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Modelling Electric Vehicles as an Abatement Technology in a Hybrid CGE Model

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Abstract:

We present a novel methodology to quantify the social costs and benefits (net social costs) of electric vehicles as an endogenous, demand-driven abatement technology in a general equilibrium framework. This new costing approach relates general equilibrium effects resulting from an increased market penetration of electric vehicles to the external environmental and health effects of the corresponding change in emissions. To this end, we develop a hybrid model combining a computable general equilibrium (CGE) with a discrete choice (DC) model that is capable of depicting an endogenous demand-driven uptake of alternative fuel vehicles. The discrete choice model of the consumer purchase decision between conventional, hybrid, plug-in hybrid, and electric vehicles is directly integrated into the CGE model. This hybrid CGE-DC model features a detailed accounting of vehicle fleet development, including yearly numbers of vehicle purchases and cohort depreciation. It depicts nine households differentiated by the degree of urbanization and education, accounts for detailed consumer preferences for the purchase of a passenger vehicle and mode choice decisions. The hybrid CGE-DC model is additionally hard-linked to a bottom-up module for electricity production by several technologies to provide input for an established impact pathway analysis to quantify

the external costs relating to the changed composition of the vehicle fleet and technologies to generate electricity. We apply this methodology to Austria as an empirical example, considering current measures and trends for the uptake of electric vehicles into the vehicle fleet. In particular, we quantify the net social costs of additional measures to foster the introduction of electromobility that are part of the current policy discussion in Austria, and thus provide a blueprint for further application in different national contexts.

JEL: C68; D12; D58; H22; H23; Q43; Q52; R42

Keywords: hybrid CGE model; discrete choice; electric vehicles; environmental benefits

1. Introduction

Depending on the fuel-mix to generate energy and modal split, individual motor vehicle transportation is responsible for up to 40% of total greenhouse gas (GHG) emissions, and for up to 30% of total emissions causing acidification and smog formation (Kerkhof et al., 2009), (Mach et al., 2018). It is crucial for policy makers to select a cost-efficient way of approaching emission policy targets, such as the Climate-Energy targets set at 20-20-20 by 2020 or 40-27-30 by 2030, and the technology and emission standards set for producers of vehicles, in particular the EU Regulation 333/2014 setting the average emission target for new vehicle fleet at 95 g CO₂ per km in 2020.¹

When assessing economy-wide implications of abatement technologies, it is key to look at an economy from the macroeconomic perspective to understand the broad welfare impacts of abatement measures. Thus, the top-down approach, most often represented by a computable general equilibrium (CGE) model, has been increasingly used in the literature. CGE models maximize social welfare through the substitution of production factors. However, Kiuila and Rutherford (2013) suggest that in CGE models abatement technologies are either not incorporated due to lack of technology detail or, if they are modeled, their cost is disproportionately higher in comparison to substitution of fuels, which then becomes the preferred abatement channel in such models. Consequently, abatement is exogenous in CGE models and therefore the only way to decrease GHG or air emissions is through a KLEM factor switch, or by reducing sector output leading to higher sectoral unemployment. This is problematic because the disregard of abatement technologies in a CGE modeling setup considerably biases the economic cost of environmental policies upward (Nestor and Pasurka, 1995). Therefore, it is essential to incorporate abatement technologies and abatement costs into a CGE model in an endogenous manner. Moreover, this lack of technological explicitness results in decreased capacity of CGE models to evaluate the full scope of energy-related policies (Jaccard, 2009) - hence they are unable to control for fundamental restrictions on matter and energy conservation (Böhringer and Rutherford, 2009).

A detailed representation of the energy sector is the domain of engineering partial equilibrium bottom-up models, such as TIMES (Rečka and Ščasný, 2016). These models are also able to capture interactions between energy carriers, energy technologies, and other aspects of the energy sector, including restrictions on fuel availability or technology deployment. The models optimize a technology-mix to satisfy pre-defined electricity demand or demand for energy services. However, the energy system models disregard the economy-wide impacts and consider behavioral aspects and decisions in a limited way. While top-down models can capture indirect abatement costs but usually disregard the technology detail, the bottom-up class of models is the best choice to determine direct abatement costs (Kiuila and Rutherford, 2013).

In order to overcome their shortcomings while combining their strengths, these two modelling approaches - top-down and the bottom-up models - have been soft-linked, hard-linked, or fully integrated².

¹At the EU level, Directive EC/443/2009 and EC/510/2011 amended by Regulation 333/2014, set the operating framework for reaching the CO₂ emission targets for producers of passenger cars and vans, respectively. The Fuel Quality Directive 2009/30/EC and the Renewable Energy Directive 2009/28/EC impose a reduction in the GHG intensity of passenger vehicles and set a target of 10% share of renewable energy sources in the transport sector by 2020. The Climate-Energy packages then set the 20-20-20 and 40-27-27 targets to be achieved by 2020, and 2030, respectively, for reduction in overall GHG emissions, the share of renewable energy, and energy efficiency. In the long run, the 2020 and 2030 targets are integrated with the EU Roadmap for Moving to a Competitive Low-Carbon Economy in 2050. In this Roadmap, the European Commission sets out a pathway to achieve deeper emission cuts, requiring the reduction of EU GHG emissions to 80 % below the 1990 levels by 2050. Deep decarbonisation policy has also been supported by the COP21 Agreement adopted on December 12, 2015.

²Böhringer and Rutherford (2008, 2009) identify three broad categories of linking the top-down and bottom-up models. As stated by Kumbaroglu and Madlener (2003), "soft-linking" is based on iterative convergence of central parameters, which is fully dependent on the user's decision whether and how to interchange the information and adjust model inputs. It may suffer from the methodological and structural differences be-

Abatement technologies have been treated in a CGE framework either as an input to production or through activity analysis. Mayeres and Van Regemorter (2008) adopted the former approach in the GEM-E3 model, where emission abatement costs enter the model as an input to production. Since the costs enter the production of sectors producing emissions, household and firm decisions are influenced by a shadow cost generated via exogenously constrained emissions (Vrontisi et al., 2016). Emissions are reduced via substitution of fuels as production factors in a nested CES function, where the reductions result from increased prices induced by additional costs due to environmental policies that will incentivise sectors to substitute emission-intensive production inputs for more environmentally friendly ones. Emissions may also be decreased through restructuring of production sectors due to different additional costs across sectors implied by their dissimilar opportunities for substitution or abatement (Kouvaritakis et al., 2005). Additionally, emissions can be reduced as a result of end-of-pipe abatement technologies explicitly given by abatement cost functions of production sectors. Similarly to this approach, Vrontisi et al. (2016) linked the GEM-E3 modeling framework to the GAINS simulation model that supplied emission abatement expenditures by households and sectors to the GEM-E3 model as an input to production. However, as Vrontisi et al. (2016) stated, this approach makes it harder to distinguish interactions among different climate and air quality policies.

As an alternative solution, Kiula and Rutherford (2013) developed an approach based on activity analysis for treating abatement costs in a CGE framework. In activity analysis, the constant elasticity of substitution (CES) production function is specified explicitly in terms of pollution abatement. The difference between the abatement function and other production functions lies in their calibration. Non-abatement production is calibrated through a smooth CES function, whereas the abatement function is calibrated in a step-wise manner where abatement technologies are represented by a Leontief function making these technologies either active or inactive in the equilibrium. This feature allows the direct linking of a bottom-up abatement technology model and a top-down macro model. Kiula et al. (2014) implemented this approach in a CGE set up to analyse the impacts of air emission and carbon taxation, imposed separately or jointly. The emission reduction in their hybrid model is possible via three channels - via production factor substitution, decline in sector output, and installations of the end-of-pipe abatement technologies.

To avoid the mentioned disadvantages and address this long-standing problem in the literature, we adopt a novel and different approach to endogenise abatement technologies based on the "integrated modeling" and "hard-linking" approach as defined and developed by Böhringer and Rutherford (2008). Specifically, we directly integrate a bottom-up consumer decision (CD) on technology uptake represented by a discrete choice model estimated according to survey data specifically designed for this purpose, see Bahamonde-Birke and Hanappi (2016), into a top-down CGE model hard-linked with a bottom-up technology-specific electricity sector model via a mixed complementarity problem (MCP). These three models that together form a hybrid CGE-CD model are run inseparably and evaluated jointly in one common framework.

We apply this advanced methodology to the problem of quantifying costs and benefits of passenger vehicle technologies as one solution to abate GHG and local air emissions. Specifically, we introduce four competing passenger vehicle technologies with different demand for fuel and electricity, and hence generating different volumes of emissions. Electricity to charge vehicle batteries, heat buildings, light bulbs, and power appliances is generated by an optimal mix of generating technologies (natural gas, coal, several types of renewables) in the electricity bottom-up module. The explicit depiction of a detailed electricity production sector allows us to include

tween the two modeling approaches, which may induce unsuccessful convergence in parameters (Böhringer and Rutherford, 2009). "Hard-linking" of the two models resides in formalized and algorithmically automated model processing and information transmitting, generating one unique result for each set of data and assumptions (Helgesen, 2013). The drawback possibly generated by the soft-linked models may be decreased by hard-linking. "Integrated modeling" integrates top-down and bottom-up models in the same mathematical optimization problem, so that the models are run jointly in one common framework.

the additional electricity demand by battery electric cars. As a baseline model, we use a fully dynamic CGE model, which is based on the structure of Böhringer and Rutherford (2009). Since standard CGE models do not allow for substitution between materials when the demand is intermediate, for instance, between vehicle costs and fuels (Kiuila and Rutherford, 2013), the integration of a bottom-up model into a top-down model is essential for correctly assessing the full scope of economic costs of abatement technologies.

In the consumers choice on the uptake of vehicles, we build on Truong and Hensher (2012), who provide a theoretical modelling framework to integrate a discrete choice (DC) model into a continuous-demand general equilibrium (GE) model. We extend this approach theoretically in that we include a vehicle fleet stock model accounting for stocks and new registrations in numbers of vehicles into the combined GE-DC framework. The choice alternatives for consumers in their vehicle purchase decision are conventional vehicles (CV), and different kinds of at least partially electrified vehicles that we subsume under the label AFVs (alternative fuel vehicles), namely hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). PHEVs and BEVs are then taken together as electric vehicles (EVs). The model is calibrated to Austrian data as an empirical example of a country actively aiming at meeting the target of decreasing GHG emissions by promoting, among other measures, the uptake of electric vehicles. We distinguish nine consumer agents (or households) by education level and living area (degree of urbanisation). For each householdm the DC model yields choice probabilities for each vehicle type in the purchase decision, depending on purchase prices, fuel and electricity costs, and technological attributes of the vehicles. Furthermore, we include a mode choice decision in the model, giving consumers the possibility to decide between public and individual transport. Mobility preferences and vehicle purchase choices of these agents were analysed using the discrete choice data from a representative household survey for Austria that was especially designed and conducted to provide the necessary input into the CGE model, see Bahamonde-Birke and Hanappi (2016). By furthermore introducing a vehicle fleet stock model, we distinguish between consumer expenditures on vehicle purchases and the use of the existing vehicle stock (i.e. fuel and maintenance expenditures), which enables us to link the electrified fleet to increased demand for electricity and the electricity production system. Our modeling procedure is designed to endogenously depict the entry of a new technology based on consumer preferences and the thereby induced demand for specific technologies. For the first time in the literature, it simultaneously allows for a distinction between consumer 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 – within an empirically calibrated and estimated CGE-DC framework.

