Project:
DEFINE - Development of an Evaluation Framework for the INtroduction of Electromobility

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The Economic Costs of Electric Vehicles

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Abstract

We assess the economic costs necessary to reach an electric vehicle target in Austria. These costs include tax revenue changes and effects on government budget, private infrastructure expenditures, and effects on GDP. To this end a discrete choice model of the consumer purchase decision between conventional, hybrid, plug-in hybrid and electric vehicles is implemented into a computable general equilibrium model in a "hard-link" fashion. The combined model features a detailed accounting of stock development, including yearly numbers of vehicle purchases and cohort depreciation. It depicts 9 households differentiated by degree of urbanization and education, and accounts for detailed consumer preferences, mode choice decisions, and includes several electricity producing technologies. We assess the influence of two policy measures on the market penetration of electric vehicles: A rise in the mineral oil tax and a penalty on the car purchase tax, which in Austria is connected to CO_2 emissions. Thereby we account for the overall economic effect on GDP growth and the effect on the government's budget. This enables us to compare the economic costs of electromobility to the connected environmental benefits.

Keywords: CGE, discrete choice, fleet, taxation, EV, PHEV, HEV

1 Introduction

There has been an ongoing debate whether alternatively fuelled vehicles, especially battery electric vehicles or plug-in hybrid electric vehicles, offer an solution to obtain a low-carbon emission transport system that still heavily relies on individual transport using passenger cars. Even though a high-price alternative to conventional vehicles powered by gasoline or diesel, rapid technological development by the automobile industry together with a shift in preferences by consumers, both possibly incentivized by state subsidies, could lead to an increased penetration of electric vehicles in the coming years and decades.

For a comprehensive analysis, electric mobility should be viewed in a systemic perspective in order to assess whether it is an economically viable option to reduce greenhouse gas (GHG) emissions in the transport sector. On the one hand, the take-up of electric cars by consumer depends on their car purchase preferences as well as on the choice of products offered by the automobile industry. On the other hand, emissions attributed to electric vehicles, who themselves do not directly emit GHGs when operated, arise in the electricity production sector providing the electric fuel.

This paper relates to existing research by assessing the economic costs and benefits of market penetration scenarios of electric vehicles in a comprehensive modelling framework. By applying the methodology of Truong and Hensher (2012) and linking the discrete choice model to a continuous demand computable general equilibrium (CGE) model, we aim for a realistic characterisation of the household vehicle purchase decision while keeping track of the physical quantities (new registrations and stock of cars) in a stock-flow consistent way and in relation to the electricity system as well as the macroeconomy in sectoral decomposition. This approach extends on the existing literature by integrating the energy system, consumer preferences and a stock-flow consistent vehicle fleet turnover model in one coherent economic framework based on general equilibrium theory.

In recent years, several modelling approaches have been applied to examine the electrification of individual passenger transport from an analytical perspective. On a global level, the MIT EPPA model, a recursive-dynamic CGE model, was used and extended to assess market entry and emission reduction potential of plug-in hybrid electric vehicles (PHEVs) facing a strong global carbon constraint, see Karplus et al. (2010). In a later version of the model, it is expanded to project the physical demand for transport services from passenger cars including the option of alternatively fuelled vehicles (AFVs) in individual passenger transportation with a focus on electric vehicles, see Karplus et al. (2012). While taking account of the physical stock of cars and related energy use in the later version of the model, the technological options of AFVs are modelled as so-called backstrop technologies that are not cost-competitive in the benchmark year of the modelling periond, but may become so according to price changes in future periods.

While this approach offers a possibility to model the gradual shift-in of a new technology, it has no explicit depiction of consumer demand based on heterogenous preferences.

Several studies rely on discrete choice models based on survey data to forecast market penetration of electric vehicles such as Öko Institut (2011) (Germany), Hanappi et al. (2012) or Link et al. (2012) (Austria). They usually find substantial market potential of electric vehicles based on stated preferences by consumers.

Another approach is a scenario analysis using total cost of ownership (TCO) models, where the total costs of purchase, operation and maintencance of a vehicle determine the choice of vehicle technology by consumers, in combination with bottom-up vehicle fleet models. Examples include Plötz et al. (2013) or Kloess and Müller (2011). As fully electric vehicles (EVs) and PHEVs are cheaper in operation and maintenance, these models often allow for higher penetration of electric vehicles in their policy scenarios.

While all these modelling approaches offer a certain angle on the economic effects of certain penetration rates, they all have to abstract either from consumer preferences, the macroeconomy, the energy system or detailed vehicle accounting.

The model presented in this paper, which has been developed as part of the project DEFINE[1] aims most of all to integrate consumer preferences into a hybrid energy-economy model. This approach offers a viable explanation for the fact that rational agents would make a car purchase decision for a product that is more expensive than its substitute.

In the absence of elicited market data, stated preferences offer a feasible way to estimate consumer preferences in relation to vehicle purchase choice. By wrapping a simplified discrete choice model in a sectoral hybrid energy-economy CGE model, a realistic and feasible way to introduce a high-priced alternative to CVs in their car purchase decision is reached. This improves on existing CGE models related to the assessment of electric vehicle take-up such as Karplus et al. (2012) by directly implementing empirically derived consumer preferences into the model, and adds a macroeconomic perspective founded on general equilibrium theory. Including an addditional detailed stock-flow consistent vehicle fleet accounting, the relation to physical quantities in the model is kept. With these features, the model offers a comprehensive simulation tool for various tax and subsidy policy instruments.

The model is implemented in MCP/GAMS, see Rutherford (1995), and incorporates the structure from Böhringer and Rutherford (2008), including different electricity producing technologies. The combination of a detailed electricity sector and vehicles fuelled by electricity replacing conventional vehicles in a CGE framework allows us to assess total economic costs of different penetration levels of electric vehicles. The vehicle types conventional vehicles (CV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and electric vehicles (EV) are the choice alternatives for the consumers in their purchase decision in the model. We distinguish 9 consumer agents (or households) by education level and living area (degree of urbanisation). Mobility preferences of these agents were assessed in a household survey carried out in the DEFINE. Based on the resulting micro dataset a discrete choice (DC) model, see Train (2003), was estimated for each agent. For each household this DC model yields choice probabilities between the vehicle types in the purchase decision, depending on prices, socio-demographic characteristics of the household, and technological attributes of the vehicles.

