cls}}}, \tag{1}$$

where θ^{cls} captures the value shares of the consumption-leisure composite and of savings in total utility and θ^{cl} the relative importance of consumption and leisure in the consumption-leisure bundle.

Composite consumption of non-energy, energy and transport goods C is also assumed to follow a CES aggregation.

Assumption 2.2 (Composite consumption)**.** *Composite consumption is given by*

$$C = \left[\theta^c CNE^{\rho^c} + \theta^{ce} CE^{\rho^c} + (1-\theta^c-\theta^{ce}) TP^{\rho^c} \right]^{\frac{1}{\rho^c}}, \tag{2}$$

where θ^c represents the value shares of non-energy consumption and θ^{ce} the value share of energy consumption.

Consumption of non-energy good is obtained as

$$CNE = \left(\sum_{ne} \theta^{ne}_{ne} (X^c_{ne})^{\rho_{cne}} \right)^{\frac{1}{\rho^{cne}}},$$

where X^c_{ne} are non-energy goods and θ^{ne}_{ne} is the value share of each individual good in non-energy

[4] The goods are perfect substitutes when the substitution elasticity approaches infinity and perfect complements when it approaches zero.

[5] The elasticity of substitution σ is given by $\frac{1}{1-\rho}$.

good consumption. Similarly, consumption of energy goods reads

$$CE = \left(\sum_e \theta_e^e (E_e^c)^{\rho_{ce}} \right)^{\frac{1}{\rho^{ce}}},$$

where E_e^c are energy goods and θ_e^e is the value share of each individual good in energy good consumption. We consider the transportation good TP as the distance an individual wants to travel with passenger cars given its endowments. In our framework, we separate the cost of private transport into variable costs, PC_{vc}, and fixed costs, PC_{fc}. The fixed costs, which are the annualized cost of having a car, enter the CGE model as negative endowments. Total transport is given by

$$TP = \left[\theta^{pr} \, TP_{car}{}^{\rho^{tp}} + (1 - \theta^{pr}) \, TP_{public}{}^{\rho^{tp}} \right]^{\frac{1}{\rho^{tp}}}, \tag{3}$$

where TP_{car} is the distance covered with the passenger car at the expense of PC_{vc} per kilometer and TP_{public} the distance covered with public transport. The parameter θ^{pr} captures the share value of private transportation and ρ^{tp} represents the substitution parameter between private and public transport. In this framework, the variable costs appear in the utility function and reflect the decision of the consumer to drive fewer or more kilometers with the car. In addition to that, the number of passenger cars influences the total number of kilometers driven by passenger cars in the economy. To calculate the number of passenger cars, we use a regression model regressing them on the population projection for Switzerland (see Appendix A.1). In Section 2.2 and 2.3, we derive the number of new passenger cars, their type, and the variable and fixed costs.

The income for the representative agent is defined by

$$I^{RA} = w(\overline{L} - LS) + rK + TR - T^{RA} - PR_{fc}, \tag{4}$$

where $\overline{L}$ is the time endowment, LS the demand for leisure, r the rental price of capital endowment K, T^{RA} represents tax expenditures and TR are transfers. The income for the government is given by

$$I^{Gov} = T^{RA} + T^{CP} - TR, \tag{5}$$

where T^{CP} are the taxes on consumption and production. The labor endowment of the government (and therefore its leisure demand in the utility function) is zero.[6] The behaviour of the representative consumer and the government in the model is now explicitly described by the maximization of the utility function (Equations (1) and (2)) subject to their respective income constraints (Equations (4) and (5)).

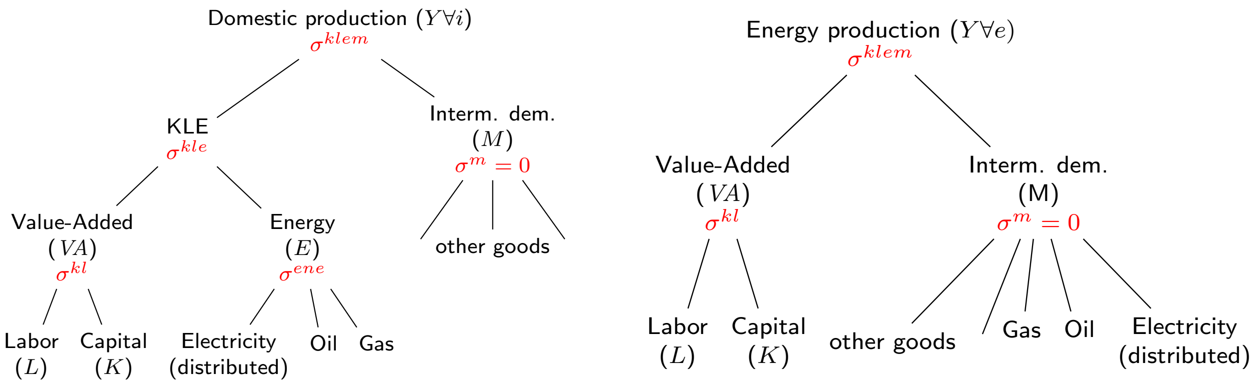
[6]Note, that people working for the government in sectors like public transport are private persons and their labor endowment is part of the endowment of the representative agent.

Besides the income constraint, the government is also not allowed to change its growth- and population adjusted deficit ("equal-yield constraint"). A lump-sum tax/transfer is used to keep the adjusted deficit unchanged.

2.1.2 Producers

Each producer maximizes profits, for each good $j \in N$. Under perfect competition, the producer takes the prices of outputs and inputs as given. We formulate the production technology as a nested CES function as shown in Figure 3. We make a distinction between non-energy (indexed over i) and energy sectors (indexed over e). In the non-energy sectors, substitution between energy E and value-added VA (capital and labor bundle) is allowed. Energy producing sectors can not substitute the energy input with other inputs to keep the link between the quantity of energy input and output constant.[7]

We follow van der Werf (2008) in the choice of the substitution possibilities between capital K, labor L, energy E and intermediate demand M. The author estimates and compares the substitution elasticities of six industrial sectors for several nesting structures KE-L, KL-E, KLE and finds the highest statistical significance for the elasticities of the KL-E structure. The substitution elasticity in the intermediate nest, σ^m, is set to 0, which is common practice in applied CGE work.[8]



(a) Production sector (not energy sector)

(b) Energy production sector

Figure 3 – Domestic production function.

[7]This formulation excludes that, for example, the input of nuclear fuels can be reduced to a minimum by substituting it for capital.

[8]A substitution elasticity of zero implies complementary goods: cars need four wheels. However, one reason for setting this value to zero, was the reduction of the complexity of the model in times when computer power was an issue.

Assumption 2.3 (Production of non-energy sectors)**.** *The production function for the non-energy sector i can be written as*

$$Y_i = \left\{ \theta_i^{kle} \left[\left(\theta_i^{va} VA^{\rho_i^{kle}} + (1-\theta_i^{va}) E_i^{\rho_i^{kle}} \right)^{\frac{1}{\rho_i^{kle}}} \right]^{\rho_i^{klem}} + (1-\theta_i^{kle}) \left(\min_j M_{ji} \right)^{\rho_i^{klem}} \right\}^{\frac{1}{\rho_i^{klem}}}, \tag{6}$$

where M_{ji} is the intermediate demand of sector i. The parameter θ_i^{kle} represents the value share of the composite KLE in non-energy production and θ_i^{va} the value share of value-added in the KLE composite. ρ_i^{kle} is the substitution parameter for the KLE nest and ρ_i^{klem} the substitution parameter of the top nest.

The value-added subnest of the production function is given by

$$VA_i = \left[\theta_i^k K_i^{\rho_i^{kl}} + (1-\theta_i^k) L_i^{\rho_i^{kl}} \right]^{\frac{1}{\rho_i^{kl}}}, \tag{7}$$

where K_i represents capital services and L_i is labor. The parameter θ_i^k captures the value share of capital and ρ_i^{kl} is the substitution parameter for the KL nest. The composite good of energy inputs E is, in turn, defined as

$$E_i = \left[\sum_e \theta_{ei}^{ene} E_{ei}^{\rho^{ene_i}} \right]^{\frac{1}{\rho^{ene_i}}}, \tag{8}$$

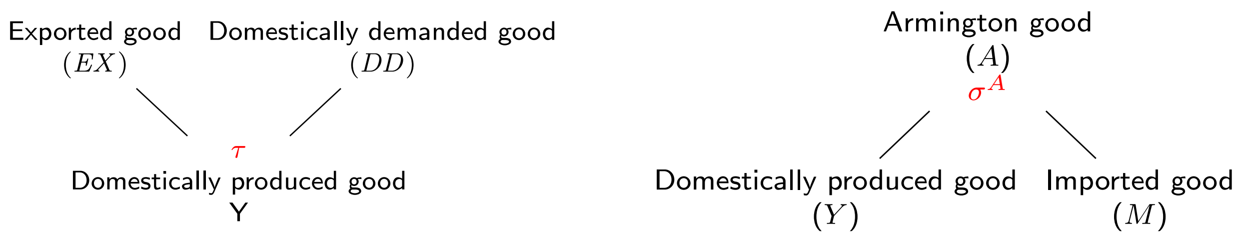
where E_{ei} is the specific energy good input (like gas, oil, etc) in sector i and θ_{ei}^{ene} is its share value. The parameter ρ^{ene_i} is the substitution parameter of the energy nest. In our model, energy can be produced using several technologies (nuclear, hydro, etc.). Each technology s is modeled as a Leontief-function

$$ELE_s = \min\left(L_s, K_s, E_{es}, X_{is}\right), \tag{9}$$

where ELE_s is the technology s producing energy and E_{es} is the energy good input used by technology s. The relative costs of the technologies and the available capacity determine the production mix. The producer behavior can explicitly be described as the maximization of profits given the production function as defined in equations (6), (7), (8) and (9).

2.1.3 International trade

In our model, sectoral output is transformed into goods produced for the domestic market and exports (see Panel (a) in Figure 4). Goods for the domestic market are a composite of imports and domestically produced goods, the so-called Armington good (see Panel (b) in Figure 4). The producer uses the domestically produced goods for domestic supply and exports to maximize



(a) Exports

(b) Imports

Figure 4 – Illustration of the treatment of imports (Armington) and exports.

its profits given the transformation function

$$\max \Pi_i = P_i^E EX_i + P_i^D DD_i - P_i^A A_i, \tag{10}$$

where P_i^E is the price of exported goods EX_i, P_i^D is the price for domestically demanded goods DD_i and P_i^A is the price of the Armington good A_i. The transformation technology for domestically produced goods follows a CES structure.

Assumption 2.4 (Domestically produced goods)**.** *Domestically produced goods follow the transformation function*

$$Y_i = \left[\theta_i^E EX_i^{\psi_i} + (1-\theta_i^E) DD_i^{\psi_i}\right]^{\frac{1}{\psi_i}}, \tag{11}$$

where θ^E capture the value shares of exported good and ψ_i is the transformation parameter (with $\psi = (\tau - 1)/\tau$ where tau is transformation elasticity).

We consider imports as imperfect substitutes for similar domestically produced goods to allow for cross hauling (importing and exporting the same kind of good). Hence, we replace the domestic consumption by an (Armington) function which converts imported and domestically produced goods into a composite good (Armington, 1969).

Assumption 2.5 (Imported goods)**.** *Imported goods are defined by the transformation function*

$$A_i = \left[\theta_i^D Y_i^{\rho_i^a} + (1-\theta_i^D) IM_i^{\rho_i^a}\right]^{\frac{1}{\rho^a{}_i}}, \tag{12}$$

where IM_i is the import good, θ^D capture the value shares of domestically produced and ρ_i^a is the transformation parameter (with $\rho^A = (\sigma^A - \sigma^A)/\tau$ where σ^A is the substitution elasticity).