In this specification, we attribute different emission coefficients to the four vehicle types and to several technologies to generate electricity, making the emission levels and hence abatement an endogenous result of the model without introducing abatement inputs or the abatement sector into the model. In addition to the three standard channels, which are change in sector output, change in economic structure, and KLEM factor substitution, emissions in our hybrid CGE-DC model are additionally reduced via substitution of fuel to fill CVs, HEVs, and partially also PHEVs, with electricity for charging BEVs and PHEVs. This substitution is demand-driven and endogenous in the hybrid model. With the demand for electricity also comes a technology mix change so that the increased demand for electricity coming from the top-down CGE model is satisfied in a cost-optimizing way in the bottom-up electricity model.

In order to quantify environmental benefits, we derive GHG and air quality emission intensities for domestic production as well as for imports using the CREEA database (CREEA, 2013). These intensities are then linked to production data and vehicle use in the CGE model to derive emission levels for each scenario. Using damage factors for each pollutant based on the ExternE’s impact pathway analysis (ExternE, 2005), we estimate the external costs associated with the impacts on human health, building materials, crops, and the environment. These external costs (i.e.

environmental and health benefits) are added to economy-wide costs to obtain the net social costs of electric vehicles as an abatement technology.

The overall aim of our paper thus is to extend previous literature by providing for the first time a comprehensive methodology and simulation tool to quantify the total social costs and benefits of the uptake of EVs as an endogenous abatement technology induced by various policy instruments, preference shifts, and technological innovations. We apply this methodology to Austria as a concrete empirical example, deriving the social costs and benefits of electric vehicle as an endogenous abatement technology in relation to policy discussion relevant for a particular national context. To this end, we evaluate two counterfactual scenarios for which we quantify the overall social costs and benefits of the penetration of an estimated fleet size of AFVs until 2030 and compare their results to the Business-as-usual (BAU) scenario. In the first counterfactual scenario (MODEST), the shift is moderate and preference-driven, while being accompanied by moderate investment in charging infrastructure. In the second counterfactual scenario (EM+), we assume a higher charging station availability and political incentive measures that would boost the uptake of AFVs, such as an increase of the mineral oil tax on fossil fuels and a rise in the vehicle purchase prices for CO₂-intensive vehicles relating to vehicle fleet emission targets. With Austria as a particular example, we provide a blueprint for the further application of this methodology to other national economies.

One of our key findings is the significant shift away from CVs towards EVs. The stock of CVs represent less than 60 % of the fleet in 2030 and the joint share of EVs reaches 28 %. In 2030, EVs represent the majority of newly registered cars with a 68% share. The increased penetration of EVs induces a demand for electricity higher by 2.3 %, which is mainly supplied by gas-fired power plants. The consumers' shift towards EVs results in a decline in fuel used in personal transport by 5.4 % and an overall reduction of fuel demand by 10.7 % in EM+ in comparison to BAU. Further, EM+ induces a 0.5 % cut in domestic and 0.2 % cut in total air quality emissions. The monetary value of these positive net benefits represent about 10 % of the GDP loss caused by policy measures in the EM+ scenario. The reduction in fuel use exceeds the higher damage induced by an increased demand for electricity to charge vehicle batteries and together with the other abatement channels create positive net environmental benefits.

This paper is structured as follows. In chapter 2 we present the core CGE model structure and explain our hybrid modelling approach in detail. We discuss how stocks of vehicles accumulate and depreciate, and how we model expenditures on these stocks by households. We also introduce the concept of a discrete choice model and show how we establish a hard-link between the DC model and a CGE model with respect to vehicle purchases. We provide scenario results in chapter 3, and chapter 4 concludes.

2. Methodology

2.1. The core CGE model

The model is implemented in MCP/GAMS, see Rutherford (1995), and based on the structure of Böhringer and Rutherford (2008). On the production side, we distinguish 21 different cost competitive sectors with inputs labor, capital and intermediate goods. The complete overview of all included sectors is attached in Table A of the Appendix. Table F provides the description of model variables and parameters. Households solve a standard intertemporal utility maximisation problem, including a labour supply decision.³ We distinguish nine types of households (indexed

³Data on household income include wages, pension benefits and capital revenues were derived from Austrian input-output tables (see http://www.statistik.at/web_en/statistics/Economy/national_accounts/input_output_statistics/index.html [Last accessed March 16th, 2018]), EU-SILC (European Union Statistics on Income and Living Conditions), see <http://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions> [Last accessed March 16th, 2018], social benefits provided by Statistics Austria and other transfers (Statistics Austria).

by h) by three levels of education (low, medium, high) and three degrees of urbanisation (rural, suburban, urban). These distinctions are important because on the one hand, preferences and habits concerning transportation are clearly subject to regional differences; on the other hand, education is used as a proxy for income and environmental attitudes, which both may increase preferences for using environmentally friendly and advanced technologies. Household consumption decisions are modelled through a nested CES function, as is standard in applied sectoral CGE models. The CES is calibrated in a share form, as proposed by Rutherford (2002). Each consumer has the same consumption structure, but different values of elasticities and different initial levels of consumption according to their level of income.

The starting point for calibrating the CGE model is the Social Accounting Matrix (SAM) depicting income and expenditure flows between households, the government, production sectors and the rest of the world at a given point in time⁴. The SAM is constructed using input-output (IO) tables provided by Statistics Austria, which are complemented by data from EU SILC, Labour Force Survey data, and the survey data on consumer choices as described in Bahamonde-Birke and Hanappi (2016). It especially comprises electricity production, transmission and distribution sectors, disaggregated road passenger transport technologies (CV, HEV, PHEV, EV), as well as transport-related products and services. In Figure 1, we distinguish between consumption of mobility and non-transport goods in the top nest. The agents can substitute between transport and non-transport goods according to the elasticity σ_{trans} . To focus on the mobility sector and to avoid large disturbances from the rest of the economy, we choose reasonably small values for this elasticity, and for the one between all non-transport goods in the economy, σ_{goods} .

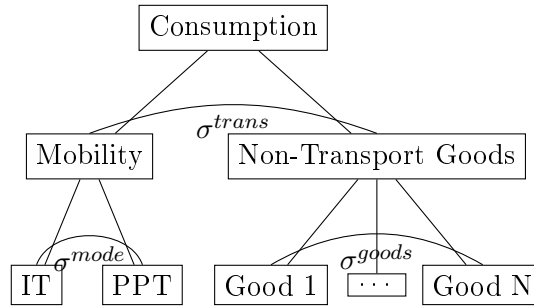


Figure 1: Consumption structure of households (Nested CES functions)

In the modal choice branch, each consumer has the possibility to substitute between public passenger transportation (PPT) and individual transportation (IT), with the elasticity σ_{mode} . This allows us to model the effect of consumers substituting away from individual transport to public transport if the cost for IT should rise. Demand elasticities for PPT were estimated using above-mentioned survey data (Bahamonde-Birke and Hanappi, 2016), and used to calculate values for cross-price elasticities between IT and PPT, which are given in Table B.

The expenditures on IT include purchases of new vehicles, and expenditures connected to the use of the vehicle stock (fuels incl. taxes, service and maintenance). Vehicle purchases by consumers are determined by their preferences, as well as by the purchase price of vehicle technologies and their technological characteristics (for instance driving range or engine power). Expenditures on the use of the vehicles are a linear function of the size of the vehicle stock. Unlike in other nests in their utility, households are not able to substitute between the vehicle purchase and the use of their vehicles. The share between these two expenditures is determined endogenously over time, see the equation (24). Any rise in vehicle purchases that exceeds the number of depreciating vehicles will lead to an increase in the vehicle stock. In this way, the

⁴2008 is the baseline year of our model.

purchase decisions also determine the development of the vehicle stock, with some inertia.

In order to depict these developments correctly, we include a detailed vehicle fleet accounting module (see section 2.2) and a vehicle discrete choice model (see section 2.3) within the CGE model. In the remainder of this section, we outline how we include these components in the CES logic. A graphical illustration is given in Figure 2.

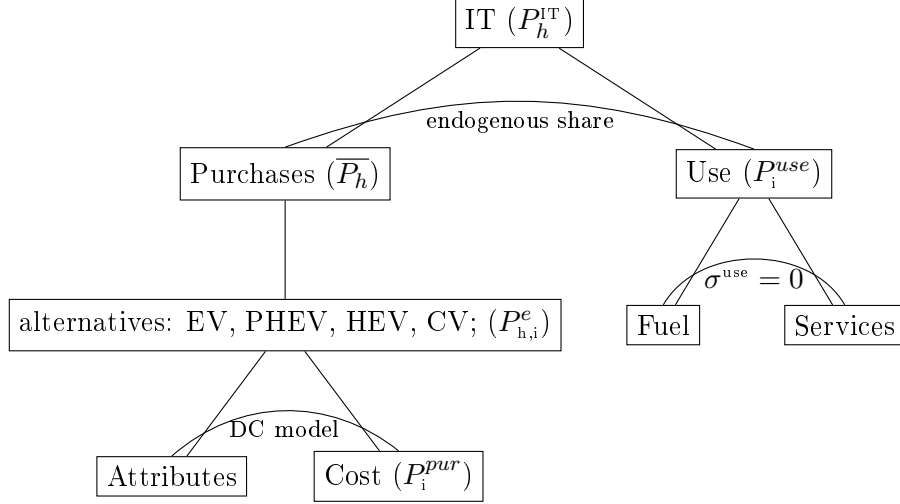


Figure 2: Individual transport consumption structure (DC model of the purchase decision)

Similarly to PPT and other consumption goods, one can think of 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. The price of this activity P_h^{IT} , is an endogenously adapting Leontief composite of the price for purchasing a vehicle of any type, i.e. the aggregate price index \bar{P}_h , and the price of vehicle use P_i^{use} , see equation (21). The latter is a simple Leontief combination of the prices of fuel, electricity, and service inputs in vehicle use, while the former is determined from "the effective prices" $P_{h,i}^e$ for each of the choice alternatives CV, HEV, PHEV and EV. These The effective prices are derived from the discrete choice model (see section 2.3); they depend on the purchase price of vehicle i , P_i^{pur} , but also on the socio-demographic characteristics of the households and technological attributes of the vehicles.

The purchase price for vehicles of type i , $P_i^{pur}(t)$, is given by a simple Leontief combination of the prices for the input goods, which in this case are car chassis (P^C) and vehicle engines (P^E), produced by CAR and ENG sectors in the model,

$$P_i^{pur}(t) = \theta_i^{CE} P^C(t) + (1 - \theta_i^{CE}) P^E(t) \quad \forall i, \forall t. \quad (1)$$

The cost share given by parameter θ_i^{CE} is different for each technology i , but is assumed to stay constant over time. The share parameter θ_i^{CE} is the vehicle type specific cost share between the two input goods. Any vehicle is sold at this price in the model.

Similarly, P_i^{use} , the price for using a vehicle, is a Leontief CES combination of the prices for fuel (gasoline/diesel and electricity composite, P^F) and service and maintenance (P^S),

$$P_i^{use}(t) = \theta_i^{FS}(t) P^S(t) + (1 - \theta_i^{FS}(t)) P_i^F(t) \quad \forall i. \quad (2)$$

The share θ_i^{FS} remains constant over time for each technology i ; P^F and P^S also include excise taxes.