Following Truong and Hensher (2012), we integrated this DC model into the CGE

[1]Development of an Evaluation Framework for the INtroduction of Electromobility, funded as part of the ERA−Net Transport electromobility+ call, and coordinated by the Institute for Advanced Studies (IHS). For further information, see `https://www.ihs.ac.at/projects/define/`.

model by deriving an "effective price" for each choice alternative, an "aggregate price" for the purchase of a car of any type (both of which depend on the household′s preferences) and, using Shephard′s Lemma, demand for overall car purchases. The choice probabilities are interpreted as market shares, and serve to split up this overall demand into demand for vehicle purchases of each type. This creates a "hard-link" between the models, which is in line with micro-founded economic theory. Endogenous variables in the CGE model (e.g. prices for vehicles, fuel and taxes, maintenance costs) enter the DC model, which, completely integrated in the CGE model, determines the purchase decision between and hence expenditures on the different vehicle types.

While the numbers of new registrations develop according to this purchase decision, stocks for each of the four alternatives develop according to a standard accumulation and depreciation process. The stock equals last period's stock plus newly registered cars less depreciation of worn out cars.[2] For depreciation, we assume a constant rate of 0.05 for CVs, while for HEVs and xEVs (i.e. PHEVs and EVs), since these are still at the beginning of their lifecycle as a technology, we do not assume depreciation for the first 12 years.[3] After that, the exact amount of vehicles that was purchased 12 periods before depreciates. In this way a detailed and consistent accounting of vehicle stocks and newly registered vehicles is assured.

In order to depict the development of expenditures on the use of the existing fleet for each household over time, we introduce an appropriate consumption structure in the model: Each consumer has the possibility to substitute between public passenger transportation (PPT) and individual transportation (IT) in their mobility behavior.[4] Expenditures on IT include expenditures on purchases of new cars, and expenditures connected to the use of the vehicle stock (fuels incl. taxes, service and maintenance). The share between these expenditures adapts endogenously over time, according to the number of newly purchased vehicles and the size of the vehicle stocks.

Our modeling procedure is designed to appropriately depict the entry of a new technology. It simultaneously allows a distinction between expenditures on purchases and on the use of differently fuelled vehicle types, as well as an assessment of detailed preference-driven shifts between these vehicle technologies, taking account of the time lag that occurs in the stock development.

In our first simulation scenario we use the model to estimate the overall economic costs of the penetration of an estimated fleet size of xEVs until 2030. The shift is moderate and purely preference-driven. We also simulate a moderate investment in charging infrastructure.

In the second scenario we assume a higher charging station availability, and political incentive measures that would boost the uptake of xEVs. Among them an increase in the mineral oil tax on fossil fuels and a raise in the car purchase targets for CO_2-intensive vehicles. In order to correctly assess the reduction in CO_2 emissions of electric vehicles,

[2]We explicitly account for numbers of vehicles (for stocks, newly registered, and depreciating cars) in physical units.

[3]See also Gruden (2008).

[4]The corresponding elasticities of substitution, σ^{mode}, were estimated for each agent on the basis of the results of the survey conducted within DEFINE.

we also account for emissions from the production of electricity, which serves as fuel input for PHEVs and EVs.

The remainder of the paper is as follows. We introduce the concept of a discrete choice model, and show how we establish a hard-link between such a DC model and a CGE model with respect to car purcases in chapter 2. Chapter 3 then discusses how stocks of cars accumulate and depreciate, and how we model expenditures on these stocks by their owners. We describe how the model is calibrated to actual data, and provide scenario results in chapters 4 and 5 respectively. Chapter 6 concludes.

2 Methodology

2.1 The DC Model

In this section we introduce the concept of a discrete choice model, and describe how we use such a DC model at an aggregate level to determine market shares of vehicel purchases among the 4 vehicle types in the CGE model.

The DC model used in this paper was estimated in the DEFINE project, and is based on a representative household survey in Austria in 2013. This allows us to analyse consumption behaviour from a micro perspective, and to derive demand for the choice alternatives (CV, HEV, PHEV and EV, indexed by i). In our modelling framework, we distinguish 9 agents, or household types (indexed by h), by education level and living area (degree of urbanisation). These distinctions are important due to the following. On the one hand, preferences and habits concerning transportation are clearly subject to regional differences. The degree of education, on the other hand, is used firstly as a proxy for income, which definitely has an effect on the affordability of more expensive xEVs, and secondly because we suspected environmental sensitivity to be dependent on the degree of education.

For each of these aggregated household groups, a seperate multinominal logit model was estimated. The alternative specific attributes or variables in these models are purchase price (pp), fuel cost (fc), maintenance cost (mc), power (ps) and range of EVs (ra). The estimations yield for each agent a vector $\beta_{h,i}$ of shadow prices of each of these variables, explaining the representative indirect utility of choice alternative i for household h.

Multiplying the vector of shadow prices with a vector of initial levels $x_{h,i}$ of the variables yields for each household h the indirect utility $V_{h,i}$ of buying a car of type i,

$$V_{h,i} = \beta_{h,i} x_{h,i} + \alpha_{h,i}. \tag{1}$$

Here $\alpha_{h,i}$ is the alternative specific constant (ASC), or base-preference, that denotes that part of the utility of household h for alternative i, which is unexplained by the other variables. Table 1 provides values for the ASCs, and the marginal utility values of the vehicle attributes (components of $\beta_{h,i}$), while table 2 provides the levels of the vehicle attributes (components of $x_{h,i}$), as used in our scenario simulations.

With the help of the indirect utility, the probability $Prob_{h,i}$ of agent h to choose alternative i, given the prior decision to purchase any car at all, is given as

$$Prob_{h,i} = \frac{e^{V_{h,j}}}{\sum_j e^{V_{h,j}}} \qquad \forall h, \forall i. \tag{2}$$

Equations (1) and (2) are referred to as a logit model, or discrete choice model in the literature (see e.g. Train (2003)). In the CGE model these probabilities, since they represent the aggregate level of the 9 agents, can be interpreted as market shares. The share of purchases of car i in total car purchases of household h, $\theta_{h,i}$, is hence

$$\theta_{h,i} := Prob_{h,i} \qquad \forall h, \forall i. \tag{3}$$

So once demand for overall car purchases is known for each agent, demand for cars of type i equals $\theta_{h,i}$ times this overall demand.