We treat Switzerland as a small, open economy; hence, the world market prices for goods and services are taken as given. The domestic prices P_i^E (P^{IM_i}) for exports EX_i (imports IM_i) are given by

$$P_i^E = PFX\overline{P}_i^{E_w} \quad \text{and} \quad P_i^{IM} = PFX\overline{P}_i^{IM_w}, \tag{13}$$

where PFX is the exchange rate, and $P_i^{E_w}$ ($P_i^{IM_w}$) the world market price for exported (imported) goods in foreign currencies.

2.1.4 Market Clearing

The third set of conditions for a general equilibrium demands that supply should cover demand in each market (note that this also includes the case of excess supply resulting in a zero price). The CGE model contains market clearing conditions for the factors (labor, capital), and produced goods (Armington goods, domestically produced goods and an investment good, i.e. a composite of the demand in the IOT for investments).

The market-clearing conditions for the factor markets (labor L and capital K) are given by

$$\sum_i L_i = \overline{L} - LS \text{ and } \sum_i K_i = \overline{K}, \tag{14}$$

while the market-clearing conditions for the domestically produced and the Armington goods are given by:

$$Y_i = DD_i + EX_i, \text{ and } A_i = \sum_j M_{ij} + X_i^c + X_i^g + X_i^{inv}, \tag{15}$$

for the non-energy goods and

$$Y_e^E = DD_e + EX_e, \text{ and } A_e = \sum_j M_{ej} + E_e^c + E_e^g + X_e^{inv}, \tag{16}$$

where $X_i^{c/g}$ is the household/governmental demand for good i (non-energy goods), $E_e^{c/g}$ the demand for energy goods, and X_i^{inv} is the demand for good i in the investment function. In the last forty years, except for 1981 and 2008, Switzerland faced a current account surplus.[9] We assume that the surplus is fixed leading to the additional market clearing constraint

$$\sum_i \overline{P}_i^{E_w} EX_i + \overline{CA} = \sum_i \overline{P}_i^{M_w} M_i, \tag{17}$$

where $\overline{CA}$ is the level of the current account surplus. Additionally, the investment good INV is linked to the investment demand for sectoral goods by introducing a Leontief production function

$$INV_t = \min_i \left(X_i^{inv} \right), \tag{18}$$

where the market clearing for the investment good is given by the savings-investment equality

$$\frac{S}{P^{inv}} = INV. \tag{19}$$

[9] See https://tradingeconomics.com/switzerland/current-account, visited March 9, 2018.

Lastly, the market clearing function for the utility goods of the representative agent (RA) and the government (Gov) is given by

$$U = \frac{I^{RA}}{PU}, \text{ and } UG = \frac{I^{Gov}}{PUG}, \tag{20}$$

where PU and PUG are the prices of the utility good for the consumer and the government, respectively. The CGE model is set up and solved as a mixed-complementarity problem (MCP), as described in Appendix A.2.

2.1.5 Dynamics in the CGE model

There are several approaches to incorporate time in a CGE model. The prevalent methods are either Ramsey-type or recursive dynamics.[10] In the Ramsey setting, agents are assumed to have perfect foresight and decide at the beginning of the time horizon for all the following years. This approach is not feasible for this study due to the complexity of the solving process of our model. Therefore, we implement the recursive dynamic approach in which the agents do not form consistent expectations of future prices as their decisions are based on the actual information. Using a recursive dynamic framework, the CGE model and the bottom-up models can be solved and updated for the next year.

A key input variable for the implementation of recursive dynamics is the gross investment in the previous period. This variable is used to update the available capital stock with the capital movement equation

$$K_{t+1} = (1-\delta)K_t + I_t, \tag{21}$$

where the capital in the next period, K_{t+1}, is defined as the depreciated capital in the current period, K_t, plus the actual investments, I_t, where δ is the depreciation rate. Based on that, we can set up the maximization problem as

$$\begin{aligned} \max \mathcal{L}(K_t, I_t) = p_t \left(F_t(K_t) - I_t\right) - \lambda_t \left(K_t - (1-\delta)K_{t-1} - I_{t-1}\right) \\ - \lambda_{t+1} \left(K_{t+1} - (1-\delta)K_t - I_t\right), \end{aligned} \tag{22}$$

where $F_t(K_t)$ is the production function, p_t the price of the selling good, r the exogenous interest rate and λ can be interpreted as the marginal value or price of one capital unit. Solving Equation

[10] A third approach would be to endogenize growth using a Romer-type model (see for example Bretschger et al. (2011)).

(22) gives us

$$\frac{\partial \mathcal{L}}{\partial K_t} = p_t \frac{\partial F_t}{\partial K_t} - \lambda_t + (1-\delta)\lambda_{t+1} = 0 \tag{23}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_t} = K_{t+1} - (1-\delta)K_t - I_t = 0 \tag{24}$$

$$\frac{\partial \mathcal{L}}{\partial I_t} = -p_t + \lambda_{t+1} = 0. \tag{25}$$

Equation (23) tells us that the additional value in production of one additional unit of capital is equal to the additional cost of capital. This additional cost is equal to the cost of the investment of one unit of capital in the previous period minus the value of the remaining capital in the actual period.

Assuming a steady state, all the quantities grow at the rate γ and, as the interest rate is constant, the future price is given by

$$K_{t+1} = (1+\gamma)K_t \tag{26}$$

$$p_{t+1} = \frac{p_t}{1+r}. \tag{27}$$

Using Equations (25) and (26), the steady state condition for investment is given by

$$I_t = (\gamma + \delta)K_t. \tag{28}$$

2.2 Cohort model

The cohort model is used to simulate the number of passenger cars surviving each year. This is necessary to evaluate the inflow of passenger cars and the change in the composition of the stock. As the age of a passenger car is particularly relevant to determine its survival rate in the market, we estimate an age function for passenger cars, which tells us how passenger car presence in the market evolves depending on age.

To estimate the age-function for Switzerland, we use data from Bundesamt für Statistik (2019b) on the composition of the stock of passenger cars from 1990-2018. We obtain the share of passenger cars registered in a given year which are present in the stock of passenger cars at a particular year (e.g. we have the share of cars registered in 2011, which are present in the stock of 2012). The dataset provides the registration year aggregated into ranges of five years (cars registered in 2000-2004) for the period 1990-2010. From 2010 onwards, registrations are yearly. To get the best fit for our age-function, we apply a stepwise OLS estimation combined with a machine learning algorithm. We first use an OLS estimation of the original aggregated dataset. Next, we take the outcome of that estimation and apply it to the original dataset, which allows us to disaggregate the stock of passenger cars into yearly registration years for the entire time. Then, we take this manipulated dataset as input for another OLS estimation, which, applied to the manipulated dataset, updates the data again. We continue that approach until we reach convergence between the input and the output, meaning that we find the OLS estimation that does not change the manipulated data anymore. With this method, we compute the best fit for the age structure of passenger cars using a fourth-order polynomic function of age.

The results of our estimation are shown in Figure 5, which plots the passenger cars for each registration year against the age of the car. Notice that age equal to zero implies that the registration year is equal to the year in which the stock is computed.[11]

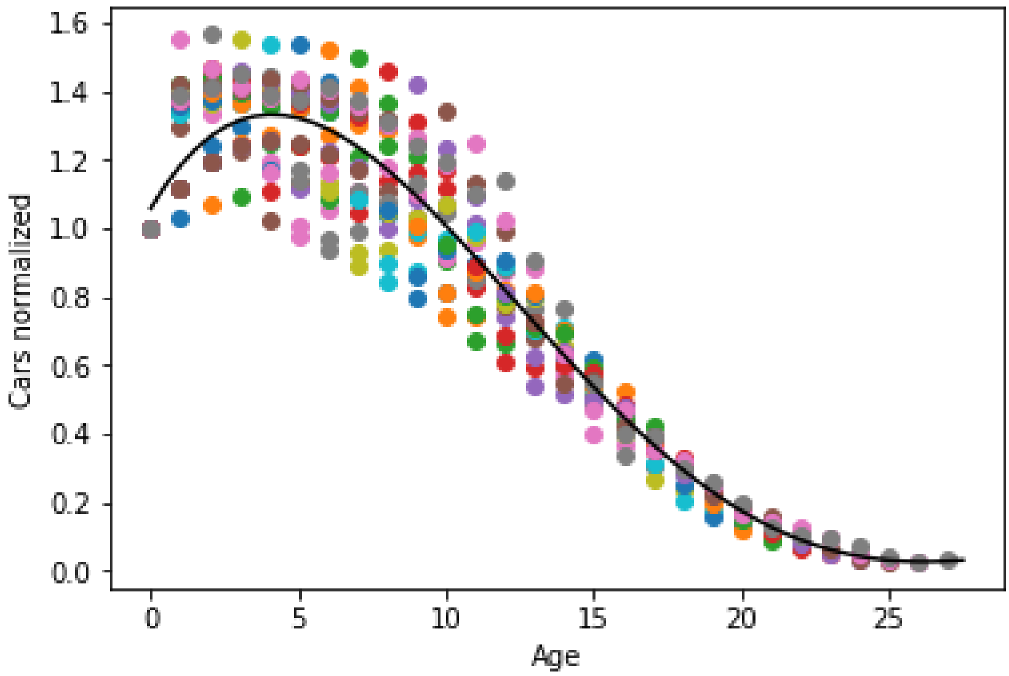


Figure 5 – Age-function.

Our basic assumption is that the age function is the same for all the registration years and thus identical across time. This function combined with the total passenger cars estimation allows us to compute the demand for new passenger cars, $Cars_{ay}^{new}$, according to

$$Cars_{ay}^{new} = Cars_{ay}^{est} - \sum_{y<ay,t} Cars_{y,ti}^{old}, \tag{29}$$

where $Cars_{ay}^{est}$ are the estimated total passenger cars in the actual year ay and $Cars_{y,t}^{old}$ are the passenger cars from type ti in year y.

[11]The bump in the age function can be explained by measurement issues and imports of passenger cars. First, data on registration are from January to December, whereas the stock is measured from September to September. This explains why in the subsequent year the number of passenger cars registered in a given year might be larger than in the registration year. Second, the stock can increase because of passenger cars registered in other countries, which enter the Swiss stock either because they are bought by Swiss residents or because of people moving to Switzerland together with their passenger cars. In both cases, passenger cars enter the stock in a given year but the registration year remains the original one. Supposedly, this happens for relatively young passenger cars as older passenger cars are less likely to be imported.

2.3 The Choice Model

Finally, the choice model is used to obtain the number of new passenger cars disaggregated according to 20 types in terms of fuel type and power. We include six fuel types: "Gasoline", "Diesel", "Gasoline-Electric", "Gas", "Electric", and "Fuel cell".[12] Each fuel type is further specified according to the power of the engine ("$< 60kW$", "60-100kW", "100-140kW", "$>$ 140kW"). In order to compute the endogenous shares of different passenger car types, we use a multi logit model. Our specification follows Rivers and Jaccard (2006), Jaccard (2009), and Mulholland et al. (2017). The market share algorithm uses capital costs CC, maintenance and operating costs MC, energy (fuel) costs EC, intangible costs perceived by consumers, ic, and the weighted time preference ω to calculate the market share θ_j of a passenger car type j in a given year when competing against Z passenger car types. Hence, we can write

$$\theta_j = \frac{\left(\frac{\omega}{1-(1+\omega)^{-n_j}} CC_j + MC_j + EC_j + ic_j\right)^{\nu}}{\sum_{z=1}^{Z} \left(\frac{\omega}{1-(1+\omega)^{-n_z}} CC_z + MC_z + EC_z + ic_z\right)^{\nu}}, \tag{30}$$

where n is the average life span of a passenger car type. The parameter ν captures the heterogeneity in the market and determines the shape of the inverse power function that allocates market share to technology. A low value results in an even distribution even if the life cycle costs of the different technologies differ widely. An infinite value (and ic equal to zero) leads to the cheapest technology capturing the whole market. Of particular interest for our analysis are intangible costs, which can explain the adoption of BEV and PHECV although being more expensive than ICEV. These costs capture general preferences of consumers, including, amongst others, hesitation toward new technologies (alternative-fueled vehicles), range anxiety due to uncertainty about the battery performance, or peer effects.