Obtaining the demand variables for vehicle purchases and vehicle use is not straightforward given this price structure. Shephard's Lemma cannot be used directly. Specifically, we are interested in demand for vehicle purchases of type i by household h , $D_{h,i}^{pur}$, as well as demand for

the use of vehicles of type i by household h , $D_{h,i}^{\text{use}}$. The latter will be derived in the next section, the former in section 2.3.

2.2. The vehicle fleet model

A detailed stock-flow consistent accounting of the vehicle stocks, new registrations, and depreciation for each CV, HEV, PHEV, and EV technology is implemented in the hybrid CGE model. We follow a standard accumulation and depreciation process, and thereby account for the size of the vehicle stocks and for the new purchases in physical units, not in monetary units. This allows us to avoid a problem related to intertemporal price changes and their impact on the monetary value of the vehicle stock when converting the money flows and stocks into physical units of vehicles. We also use a cohort depreciation model, i.e. we assume that vehicles that are bought will have a fixed lifetime, and exit from the vehicle stock when they reached that age. The average lifetime of each vehicle is assumed to be 12 years, as in Gruden (2008).

The vehicle stock $st_i(t)$ of vehicle type i equals the last period's stock plus new registrations $nr_i(t)$ less depreciation of worn out vehicles $dc_i(t)$. 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

$$st_i(t) = st_i(t-1) + nr_i(t-1) - dc_i(t-1) \quad \forall i, \forall t. \quad (3)$$

We adhere to the convention that vehicles are bought at the end of each period and are only added to the stock in the next period.

The development of new vehicle registrations is the core of the vehicle module. They are determined from the unit demand for purchases of new vehicles $D_{h,i}^{\text{pur}}(t)$, as described in the previous subsection, and determine the stock development. Specifically, new registrations are defined as

$$nr_i(t) = \frac{e_{h,i}^{\text{pur}}(0)D_{h,i}^{\text{pur}}(t)}{P_i^{\text{pur}}(t)p_i^{\text{av}}(t)} \quad \forall i, \forall t, \quad (4)$$

where $e_{h,i}^{\text{pur}}(0)$ denotes the volume of expenditures on type i vehicle purchases by household h in the starting period, and $p_i^{\text{av}}(t)$ is the exogenous average monetary price⁵ for a vehicle of technology i .

For depreciation, we assume a constant depreciation rate for CVs of $\delta_{\text{CV}} = 5.85\%$ for the first 12 periods in the model. For the other vehicle types, since these markets are not yet matured, we do not assume any depreciation for the first 12 years. It implies that the vehicle stock of AFVs only increases in the first twelve years. Subsequently, the vehicles that were registered 13 periods before are depreciating for all technologies.

$$\begin{aligned} dc_i(t) &= st_{\text{CV}}(t)\delta_{\text{CV}} \text{ for } t \leq 12, i = \text{CV}; \\ &= 0 \text{ for } t \leq 12, i = \text{AFVs}; \\ &= nr_i(t-12) \text{ for } t > 12. \end{aligned} \quad (5)$$

Since there is no depreciation of AFVs in the first twelve years, the stock-expenditures grow much more rapidly than the flow-expenditures. After some years, assuming the new technology successfully enters the vehicle market, a stabilization of the growth rate may be expected due to depreciation of old vehicles. Only then may the stock and flow expenditures eventually reach the steady state growth rates of the economy, and grow at the same rate as is the case for CVs. Depending on the extent that AFVs will enter the market, demand for new CVs may decrease, implying a reduction in their stock, and an endogenous shift between the technologies.

⁵Any prices in the model are unit prices. In equation (4), we need a price that denotes Euro per vehicle, in order to calculate numbers of cars. The values of $p_i^{\text{av}}(t)$ are derived by projections based on the vehicle technology database described in Ibesich et al. (2014).

We also know $D_{h,i}^{\text{use}}(t)$, unit demand of household h for using vehicles of type i ; since we assume the use of vehicles to develop in a constant relationship to the size of their stock, we have

$$D_{h,i}^{\text{use}}(t) = \frac{st_i(t)}{st_i(0)} \quad \forall h, \forall i, \forall t. \quad (6)$$

Household demand for new purchases of vehicles i , $D_{h,i}^{\text{pur}}$, and household demand for using a vehicle, $D_{h,i}^{\text{use}}$, are the two main variables to be determined in our hybrid modelling framework. The latter clearly depends on the development of the former, since the size of the vehicle stock depends on the number of new purchases of vehicles. In order to determine $D_{h,i}^{\text{pur}}$ we need the vehicle discrete choice model.

2.3. Integration of vehicle discrete choice into the CGE model

The vehicle discrete choice model (VDC) plays two roles in the integrated modelling framework. Following Truong and Hensher (2012), we use the VDC model to derive a price index for aggregated vehicle purchases \bar{P}_h , used to determine demand for overall vehicle purchases. To derive \bar{P}_h we first infer an effective price $P_{h,i}^e$ for each choice alternative i and each household h , accounting for the vehicle attributes $x_{h,i}$ (like range and power, see below). The effective price $P_{h,i}^e$ can be interpreted as the consumer's perceived value of the vehicle at the purchase decision. Secondly, the VDC model allows us to analyse consumption behaviour from a micro perspective providing aggregate vehicle choice probabilities, which are used to split up the demand for overall vehicle purchases into demand for the vehicle purchase choice alternatives (CV, HEV, PHEV and EV).

For each of the nine aggregated household groups, distinguished by education and living area, a separate conditional logit model was estimated based on consumer preferences data elicited through a specially designed representative survey within which 1,449 Austrian respondents were interviewed (Bahamonde-Birke and Hanappi (2016)). The vehicle specific attributes in the logit model are purchase price (pp), fuel cost (fc), maintenance cost (mc), engine power (ps) and driving range of BEVs (ra). The deterministic part of the indirect utility $V_{h,i}$ of buying a vehicle of type i , is given in equation (7), where $x_{h,i}$ is the vector of initial levels for the attributes (see e.g. Train (2003)).

$$V_{h,i} = \beta_{h,i}^{\text{mc}} x_{h,i}^{\text{mc}} + \beta_{h,i}^{\text{fc}} x_{h,i}^{\text{fc}} + \beta_{h,i}^{\text{pp}} x_{h,i}^{\text{pp}} + \beta_{h,i}^{\text{ps}} x_{h,i}^{\text{ps}} + \beta_{h,i}^{\text{ra}} x_{h,i}^{\text{ra}} + \alpha_{h,i} \quad \forall h, \forall i, \quad (7)$$

The econometric estimations of conditional (or random parameter) logit yield the values for the vector $\beta_{h,i}$ of shadow prices (marginal utilities) of each of these attributes, and the alternative (i.e. technology) specific constant, $\alpha_{h,i}$, or base-preference, denoting a part of the utility for all other characteristics of given alternative not explicitly described in the discrete choice model. Table D reports the estimates of the utility parameters, while Table E provides levels of the vehicle attributes $x_{h,i}$, as used in our scenario simulations.

Following random utility model (McFadden, 1981) and assuming the error term ϵ is i.i.d standard type I extreme value, the probability $\mathbb{P}_{h,i}$ of agent h to choose alternative i , given the prior decision to purchase any vehicle at all, is given as

$$\mathbb{P}_{h,i} = \frac{\exp(V_{h,i})}{\sum_j \exp(V_{h,j})} \quad \forall h, \forall i. \quad (8)$$

The probability to choose alternative j contributes to the likelihood in the conditional logit model (Train, 2003)). In the CGE model these probabilities are interpreted as market shares of vehicles. The share of purchases of vehicle i in total vehicle purchases of household h , $\theta_{h,i}$, is hence

$$\theta_{h,i} := \mathbb{P}_{h,i} \quad \forall h, \forall i. \quad (9)$$

So once demand for overall vehicle purchases is known for each agent, demand for vehicles of

type i equals $\theta_{h,i}$ times this overall demand.

It shall be emphasized here, that these market shares are endogenous in our integrated modelling framework. They depend on price developments that are endogenously determined in the CGE model (e.g. vehicle purchase prices, fuel prices, taxes, and service and maintenance costs), and enter the logit module in each time period. The technological attributes and household preferences are exogenous.

In difference to Truong and Hensher (2012), we derive a money cost variable, $x_{h,i}^{\text{money}}$, defined as

$$x_{h,i}^{\text{money}} := \frac{\beta_{h,i}^{\text{cm}}}{\beta_{h,i}^{\text{money}}} x_{h,i}^{\text{cm}} + \frac{\beta_{h,i}^{\text{cf}}}{\beta_{h,i}^{\text{money}}} x_{h,i}^{\text{cf}} + \frac{\beta_{h,i}^{\text{pp}}}{\beta_{h,i}^{\text{money}}} x_{h,i}^{\text{pp}} \quad \forall h, \forall i, \quad (10)$$

where $\beta_{h,i}^{\text{money}} := \beta_{h,i}^{\text{cm}} + \beta_{h,i}^{\text{cf}} + \beta_{h,i}^{\text{pp}}$. Since the marginal utility of money is unique for each agent, the shadow prices of all monetary attributes do not depend on technology (and so the subscript i can be subtracted). Hence we have

$$\beta_h^{\text{money}} := \beta_{h,i}^{\text{money}} = \beta_{h,j}^{\text{money}} \quad \forall i, j, \forall h, \quad (11)$$

Now $V_{h,i}$ can be expressed in terms of β_h^{money} , as

$$V_{h,i} = \beta_h^{\text{money}} x_{h,i}^{\text{money}} + \sum_{rest} (\beta_{h,i}^{rest} x_{h,i}^{rest}) + \alpha_{h,i} \quad \forall h, \forall i, \quad (12)$$

where *rest* comprises non-monetary variables *ra* and *ps*.

The effective price for vehicle purchases 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 $P_{h,i}^e$ of choice alternative i is known, the indirect utility function can be expressed as

$$V_{h,i} = \beta_h^{\text{money}} P_{h,i}^e + \alpha_{h,i} \quad \forall h, \forall i, \quad (13)$$

Knowing the explicit form of the indirect utility function, (7), one can actually calculate the effective price for choice alternative i as

$$P_{h,i}^e = \frac{V_{h,i} - \alpha_{h,i}}{\beta_h^{\text{money}}} = \sum_n \frac{\beta_{h,i}^n}{\beta_h^{\text{money}}} x_{h,i}^n \quad \forall h, \forall i. \quad (14)$$

Given these effective prices, we derive for each agent the aggregate price of purchasing any type of vehicle i . The aggregation procedure can not follow a simple CES logic, since purchase shares of different vehicle types will change endogenously according to non-monetary vehicle attributes. 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, \bar{V}_h of all vehicle types as

$$\bar{V}_h := \ln \sum_{i \in I} \exp(V_{h,i}) \quad \forall h. \quad (15)$$

The logsum 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

$$d\bar{V}_h = \sum_{i \in I} \mathbb{P}_{h,i} dV_{h,i} \quad \forall h. \quad (16)$$

Substituting (13) for $V_{h,i}$ one gets

$$\begin{aligned} d\overline{V}_h &= \sum_{i \in I} \mathbb{P}_{h,i} d(\alpha_{h,i} + \beta_h^{\text{money}} P_{h,i}^e) \\ &= \beta_h^{\text{money}} \sum_{i \in I} \mathbb{P}_{h,i} dP_{h,i}^e \quad \forall h, \end{aligned} \quad (17)$$

and defining the change in the aggregate price for vehicle purchases \overline{P}_h as

$$d\overline{P}_h := \sum_{i \in I} \mathbb{P}_{h,i} dP_{h,i}^e \quad \forall h, \quad (18)$$

yields

$$d\overline{V}_h = \beta_h^{\text{money}} d\overline{P}_h \quad \forall h. \quad (19)$$

This represents economic intuition, since the marginal value of the utility of money (β_h^{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 (19) we have

$$\overline{P}_h = \frac{\overline{V}_h}{\beta_h^{\text{money}}} + c_h \quad \forall h, \quad (20)$$

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 vehicle, \overline{P}_h , as would be expected.