	Households by living area		
β entries	**Urban**	**Suburban**	**Rural**
PP	-0.162	-0.152	-0.168
FC	-14.600	-22.300	-13.300
MC	-15.100	-14.200	-15.900
PS_{CV}	0.029	0.033	0.023
PS_{HEV}	0.017	0.017	0.018
PS_{PHEV}	0.025	0.022	0.018
PS_{EV}	-	0.010	0.007
RA	0.003	0.003	0.003
CS_{medium}	-	0.325	0.195
CS_{high}	0.707	0.705	0.558
$IM_{pub.tr.}$	0.436	-	-
MS_{CV}	0.702	0.529	-
MS_{HEV}	0.461	-	-
MS_{PHEV}	0.992	-	-
HS_{EV}	-	0.561	0.855
HS_{PHEV}	-	0.025	-
HS_{EV}	-	0.485	-
α_{CV}	-	-	-
α_{HEV}	0.288	-0.159	-1.120
α_{PHEV}	-0.624	-0.724	-0.698
α_{EV}	-0.279	-2.240	-1.450

Table 1: Marginal utility values of the vehicle attributes (β-entries)

It shall be emphasized here, that these market shares are endogenous in the CGE model, as will be explained in the next section. Apart from exogenous parameters, such as technological assumptions and household preferences, they also depend on price developments, which are endogenously determined in the CGE model: the purchase prices, the fuel prices, taxes, and service and maintenance costs of the different vehicle types.

The resulting numbers of car purchases of each type feed into the build up of vehicle stocks per type. Demand for fuel input, service and maintenance will be determined according to the development of these stocks over time.

Attributes	**Values**
PP_{CV}	25,502
PP_{HEV}	28,801
PP_{PHEV}	35,293
PP_{EV}	51,027
FC_{CV}	0.08
FC_{HEV}	0.07
FC_{PHEV}	0.05
FC_{EV}	0.04
MC_{CV}	0.06
MC_{HEV}	0.06
MC_{PHEV}	0.06
MC_{EV}	0.06
PS_{CV}	122
PS_{HEV}	160
PS_{PHEV}	186
PS_{EV}	146
RA	150
CS_{medium}	-
CS_{high}	-
$IM_{pub.tr.}$	-

Table 2: Attribute levels (initial steady state calibration)

2.2 The Hard Link - Demand For Vehicle Purchases

This chapter describes how we implement the DC model into the CGE model, which enables us to model car purchases as explicit preference-induced decisions by the 9 agents. Their implemented preference structure also allows them to decide to use public transportation as a substitute. When a household decides to purchase a car, then the decision which car to buy occurs in a second stage. In the following we describe how this decision process is modelled and technically implemented.

As is standard practice in applied sectoral CGE models, each household's consumption structure of goods is modelled as a nested CES function. Consumers can substitute between certain consumption goods as shown in Figure 1. We make use of the CES functions in calibrated share form, as proposed by Rutherford (2002).

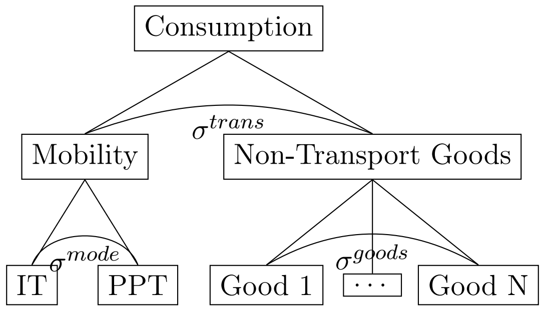

Figure 1: *Consumption structure of households (Nested CES functions)*

Similar as for public passenger transportation (PPT), and other consumption goods, one can think of the individual transport consumption composite (IT) as an economic activity, with a price that we shall call P_h^{IT}. This activity provides the aggregate good individual transportation to households, which includes all vehicle-type-specific mobility goods CV, HEV, PHEV, or EV. From an accounting point of view, expenditures on IT include monetary flows connected to purchases of cars, as well as to the use of the vehicle stock, i.e. expenditures on fuels, taxes, service and maintenance.

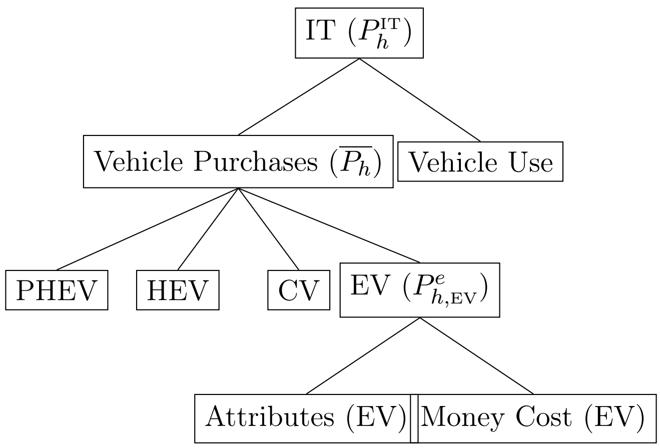

Figure 2: *Individual transport consumption structure (DC model of the purchase decision)*

In order to derive demand for overall car purchases for each consumer household, $\overline{D_h}$, we need a price for the abstract consumption good of aggregate car purchases per agent which we shall call aggregate price for overall car purchases, $\overline{P_h}$. Then we can derive unit final consumption demand for car purchases using Shephard's Lemma.

Usually in cases where many single goods (here different car types) are combined into a consumption bundle (here cars in general), such an aggregate price is derived in CGE models via a CES combination of the prices of the single components. However, the purpose of this paper is to model the choice between the different vehicle types as endogenously depending on more attributes than just on the purchase prices of the different car types, specifically on several vehicle-type-specific variables and on consumer-specific preferences. Hence a CES combination is not the appropriate method.

Following Truong and Hensher (2012) we use an effective price $P^e_{h,i}$ for each choice alternative i and each agent h, which accounts for all the attributes and characteristics $x_{h,i}$, and can be interpreted as the consumer's perceived value of the vehicle at the purchase decision. We then derive the aggregate price for overall car purchases $\overline{P_h}$ with the help of the effective prices $P^e_{h,i}$. Demand for overall car purchases, $\overline{D_h}$, is determined according to Shephard's Lemma, and finally, the logit probabilities are used to determine demand for each vehicle type $D^{\text{pur}}_{h,i}$.