We solve for the intangible costs by calibrating the logit function to the known shares obtained from the data of passenger car technologies in the base year (2014). The choice model is a crucial element of the inner loop of our general framework: after being initialized, it uses the output of the two models solved beforehand to calculate the market shares per specific passenger car type. Then, we use this information as input for the CGE model to check whether its output differs from the CGE output in the previous iteration. If the difference is significant, we perform another run based on the updated market share information until we reach convergence.

[12] "Gasoline-electric" vehicles refer to the technology plug-in hybrid (PHEV) and "electric" vehicles to BEV.

3 Calibration

The models for the business-as-usual scenario (BAU) are calibrated to projections and actual data taken from several sources. The idea is to reproduce this data by adjusting parameters of the model (substitution elasticities, shares in the production and demand functions, etc.). Table 1 summarizes the most important input data and the sources required to calibrate the model.

In Table 2, we list the periodic output of the framework serving as input for the calibration of the next period (outer loop). Those data that are input from or sent to another model through an interface are noted with an asterisk (*) (inner loop). Inputs and outputs are all yearly and for Switzerland.

Table 1 – Data inputs

Inputs	**Unit**	**Source**
Input-Output-Table 2014	CHF	Nathani et al. (2019)
Macroeconomic data like GDP, etc.	CHF	Bundesamt für Statistik (2019a)
Elasticities		Various Sources
Energy inputs	Joules, kWh	Swiss Federal Office of Energy (2019) and Prognos (2012)
CO2-Emissions	Tonnes	Federal Office for the Environment (2019)
Population and employment	Full-time equivalents	Bundesamt für Statistik (2015)
Passenger car fleet according to registration year		Bundesamt für Statistik (2019b)
Passenger car costs	Total cost of ownership in CHF	Touring Club Switzerland (2019)
Kilometers per passenger car, capacity use per passenger car, motor efficiency		Various Sources

Table 2 – Periodic output

Output	**Units**
GDP, exports, imports, sectoral production	CHF
Consumption, investments/savings, tax revenue	CHF
Capital and labor input	CHF
Welfare	percentage change
Sectoral prices and production, cost indices*	indexed CHF
CO_2 price of permits and CO2 tax*	CHF
Fuel demand overall and car specific	TWh
CO2-Emissions	tonnes
Passenger car fleet	number of cars
Vehicle kilometers	km
Person kilometers	km
Public transport kilometers	km

In what follows, the data used for the calibration of the individual building block of the CGE model is described.

3.1 Consumption

The composite consumption good is defined over the available consumer goods categorized according to the divisions of the Classification of the Purposes of Non-Profit Institutions Serving Households (United Nations, 1999). These goods are listed in Table 9 in Appendix B.1.
In empirical work with CGE models, the elasticities for the nested utility function of consumers are mostly taken from econometric studies. Table 3 shows the values for the substitution elasticities adopted in this paper as well as the studies they are taken from.

Table 3 – Utility function: values for the substitution elasticities and their sources

Parameter	Value	Source
σ^{cls}	0.28	Havránek (2015)
σ^{cl}	0.7	Own calculations based on Jäntti et al. (2015)
σ^{c}	0.9	Own assumption
σ^{ce}	0.5	Papageorgiou et al. (2017)
σ^{cne}	0.9	Own assumption
σ^{tp}	0.8	Own calculation based on ARE (2016)

3.2 Production

Our CGE model contains over 70 sectors (see Table 10 in Appendix B.2) taken from the Swiss IOT. For each sector we focus on a representative producer. The electricity sector in the Swiss IOT is disaggregated in distribution and several generation technologies (CPA 40a-40d3 in Table 10 in Appendix B.2). The generated electricity serves as input in the distribution sector (CPA 40e). The relative costs of the technologies and the available capacity (taken from Swiss Energy Modelling Platform (2018) and Prognos (2012)) determine the production mix. Table 4 contains the values or range of the chosen sectoral elasticities for production and Table 5 for international trade.

Table 4 – Production: values for the substitution elasticities and their source

Parameter	Value or range	Source
σ_i^{klem}	0.11 - 1.15	Koesler and Schymura (2015)
σ_i^{kle}	0.09 - 1.27	Koesler and Schymura (2015)
σ_i^{kl}	0.06 - 3.36	Koesler and Schymura (2015)
σ^{ene}	0.5	Papageorgiou et al. (2017)
σ^{m}	0	Common practice in CGE modelling

Table 5 – International trade and Armington elasticities

Parameter	Value or range	Source
σ^A	1.2 - 8.0	Own calculations based on Imbs and Méjean (2010) and Lofgren and Cicowiez (2018)
τ	1.3 - 8.0	Own calculations based on Imbs and Méjean (2010) and Lofgren and Cicowiez (2018)

3.3 Private Transport

3.3.1 Calibration of total passenger cars and car shares

Private transport is calibrated according to projections developed in Infras (2019) until 2050. The main calibrated variables are the total passenger cars, the new passenger cars purchased, and the share of passenger cars according to fuel. Table 11 in Appendix B.3 presents the passenger car costs for the benchmark year.[13] Moreover, Table 12 and 13 in Appendix B.3 show the yearly change in these costs and the change in fuel efficiency per fuel type taken from Infras (2019). Using this information and the projection of the fleet mix in 2050 displayed in Table 6, the choice function (Equation (30)) is calibrated by solving for the intangible costs.[14] The procedure adopted to harmonize the cost information on passenger cars with the data from the IOT is described in Appendix B.4.

Table 6 – Projection of passenger car stock and fuel efficiency

Fleet mix (stock)	2014	2050
Gas	0.21%	2%
Gasoline	72.5%	33%
Gasoline-Electric	0.9%	6%
Diesel	26.28%	21%
Electric	0.11%	35%
Fuel cell	0%	3%

3.4 Dynamics

We calibrate the recursive model to a steady-state baseline equilibrium growth path. To do so, we use the fact that on a steady-state growth path, all quantities grow at the same steady-state rate γ. Thus, capital also grows according to

$$K_{t+1} = (1 + \gamma)K_t. \tag{31}$$

[13] Taken from https://www.tcs.ch/de/testberichte-ratgeber/ratgeber/fahrzeug-kaufen-verkaufen/autosuche-vergleich.php. The costs were slightly adjusted after discussions with experts.

[14] As our model does not follow a forecasting approach, we set the projections of the fleet mix close to the one of Infras (2019) and BFE (2021) in 2050. Some minor differences, however, exist due to the complexity of the model. We are aware of the difficulty predicting the development of the fast-changing BEV technology until 2050. Some projections expect a higher share of BEVs than we do in 2050, which, if they are moderate, do not substantially change our qualitative result.

We can now use Equations (21) and (31) and information from the IOT to calibrate the model to the given growth path. For Switzerland, we assume a steady-state growth rate of 1.5% (see Table 7 for the growth projections until 2050). The depreciation rate is calibrated in such a way that the investments reflect the investments according to the IOT.

This steady-state growth path does not consider the changes in the working population. Therefore, we use the projections on the working population to calculate the yearly percentage change γ_t^{WP}. The total GDP growth rate γ^{GDP} is now given by

$$\gamma_t^{GDP} = (1 + \gamma^{GDP/Cap})(1 + \gamma_t^{WP}) - 1. \tag{32}$$

We assume that government expenditure and the current account grow at the same growth rate as GDP. If governmental income falls below this level, a per-capita tax is raised (and a per-capita subsidy is paid in the opposite case). This ensures that the welfare effects of the implemented policies are not influenced by changes in the governmental budget.

The energy demand projections (electricity and fossil fuels) are shown in Table 7. The projection for electricity demand is growing at a slower rate than GDP. Total energy demand is falling and total employment remains almost the same for the next 35 years. To reach the given levels in the model, we adjust the technical progress for the energy goods to calibrate demand to the projections from Prognos (2012) using the technique developed in Böhringer et al. (2009).

Table 7 – Assumed projections for Swiss population, GDP and energy demand

Parameter	**2010**	**2020**	**2035**	**2050**	**Reference**
Population (million)	7.79	8.68	9.8	10.3	Scenario A-00-2015 from Bundesamt für Statistik (2015)
Working population (million full time equivalents)	3.853	4.31	4.58	4.63	Scenario A-00-2015 from Bundesamt für Statistik (2015)
GDP potential (relative to 2010)	1	1.18	1.43	1.66	Projections from Bundesamt für Statistik (2019a)
Energy demand (relative to 2010)	1	0.937	0.839	0.782	BAU (WWB) scenario from Prognos (2012) (p. 96)
Electricity demand (relative to 2010)	1	1.05	1.097	1.175	BAU (WWB) scenario from Prognos (2012) (p. 97)
Fossil energy demand by ETS sectors (relative to 2010)	1	0.858	0.621	0.388	Swiss Energy Modelling Platform (2018)

4 Edge Case Scenarios

In addition to the BAU, we study the impact on economic variables, energy usage and emissions under three edge case scenarios. Each scenario focuses on an alternative approach towards a decarbonization of the passenger transport system. Specifically, we include the following three scenarios: (1) The technology and BEV diffusion scenario (TECHS); (2) The capacity use scenario (CAPU); (3) The modal shift scenario (SHIFTP). For each scenario, we define the key parameters that differ from the BAU. In TECHS, we vary the fuel/engine efficiency of passenger cars and the share of BEVs in 2050. The latter is achieved thanks to subsidies designed such that they favor the diffusion of BEVs, as, for example, subsidies that improve the private and public charging infrastructure of Switzerland or decrease the costs of BEVs.[15] Those subsidies are financed by taxes on fossil fuel for passenger cars. CAPU includes behavioral changes towards a more prominent role of car- and ride-sharing, which increases the capacity use of passenger cars. In SHIFTP, we incorporate a policy scheme including subsidies for public transport, which leads to a change in the modal split towards this mean of transport. We set the parameters for the different scenarios to the upper bound of their range for Switzerland, in accordance with the literature and based on discussions with experts. Thus, we analyze edge case scenarios and draw results on their emission-savings potential and economic impact. Table 8 displays the underlying assumptions for the three edge case scenarios, where personal kilometers are denoted by pkm and the asterisk means model output. In what follows, we describe the three edge case scenarios more in detail.

[15] In what follows, I refer to those subsidies as "subsidy for BEVs".