We now define the price for the IT composite as an *endogenously adapting Leontief composite* of the aggregate price for vehicle purchases and the price for the use of existing vehicles,

$$P_h^{\text{IT}}(t) = \Theta_h^{\text{pur}}(t) \overline{P}_h(t) + (1 - \Theta_h^{\text{pur}}(t)) \sum_i \theta_{h,i}^{\text{st}}(t) P_{h,i}^{\text{use}}(t) \quad \forall h, \forall t. \quad (21)$$

Here the share parameter $\Theta_h^{\text{pur}}(t)$ denotes the share of expenditures on vehicle purchases in total expenditures for individual transportation for household h in period t . We use the capital Greek letter Θ to denote the endogeneity of this share. This implies a qualitative change in the Leontief consumption nest over time; as new vehicle purchases rise and fall, and as the vehicle stocks build up or shrink, also the expenditures on, and hence the price for the overall IT composite changes.

⁶

The share $\theta_{h,i}^{\text{st}}(t)$ in equation (21) is the share of the size of the stock of vehicles of type i in the total stock of vehicles owned by household h ,

$$\theta_{h,i}^{\text{st}}(t) = \frac{st_i(t)}{\sum_j st_j(t)} \quad \forall h, \forall i, \forall t, \quad (22)$$

with

$$\sum_i \theta_{h,i}^{\text{st}}(t) = 1 \quad \forall h, \forall t. \quad (23)$$

This share is known at the beginning of each period t , since the vehicle stock $st_i(t)$ is known at the beginning of each period by our convention.

⁶The share is exogenous in the first period, and endogenously adapts according to the households purchase decisions and the thereby induced vehicle stock developments over time.

The determination of the endogenous share parameter in equation (21), $\Theta_h^{\text{pur}}(t)$, depends on both the beforementioned unit demand variables,

$$\Theta_h^{\text{pur}}(t) = \frac{\sum_i e_{h,i}^{\text{pur}}(0) D_{h,i}^{\text{pur}}(t)}{\sum_j [e_{h,j}^{\text{pur}}(0) D_{h,j}^{\text{pur}}(t) + e_{h,j}^{\text{use}}(0) D_{h,j}^{\text{use}}(t)]} \quad \forall h, \forall t. \quad (24)$$

Here $e_{h,i}^{\text{pur}}(0)$ is the volume of expenditures on purchases of vehicles and $e_{h,i}^{\text{use}}(0)$ denotes the volume of expenditures on fuel and services (which is associated with using the vehicles), both in the starting period. This share will hence rise in times when more new vehicles are bought, as compared to a steady state development of purchases and the size of the stock, and shrink in times when less new vehicles are bought.

The price for individual transportation, $P_h^{\text{IT}}(t)$, can be used to determine overall demand for IT in the standard manner by Shephard's Lemma: differentiating the unit expenditure function of each household with respect to the price for IT yields unit demand for IT,

$$D_h^{\text{IT}}(t) = \frac{\partial e(p_{x1}, p_{x2}, \dots, P_h^{\text{IT}}(t))}{\partial P_h^{\text{IT}}(t)} \quad \forall h. \quad (25)$$

This can also be done at one deeper level, and yields unit demand for purchases of any kind of vehicle as

$$\overline{D}_h(t) = D_h^{\text{IT}}(t) \frac{\Theta_h^{\text{pur}}(t)}{\Theta_h^{\text{pur}}(0)} \quad \forall h, \quad (26)$$

since the derivation of (21) with respect to \overline{P}_h , the only additional inner derivative when applying Shephard's Lemma at this level, just yields the share Θ_h^{pur} .

In (26) $\Theta_h^{\text{pur}}(0)$ is the base-year value of this share, which stays constant for all time periods. The reason for this share to be in the denominator in (26) is because all unit demand variables have to equal the reference growth path in the initial steady state: If the demand variables were expressed in real monetary terms, say $\overline{\mathbb{D}}_h$ and \mathbb{D}_h^{IT} , then (26) would become

$$\overline{\mathbb{D}}_h(t) = \mathbb{D}_h^{\text{IT}}(t) \Theta_h^{\text{pur}}(t) \quad \forall h, \forall t. \quad (27)$$

However, since in the initial steady state we have

$$\overline{D}_h(t) = \frac{\overline{\mathbb{D}}_h(t)}{\overline{\mathbb{D}}_h(0)} \quad \text{and} \quad D_h^{\text{IT}}(t) = \frac{\mathbb{D}_h^{\text{IT}}(t)}{\mathbb{D}_h^{\text{IT}}(0)} \quad \forall h, \forall t, \quad (28)$$

and, as a special case of (27),

$$\overline{\mathbb{D}}_h(0) = \mathbb{D}_h^{\text{IT}}(0) \Theta_h^{\text{pur}}(0) \quad \forall h, \quad (29)$$

it becomes clear that (26) is the correct formula to use for unit demand variables. More on calibration to the initial steady state is said in section 3.2.

Having derived unit demand for overall vehicle purchases, \overline{D}_h , we can now use the share of purchases of vehicles of type i in total vehicle purchases of household h , $\theta_{h,i}$, as determined by equations (8) and (9), to arrive at unit demand for purchases of vehicles of type i :

$$D_{h,i}^{\text{pur}}(t) = \overline{D}_h(t) \frac{\theta_{h,i}(t)}{\theta_{h,i}(0)} \quad \forall h. \quad (30)$$

As in equation (26), also here the initial value of the share appears in the denominator, since we use unit demand variables.

We now have determined for all periods t the two variables that we wanted to determine: unit demand for vehicle purchases of type i by household h , $D_{h,i}^{\text{pur}}(t)$, and unit demand for the use of

vehicles of type i by household h , $D_{h,i}^{\text{use}}(t)$.

With this method, we end up with the price \overline{P}_h , the demand \overline{D}_h for overall vehicle 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.

2.4. CGE hard-link to electricity bottom-up model

The electricity sector is represented by a bottom-up cost optimisation energy model. It is divided into multiple technologies that generates electricity (tec), including coal, gas, oil, nuclear power, hydro, wind, biomass, solar photovoltaic and other (mostly from processed gas as LPG). All technologies produce electricity subject to different input structures, production costs⁷, and resource constraints (33).

In the bottom-up model, as in Böhringer and Rutherford (2008), we solve the following linear optimisation problem

$$\min \sum_{tec} \bar{c}_{tec} y_{tec} \quad (31)$$

subject to

$$\sum_{tec} a_{j,tec} y_{tec} = \bar{d}_j \{energy\ goods\} \quad (32)$$

$$\sum_{tec} b_{k,tec} y_{tec} \leq \kappa_k \{energy\ resources\} \quad (33)$$

$$y_{tec} \geq 0 \quad (34)$$

where

where

y_{tec}	denotes the activity level of the energy technology tec ,
$a_{j,tec}$	stands for the "netput" of energy good j by technology tec ,
$\bar{c}_{tec} y_{tec}$	is the exogenous, constant marginal unit cost of producing the energy good by technology tec ,
\bar{d}_j	denotes the market demand for energy good j (which is derived from the top-down general equilibrium part of the model),
$b_{k,tec} y_{tec}$	represents the unit demand for the energy resource k by technology tec , and
κ_k	stands for the aggregate supply of the energy resource k .

⁷Although different technologies operate with different production costs, there is a unique market price for electricity that is determined by the production cost of the most expensive (marginal) technology supplying electricity to market. The difference between production costs and revenues (i.e. the profit that arises for some cheaper technologies) is being paid to the households, and can be interpreted as rents on natural resources and capacities. This makes simultaneous modelling of different technological production costs and a unique output price of electricity possible.

The complementarity conditions between Lagrange multipliers and constraints are used to solve the linear problem together with the top down macroeconomic equilibrium of the overall economy. This is done by including the market price for a unit of electricity, the shadow price of the capacity constraint and the shadow price of the resource constraint as additional variables, and by adding equations (32) and (33) as additional zero profit or market clearance conditions. As a result, the aggregate supply of electricity delivered by the bottom-up electricity model meets the aggregated demand for electricity in the CGE model. Similarly, demand for energy goods, \bar{d}_j , which is derived from the top-down CGE model equals to their use by electricity generating technologies (32). We thereby obtain a hard-link between the bottom-up and top-down models.

Data on electricity production and energy balances were provided by the Statistics Austria and E-Control Austria. These data were then amended by technology-specific 2008 supply-use data for electricity production taken from the EXIOBASE database (CREEA, 2013)⁸.

2.5. Emission abatement and associated benefits

Quantification of externalities covering the impacts on premature mortality, morbidity, building materials, crops, and ecosystems (Ščasný et al., 2015) attributable to both direct and indirect emissions stemming from domestic economic production, imports, fuel use, and electricity production completes our economic impact assessment.

Abatement of GHG and air emissions occurs in the model via five channels affected by optimisation: 1) change in sector output implying a change in economic structure, 2) factor substitution, 3) demand for fuel to fill CVs, HEVs, and partially PHEVs, 4) demand for electricity for charging BEVs and PHEVs, and 5) technology-mix to generate electricity. The first two channels represent options to abate emission in standard macroeconomic models. The next two channels are activated mainly thanks to the integration of the vehicle DC model into the CGE model. Further, linking the electricity bottom-up model allows the activation of the last channel.

Our approach is based on linking the ExternE's Impact Pathway Analysis (IPA) (ExternE, 2005) and the results from our integrated hybrid CGE model. Climate change impacts are valued by Social Cost of Carbon (see, Tol (2013) for a review). Using emission factors, we quantify direct emissions stemming from domestic economic production and released by vehicles, and indirect emissions attributable to all imported goods produced worldwide. The emission factors are expressed in tons of pollutant per unit of economic output or import and are based on the MRIO database compiled within the CREEA project⁹. We quantify the external costs attributable to electricity generation (either used by sectors or to charge vehicle batteries) outside of the economic production. Externalities are based on damage factors expressed per unit of kWh per technology, including renewable sources, following the CASES database (Cases database, 2018). The emission factors per fuel use in passenger vehicles and freight transport are based on the Transport and Emissions simulation model (TREMOVE, 2005) from which we generate time variant emission factors. Air pollutants considered in the model are CO₂ emissions and five local air pollutants (particulate matter - PM, SO₂, NO_x, CO and volatile organic compounds VOC) similarly to Kiuila et al. (2014).

⁸For the base year 2008, CREEA (2013) distinguishes seven specific technologies to generate electricity in Austria - run of the river hydro power (39 %), pump storage hydro (21 %), natural gas (17 %), coal (13 %), biomass (5 %), wind (3 %), landfill and sewage gas (1 %), biogas (1 %), and photovoltaics (less than 1 %).

⁹We use the emission data from Compiling and Refining Environmental and Economic Accounts (CREEA) based on multi-regional environmentally-extended input-output analysis that describes the state of the economy in 2008. Assuming the emission factors for most sectors are constant over time, we do not capture the effect of end-of-pipe abatement, as for instance in Kiuila et al. (2014).