Specifically, the indirect utility $V_{h,i}$, can be written as

$$\begin{aligned} V_{h,i} = {} & \beta^{\text{cm}}_{h,i} x^{\text{cm}}_{h,i} + \beta^{\text{cf}}_{h,i} x^{\text{cf}}_{h,i} + \beta^{\text{pp}}_{h,i} x^{\text{pp}}_{h,i} + \\ & \sum_{\text{rest}} (\beta^{\text{rest}}_{h,i} x^{\text{rest}}_{h,i}) + \alpha_{h,i} \qquad \forall h, \forall i, \end{aligned} \tag{4}$$

for each choice alternative, where the superscript indices denote the single components of the vectors $x_{h,i}$ and $\beta_{h,i}$, purchase price (pp), fuel costs (cf) and maintenance costs (cm). In difference to Truong and Hensher (2012), we derive a money cost variable, $x^{\text{money}}_{h,i}$, defined as

$$\begin{aligned} x^{\text{money}}_{h,i} := \frac{\beta^{\text{cm}}_{h,i}}{\beta^{\text{money}}_{h,i}} x^{\text{cm}}_{h,i} + \frac{\beta^{\text{cf}}_{h,i}}{\beta^{\text{money}}_{h,i}} x^{\text{cf}}_{h,i} + \frac{\beta^{\text{pp}}_{h,i}}{\beta^{\text{money}}_{h,i}} x^{\text{pp}}_{h,i} \\ \forall h, \forall i, \end{aligned} \tag{5}$$

where $\beta^{\text{money}}_{h,i} := \beta^{\text{cm}}_{h,i} + \beta^{\text{cf}}_{h,i} + \beta^{\text{pp}}_{h,i}$. This additional aggregation is necessary for deriving the effective price, since this derivation requires the marginal utility value of money, which is unique. Now $V_{h,i}$ can be expressed in terms of $\beta^{\text{money}}_{h,i}$, as

$$\begin{aligned} V_{h,i} = \beta^{\text{money}}_{h,i} x^{\text{money}}_{h,i} + \sum_{rest} (\beta^{rest}_{h,i} x^{rest}_{h,i}) + \alpha_{h,i} \\ \forall h, \forall i, \end{aligned} \tag{6}$$

a formulation that distinguishes the input variables into a monetary variable and the other non-monetary variables. Here it is obvious that $\beta^{\text{money}}_{h,i}$ is the marginal utility value of money, since it denotes the value of monetary costs compared to the value of other variables' contribution to household's utility of choice alternative i.

The effective price for vehicle purchases, as stated above, is an aggregate variable that includes all characteristics and attributes of a choice alternative, and translates them into monetary terms. So if the effective price $P^e_{h,i}$ of choice alternative i is known, the indirect utility function can be expressed as

$$V_{h,i} = \beta_{h,i}^{\text{money}} P_{h,i}^{e} + \alpha_{h,i} \qquad \forall h, \forall i, \tag{7}$$

where $\alpha_{h,i}$ is the alternative specific constant.

Making use of this formulation and knowing the explicit form of the indirect utility function, (1), one can actually calculate the effective price for choice alternative i to be

$$P_{h,i}^{e} = \frac{V_{h,i} - \alpha_{h,i}}{\beta_{h,i}^{\text{money}}} = \sum_{n} \frac{\beta_{h,i}^{n}}{\beta_{h,i}^{\text{money}}} x_{h,i}^{n} - \frac{\alpha_{h,i}}{\beta_{h,i}^{\text{money}}} \qquad \forall h, \forall i. \tag{8}$$

For each agent, we now derive with the help of the effective prices $P_{h,i}^{e}$, the aggregate price of purchasing any type of car $\overline{P_h}$, which will enable us to derive total demand for car purchases $\overline{D_h}$. The aggregation procedure can not follow a simple CES logic, since purchase shares of different vehicle types will change endogenously according to non-monetary variables. Hence, as proposed by Truong and Hensher (2012), one needs to go back to the indirect utility function and define the logsum, or inclusive value, $\overline{V_h}$ of all vehicle types as

$$\overline{V_h} := \ln \sum_{i \in I} \exp(V_{h,i}) \quad \forall h. \tag{9}$$

It represents total consumer surplus associated with all choices for a particular choice set, and indicates the expected maximum utility for these choices. The total differential of this inclusive value, i.e. its change due to an infinitesimal change in all attribute variables is denoted by

$$\mathrm{d}\overline{V_h} = \sum_{i \in I} Prob_{h,i}\ \mathrm{d}V_{h,i} \quad \forall h. \tag{10}$$

Substituting (7) for $V_{h,i}$ one gets

$$\begin{aligned} \mathrm{d}\overline{V_h} &= \sum_{i \in I} Prob_{h,i}\ \mathrm{d}(\alpha_{h,i} + \beta_{h,i}^{\text{money}} P_{h,i}^{e}) = \\ &\beta_{h,i}^{\text{money}} \sum_{i \in I} Prob_{h,i}\ \mathrm{d}P_{h,i}^{e} \quad \forall h, \end{aligned} \tag{11}$$

and defining the change in the aggregate price for car purchases $\overline{P_h}$ as

$$\mathrm{d}\overline{P_h} := \sum_{i \in I} Prob_{h,i}\ \mathrm{d}P_{h,i}^{e} \quad \forall h, \tag{12}$$

yields

$$\mathrm{d}\overline{V_h} = \beta_{h,i}^{\text{money}} \mathrm{d}\overline{P_h} \quad \forall h. \tag{13}$$

This represents economic intuition, since the marginal value of the utility of money

($\beta_{h,i}^{\text{money}}$) is by definition equal to the marginal change in utility due to a marginal change in the price for the good in question. However, the crucial point here is that $P_{h,i}^{e}$ includes not only "real" monetary costs as purchase price, fuel and maintenance costs, but also all non market attributes and their shadow prices by construction. Since the operator d is linear and since the integral of any function is unique up to a constant, by integrating (13) we have

$$\overline{P_h} = \frac{\overline{V_h}}{\beta_{h,i}^{\text{money}}} + c_h \quad \forall h, \tag{14}$$

The constant c_h is determined in the calibration procedure, in such a way that the equation holds with the initial values of the other variables and parameters. Here one can see from the definition of $\overline{V_h}$ that changes in the utilities of the choice alternatives determine changes in the aggregate price of purchasing a car, $\overline{P_h}$, as would be expected.

Overall demand for car purchases of any kind, $\overline{D_h}$, is derived in a standard manner according to Shephard's Lemma by differentiating the expenditure function of each household with respect to the aggregate price for car purchases

$$\overline{D_h} = \frac{\partial e(p_{x1}, p_{x2}, ..., \overline{P_h})}{\partial \overline{P_h}} \quad \forall h, \tag{15}$$

where $e(.)$ is the unit expenditure function of household h. This aggregate demand level is now split up between the choice alternatives according to the market shares as derived in (3). Demand for vehicle purchases of type i by agent h, $D_{h,i}^{\text{pur}}$, is hence equal to

$$D_{h,i}^{\text{pur}} := \overline{D_h} Prob_{h,i} \quad \forall h, \forall i. \tag{16}$$

With this method, we end up with the price $\overline{P_h}$, the demand $\overline{D_h}$ for overall car purchases, and the demand for purchases of each single vehicle type $D_{h,i}^{\text{pur}}$, depending on consumer preferences $\beta_{h,i}$ and vehicle attributes $x_{h,i}$, which can be exogenously varied in scenario simulations. However, these three variables, $\overline{P_h}$, $\overline{D_h}$ and $D_{h,i}^{\text{pur}}$, are all truly endogenous variables, since they depend on the money costs of each choice alternative in particular. This monetary cost is the sum of maintenance, purchase and fuel costs, all of which are endogenous variables in the CGE model, determined in the overall economic equilibrium. Hence, this representation of the purchase decisions reflects detailed consumer behaviour, and accounts for changes in prices and also exogenous variables, while it does not leave the borders of micro-founded economic theory.