Table 8 – Edge case scenarios

	BAU			TECHS		CAPU		SHIFTP		
Parameter	2014	2030	2050	2030	2050	2030	2050	2030	2050	Main Sources
Fleet mix (stock)										
Share of BEV	0%	17.83%*	35%	34.13%*	65%					Infras (2019)
Share of gas	0%	1.98%*	2%	1.36%*	1%					BFE (2021)
Share of gasoline and diesel	99%	68.77%*	54%	54.68%*	29%					
Share of PHEV and FCEV	1%	11.42%*	9%	9.83%*	5%					
Change in fuel efficiency										
BEV, FCEV	0%	0%	0%	0%	0%					Infras (2019)
PHEV	0%	+3%	+10%	+5%	+10%					Öko Institut et al. (2016)
ICEV	0%	+30%	+50%	+40%	+50%					
Occupancy rate										
Number of persons per vehicle	1.56	1.56	1.56			1.84	2.2			BFS (2015) Hörl et al. (2019)
Modal split pkm										
Share of motorized private transport	79%	77%	75%					72%	59%	ARE (2016) Öko Institut et al. (2016)
Share of public transport	21%	23%	25%					28%	41%	

4.1 Technology and BEV diffusion Scenario (TECHS)

TECHS describes a future where the majority of passenger cars are BEVs. The government is assumed to use subsidies for BEVs to foster their diffusion and to finance these subsidies through taxes on fossil fuels for passenger cars. Moreover, we assume that the technological progress in fuel efficiency takes place earlier compared to BAU. The maximum improvement possible in fuel efficiency up to 2050 is derived based on Öko Institut et al. (2016), BFE (2021) and experts know-how. Öko Institut et al. (2016) assume in their "Efficiency Scenario" that the efficiency of passenger cars increases by 40% (90%) until 2030 (2050) relative to 2010. However, according to the validation of experts and the underlying assumptions in BFE (2021), the value for 2050 should not differ from BAU (50% according to BFE (2021)). Thus, we assume that the fuel efficiency increases by 40% (30%) until 2030 in TECHS (BAU), but is the same in 2050.

In TECHS, 65% of the passenger cars are BEVs in 2050. These assumptions are based on the BFE (2021) and discussions with experts, who estimate the maximal possible share of BEVs in 2050 considering the efficiency gain and reasonable subsidies for BEVs financed by taxes on fossil fuels for passenger cars.

4.2 Capacity Use Scenario (CAPU)

In CAPU, we focus on a future where individuals use their vehicles more efficiently. The government can impose measures such as mobility pricing focusing on capacity use, reserved parking spaces, or lanes for passenger cars used by more than 3 persons to increase the average number of persons per passenger car. Implementing these measures is not cost-intensive, and their success relies on the willingness to intensify car- and ride-sharing. Thus, this scenario assumes a change in the occupancy rate, which is not caused by costly measures but by behavioral changes. Our assumptions on increasing the occupancy rate from 1.56 in BAU to 2.2 in CAPU are based on Mühlethaler et al. (2011) and Hörl et al. (2019).

4.3 Modal Shift Scenario (SHIFTP)

SHIFTP depicts a future with a shift towards less carbon-intensive transport. We thereby focus on a shift of passengers traveling by passenger car towards traveling by public transport. We assume that the government implements a subsidy for public transport, which is financed by taxes on fossil fuels for passenger cars. The subsidy is set such that the target share of 28% (41%) of public transport in 2030 (2050) is reached. Our assumptions are based on Öko Institut et al. (2016) and interviews with experts.

5 Simulation Results

In this section, we first conduct an economic impact analysis to understand how each of the three edge case scenarios contribute to the decarbonization of the Swiss passenger transport system. Then, we combine these scenarios to evaluate the optimal policy mix.

5.1 Economic Impact Analysis

The economic impact analysis allows us to derive results in terms of the passenger transport system, energy use and emissions, as well as macroeconomic variables.

5.1.1 Results on the passenger transport system

This section presents the result related to the passenger transport system. Figure 6 shows the development of the passenger car stock in terms of fuel mix until 2050 for all edge case scenarios. We see that in TECHS, the stock of passenger cars develops similar to BAU.[16] In CAPU, fewer passenger cars carry more individuals due to a higher occupancy rate. That leads to a decrease in the stock of passenger cars. In SHIFTP, a subsidy scheme towards public transport makes passenger car transport relatively more expensive. Thus, more individuals switch to public transport, resulting in a lower passenger car stock relative to BAU.

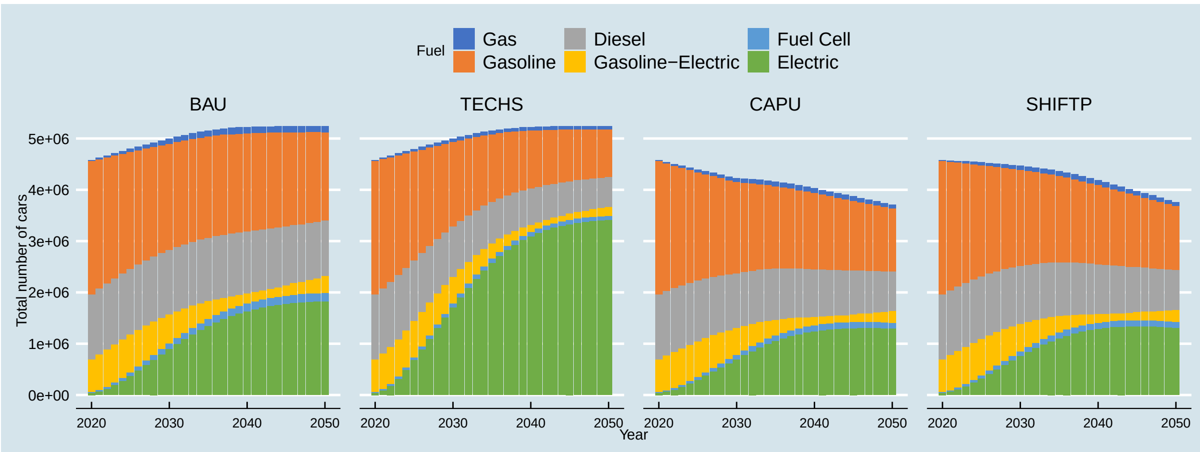


Figure 6 – Passenger car stock and fuel mix

Figure 7 shows the percentage change of transport performance of the three edge case scenarios for the transport sector relative to BAU. In TECHS, the development of pkm in private transport is based on the following effects. First, improving the fuel efficiency in TECHS sets an incentive to drive more. Second, switching from ICEVs to BEVs induces a decrease in pkm in private transport as a BEV is driven less on average than ICEV (see Infras (2019)). The

[16] We calculate the stock of passenger cars for BAU until 2050 with the regression model described in Appendix A.1. In the scenarios CAPU and SHIFTP we adjust the demand for new passenger cars in line with the change in capacity and increasing demand for public transport respectively. As the occupancy rate and modal split remain untouched in TECHS, we have the same level of passenger cars in BAU and TECHS.

latter effect prevails, which leads to a decrease in pkm in private transport until 2050 relative to BAU, but in a slight increase in pkm in public transport. In addition, from 2040 onwards, increasing electricity prices lower the incentives to drive BEVs, which fosters the decline of pkm in private transport in TECHS relative to BAU due to the high share of BEVs in TECHS (see Figure 15 in Appendix C). In CAPU, the improved efficiency of using passenger cars leads to a sharp decrease in the accumulated amount of vehicle kilometers (vkm). A higher number of persons per passenger car decreases their stock (see Figure 6) and, thus, also the total vkm traveled. The total pkm in public transport is more or less the same as in BAU as the relative prices between the two modes of transport hardly change. In SHIFTP, the subsidies for public transport decrease its price in relative terms to private transportation. That leads to a shift from private to public traveling. Moreover, the tax on fossil fuels increases the cost of using passenger cars in relative terms resulting in lower vkm.

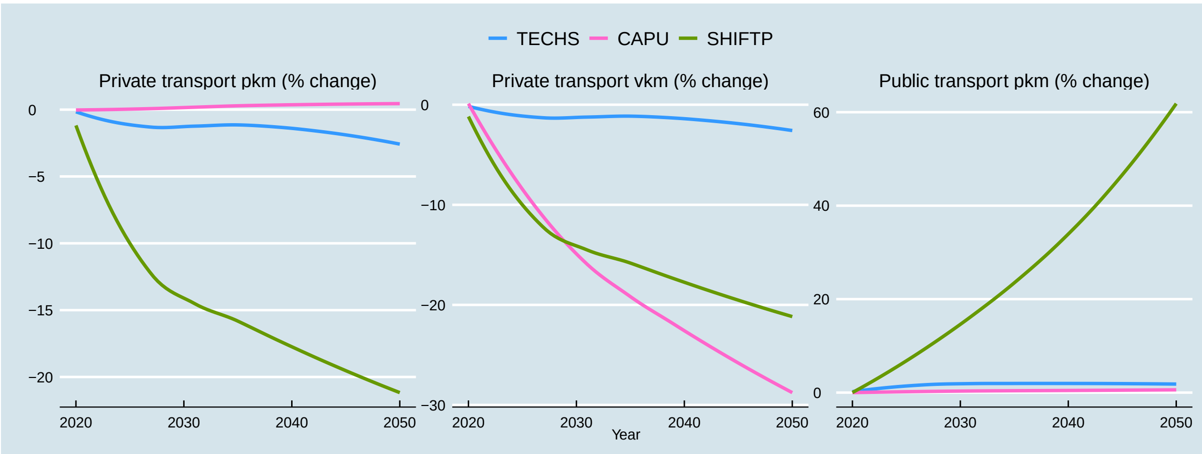


Figure 7 – Transport performance relative to BAU

5.1.2 Results on Energy use and Emissions

We now turn to the results in terms of energy use and emissions. Figure 8 shows the development of gasoline, diesel, and electricity consumption for passenger cars in Terawatthour (TWh). In TECHS, the consumption of gasoline and diesel for passenger cars is decreasing, whereas electricity is increasing. This is due to the improved fuel efficiency and the larger share of BEVs. In CAPU and SHIFTP, the consumption of fossil fuels decreases heavily because of lower vkm. In all scenarios, the demand for electricity for passenger cars grows compared to 2020 due to the increasing share of BEVs. The stabilizing electricity demand after 2040 is mainly caused by increasing electricity prices, which decreases the incentive to drive with BEVs (see Figure 15 in Appendix C). In Figure 9, we see that TECHS has the highest energy demand for passenger cars comparing to CAPU and SHIFT, which is due to its higher stock of passenger cars.