3. Simulation results

3.1. Steady state and business-as-usual scenario

The hybrid CGE model is calibrated to a steady state implying identical growth rate for all endogenous variables and identical development of the path of all prices. It implies that the structure of the economy does not change over time and all relative prices develop according to the benchmark price reference path. The exogenous steady state growth rate also applies for the growth of expenditures on vehicle use (fuel and maintenance costs) and vehicle purchases. The vehicle stock in each period is equal to the preceding period's vehicle stock plus new registrations minus depreciated cars of the preceding period. The numbers of new registrations and average prices by vehicle type are derived by Ibesich et al. (2014), see Appendix for more details.

Results for policy scenarios are compared to the business-as-usual (BAU) scenario. BAU differs from the initial steady state in that it depicts the development of the economy without policy actions but it includes assumptions about a realistic capacity expansion for energy producing technologies up to 2030 as derived by Ibesich et al. (2014). Anticipated or to date implemented changes in fuel costs and car purchase prices are considered. The mineral oil tax rate was increased in 2011 in Austria and hence is part of BAU. Moreover, since Austria has been applying a registration tax for newly purchased vehicles with a bonus for AFVs, this measure is a part of BAU as well. Consecutively, there is a very small shift-in of AFVs, since consumer preferences do not change and the price effects have very little influence on mobility preferences, this shift is barely of any significance for the vehicle market.

3.2. Policy scenarios

We compare the results of two policy scenarios (MODEST and EM+) to BAU. In the MODEST scenario, we consider to-be-expected investments into the expansion of EV charging infrastructure. According to our calculations on the costs of charging stations relating to the assumptions on their local availability, as in the representative household survey conducted to elicit Austrian consumer preferences regarding electromobility (Bahamonde-Birke and Hanappi, 2016), and to information regarding the costs of charging stations in Austria taken from WIFO (2011), Huetter and Stigler (2012), Bliem et al. (2013), a low private investment into the charging infrastructure of about 1.5 billion Euro until 2030 results in a rather low number of charging stations in semi-public (workplace) and public locations. The investment is attributed to the building sector (56 %), engineering sector (34 %) and service sector (10 %) according to Bliem et al. (2013).

The second feature of the MODEST scenario is a simulated preference shift of households to electromobility, accompanied by technological developments projected by Ibesich et al. (2014). This shift is based on the survey on Austrian consumer preferences (Bahamonde-Birke and Hanappi, 2016), Ibesich et al. (2014), which reports a high environmental awareness of the Austrian population and a thus-induced increased inclination for the purchase of EVs, given a certain technological development. Table 1 shows assumptions about vehicle purchase price trajectories in MODEST. Purchase prices of CVs, HEVs and EVs are assumed to not differ the same across scenarios in the starting year 2008.

In the EM+ scenario, we assume a charging infrastructure expansion in three stages from low to medium to high until 2030¹⁰ carrying capital costs of about 4.2 billion Euro mainly invested towards the end of the period.

Further, EM+ focuses on policy measures, see Table 1 for details. Additionally, we assume a different purchase price trajectory for each of the four vehicle technologies, as an effect of technological development and economies of scale. Furthermore, the cost of fuel used in CVs

¹⁰Penetration to low, medium, and high level is reached in these three stages. The low level of penetrations means that loading stations are available only at parking areas and garages; medium level adds shopping centers, car-parks, working places and P+R facilities as well as accelerated and fast-mode charging stations. The high level of penetration assumes 45 % of charging stations are available in semi-public or public spaces.

risers by 3% between 2015 and 2019 and then by 7 % after 2020, while the fuel cost for PHEVs rises by even 10% after 2020 due to vehicle efficiency and overall declining fuel demand induced by the implemented mineral oil tax.

Table 1: Overview of counterfactual scenarios

MODEST	EM+
<ul style="list-style-type: none"> • Low charging infrastructure investments (€1.5 bln., €540 per EV in 2008 → €210 per an EV in 2030, 1.25 charging stations per EV) • Purchase price of CVs rises linearly resulting in a 5% increase in 2030, purchase price of HEVs, PHEVs and BEVs declines by 4 %, 15 %, and 20 % with respect to 2008, respectively. • Shift in household preferences towards AFVs. 	<ul style="list-style-type: none"> • High charging infrastructure investments (€4.2 bln., €1,430 per EV in 2020 → €800 per EV in 2024 then 1,340€per EV in 2025 → €620 per EV in 2030, 1.5 charging stations per EV). • Purchase price of CVs rises linearly resulting in a 15% increase in 2030, purchase price of HEVs, PHEVs and BEVs declines by 7 %, 21 %, and 22 % with respect to 2008, respectively. • Mineral oil tax rise by 5 cents in 2015 and 2019. • New registration tax for vehicles based on emission standards 105 g/km and 95 g/km from 2015 and 2020, respectively.

3.3. Macroeconomic impacts of policy scenarios

We identify the following important macroeconomic results:

- Building of the charging infrastructure has positive impacts on GDP due to additional investments to domestic participating sectors. The GDP deviation reaches +0.02 % in MODEST and +0.1 % in EM+.
- However, the shift in household preferences towards AFVs leads to a 0.03 % reduction in GDP. The increase in relevant taxes focused on electromobility incentivization reduces GDP more, by up to 0.2 % in 2030.
- Both scenarios negatively influence household income, and consequently welfare measured by the equivalent variation.

Compared to BAU, the expansion of charging stations at the low level has positive, although quite small in magnitude, effects on domestic GDP due to the stimulating effect of infrastructure investments primarily in the building sector. The deviation from BAU, reaching 0.03 % in 2020 and 0.02 % in 2030. However, when adding the second scenario feature, shift in consumer preferences, the positive effect on GDP is neutralized from 2020 and leads to a small GDP loss of up to 0.03 % in 2030 with an almost linear progression in-between. A smaller part of the GDP loss can be attributed to shifts in the structure of intermediate inputs relating to an increased import share for the Austrian economy as EVs replace CVs.

A lower demand for IT resulting in decreased output of the vehicle production and trade sector by 5.2 % and fuel output by 2.2 % in 2030 has higher negative impacts. PHEVs and BEVs have a higher purchase price on average, and thereby the price for the IT bundle rises in the model shifting part of household demand for transport services to PPT and reduce their transport demand by a small amount. However, the MODEST scenario does not entail an absolute reduction in GDP since the balanced growth path is conservatively set to 1 % yearly, maintaining the Austrian economy on a growth path, with 0.97 % rate on average.

In the EM+ scenario, the infrastructure investments induce positive net effects amounting to between 0.05 % of GDP in 2020 and 0.1 % in 2030. Adding the tax policy measures to EM+, however, results in a slightly reduced GDP by 0.27 % in 2020 and by 0.18 % in 2030, see

Table 2 and Figure 3 for the effect for each policy measure and scenario. The reduction can be attributed to several aspects. First, a higher purchase price of EVs reduces the demand and hence the economic output. Second, the batteries for EVs are manufactured by the engineering (ENG) sector, which uses a higher share of imported intermediate inputs than the car production and trade sector (CAR) providing most inputs for CVs. Consequently, the production of the ENG sector increases by 2.6 %, while the fuel and CAR sectors' outputs are reduced by 8.6 % and 7.6 %, respectively. The output of car services decreases accordingly by 2.5 %. Table 2 reports selected sectoral output deviations for both scenarios.

Further effects dragging down growth mainly between 2015 and 2019 are a higher tax burden, and the loss in revenues from the price-induced fuel export ("tank tourism"). The decline in the demand of foreign consumers for mineral oil (MO) products results in lower domestic MO tax revenues. However, due to the still relatively large stock of CVs and the adaptation behaviour by households occurring after 2020, the domestic demand for fuel slightly increases. Revenues from the MO tax paid by households increase by 13.25 % in 2020 and by 9.72 % in 2030, while economic sectors contribute by 16.74 % and 16.81 % in 2020 and 2030, respectively, resulting in a budgetary surplus of 0.02 % in 2023. By the end of the period until 2030, costs rise because of the long-term impact of negative effects on investment rate and capital stock due to the loss in price-induced fuel exports as well as the higher tax burden, among others.

Household income is negatively affected across all nine household types for the whole observed period until 2030. The change in the economic welfare due to change in market prices is measured by the equivalent variation. In MODEST, the equivalent variation remains mostly positive across all households until 2015, becoming negative from then on. In EM+, the equivalent variation is negative across all years due to the decreased household income, the increased mineral oil tax rate, and new registration tax on CVs and partly also on HEVs, see Table 3.

Table 2: Output and GDP impact, deviations from BAU

Year	2010		2015		2020		2025		2030	
Scenario	MOD	EM+	MOD	EM+	MOD	EM+	MOD	EM+	MOD	EM+
Sector impact										
ENG	0.00%	0.01%	0.02%	-0.01%	0.72%	1.17%	1.45%	2.07%	1.93%	2.56%
CARS	0.01%	-0.05%	-0.13%	-0.07%	-1.88%	-2.77%	-3.67%	-5.02%	-5.19%	-7.58%
PT	0.00%	-0.05%	0.00%	-0.02%	0.02%	-0.04%	0.05%	-0.01%	0.07%	-0.04%
CAR-SERV	0.00%	-0.29%	-0.04%	-1.93%	-0.51%	-4.01%	-0.92%	-4.05%	-0.35%	-2.46%
ELE	0.01%	-0.10%	0.00%	-0.11%	0.05%	0.09%	0.23%	1.00%	0.54%	2.27%
FUEL	0.00%	-0.39%	-0.02%	-3.49%	-0.41%	-6.85%	-1.44%	-8.26%	-2.18%	-8.65%
GDP impact	0.02%	-0.28%	-0.002%	-0.32%	-0.02%	-0.27%	-0.02%	-0.12%	-0.03%	-0.18%

3.4. Vehicle fleet shift towards electromobility

Key conclusions based on the integrated vehicle DC model are:

- The joint share of EVs reaches 28 % in 2030, while the stock of CVs decreases to less than 60 %.
- The measures incentivizing electromobility in EM+ lead to a continuously rising share of EV registrations, reaching 68 % in 2030.
- Overall, the number of newly registered cars declines over time with respect to BAU due to a shift in consumer preferences away from IT to PPT, as an effect of the increased price of the IT bundle.