Equation (15) is still very abstract. In order to explicitly arrive at the aggregate demand level for car purchases of any kind, $\overline{D_h}$, one needs to take into account the detailed expenditure structure of vehicle purchases and vehicle use. This is explicitly done in the next chapter. Before, however, we introduce a detailed way of how to account for the development of the stocks of the different vehicle types.

3 Modelling Stock Development

An important matter of modelling the diffusion of new types of cars is the modelling of consumer expenditures that are connected to cars. In the following, we will refer to expenditures on purchases of cars as "flows-expenditure", denoting an expenditure that is connected to the new flow, or increase, of cars that adds to the vehicle stock. We will call expenditures on fuels, taxes and maintenance "stock-expenditures", since these are expenditures that occur to each household in direct proportion to the size of the vehicle stock owned.

Vehicle stocks for the alternatives CV, HEV, PHEV and EV in the model develop according to a standard accumulation and depreciation process. We account for the vehicle stocks in physical units, not in monetary units, in order to avoid issues with price changes and their influence on the monetary value on the worth of the vehicle stock. The average lifetime of a car is assumed to be 12 years.[5]

The vehicle stock $st_i(t)$ of vehicle type i equals last period's stock plus new registrations $nr_i(t)$ less depreciation of worn out cars $dc_i(t)$. We follow the convention that purchases of new vehicles and depreciation of old vehicles both take place at the end of each period, hence the stock in each period t is

$$st_i(t) = st_i(t-1) + nr_i(t-1) - dc_i(t-1) \quad \forall i, \forall t. \tag{17}$$

One might say that the level of new registrations is the core of the modelling framework. It is determined by the demand for purchases of new vehicles $D^{\text{pur}}_{h,i}(t)$, as described in the previous subsection, and determines the stock development. Specifically, new registrations are defined as

$$nr_i(t) = \frac{e^{\text{pur}}(0) D^{\text{pur}}_{h,i}(t)}{P^{\text{av}}_i(t)} \quad \forall i, \forall t. \tag{18}$$

Here $e_{\text{pur}}(0)$ denotes the volume of expenditures on car purchases in the starting period, hence the zero argument, and $P^{\text{av}}_i(t)$ is the average monetary price of purchasing a vehicle of type i, which is also an endogenous varibale in the model. It must be noted, that the number of new registrations of vehicles depends on this average price in two ways. Firstly, the demand for purchases of new vehicles $D^{\text{pur}}_{h,i}(t)$ is formed taking account of this average monetary purchase price. Secondly, once the amount of money that will be spent on cars is determined, the average monetary purchase price for cars also determines the quantity of cars that are bought with that allocated amount of funds.

For depreciation of CVs, since we do not know the distribution of the age of cars among the current vehicle stock, we assume a constant depreciation for the first 12 periods in the model,

$$dc_{\text{CV}}(t) = st_{\text{CV}}(t)\delta_{\text{CV}} \text{ for } t \leq 12. \tag{19}$$

For other vehicle types, since we are still at the moment of introduction to the vehicle market, we do not assume depreciation for the first 12 years. After the 12th period, however, the exact amount of vehicles that was purchased 12 periods before depreciates:

[5] See also Gruden (2008)

$$dc_i(t) = nr_i(t-12) \text{ for } t > 12. \tag{20}$$

In this way a detailed stock-flow consistent accounting of the vehicle stocks, new registrations, and depreciation is assured.

As xEVs currently enter the market, and are at the beginning of their lifecycle as a technology, the vehicle stock is only increasing in the first years. This means that there is no depreciation of old cars yet, since they are newly bought and still below their average life expectancy. This is why stock-expenditures will, after an initial lag grow much stronger than flow-expenditures, however depending on the growth of new registrated vehicles. After some years, assuming the technology successfully entered the market, a stabilization of the procedure may be expected due to depreciation of old cars. Only then can stock and flow expenditures eventually reach the steady state growth rates of the economy, and grow at the same rate, as is more or less the case for CVs at the moment.[6] Depending on the extent that xEVs will enter the market, demand for new CVs may be expected to decrease, reducing the stock of CVs, again with a time lag.

In order to be able to depict such developments in the model, we introduce a new nesting structure. The consumption bundle of households in the model enters, together with their leisure, their overall intertemporal utility, which they try to maximize over the model horizon, see Figure 1.

One component of the consumption bundle is individual transportaton. We split individual transportation into two components: expenditures on purchases of new cars, and expenditures on the use of existing cars. The latter consists of expenditures on fuels, and maintenance, the shares between which are assumed to stay constant over time.

The amount spent on purchases and on the use makes up the total value of individual transportaton. Unlike in other nests in the consumption function, here households are assumed to be unable to substitute between these two components. This is because we assume household's purchase decisions to be independent from the intensity at which they drive thier cars.

Hence, the total value of expenditures on individual transport depends on the total demand for purchasing new cars $\overline{D_h}$, as well as on the demand for vehicle use, which is determined by the development of the vehicle stocks, and shall be denoted by $D^{\text{use}}_{h,i}$. The share between these two components will endogenously be determined, accordingly. Hence, as shown in Figure 2, the individual transportation nest is also modelled as a two-stage Leontief nest, where the shares are exogenous in the first period, and endogenously adapt according to the households purchase decisions and the thereby induced vehicle stock developments over time.

We consider this modeling procedure a very realistic depiction of circumstances, since it allows expenditures on vehicle purchases to develop with new registrations, and expenditures on the use of vehicles to develop with the vehicle stock.