To analyze the impact on CO_2 emissions, we need to incorporate the electricity production mix for Switzerland. In accordance with the findings of Swiss Energy Modelling Platform (2018)

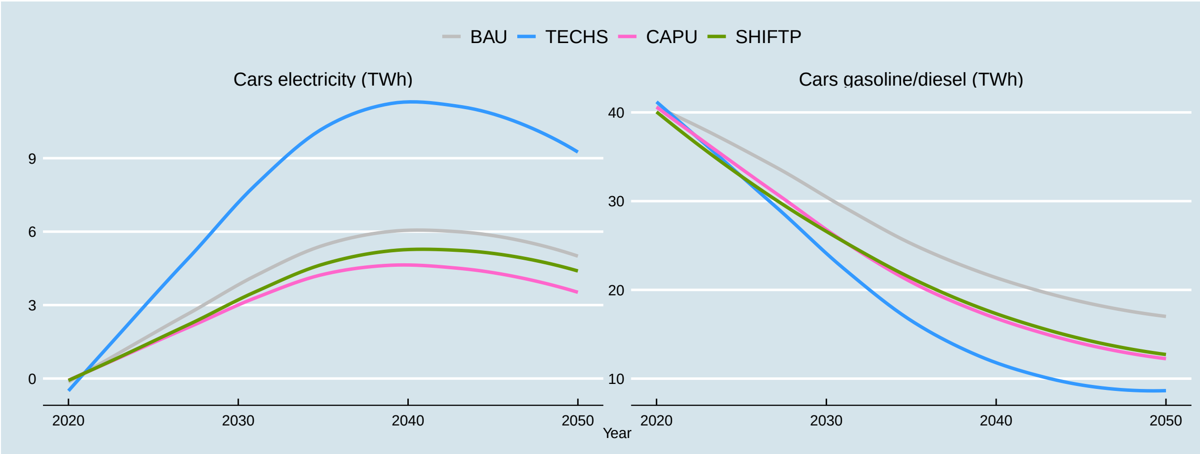


Figure 8 – Development of disaggregated energy use of passenger cars

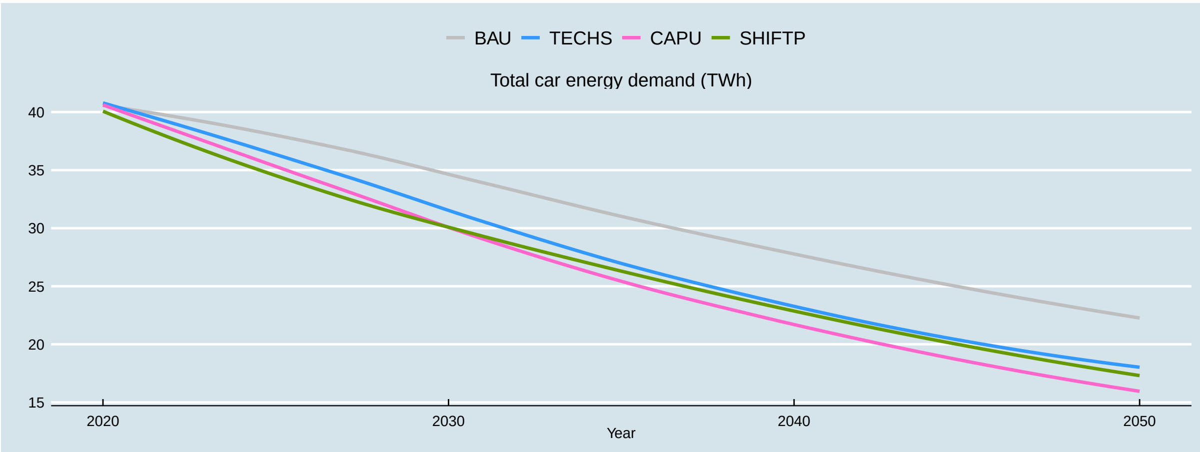


Figure 9 – Total Energy use for passenger cars

and Prognos (2012), we derive the mix by setting the electricity production of each technology to its capacity limit (see Figure 16 in Appendix C). The sequential drops in the picture are the nuclear phase-outs which decrease domestic electricity production. Consequently, Switzerland has to partly rely on importing electricity to meet its demand in the future (see Figure 17 in Appendix C). In TECHS, import of electricity is higher compared to the other scenarios due to the large share of BEVs. In CAPU and SHIFTP, the smaller stock of passenger cars comes with a smaller amount of BEVs relative to the BAU, which results in relatively low electricity import.

The CO_2 emissions of passenger transport in each scenario are displayed in Figure 10.

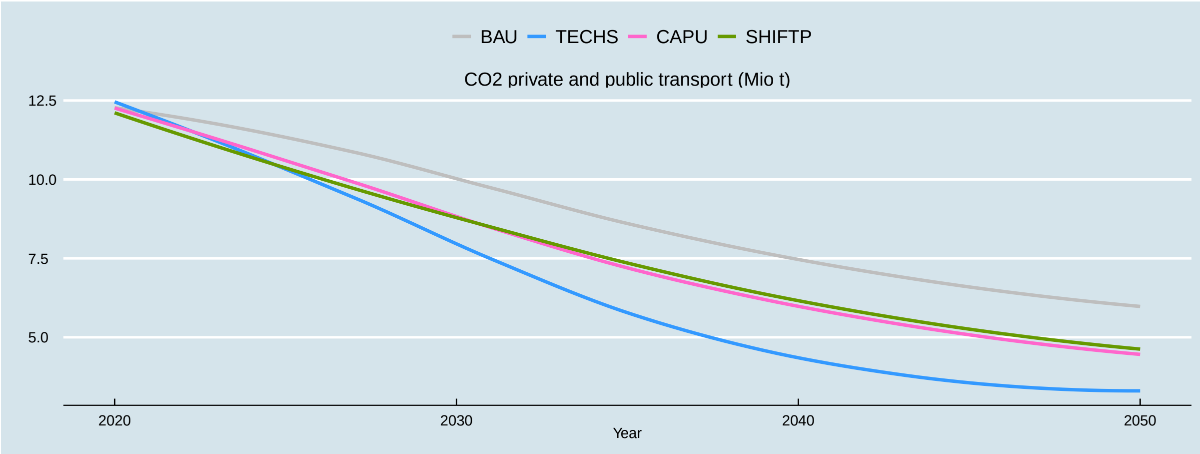


Figure 10 – CO_2 emissions of passenger transport

TECHS is the most promising edge case scenario considering the reduction of CO_2 emissions from passenger cars. The boost of BEVs decreases the CO_2 emissions from passenger transport by 45.7% relative to BAU to 3.2 million tons in 2050. An increase in the capacity use of cars in CAPU reduces the CO_2 emissions from passenger transport by 25.7% to 4.4 million tons. Incentivizing people to rely more on public transport as in SHIFTP results in a decrease by 22.7% to 4.6 million tons CO_2 in 2050. Although each edge case scenario decreases the emissions substantially, none of them allows to achieve the net-zero emissions target of Switzerland.

5.1.3 Economic Results

This section discusses the effects of the three edge case scenarios on different macroeconomic indicators. Figure 11 displays the change of per capita consumption, leisure, and savings in the three edge case scenarios relative to BAU.

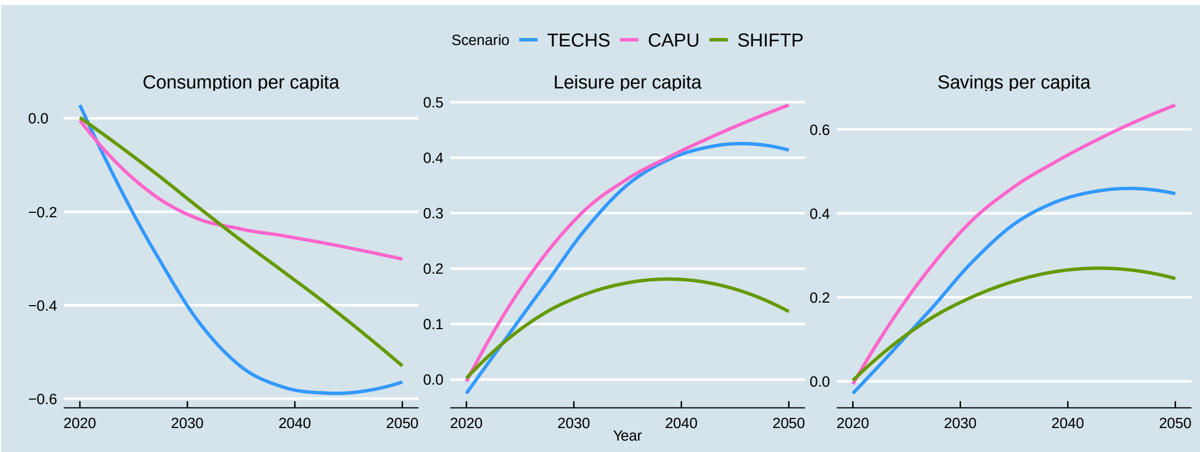


Figure 11 – Household's choices relative to BAU

All edge case scenarios increase the efficiency of passenger transportation. That, in turn, decreases the cost of transport for households, which leads to an increase in real income per hour. In the calibrated version of the model, the income effect outweighs the substitution effect in the labor choice. Thus, an increase in real income results in a lower labor supply. Moreover, increasing income incentivizes to save. We identify three main drivers for our outcome: the cost-saving effect, the policy-cost effect, and the fleet-mix effect. In TECHS, all three effects are present. First, increasing fuel efficiency leads to a cost-saving effect. Initially, that effect is marginal because only the new passenger cars are affected by increasing fuel efficiency. Over time, however, the new composition of the stock with more efficient passenger cars results in a significant decline in transport costs. Second, TECHS embeds a policy-cost effect as the subsidy for BEVs is financed by the households through taxes on fossil fuels for passenger cars (see Figure 18 in Appendix C), which increases the relative price of consumption. That mitigates the incentive for more leisure and savings. Moreover, it amplifies the negative response in consumption. Last, considering that BEVs are cheaper after 2030, increasing the share of BEVs leads to a fuel-mix effect that positively affects real income. In CAPU, the economic gains are based on the cost-saving effect: fewer passenger cars are needed to meet the demand for transport. Thus, the representative households spends less on transportation resulting in a decrease in consumption, whereas leisure and savings increase.[17] SHIFTP, instead, incorporates a cost-saving and policy-cost effect. On the one hand, the subsidies for public transport in SHIFTP incentivize households to change to a cheaper means of transport. That increases their real income and thus leisure and investment. On the other hand, the subsidy for public transport is financed by the households through taxes on fossil fuels for passenger cars (see Figure 18 in Appendix C), which increases the relative price of consumption. Thus, the policy-cost effect negatively affects leisure, savings, and consumption.

From the firm perspective, increasing leisure and savings means that labor is becoming relatively more expensive compared to capital. Thus, in all edge case scenarios, the economy gets more capital-intensive relative to BAU (see Figure 19 in Appendix C). On a sectoral level, the results indicate that the edge case scenarios particularly favor the capital-intensive sectors.

Figure 12 displays the resulting change in GDP per capita and welfare relative to BAU.

[17] In our model, passenger cars are included as negative endowment necessary to be able to drive them. Thus, buying fewer passenger cars (without lowering their ability to drive them) increases their “income” by decreasing the cost of passenger cars.

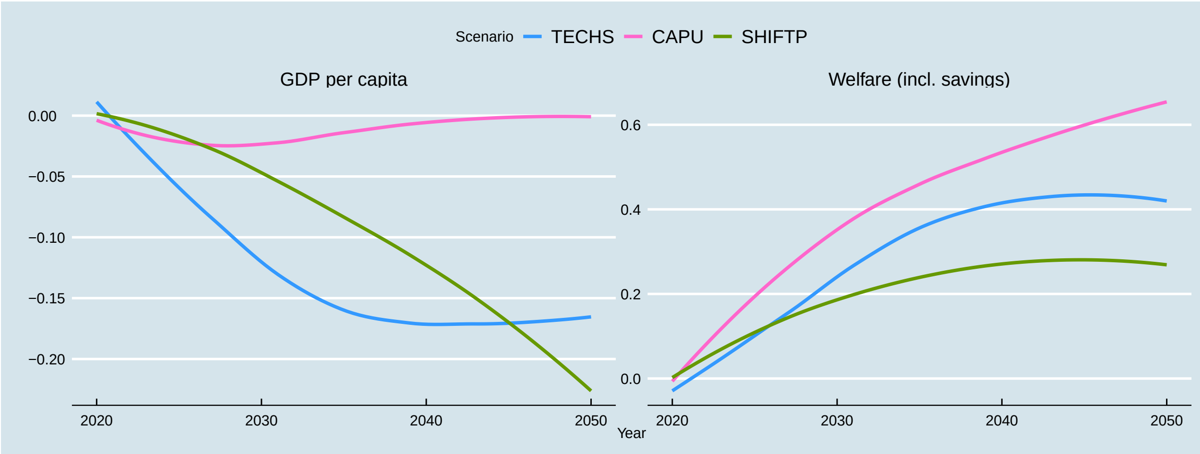


Figure 12 – Change in GDP per capita and Welfare relative to BAU

While GDP per capita slightly decreases due to a lower consumption level and labor supply, all edge case scenarios result in higher welfare mainly due to increasing leisure.
Summarising the transportation, energy, emission, and welfare effects, we see that while welfare is slightly positively affected in the edge case scenarios, the passenger transport system and the CO_2 emissions change substantially. However, in Section 5.1.2 we showed that none of the edge case scenarios result in complete decarbonization of the Swiss passenger transport system. Thus, in the next section, we analyze whether an optimal combination of all measures used in the scenarios is sufficient to reach the net-zero emissions target.