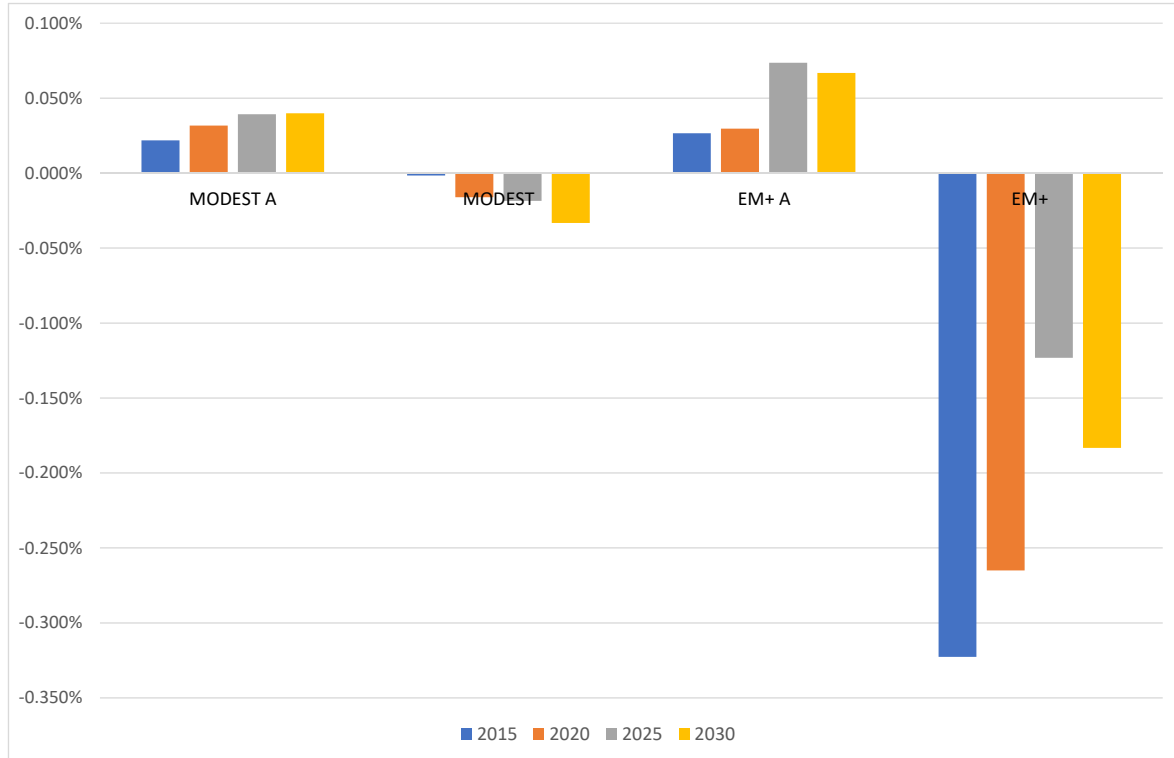


Figure 3: Gross Domestic Product - MODEST and EM+, positive and negative effects

*Note: MODEST A: effect of mild infrastructure investments only without any other additional scenario features on GDP
EM+ A: effect of high infrastructure investments only without any other additional scenario features on GDP*

The stock of EVs is barely of any importance in the base year, amounting to 0.02 % of the vehicle fleet. The mild reinforcement of charging infrastructure in MODEST is not sufficient to affect their uptake in any significant way. The shift in consumer preferences influences the penetration of EV after 2025 when the share of BEVs increases each year by around 2 p.p. to 16.3 % of the vehicle stock in 2030, reducing the share of CVs to less than 74 %. The overall vehicle fleet size decreases by 0.2 to 0.6 % in 2019-2026 and then increases by 1 % towards 2030.

In EM+, the stock of electric vehicles grows strongly after 2025 motivated by accelerated investments into the charging infrastructure. Further, households react to the increase in mineral oil tax and the new registration tax discouraging CVs and HEVs as higher emission vehicles. While in 2020 the EVs still form only 3 % of the vehicle fleet, their share surpasses 13.4 % in 2025, and continues to rise by 3 p.p. each year to nearly double their share in 2030, reaching almost 28 % of the vehicle fleet. In absolute terms, there are 1,525,500 EVs with a major part of PHEVs (BEVs: 175,500 plus PHEVs: 1,350,000). In 2030, CVs account for less than 60 %, see Figure 4. While the overall vehicle fleet size in EM+ is smaller by 0.6 to 3.4 % during 2010-2027 as a consequence of the higher fuel cost and price of AFVs, it becomes larger by 2.3 % towards the end of the period

The share of EVs on new registrations exceeds 10 and 24 % after 2020 in MODEST and EM+, respectively, reaching more than 48 % in 2025 in EM+. In 2030, EVs constitute almost a half in MODEST and even 68 % of all new registrations in EM+ of which 65 % (132,300) are PHEVs and 35 % (71,900) BEVs, see Figure 5. The total number of new registrations begins to decline in 2017, becoming smaller by 10 % and 17.5 % in 2030 in MODEST and EM+, respectively.

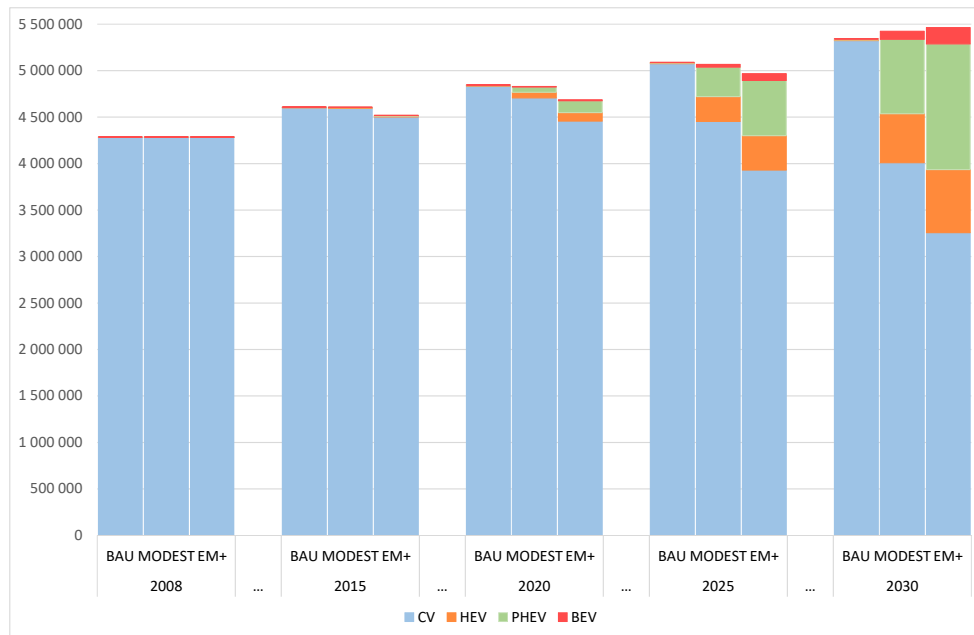


Figure 4: Number of vehicles in the vehicle stock by technology, 2008-2030 in BAU, MODEST, and EM+

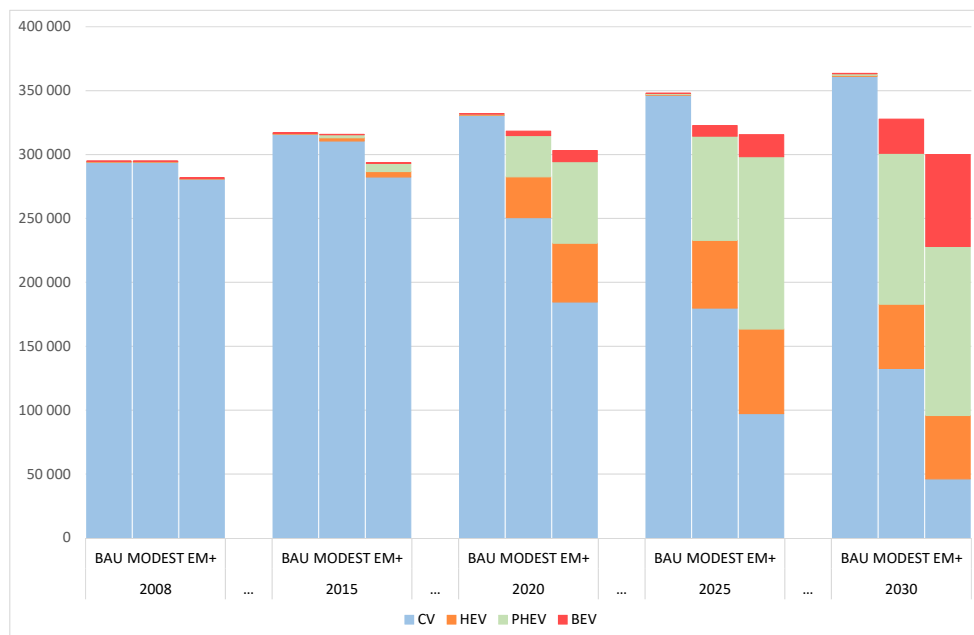


Figure 5: Number of new vehicle registration by technology, 2008-2030 in BAU, MODEST, and EM+

3.5. Changes in the electricity generating technology mix

There are following key findings from the energy modelling:

- 27.2 % and 29.4 % growth of electricity demand from 2008 to 2030 in MODEST and EM+, respectively, induced by the economy growth over time is mainly supplied by gas and renewable sources.
- Additional electricity demand for charging batteries amounts to 2.3 % of the aggregate supply (in EM+ and in 2030), and this demand is almost fully satisfied by a larger supply of gas-fired power plants.

- Renewable energy sources dominate in the generation of electricity in Austria with 72.5 % in 2008 and 70 % in 2030. The rest supplied by fossil fuels is dominated by natural gas taking between 62 % and 78 %. The shares of energy sources are very similar in BAU and the two scenarios.

Specifically, in the base year, aggregate supply in Austria is 65.4 TWh and the largest share of electricity is generated from run-of-the-river hydro power (40.2 %), followed by pumped-storage hydropower plants (21.8 %). Two fossil fuel technologies contribute by less than a third - natural gas with 17.1 % and hard coal with 10.5 %. Other renewables supply the remainder: biomass with 5.6 %, wind with 3.1 %, and other sources (biogas, photovoltaics) with less than 1.7 %.

Aggregate electricity production steadily grows to 83.2 TWh and 84.7 TWh in 2030 in MOD-EST and EM+, respectively, which is by 0.6% and 2.4 % higher than in BAU. It represents ca. 27 % more energy produced than in the base year to supply higher demand of the economy such that the output increases by almost 24 % in 2030 (reflecting the benchmark growth). The additional electricity supply in EM+ stems from demand to charge batteries in electric cars. In absolute terms, supply in EM+ is by about 2.0 TWh greater in 2030 and, as we estimate electricity demand for charging batteries at about 2.9 TWh in 2030 (which represents 3.4 % of total supply in that year)¹¹, it also implies an electricity-saving composition effect.

Looking closely at the technology mix, see Figure 6, electricity generated in run-of-the-river hydro power and water pumped-storage plants is very similar in absolute terms during whole 2008-2030 period, yielding a small relative change in the mix of -4 % and +7 %, respectively, by 2030. The use of coal declines absolutely (-1.2 TWh) and relatively (from 10.5 % to 7 %) over time, while the importance of natural gas grows (+9.0 TWh), resulting in a relative increase in gas use for electricity generation from 17 % to 24 %. Photovoltaics and wind grow by the largest rate, however, starting from low bases and growing from 0.03 TWh in 2008 to 1.8 TWh in 2030 and from 2.0 TWh to 11.0 TWh, respectively. Sewage gas used by gas engines in waste water treatment facilities which convert it to biogas also grows quite rapidly, increasing by 61.4 % in 2030.

3.6. Fuel use, emissions, and related environmental benefits

Total environmental benefits are quantified in our assessment as the sum of avoided environmental externalities attributable to emissions of air quality pollutants and greenhouse gasses attributable to both domestic production and imports. We distinguish the emission coming from domestic sectoral production, imports, electricity generation and fuel used in vehicles, and attribute to them negative externalities. The externalities comprise the effect of air quality pollutants on human health, crops, and biodiversity, while greenhouse gases contribute to climate change impacts.