Taking these ideas to formal modelling, we need, in order to arrive at the demand for purchases of any kind of cars $\overline{D_h}$, see equation (15), a price for the individual trans-

[6] More on steady state growth and the different growth rates of the vehicles will be said in the calibration chapter

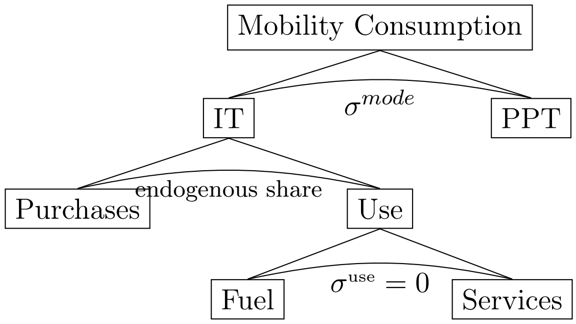

Figure 3: *Structure of households' expenditures on mobility.*

portation composite, IT, which we determine as a CES composite of car purchases and expenditures on the use of existing cars,

$$\begin{aligned} P_h^{\text{IT}}(t) \quad &= \quad \Theta_h^{\text{pur}}(t)\overline{P_h}(t) \quad + \\ (1-\Theta_h^{\text{pur}}(t)) &\sum_i \Theta_{h,i}^{st}(t)P_{h,i}^{\text{FS}}(t) \quad \forall h \end{aligned} \tag{21}$$

It determines overall demand for IT, and is implicitly used in equation (15).

Here $P_{h,i}^{\text{FS}}$ is the monetary price aggregate of fuel and service inputs in vehicle use. We assume that the use of these factors stay in constant proportion to each other over time,

$$P_{h,i}^{\text{FS}}(t) = \theta_i^{\text{FS}}(t)P^S(t) + (1-\theta_i^{\text{FS}}(t))P_i^F(t) \quad \forall h, \forall i. \tag{22}$$

The expenditure connected to this price composite, however, also depends on the rate of fuel taxes, which applied to fuel use.[7] The size of expenditures on this fuel and services input composite develops with the size of the vehicle stock.

We use the capital greek letter Θ to denote endogenous shares, typically implying a qualitative change in a Leontief consumption nest over time, as the vehicle stocks build up or shrink.[8] The endogenous share parameter $\Theta_{h,i}^{st}(t)$ in equation (3) is the share of the size of the stock of cars of type i in the total stock of vehicles owned by household h,

$$\Theta_{h,i}^{st}(t) = \frac{st_i(t)}{\sum_j st_j(t)} \quad \forall h, \forall i, \tag{23}$$

[7] The fuel tax rate is varied in scenarios, which leads to a change in the $\theta_i^{\text{FS}}(t)$ share over time, making also this share an endogenous variable. However this does not have a structural implication on the model's functioning as a whole and is therefore not explained her ein detail.

[8] The time index is naturally implied in all model equations, since the model is intertemporal. However, for reasons of simplicity, we decided to explicitly include it in the description only where it is necessary, in the sense that time plays an active role, as it does in the equations of this section. These are intertemporal equations, linking different time periods together, whereas equations in the previous section are intratemproal equations, which hold in each period, but do not link periods.

with

$$\sum_i \Theta^{st}_{h,i}(t) = 1 \quad \forall h, \forall t. \tag{24}$$

The other endogenous share paramter in equation (3), $\Theta^{\text{pur}}_h(t)$, denotes the share of expenditures on car purchases in total expenditures for individual transportation for household h in period t,

$$\Theta^{\text{pur}}_h(t) = \frac{\sum_i e^{\text{pur}}(0) D^{\text{pur}}_{h,i}(t)}{\sum_j \left[e^{\text{pur}}(0) D^{\text{pur}}_{h,j}(t) + e_{\text{FS}}(0) D^{\text{use}}_{h,j}(t)\right]}$$
$$\forall h, \forall t. \tag{25}$$

Here $e_{\text{pur}}(0)$ is the volume of expenditures on purchases of cars and $e_{\text{FS}}(0)$ denotes the volume of expenditures on fuel and services (which is associated with using the cars), both in the starting period. The new Variable $D^{\text{use}}_{h,i}(t)$ is the level of demand for using the vehicles, which is assumed to develop in a constant relationship to the vehicle stock:

$$D^{\text{use}}_{h,i}(t) = \frac{st_i(t)}{st_i(0)} \quad \forall h, \forall i, \forall t. \tag{26}$$

4 Calibration

We calibrate the model to a social accounting matrix (SAM) for Austria representing flows of funds between sectors, households, the state and the rest of the world in 2008. The SAM is constructed out of input output tables, EU SILC[9] and Labour Force Survey data, as well as data on vehicles which was specifically estimated from a vehicle consumption survey carried out in the DEFINE project.

One difficulty in the calibration procedure was the fact that the estimated logit model which is included in the CGE model, see equations (1) and (2), yields market shares for vehicle purchases by household type which do not match the consumption shares by households in the SAM. This is due to the fact that for the projections of the vehicle stocks, a much more detailed version of the discrete choice model was used than the one implemented in the CGE model. In order to reach these more detailed market shares with the implemented version of the logit module, we used the alternative specific constants $\alpha_{h,i}$ in the households' estimated utility functions 1, as an additional degree of freedom while calibrating the model.

The calibration procedure also involves assuming the economy to be in a steady state equilibrium over an infinite time horizon. This implies all quantities to grow at the same growth rate, and the expected present value of all prices to develop at the same discount rate, the long term interest rate. The initial steady state equilibrium is the result of the assumption that in 2008 all expenditures by all sectors and agents are part of the intertemporally optimal social allocation of resources.

[9]Statistics on Income and Living Conditions.

The difficulty in calibrating our model to a steady state is the connection between stocks and new registrations of the different vehicle types. Since in a steady state, all variables must grow at the same rate, we desire the expenditures on vehicle use (fuel and maintenance costs) and those on vehicle purchases to grow at the same rate, the exogenous steady state growth rate gr. This implies vehicle stock sizes and the number of new registrations to grow at this rate as well,

$$\begin{aligned} st_i(t) &= st_i(0)(1+gr)^t, \\ nr_i(t) &= nr_i(0)(1+gr)^t \forall i, \forall t. \end{aligned} \tag{27}$$

Obviously, the vehicle stock in each period also has to be that of the preceeding period plus new registrations minus depreciated cars of the preceeding period, see equation (17).

Combining these conditions one obtains that the initial number of new registrations must be in a fixed relation to the vehicle stock,

$$nr_i(0) = st_i(0)(gr + \delta_i), \quad \forall i. \tag{28}$$

Here δ_i is the depreciation rate of the vehicle stock of type i, meaning that at the end of each period, the fraction δ_i of the stock of vehicles of type i depreciates.