5.2 Optimal combination of scenarios

In this section, we analyze the emission-saving potential and the economic impact of combining the scenario measures optimally. We assume that technology develops favorably as in TECHS and behavioral changes increase the capacity use like in CAPU.[18] To evaluate the optimal combination of scenario measures, we use a Monte-Carlo simulation varying the subsidies for BEVs and public transport up to the level assumed in TECHS and SHIFTP, respectively. Figure 13 displays the resulting CO_2 emissions from passenger transport on the Y-axis and relative welfare on the X-axis for the year 2050.[19] The numbers depict the outcome of different combinations of the subsidies (see Table 17 in Appendix C). The scenario labelled "10" is the optimal combination considering the welfare and CO_2 emissions. In this mix, we set the subsidies for BEVs and public transport to the upper bound, which results, in combination with the technical improvement and increasing capacity use of passenger cars, in a sharp decline of CO2 emissions to 1.7 million tons in 2050. This is, however, not sufficient to reach the net-zero emissions target of Switzerland. In other words, the gradual effect until 2050 of our scenarios

[18] Enhancing the fuel efficiency and the capacity use results in a better outcome, as shown in Section 5.1.2 and 5.1.3. Thus, it is straightforward to set them to the maximum value when evaluating the optimal scenario measure mix.

[19] The X-axis indicates the welfare in relative terms to the mix with maximum welfare (which has 100%).

and their combination represent an ongoing decarbonization pathway, with which the Swiss passenger transport system can not be completely decarbonize until 2050. An explanation for that is that the lifespan of a vehicle is on average around 10 years, some of them surviving up to 28 years in the market.

Figure 13 – Monte-Carlo simulation

6 Conclusion

Switzerland has embarked on the ambitious challenge to decarbonize its transport sector until 2050, as a part of the net-zero emissions target. This requires a profound restructuring of the transport sector to reduce its emissions drastically. Decarbonization of the passenger transport sector depends, amongst others, on the development of new and better technologies and behavioral changes, as well as transportation policies. This paper studies the economic impact and the emission-saving potential of three decarbonization scenarios and a combination of them. In the first scenario, an improvement in technology and a widespread diffusion of electric vehicles is envisioned. In this scenario, the fuel efficiency of passenger cars develops favorably. In addition, subsidies favor the diffusion of BEVs. These subsidies are financed by taxes on fossil fuels for passenger cars. In the second scenario, behavioral changes lead to an increase in the capacity usage of passenger cars. This shift is incentivized by policies supporting car- and ride-sharing. Third, Switzerland could adopt policies inducing a modal shift by favoring public compared to private transport. In accordance with the literature and experts, we set the values of the parameters in the scenarios to the upper limit reasonable for Switzerland, making them edge case scenarios. We evaluate the impact of these edge case scenarios using a multi-model framework, where we interlink a CGE model capturing the economy of Switzerland with two external transport models. That allows us to incorporate a highly disaggregated passenger transport system into the economic analysis. We show that all edge case scenarios lead to a substantial reduction in CO_2 emissions and slight welfare improvements. TECHS is most promising in reducing emissions: it results in a decrease by 45.7% relative to BAU in 2050, followed by 25.7% in CAPU and by 22.7% in SHIFTP. None of them, if implemented alone, however, allow achieving complete decarbonization of the passenger transport system. The same holds for the optimal combination of all measures used in the three scenarios, which reduces emissions even further by 71.3% relative to BAU in 2050 to 1.7 million tons CO_2, but still not sufficiently to achieve the net zero. An explanation for that is that the considered scenarios have an ongoing impact until 2050, meaning that they gradually influence the passenger transport system with reasonable technical improvements, market-based instruments, and behavioral changes for Switzerland over time. Considering that a specific vehicle type can survive up to 28 years in the market, that is not enough to completely decarbonize the sector until 2050. We, therefore, conclude that Switzerland should consider additional actions to reach its commitment. These might include abrupt policies, such as the ban for buying new internal combustion engine vehicles or excluding emitting vehicles that exceed a specific age. The analysis of such alternative policies is left to future research.

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A CGE Model

A.1 Regression Model

We use a regression model to calculate the total number of passenger cars in the economy. In the last twenty years, the number of passenger cars in Switzerland follows the development of the population; growing income does not play a role anymore. The total number of passenger cars followed the growth of GDP from 1995 until 2000 (see the left part of Figure 6 which shows the indexed values for GDP, population, and total passenger cars). Starting in 2000 the passenger cars grow much slower than GDP. However, over the whole period of 1995 until 2014, the passenger cars grow more or less with the population. We, therefore, assume that in the CGE model, passenger cars are not depending on income (the type of car, however, is). We used a simple Ordinary-Least-Squares (OLS) procedure to estimate the relation between total passenger cars and population for the period 2014 - 2050.

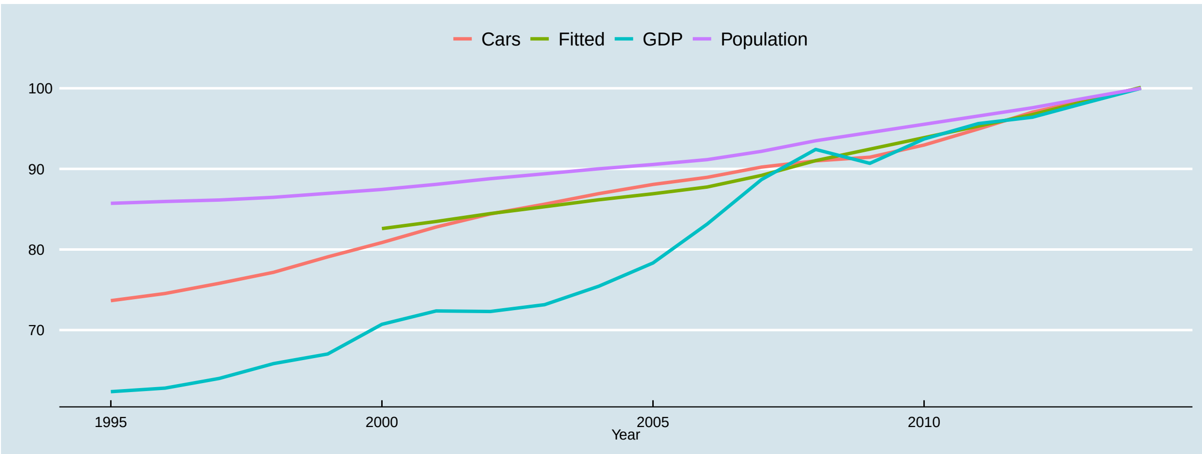

Figure 14 – Estimation of passenger cars using data from 1995-2014

A.2 MCP-format

Mathiesen (1985) showed that the three Arrow-Debreu conditions for a general equilibrium as discussed above can be cast as a (mixed) complementarity problem (MCP). The MCP format is a special case of a variational inequality problem in which all the variables lie in the positive orthant (see Facchinei and Pang (2003)). The MCP format suits itself for solving general equilibrium models. As Mathiesen (1985) writes, although the first-order optimality conditions of a mathematical programming model also satisfy a CP problem, there may be no optimization problem for a general equilibrium model that leads to this CP problem (the so-called "integrability-problem" (see Samuelson (1950)). This can happen if, for example, the model contains several households with distinct endowments and preferences, or if there are ad-valorem taxes or constraints on prices.

A complementary problem can be described as a system of (non-)linear constraints where the system variables are linked to the constraints with complementarity conditions (Ferris and Munson, 2014). More formally, given a function $F : \mathbb{R}^n \to \mathbb{R}^n$, lower bounds $l \in \{\mathbb{R} \cup -\infty\}^n$ and upper bounds $u \in \{\mathbb{R} \cup \infty\}^n$, we try to find $x \in \mathbb{R}^n$ such that precisely one of the following holds for each $i \in 1, \ldots, n$:

$$\begin{aligned} F_i(x_i) = l_i \quad & \text{and} \quad F_i(x_i) \geq 0, \quad \text{or} \\ F_i(x_i) = u_i \quad & \text{and} \quad F_i(x_i) \leq 0, \quad \text{or} \\ l_i < x_i < u_i \quad & \text{and} \quad F_i(x_i) = 0 \end{aligned}$$

This means that the variable x_i is at one of its bounds or the linked function is equal to zero.

In the mixed complementarity problem (MCP), we not only have inequalities with complementary nonnegative variables but also equations where the associated variables are free. The complementarity conditions can then be written as:

$$\begin{aligned} & F_i(x_i, x_j) \geq 0, \quad x_i \geq 0, \quad x_i F_i(x) = 0, \\ & F_j(x_i, x_j) = 0, \quad x_j \text{ free}, \end{aligned}$$

where we partition the set n in the sets i and j.

Often the following shorthand notation is used, where the perpendicular symbol ($\perp$) indicates the complementarity slackness between the constraint and the variable:

$$0 \geq F(x) \perp x \geq 0. \tag{33}$$

Complementarity models can be used for solving linear, quadratic and nonlinear programs by writing the Karush-Kuhn-Tucker optimality conditions. In the case of minimizing a function $f(x)$, where $x \in \mathbb{R}^+$, the first-order condition is given by:

$$\frac{\partial f}{\partial x} \geq 0, \quad x \geq 0. \tag{34}$$

If x is at its lower bound, we must must have that the function is increasing in x. If we have an interior solution, the derivative must be equal to zero. Combining these two pieces of information, we get the mixed complementarity formulation:

$$\frac{\partial f}{\partial x} \leq 0, \quad x \geq 0, \quad x \frac{\partial f}{\partial x}. = 0 \tag{35}$$

As the complementarity problem can often be formulated using the optimality conditions of the original problem, it is easy to write down the model equations. However, there is not always an optimization problem that corresponds to the complementarity conditions. This means that a MCP formulation allows us to solve a wider class of problems.

Complementary models have been used for expressing a variety of economic equilibrium models for both markets and games, where the underlying problem cannot be written down as a single optimization problem or if no equivalent optimization problem exists, for example, due to non-integrability conditions.[20] Many examples in MCP format can be found in Ferris and Munson (2014), Rutherford (1995) and Dirkse and Ferris (1995). The development of the complementarity modeling format was motivated by theoretical and practical developments in algorithms for nonlinear complementarity problems and variational inequalities. The most recent techniques are based on ideas from interior-point algorithms for linear programming (Kojima et al., 1991). Computational evidence suggests that algorithms for solving MCPs are relatively reliable and efficient, particularly for models that are not natural optimization problems. A survey of developments in the theory and applications of these methods is provided by Harker and Pang (1990).