We note, however, that our calculation does not assume time variant emission-coefficients for sector production nor for electricity generating technologies. Wealth-adjusted WTP values to avoid damage is also not assumed. Damage attributable to electricity power plants is not linked to emissions directly, rather it is quantified based on the implicit damage factors per technology, taking into account the technology's whole life cycle.

The key conclusions are the following:

- The increase in the fuel use accompanying a larger vehicle stock is offset by the consumers' shift towards EVs resulting in a decline of fuel used in personal transport by 5.4 % and an overall reduction of fuel demand by 10.7 % in 2030 in EM+ in comparison to BAU.

¹¹Taking the expenditure data from the SAM, the unit costs of electricity generation attain 424 Euro per one BEV and 111 Euro per one PHEV. The electricity generation costs represent 21 % of overall electricity costs including distribution. We suppose an average electricity price of 76.7 Euro/MWh, which then yields the average yearly electricity consumption of 1.44 MWh per PHEV and 5.5 MWh per EV. In 2030, there are 175,500 BEVs and 1,350,000 PHEVs, yielding 2.9 TWh of electricity used by electric vehicles in 2030

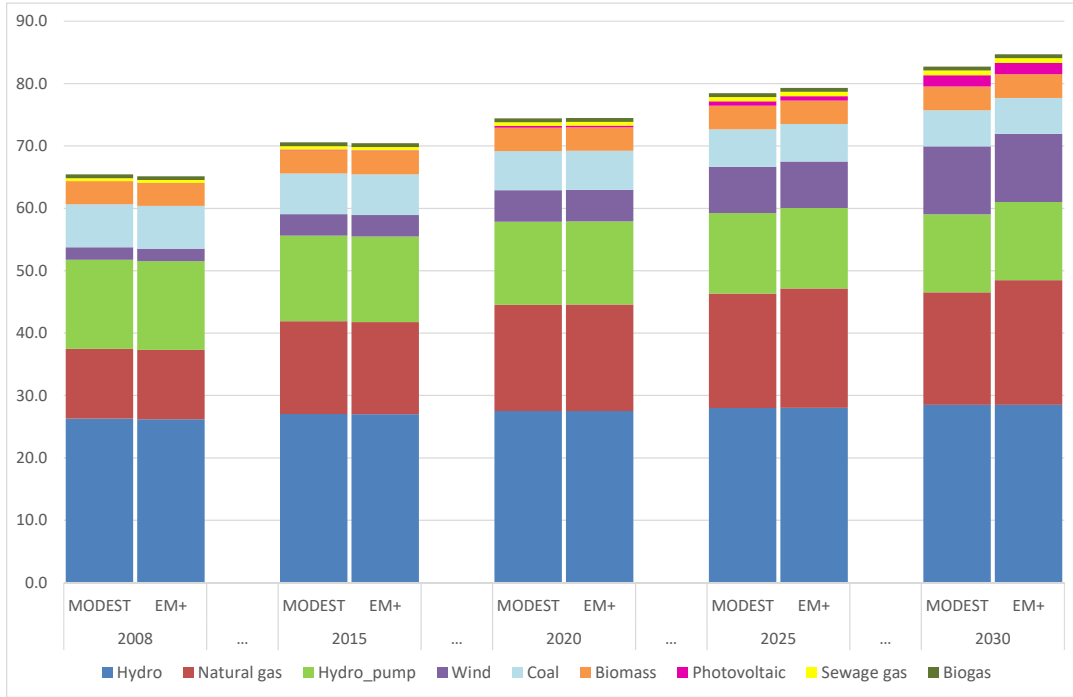


Figure 6: Electricity generation technology mix in MODEST and EM+

- The EM+ scenario helps to reduce all considered domestic air quality emissions with the avoided damage amounting to 0.5 % compared to BAU. This benefit helps to reduce the GDP loss by about 10 %.
- The monetary value of the fuel use reduction exceeds the higher damage induced by an increased demand for electricity to charge vehicle batteries and together with the other abatement channels create positive net environmental benefits.

Fuel use is endogenously determined by the hybrid CGE model and there are two counter effects in their use. First, the increasing stock of vehicles induced by the benchmark growth increases fuel use in BAU, MODEST, and EM+, by 10.9 %, 9.9 %, and 2.1 % in 2020 and 22.3 %, 15.7 %, and 9.2 % in 2030, respectively. Consumers' shift in vehicle technologies partly balances this effect despite the fact that fuel use by HEVs and PHEVs rises proportionally to the growing stock of these vehicles in both scenarios. The increase of new vehicle registrations results in lowering fuel use of CVs by 2.9 % by 2020 and 25.8 % by 2030 even in MODEST. Overall, fuel use by individual transport is reduced by 0.9 % in MODEST and 5.4 % in EM+. The effect on fuel demand is more pronounced in EM+. Fuel use to drive CVs declines by 11.6 % in 2020 and 41.3 % in 2030, resulting overall in fuel demand by individual transport that is 8.0 % lower in 2020 and 10.7 % in 2030 than in BAU. Reductions in fuel demand consequently imply fewer emissions and hence lower damage.

Considering all abatement channels activated in our hybrid model, EM+ reduces total air quality emissions (abatement in Austria as well as abroad). Emissions of SO₂ are reduced by 0.2 %, NO_x by 0.3 %, PM by 0.2 %, and VOC by 1 % in 2030. Over the whole period (2008-2030), these reductions are 0.2 %, 0.3 %, 0.2 %, and 0.7 %, respectively. The highest absolute reduction of carbon emissions is achieved around the year 2019, when about 1.1 mT of CO₂ are reduced both domestically and abroad. However, EM+ is not a strong carbon mitigation policy since, in relative terms, EM+ reduces CO₂ emitted in Austria by 0.5 % only at maximum, and by 0.2 % over the whole period.

Monetizing all of these emissions into external costs, we get damage attributable to domestic emissions of about 10.8 billion Euro in the base year. This corresponds to about 3.7 % of GDP

in that year, whereas damage attributable to total emissions is about 27.4 bln. Euro (9.4 % of Austrian GDP). Damage attributable to domestic emissions increases over time to 12.6 billion Euro in 2030, i.e. +17 % in relative terms (and to 33.3 billion Euro and +21 % due to total emissions). About half of this damage is associated with climate change impacts, 43 % to adverse health impacts, and the remainder includes environmental impacts. These shares hold more or less for the whole period and across the scenarios.

We conclude that both MODEST and EM+ are damage-saving policies, although the overall net effect is quite small and mainly due to some improvement in air quality. EM+ leads to damage attributable to domestic emissions of 12.6 billion Euro in 2030, which is about 0.5 % less than in BAU (and is 0.51 % less over the whole period). Considering total emissions, damage of EM+ is 33.2 billion Euro in 2030, which is 0.21 % less than in BAU (0.27 % less over the whole period). These positive net benefits represent about 10 % of GDP loss, which attains 0.23 % on average. The benefits hence partly reduce the negative impact on the economy.

Since the technology mix to generate electricity does not differ substantially across the scenarios, the main effect on emissions and related external costs is due to higher demand of electricity for charging batteries appearing mainly at the end of the period. Compared to BAU, EM+ generates damage of 10 million Euro more in 2023, which increases to 45 million Euro in 2030. However, the increasing market share of EVs also implies lower use of motor fuels and, as a consequence, also leads to avoided negative externalities of between 41 million Euro (2015) and 69-86 million Euro (2019-2030) per year in EM+. In each year, the positive effect of fuel use reduction exceeds the negative effect of increased electricity demand on the total net environmental benefits. Changes in the economic structure and imports always generate a net environmental benefit, see Table 3.

3.7. Sensitivity analysis

In order to validate the model's stability, we performed a sensitivity analysis, which ensures that the selection of parameter values does not lead to unstable results and singularity in the model's solution. For a stable model, a slight change in parameter values of crucial elasticities should neither yield a significant change in the size of the model variables, nor a qualitative change in the direction of the results.

The simulations of MODEST and EM+ scenarios were repeated several times with a structural change in all values of elasticities. Therefore, we varied the values of the elasticities by $\pm 25\%$, $\pm 50\%$, $\pm 100\%$, $\pm 150\%$, $\pm 200\%$, and $\pm 300\%$.

Depending on the initial value of each elasticity, a rise of e.g. $+300\%$ may not be very realistic. However, for the simulation runs with elasticity values in a realistic range, the changes in the variables' values were also in a realistic order of magnitude. Qualitatively speaking, the directions of variables' reactions to scenario simulations are not reversed by any alteration of elasticities. Hence our results can be perceived as robust. A complete record of the results of the sensitivity analysis is available on request. Among the most reactive parameters are consumption elasticities (for all households) since our hybrid CGE model is mostly demand-driven. With regard to production, a variation in the elasticity between energy and electricity inputs had a slightly stronger impact than variations of other elasticities in production. A comparison of the GDP levels in an ordinary EM+ scenario-run (i.e. without a variation of any elasticities) with the GDP levels of all sensitivity analysis simulations of the EM+ scenario yielded a deviation in 2030 within the range of $\pm 20\%$.

Table 3: Environmental benefits of EM+ in comparison to BAU

Year	GDP loss (mil. €)	Equivalent variation (mil. €)	Total (mil. €)	Domestic sectors (mil. €)	FUEL (mil. €)	ELE (mil. €)	Imports (mil. €)	Damage as % of GDP loss	Δ CO ₂ (ths. t) total =domestic +indirect	Domestic ancillary benefits per tonne of domestic CO ₂ abated (€/t)	Total ancillary benefits per tonne of total CO ₂ abated (€/t)
2008	-838	-1835	-17	-4	-1	-2	-9	1%	-139	128	104
2009	-877	-6476	-22	-6	-3	-1	-12	1%	-204	106	89
2010	-832	-2062	-24	-6	-5	-1	-12	1%	-222	110	88
2011	-800	-3023	-26	-6	-6	-1	-12	2%	-235	119	90
2012	-778	-4146	-28	-7	-8	0	-13	2%	-261	114	87
2013	-767	-5332	-32	-8	-9	-2	-14	2%	-280	134	96
2014	-757	-6564	-33	-8	-10	-1	-14	2%	-291	129	92
2015	-1008	-7799	-103	-21	-41	-4	-37	7%	-816	153	106
2016	-940	-9221	-101	-21	-41	-2	-36	7%	-821	146	103
2017	-879	-10622	-97	-21	-42	0	-34	7%	-798	146	102
2018	-813	-1345	-94	-20	-42	-1	-30	8%	-736	157	107
2019	-992	-508	-147	-31	-69	-1	-47	10%	-1143	155	108
2020	-869	-723	-138	-29	-70	1	-40	11%	-1035	164	113
2021	-764	-915	-132	-28	-72	4	-36	13%	-953	174	118
2022	-669	-1123	-124	-27	-74	7	-30	14%	-857	185	125
2023	-585	-1330	-117	-26	-76	10	-25	16%	-763	199	133
2024	-514	-1530	-109	-25	-77	14	-20	17%	-658	217	146
2025	-424	-1715	-98	-22	-79	18	-14	20%	-520	248	167
2026	-417	-1898	-91	-22	-81	23	-12	19%	-436	276	190
2027	-438	-2070	-87	-23	-82	28	-11	17%	-370	308	216
2028	-491	-2230	-84	-23	-83	33	-11	15%	-309	351	250
2029	-566	-2411	-78	-23	-84	39	-10	12%	-227	434	325
2030	-662	-2739	-71	-24	-86	45	-6	10%	-84	753	821

Notes: First five columns report the additional external costs for EM+ attributable to changes in domestic production, fuel use in individual transport, electricity generation, associated with imported good and the sum, respectively. External costs include cost of climate change (CO₂) and emissions of NO_x, SO₂, and particulate matters. Ancillary benefits present avoided damage due to reduction in emissions of NO_x, SO₂, and particulate matters, when benefits attributable to emission reductions in Austria are related to CO₂ emissions abated in Austria (column 8) and globally (column 9).