The numbers of new registrations and stocks per vehicle type, as well as their average prices, were derived and estimated by Umweltbundesamt (UBA) Vienna within the DEFINE project. Clearly, average prices combined with physical units of new registrations imply expenditures on vehicle purchases. This calculation was used to construct total expenditures on vehicle purchases of each type in the social accounting matrix. These expenditures were divided between the different household types according to market shares that were computed by a very detailed version of the discrete choice model mentioned above, see equations (2) and (1). In order for vehicle stocks to develop in line with new registrations and depreciation, we used equation (28) to determine steady state depreciation rates for each vehicel type. This is the only degree of freedom, since for the first time period the other parameters (new registrations and the size of the vehicle stock), are given from data. Due to the fact that xEVs are yet in the phase of entering the market, xEV-stocks are extremely small in relation to new registrations of xEVs (compared with CVs). Hence depreciation rates for xEVs resulting from (28) are unrealistically high[10].

However, this is not a problem, since the initial steady state merely serves as an initial "checkpoint" that ensures that the model is calibrated correctly. Any results of our policy scenarios are not compared to this initially calibrated steady state, but to a benchmark (BMK) scenario. This BMK scenario, or BMK growth path, differs from the initial steady state in that it depicts a realistic development of the economy without policy action. With respect to the vehicle stock, this means the following: Within the BMK scenario, and also in all policy scenarios, we do not account for xEV depreciation for the first 12 years, which is the assumed average lifetime of a car. After that, the exact number of vehicles bought 12 periods earlier depreciates. In our view, this is an extremely

[10]Steady state depreciation rates: CVs: 0.05, HEVs and PHEVs: 0.24, EVs: 0.26.

realistic depiction of depreciation, because xEV stocks were practically zero in 2008, and started to build up only after that. Clearly, this exact period-by-period depreciation accounting is more precise than using a constant depreciation rate. Especially in the feed-in phase of a new technology in a durable goods market that is subject to inertia, as is the case with cars, this is extremely important in order to assess stock developments as accurately as possible.

The model is not used to specifically forecast actual levels of economic variables, but to accurately assess policies' influences on the levels of economic variables. Model results, which are discussed in the next section, are always differences between variables' levels in one scenario and their levels in other scenarios.

5 Scenario Simulations

We calibrated the model to a steady state growth path, where we assume an average long-term growth rate of 1% per year. Then we derived a BMK growth path, which parts from the steady state due to the following reasons: We introduce realistic development of fuel costs, vehicle depreciation (as lined out in detail in the previous section), average prices for the different vehicle types, realistic capacity expansions for energy producing technologies, as well as an increase in the tax on fossil fuels and an adaption of the tax on the purchase of new vehicles (NOVA).[11] The tax adaptions took place in 2011 and are hence part of our benchmark model run. All these assumptions were derived by the Umweltbundesamt Vienna within the DEFINE project.[12] This benchmark growth path describes an economy in which there is a very small shift-in of xEVs, barely worth mentioning, since basic preferences of households do not change, and the fuel cost and price effects have very little influence on the households' mobility preferences. There is also no build-up of charging infrastructure assumed in this benchmark growth path.

5.1 The Business-As-Usual Scenario

The benchmark growth path serves as our basic scenario, to which we compare our so called business-as-usual (BAU) scenario, in which we simulate a build-up of charging infrastructure, and a preference shift in the population in favour of electric vehicles.

We assume that the build up of charging infrastructure is financed completely by private investments. In the BAU these investments are assumed to start in 2008 at 0.52 million Euro and grow with an average annual growth rate of 30% to reach 189 million Euro in 2030. The additional demand created by these investments is attributed to the engineering (34%), building (56%) and service (10%) sectors.

The shift in of electric vehicles in our model is calibrated to meet the vehicle stock projections derived by UBA in the DEFINE project. The stock of CVs grows from 4.3 million vehicles to 5 million in 2020 and then declines to 4.48 million in 2030. HEVs

[11] The NoVA (short for "Normverbrauchsagbage") is the Austrian new car registration tax, which is related to emission standards. Currently there is an additional 50 Euro penalty for each g/km between 180g/km and 220g/km, and 75 Euro for each g/km above that.

[12] see their deliverable in DEFINE at `www.ihs.ac.at/projects/define`

start at 1.529 vehicles and grow exponentially to reach a stock of 534.000 vehicles in 2030, similar as PHEVs and EVs, which start at 911 and 60 vehicles in 2008 and reach a number of 800.000 and 86.200, respectively. We model the shift-in as an unexplained prerference shift. We thereby calibrate the ASC in the logit module ($\alpha_{h,i}$) in such a way that the purchase shares of new vehicles ($\theta_{h,i}$) develop just in the right way so that the stocks of the different vehicle types meet UBA's yearly projections.[13]

GDP effects of the charging station expansion are positive throughout the time periods, since investments stimulate the economy. On the contrary, the preference-driven shift-in of electric vehicles causes a reduction of government income from mineral oil tax and NOVA revenues, as the stock and purchases of CVs are replaced by xEVs. Furthermore, the shift-in changes the structure of intermediate inputs and thus the import share of the Austrian economy, leading to a slight loss in GDP. The most important effect on GDP, however, is an increase in the price of individual transport implying a reduction of household consumption.[14] Overall the GDP still grows at a ratio of 0.97%, which equals a loss of 120 million Euro in 2030 compared to potential GDP, as in the benchmark growth path. The distribution of the vehicle stocks in 2030 shows that urban low skilled, urban high skilled, and rural low skilled households have a clear preference for PHEVs and EVs, while medium skilled households hold the same share of all vehicle types in the total population. According to UBA's projections, total CO_2 emissions go down by 1 million tons per year compared to the growth path. Hence, taking the output gap as cost measure here, the GDP costs per ton reduction of CO_2 through electric vehicles in the BAU are 120 Euro/tCO_2.[15]

5.2 The Electromobility-Plus Scenario

As opposed to the BAU scenario, where we do not assume any political incentive measures that would boost the uptake of xEVs, we present our electromobility-plus (EM) scenario in which there is clear political will and medium- to long-term committment to policies in favor of electromobility.

Among many possible political incentives to induce a higher shift-in, we concretely focussed on the following measures. The first is a two fold increase of 5 cent in the mineral oil tax on fossil fuels in 2015 and in 2019. The second is a raise in the NOVA tax of 75 Euro for each gCO_2/km exceeding a certain emission limit. This limit is currently at 220g/km, and is assumed to be set to 105g/km in 2015, and 95g/km in 2020.