Mathiesen (1985)'s MCP version of the CGE model is formulated as a nonlinear system of (weak) inequalities and equalities corresponding to the three classes of equilibrium conditions associated with the Arrow-Debreu general equilibrium. The fundamental unknowns of the system are three vectors consisting of non-negative prices (for commodities and factors), activity levels (production and utility) and household incomes. In equilibrium, each of these variables is linked to one of the inequalities or equalities. The three classes are:

1. The **zero-profit conditions** (more precise, the non-positive profit conditions). In this class the variable complementary to the equation is the activity level: If a sector in equilibrium makes a negative profit, the activity level will be zero; if the profit is zero, the activity level will be positive. Note, that because of the assumption of perfect competition in equilibrium no (excess) profits will exist: Positive profits would lead to new entrants driving the price and, therefore, the profits to zero. The zero-profit functions can be derived from the maximization or, in case of the producers of the dual cost minimization problems.

   We use the calibrated share form of the CES function (see Rutherford (1998)) to write

[20] See the paper on this topic by Samuelson (1950).

down the zero-profit condition for the utility function

$$
\begin{aligned}
P^U \leq & \left[\theta^{cls}\left(\frac{P^{inv}}{\overline{P}^{inv}}\right)^{1-\sigma^{cls}} + (1-\theta^{cls})\left[\left(\frac{P^{cls}}{\overline{P}^{cls}}\right)^{\frac{1}{1-\sigma^{cl}}}\right]^{1-\sigma^{cls}}\right]^{\frac{1}{1-\sigma^{cls}}} \perp U \\
& \text{where } P^z = \left[\theta^{cl}\left(\frac{P^{ls}}{\overline{P}^{ls}}\right)^{1-\sigma^{cl}} + (1-\theta^{cl})\left(\frac{P^C}{\overline{P}^c}\right)^{1-\sigma^{cl}}\right] \\
& \text{and } P^c = \left[\theta^{c}\left(\frac{P^{ne}}{\overline{P}^{ne}}\right)^{1-\sigma^{c}} + (1-\theta^{c})\left(\frac{P^e}{\overline{P}^e}\right)^{1-\sigma^{c}}\right]^{\frac{1}{1-\sigma^c}} \qquad (36) \\
& \text{where } P^{ne} = \left[\sum_{sne}\theta^{cne}_{sne}\left(\frac{P^A_{sne}}{\overline{P}^A_{sne}}\right)^{1-\sigma^{cne}}\right]^{\frac{1}{1-\sigma^{cne}}} \\
& \text{and } P^e = \left[\sum_{e}\theta^{ce}_{e}\left(\frac{P^A_{e}}{\overline{P}^A_{e}}\right)^{1-\sigma^{ce}}\right]^{1/1-\sigma^{ce}}
\end{aligned}
$$

Using the calibrated share form, it is straightforward to write down the other zero-profit conditions. We refrain from writing down these equations in the extensive form and use a condensed form. The zero-profit function for the government utility, the domestic non-energy and energy sectors, the Armington sectors as well as the investment sector is given by:

Government utility:	$-\Pi^G \geq 0 \perp UG$	(37)
Non-energy domestic production:	$-\Pi^D_{ne} \geq 0 \perp Y_{ne}$	(38)
Energy domestic production:	$-\Pi^D_e \geq 0 \perp Y_e$	(39)
Armington sector:	$-\Pi^A_i \geq 0 \perp A_i$	(40)
Investment sector:	$-\Pi^{inv}_i \geq 0 \perp INV_i.$	(41)

2. The **market clearing conditions**. These equations are complementary with the prices: Supply minus demand for every commodity should be non-negative. In equilibrium, a positive supply means that the complementary price is zero (the case of a free good); if supply is equal to demand, a positive equilibrium price will be the result. The market clearing conditions can be derived using Shephard's lemma. This lemma states that that the conditional demand for an input in production is equal to the derivative of the cost function with respect to the price of the input (Varian, 1992).

$$A_i = \sum_j \frac{\partial C^D_i}{\partial P^A_i} + \frac{\partial C^U_i}{\partial P^A_i} \qquad (42)$$

All other market clearing functions can be derived in the same way differentiation the cost functions in the respective production functions.

3. **Income balance or definition**: This class of equations simplifies the market clearing conditions as the expression for income in the consumer or government consumption demand functions can be replaced by a single variable (I^{RA} and I^{G}).

B Calibration

B.1 Consumers

Table 9 – Consumer goods in the model.

COICOP	Description	HABE
C01	Food and non-alcoholic beverages	A51
C02	Alcoholic beverages, tobacco, and narcotics	A52
C03	Clothing and footwear	A56
C04	Housing, water, gas, electricity, and other fuels	A57
C05	Furnishings, household equipment and routine maintenance of the house	A58
C06	Health	A61
C07	Transport	A62
C08	Communication	A63
C09	Recreation and culture	A66
C10	Education	A67
C11	Restaurants and hotels	A53
C12	Miscellaneous goods and services	A68

B.2 Producers

B.3 Passenger transport cost

B.4 Reconciliation of cost information on passenger cars with the IOT

We need to reconcile the cost information on passenger cars in Section 3.3.1 with the data of the IOT. The demand of the Swiss households in the IOT classifies individual consumption expenditures incurred by households, non-profit institutions serving households and general government according to their purpose. The COICOP division C7 contains the overall costs for private transport. Table 14 in Appendix B.4 shows the groups (three-digit) and classes (four-digit) of this division.

In the IOT these costs are mapped to the sectors. The published Swiss IOT only shows the division and not the groups and classes. However, we can use the raw, disaggregated information (see Table 15 in Appendix B.4) to infer the costs for the use of passenger cars which can be

Table 10 – Sectors in the CGE model

CPA-Code	Names	CPA-Code	Names
01	Agriculture, hunting and related service activities	40g	Gas supply
02	Forestry, logging and related service activities	41	Collection, purification and distribution of water
05	Fishing, fish farming and related service activities	45	Construction
10-14	Mining and quarrying	50	Sale, maintenance and repair of motor vehicles
15-16	Manufacture of food products, beverages and tobacco	51-52	Wholesale and retail trade
17	Manufacture of textiles	55	Hotels and restaurants
18	Manufacture of wearing apparel, dressing and dyeing of fur	60a	Passenger rail transport
19	Leather and footwear	60b	Goods rail transport
20	Manufacture of wood	60c	Rail infrastructure
21	Manufacture of pulp and paper+C77	60d	Other scheduled passenger land transport
22	Publishing, printing	60e	Taxi operation, Other land passenger transport
23a	Manufacture of coke, refined petroleum products	60f	Freight transport by road
23b	Manufacture of nuclear fuel	60g	Transport via pipelines
24	Chemical industry	61	Water transport
25	Manufacture of rubber and plastic products	62	Air transport
26	Manufacture of other non-metallic mineral products	63a	Water transport infrastructure
27	Manufacture of basics metal	63	Air transport infrastructure / Airports
28	Manufacture of fabricated metal products	63c	Other supporting and auxiliary transport activities; activities of travel agencies
29	Manufacture of machinery and equipment	64	Post and telecommunications
30-31	Manufacture of office and electrical machinery and computers	65	Financial intermediation, except insurance and pension funding (includes also part of NOGA 67)
32	Manufacture of communication equipment	66	Insurance and pension funding, except compulsory social security (includes also part of NOGA 67)
33	Manufacture of medical and optical instruments, watches	70, 97	Real estate (incl. renting by private households)

CPA-Code	Names	CPA-Code	Names
34	Manufacture of motor vehicles	71, 74	Other business activities
35	Manufacture of other transport equipment	72	Informatics
36	Manufacture of furniture, manufacturing	73	Research and development
37	Recycling	75a	Road infrastructure
40a	Running hydro power plants	75b	Other public administration and defence; compulsory social security
40b	Storage hydro power plants	80	Education
40c	Nuclear power plants	85	Health and social work
40d1	Public power plants (incl. CHP) based on fossil fuels	90a	Electricity generation in MSW incineration plants
40d2	Wood based power plants (incl. CHP)	90	Heat generation in MSW incineration plants
40d3	Wind power and PV plants	90c	Other waste treatment
40e	Electricity distribution and trade	91-92	Recreational, cultural and sporting activities
40f	Public heat supply	93-95	Private households with employed persons, other service act.

Table 11 – Assumptions on costs in benchmark year.

	lstkw	fixcosts	varcosts	fuelcosts
Gas	<60kW	4'710	1'314	752
Gas	60-100kW	6'273	2'106	640
Gas	100-140kW	8'533	2'796	889
Gas	>140kW	9'519	3'054	1'962
Gasoline	<60kW	4'188	960	735
Gasoline	60-100kW	5'223	1'365	897
Gasoline	100-140kW	6'223	1'676	933
Gasoline	>140kW	7'824	2'240	1'201
Gasoline-Electric	<60kW	9'173	1'741	611
Gasoline-Electric	60-100kW	7'928	2'517	578
Gasoline-Electric	100-140kW	7'592	2'349	522
Gasoline-Electric	>140kW	10'600	3'477	684
Diesel	<60kW	4'770	2'502	535
Diesel	60-100kW	5'751	2'587	1'055
Diesel	100-140kW	6'389	2'989	1'144
Diesel	>140kW	8'269	3'801	1'349
Electric	<60kW	6'021	669	532
Electric	60-100kW	7'750	1'160	535
Electric	100-140kW	7'843	1'313	456
Electric	>140kW	10'102	1'762	512
Diesel-Electric	<60kW	7'320	1'098	809
Diesel-Electric	60-100kW	9'422	1'904	987
Diesel-Electric	100-140kW	9'535	2'155	1'026
Diesel-Electric	>140kW	11'673	3'876	1'321

Table 12 – Yearly change in costs

	FixCosts	**VarCosts**
Gas	0.2%	0.2%
Gasoline	0.2%	0.2%
Gasoline-Electric	0.2%	0.2%
Diesel	0.2%	0.2%
Electric	-0.9%	0.2%
Fuel cell	-0.6%	0.2%

Table 13 – Projection of passenger car stock and fuel efficiency

Change in fuel efficiency	**2030**	**2050**
BEV, FCEV	0%	0%
PHEV	+3%	+10%
ICEV	+30%	+50%

found in the class 7.1.1 (Purchase of vehicles) and group 7.2 (Operation of personal transport equipment) (see Table 16 in Appendix B.4). The latter group contains also costs for other vehicles. Using the shares of newly bought passenger cars and other transport equipment we split these costs accordingly.

These costs are compared with the costs we get from multiplying the costs from Table 11 with the number of passenger cars in 2014. There, total use of electricity for the vehicles using batteries contains also the loss of load (15%). As these costs differ by a factor two from the costs in the IOT, we scale the fixed costs in such a way that they are equal.

Table 14 – COICOP classes in transport demand.

Code	**Description**
C07.1.1	**Purchase of motor cars**
C07.1.2	Purchase of motorcycles
C07.1.3	Purchase of bicycles
C07.1.4	Purchase of animal drawn vehicles
C07.2.1	**Spare parts and accessories for personal transport equipment**
C07.2.2	**Fuels and lubricants for personal transport equipment**
C07.2.3	**Maintenance and repair of personal transport equipment**
C07.2.4	**Other services in respect of personal transport equipment**
C07.3.1	Passenger transport by railway
C07.3.2	Passenger transport by road
C07.3.3	Passenger transport by air
C07.3.4	Passenger transport by sea and inland waterway
C07.3.5	Combined passenger transport
C07.3.6	Other purchased transport services

Table 15 – Expenditure of households for private transport in million CHF.

Code	Description	C07_1_1	C07_2_1	C07_2_2	C07_2_3	C07_2_4	Total
S23a	Manufacture of coke, refined petroleum products and nuclear fuel			3'668			3'668
S24	Manufacture of chemicals and chemical products			23			23
S25	Manufacture of rubber and plastic products		117				117
S31	Manufacture of electrical machinery and apparatus n.e.c.		65				65
S34	Manufacture of motor vehicles, trailers and semi-trailers	6'159	219				6'378
S40g	Gas supply			2			2
S50	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel	1'832	104	367	1'732		4'034
S71	Renting of machinery and equipment without operator and of personal and household goods					1'035	1'035
S75b	Other public administration and defence; compulsory social security					285	285
	Total	7'990	504	4'060	1'732	1'320	15'606

Table 16 – Demand for transport in the household budget survey.

Coicop	Description	Cost category
C07.1.1	Purchase of motor cars	Fixed cost
C07.2.1	Spare parts and accessories for personal transport equipment	Operation and maintenance cost
C07.2.2	Fuels and lubricants for personal transport equipment	Fuel cost
C07.2.3	Maintenance and repair of personal transport equipment	Operation and maintenance cost
C07.2.4	Other services in respect of personal transport equipment	Operation and maintenance cost

C Simulation Results

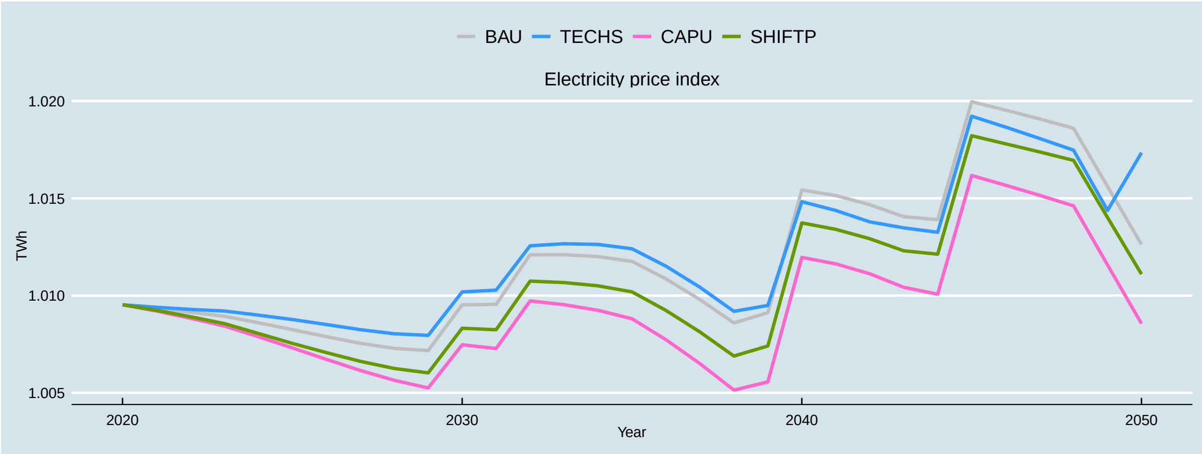

Figure 15 – Development of electricity prices

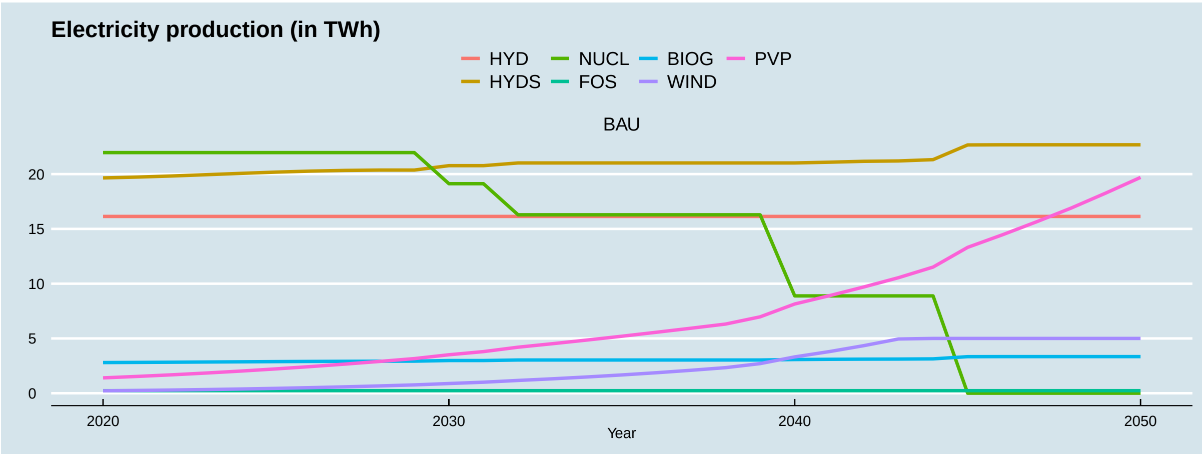

Figure 16 – Production capacity of electricity

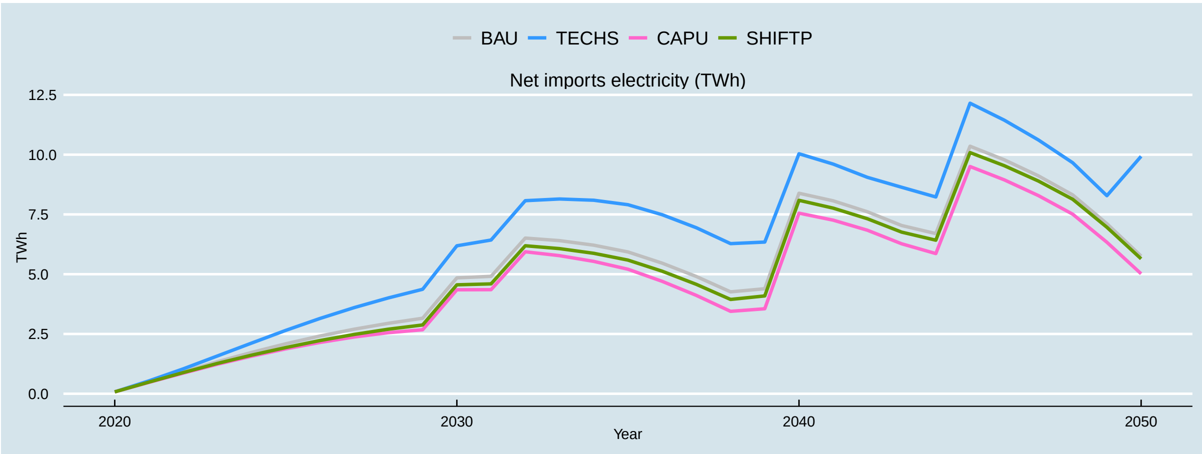

Figure 17 – Net imports of electricity

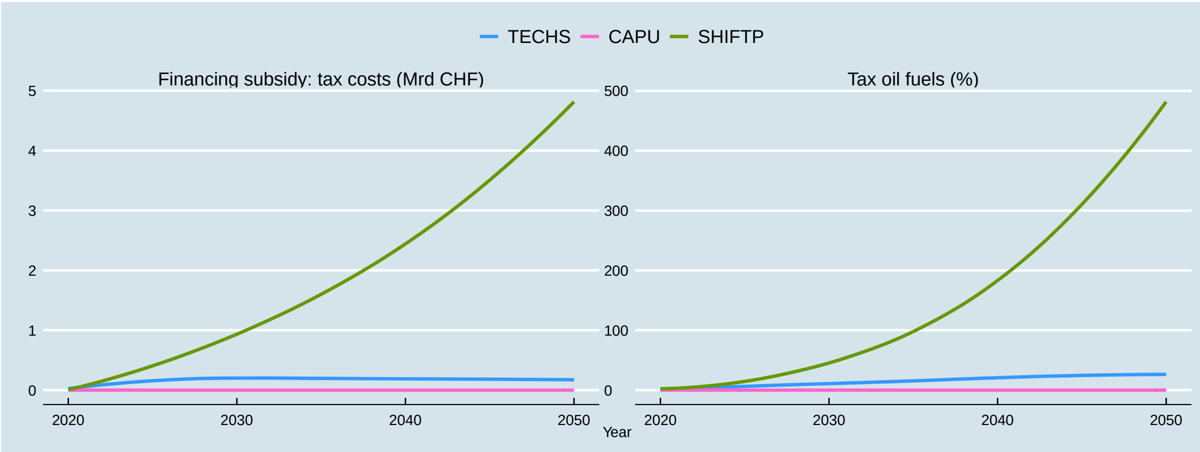

Figure 18 – Policy-cost effect

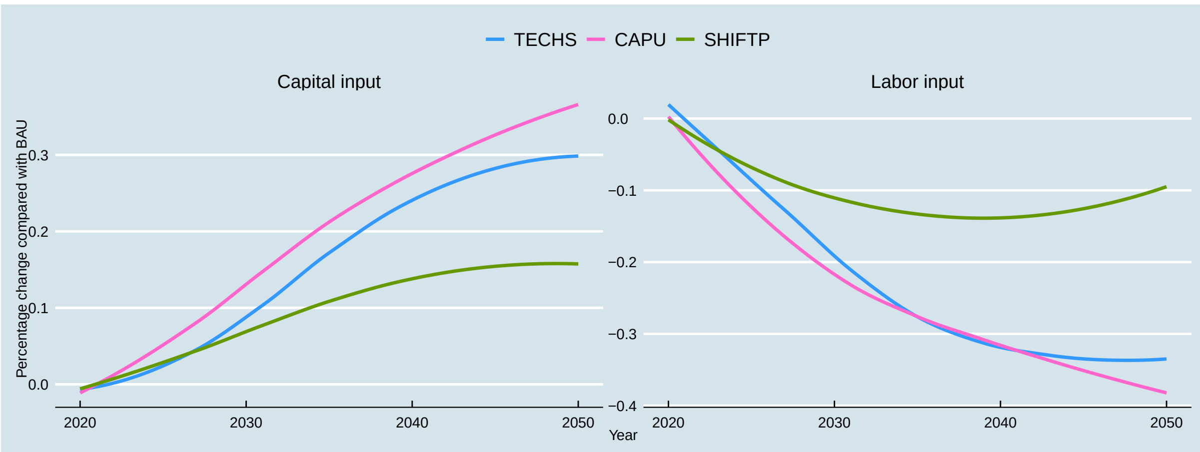

Figure 19 – Labor and Capital Input relative to BAU

Table 17 – Subsidies in the optimal scenarios in 2050

Scenario	Subsidy for BEVs relative to TECHS	Subsidy to public transport relative to SHIFTP
TECHS	1	0
CAPU	0	0
SHIFTP	0	1
1	1	1
2	0.636363636	1
3	0	1
4	0	1
5	0.887272727	0.817505212
6	0.672727273	0.814896189
7	0.723636364	0.93414739
8	0.945454545	0.748050089
9	0.774545455	0.847347338
10	1	1
11	0.734545455	0.850168654
12	0.934545455	0.756920133
13	0.701818182	0.797089126
14	0.76	0.87343404
15	0.887272727	0.904369834
16	0.883636364	0.836246877
18	1	0.87343404
19	0.650909091	0.907584369
20	0.650909091	0.907584369
21	0.883636364	0.914082485
22	0.996363636	0.772959602
23	0.84	0.941032887
24	0.985454545	0.804624529
25	0.701818182	0.739385525
26	0.858181818	0.87343404
27	0.785454545	0.748050089
28	0.76	0.825433492
29	0.869090909	0.828110535
30	0.887272727	0.743692571
31	0.814545455	0.861644328
32	0.952727273	0.820130995
33	0.974545455	0.984576094
34	0.818181818	0.75917061
35	0.978181818	0.996098896
36	0.832727273	0.973316834
37	0.807272727	0.720605503
38	0.96	0.841760513
39	0.810909091	0.917366562
40	0.68	0.973316834

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