We assume service providers, influenced by these political incentives, to invest significantly more in charging infrastructure. Compared to the BAU scenario, we assume

[13] Since we can only calibrate the purchase shares, but not the total numbers of vehicle purchases, we do not exactly meet UBA's projections. Our result is concise with UBA's xEV targets, but we miss the CV target by 400.000 vehicles.

[14] xEVs have higher purchase prices than CVs and HEVs, therefore their higher number increases the price of individual transport. As households cannot fully substitute the transport good with other goods in our consumption nesting, the overall consumption of transport is decreased.

[15] These costs seem high, however these are net social costs, accounting for the whole economic adaptation based on household preferences, and should not be confused with technology costs of CO_2 abatement.

additional average yearly investments of 65 million Euro between 2020 and 2025, and of 400 million between 2025 and 2030.

Additionally we assume a different price development of vehicles. The purchase price of CVs rises linearly to an increase of 9% in 2030, prices of HEVs, PHEVs, and EVs fall linearly and end up at a reduction of 3%, 7% and 2% respectively, compared to their BAU levels. Fuel costs for CVs rise by 3% compared to the BAU between 2015 and 2019, and by 7% after 2020, those of PHEVs rise by 10%. These additional costs may seem unrealistisc at first sight, but arise by differences in vehicle efficiency. Detailed assumptions can be read in UBA's deliverable in the DEFINE project. Finally there is an additional public incentive measure in this scenario. Purchasers of EVs receive the offer of a public railway season ticket.

Electricity demand depends on the interaction between the electricity system and the xEV fleet and on the size of the latter. Peaks in electricity production of renewables coincide with different intensities of vehicle use and charging. xEVs can be used to accomodate peaks in production as storage facilities but can also increase peak demand. We calibrated electricity production per technology in the CGE model[16] to aggregate yearly data that is built on the results of an hourly load−flow simulation model of the Austrian electricity system, which accounts for these issues.[17] This allows us to depict changes in the structure of the electricity sector.

In the EM scenario, the GDP effects of charging station expansions are positive, and as expected substantially higher than in the BAU: plus 88 million Euro (0.03% of GDP) in 2015 and 360 million Euro (0.1%) in 2030.

While in the BAU we had a reduction of tax revenues, here we do have a significant increase in domestic tax revenues, due to the raise in the tax rates, the high CV stock and the inertia of vehicle use and fuel consumption (we assumed a demand elasticity of 0.34). The rise in the NOVA also significantly reduces the NOVA revenue losses we saw in the BAU, so that overall domestic government revenues are clearly positive. However since Austria has a lower mineral oil tax than her neighbour countries, one can assume that a rise in this tax will subtract government revenues and fuel exports of the so called phenomena of "fuel tourism", i.e. people from abroad purchasing fuel in Austria due to the cheaper gross price. This occurs in passenger transport and in transport of goods and products. According to the actual loss of revenues and exports that occurred in 2011 when the mineral oil tax was raised by 5 cent, and with the help of transport estimations by UBA, we calculated price elasticities of demand for the tax loss (0.15) and export losses (0.23) due to this phenomenon, and included these in the model. Overall the government has a significant budget surplus of 508 million Euro in 2015, and still 267 million Euro in 2030, compared to the BAU.

As concerning GDP, the tax increases clearly press on household demand in this scenario, reducing consumption and GDP growth (and hence also government revenues from

[16]The CGE model is a hybrid bottom-up top-down model, see Böhringer and Rutherford (2008), depicting several electricity production technologies that differ in CO_2 intensity, production costs and capacities.

[17]See `eeg.tuwien.ac.at/HIREPS`. The results, and detailed assumptions for the electricity input in the CGE model were derived in the DEFINE project, see `https://www.ihs.ac.at/projects/define/`.

other taxes). The export loss due to the rise in fuel prices also has a negative effect. The overall effect of all measures in the EM scenario causes GDP to go down by 563 million Euro (0.18% of GDP) in 2015, 397 million in 2020, one year after the second shock, and then to go back to 223 million ? in 2025, due to long-term adaptation of household behaviour, and finally go up to 1.01 billion Euro (0.28%) in 2030, compared to the BAU scenario. This shows that the most important effect on GDP is an accumulation effect. The capital stock does not grow as fast as in the BAU scenario because of the above mentioned single negative effects, so that the total effect on GDP becomes worst towards the end of the period.

These costs are opposed with a significant effect of the policy measures in the EM scenario on the vehicle fleet. Differently than in the BAU, where we modelled an unexplained preference-driven shift-in of a certain size of the xEV fleet, in the EM scenario the number of xEVs is an endogenous model result. Households in our model react to changes in prices and taxes, and endogenously decide which vehicles to purchase, as explained in section 2 of this paper. The measures simulated in the EM scenario lead to a total stock of EVs of 175,500 vehicles in 2030 (plus 104% compared to the BAU). The stock of PHEVs equals 1.35 million vehicles by 2030. In total, this is a plus of 72% more xEVs. If one looks at the numbers of new registrations, the picture is even more drastic. By 2023 the number of newly bought PHEVs is higher than that of CVs. In 2030 EVs are bought more often than CVs and HEVs, and the number of xEVs is more than double than that of CVs and HEVs.

According to UBA's projections, total CO_2 emissions in the EM scenario go down by 1.2 million tons in the year 2030. [18]

6 Conclusion

Altogether, model simulations show that electromobility can contribute substantially to the reduction of CO_2 emissions in the transport sector under reasonable economic costs (from an environmental perspective). A crucial requirement for this possibility, however, is the preference shift by households to electromobility assumed in the BAU scenario.

Both scenarios show expansive economic effects for infrastructure investment. Furthermore, the political measures simulated in the EM+ scenario show high effectivity: they almost achieve a doubling of the amount of xEVs in the vehicle fleet (72 %) and increase government revenues at the same time - with costs of GDP growth of less than 0.3 % in 2030.

Due to the high shares of xEVs in total new registrations (68 %) in the EM+ scenario (year 2030), one can expect a virtual shift-out of CVs from the vehicle fleet beginning with the end of the decade 2030 - 2040 (given the assumptions on vehicle fleet depreciation made here). These results indicate that consumer demand might react quite flexibly in

[18]Unfortunately a more detailed emission accounting system within the CGE model, also accounting for emissions in the electricity sector, is not yet finished due to the delay of a partner's DEFINE deliverable. Hence the net social costs of CO_2 abatement due to public policy in connection with electromobility will be discussed in a later version of this paper.

the direction of a high penetration of electric vehicles. Given that supply can meet this demand, structural change in the individual transport sector away from fossil fuels to electromobility seems feasible from an economic perspective within the next decades.

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