4. Conclusion

The core aim of this paper was to develop a novel simulation tool to estimate the total social costs and benefits of the introduction of electric vehicles as an endogenous, demand-driven abatement technology. Extending previous literature, the costing methodology relies on a hybrid CGE-DC framework and on an established impact pathway analysis to quantify environmental and health externalities. We demonstrate that the social costs and benefits of using EVs to mitigate emissions are related to consumer preferences that determine the change in demand for EVs as a reaction to a given policy incentive or preference shifts. At the same time, we consider vehicle technology developments and associated purchase price and fuel efficiency changes, as well as the energy system with a bottom-up focus on the electricity sector, that altogether determine the amount of emissions by individual transportation.

We analyse the impacts for two scenarios. MODEST assumes a shift in consumer preferences to electromobility that is supported by a low-level introduction of fast-mode charging infrastructure while EM+ imposes increased mineral oil taxes and a new registration tax linked to carbon emission standards, as well as assumes a higher amount of medium-to-high level fast-mode charging stations.

As a consequence of assumed policies, new registrations of EVs rapidly increase particularly at the end of the modelling period, reaching 44 % in MODEST and 68 % in EM+ in 2030. Hence, the 28 % market share of EVs in the vehicle stock in EM+ is almost doubled in comparison to MODEST and is assumed to be further increasing and replacing CVs beyond the model horizon. However, the relatively swift uptake of EVs in Austria in both scenarios is also supported by measures to foster electromobility that are already in place (feebate system is a part of BAU) and the preferences of Austrians that are relatively more in favour of EVs than in other countries, especially in Eastern and Southern Europe.

In terms of the macroeconomic effects, investments into the charging infrastructure enhance economic growth. Thereby, we show that efforts to decarbonise the transport sector can also positively contribute to growth. However, the tax related incentives (EM+) would have a negative impact on GDP. We highlight, however, that this effect is relatively small in a range of -0.12 to -0.32 % from the BAU growth rate, and is partly balanced by avoided negative environmental externalities mainly adversely affecting human health. While these incentive measures might have slightly negative effects on GDP growth, they lead to higher net government revenues. The Austrian government receives surplus tax revenues of 0.4 % with respect to BAU in 2030. Additional demand for electricity to charge batteries installed in EVs accounts for 2.3 % of energy supply mostly satisfied by gas-fired power plants.

Despite the increasing stock of AFVs using more fuel, with 44 % of new registrations belonging to PHEVs in 2030, the effect of CV stock reduction, representing only 15 % of new registrations in 2030 in EM+, outweighs this additional consumption, and thus fuel use is reduced by 10.7 % in 2030, implying fewer emissions and damage lower by 86 million Euro in comparison to BAU. Additional demand for electricity for charging vehicle batteries generates damage higher by 7 %. However, the positive effect of fuel use reduction exceeds the negative effect of increased electricity demand on total net environmental benefits each year. Damage related to total emissions of residual sectors' domestic production and imports avoided in EM+ amounts to 0.2 % over the whole period, representing about 10 % of GDP loss and hence partly reducing the negative impact on the economy. Financial incentives to motivate the uptake of EVs would be needed to further reduce fuel use to generate larger environmental benefits since the magnitude of the negative externalities that can be avoided is not large, resulting in 65-70 million Euro of benefits delivered by EM+ each year.

The relatively small magnitude is due to two effects. First, the Austrian power sector has been relying on renewable sources of energy, and thus the impact on the fuel-mix and the power sector in terms of the volume of generated electricity is rather small. However, our modelling approach was able to capture these effects nonetheless, and as such, it can be applied to other national

economies with different energy systems relying more on non-renewable resources. External costs and social benefits of an intensified adoption of AFVs for such economies might strongly increase. Extending this framework could provide insight on to what extent the net social costs of a policy-guided shift-in of electric vehicles differ between countries, different energy systems and sets of policy measures. Second, although the new registrations of BEVs and PHEVs are increasing, this increase is becoming especially prominent after 2022-25, which has only a limited effect on the vehicle stock until the end of the observed period in 2030. As a consequence, long-lasting positive environmental effects resulting from the changing fleet composition, due to the high amount of new registrations of EVs, are expected in the years beyond 2030. This shows that the measures investigated in this study designed to support electromobility can effectively counteract the ongoing growth of emissions from individual transportation. Beyond that, the model simulations show that the vehicle market depicted in the model can react flexibly to a shift in preferences by consumers towards electromobility. The investigation of these long-term effects are left for further research.

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Appendices

A. Further modeling details

A.1. Benchmark and business-as-usual scenario

All relative prices for goods and services develop according to the benchmark price reference path $pref(t)$,

$$pref(t) = \left(\frac{1}{1+r} \right)^t \quad \forall t, \quad (35)$$

where r is the real exogenous interest rate. The reference price in period t is the expected present value of the price, i.e. discounted value from the representative agent's perspective, in the starting period. Moreover, the unit demand variables develop according to the benchmark quantity reference level, $qref(t)$,

$$qref(t) = (1 + gr)^t \quad \forall t, \quad (36)$$

where gr is the real exogenous growth rate. Since all levels of monetary flows between all agents and sectors are given in the SAM in real monetary terms, the values in the SAM can be used, in combination with the levels of unit demand and relative prices, to determine actual real prices and actual real monetary flows between agents and sectors in any period t .

The exogenous steady state growth rate gr also applies for the growth of expenditures on vehicle use (fuel and maintenance costs) and vehicle purchases. Hence, the growth paths of vehicle stock sizes and new registration numbers are

$$st_i(t) = st_i(0) (1 + gr)^t \quad \forall i, \forall t, \quad (37)$$

$$nr_i(t) = nr_i(0) (1 + gr)^t \quad \forall i, \forall t. \quad (38)$$

According to (3), the vehicle stock in each period is equal to the preceding period's vehicle stock plus new registrations minus depreciated cars of the preceding period. Combining these conditions yields the initial number of new registrations in a fixed relation to the vehicle stock as

$$nr_i(0) = st_i(0)(gr + \delta_i) \quad \forall i, \quad (39)$$

where 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.

B. Tables

Table A: Summary of producing sectors included in the Social Accounting Matrix

Abbreviation	Sector name	Link to bottom-up modeling
AGR	Agriculture, forestry, fishing	
FERR	Basic metals, nuclear fuels	
CHEM	Chemical products, pharmaceuticals	
ENG	Metal products, engineering	→ HEV, PHEV, EV
CAR	Vehicles production and trade	→ CV, HEV, PHEV, EV
VEH	Other transport equipment	
OTHER	Other production and mining	
BUI1	Building construction, civil engineering	
BUI1	Specialised construction activities	
PPT	Public passenger transport	
NCST	Other passenger transport	
FT	Freight transport	
RnD	Research and Development	
SERV	Services	
CAR SERV	Car services	→ CV, HEV, PHEV, EV
ELE	Electricity production	→ ELE INF, Electricity BU model
ELE INF	Electricity trans and distribution	→ PHEV, EV
LDH	Steam and AC supply	
GAS	Gas production and distribution	
COAL	Mining of coal and lignite	
CRUDE	Crude oil and gas extraction	
FUEL	Fuel for transport purposes	
OWNINIT	Intermediate inputs within sector	
	...rows in final demand	
CV	Conventional vehicle	→ Vehicle stock-flow model
HEV	Hybrid vehicle	→ Vehicle stock-flow model
PHEV	Plug-in hybrid vehicle	→ Vehicle stock-flow model
EV	Battery electric vehicle	→ Vehicle stock-flow model

Table B: Cross-price elasticities in household consumption

σ^{trans}	Substitution between T-composite and EEM-composite:		
	Urban	Suburban	Rural
LS	0.12	0.16	0.16
MS	0.12	0.18	0.18
HS	0.10	0.14	0.16
$\sigma^{\text{ITPT-OT-C}}$	Substitution between ITPT-composite and OT-composite:		
	Urban	Suburban	Rural
LS	0.22	0.48	0.32
MS	0.28	0.48	0.43
HS	0.16	0.23	0.23
σ^{mode}	Substitution between IT and PT:		
	Urban	Suburban	Rural
LS	0.15	0.31	0.32
MS	0.17	0.41	0.46
HS	0.15	0.26	0.40
$\sigma^{\text{EE-M-C}}$	Substitution between EE-composite and M-composite:		
	Urban	Suburban	Rural
LS, MS, HS	0.4	0.4	0.4
$\sigma^{\text{E-E-C}}$	Substitution between all energy goods:		
	Urban	Suburban	Rural
LS, MS, HS	0.4	0.4	0.4
$\sigma^{\text{Y-C}}$	Substitution between all consumption goods:		
	Urban	Suburban	Rural
LS, MS, HS	0.4	0.4	0.4

Note: LS = Low Skilled, MS = Medium Skilled, HS = High Skilled, T = transport, IT = individual transport, PT = public transport, EEM = energy-electricity-material, EE = energy-electricity, M = material, OT = other transport (planes etc.)

Table C: Other elasticities of substitution used in the CGE model

Attributes	Values
$\sigma^{\text{C-LS-W}}$	1.4
σ^{t}	0.5
$\sigma^{\text{KL-EEM-Y}}$	0.3
$\sigma^{\text{K-L-Y}}$	0.4
$\sigma^{\text{EE-M-Y}}$	0.5
$\sigma^{\text{E-E-Y}}$	0.5
$\sigma^{\text{M-Y}}$	0.5

Note: C-LS-W = substitution between consumption and leisure in household welfare, t = intertemporal elasticity of substitution for household, KL-EEM-Y = substitution between capital-labour composite and energy-electricity-material-goods-composite in production, K-L-Y = substitution between capital and labour in production, EE-M-Y = substitution between energy-electricity-composite and material-goods-composite in production, E-E-Y = substitution between energy and electricity in production, M-Y = substitution between all material goods in production

Table D: Marginal utility values of the vehicle attributes (components of β)

β entries	Households by living area		
	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 E: Attribute levels (initial steady state calibration)

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

Table F: List of model parameters and variables

Parameters & variables	meaning
$P_i^{\text{pur}}(t)$	purchase price of vehicle i
θ_i^{CE}	vehicle type specific cost share between engines and car chassis
$P^{\text{C}}(t)$	Price for vehicle chassis
$P^{\text{E}}(t)$	Price for vehicle engine
$P_i^{\text{use}}(t)$	Price of vehicle use
$\theta_i^{\text{FS}}(t)$	vehicle type specific cost share between fuel and service and maintenance
$P^{\text{F}}(t)$	Price for fuel (gasoline/diesel and electricity composite)
$P_i^{\text{S}}(t)$	Price for service and maintenance
$nr_i(t)$	new registrations of vehicle i
$st_i(t)$	vehicle stock of vehicle i
$dc_i(t)$	depreciation of worn out vehicles i
$e^{\text{pur}}(t)$	volume of expenditures on type i vehicle purchases by household h
$D_{h,i}^{\text{pur}}(t)$	unit demand for purchases of new vehicles
$p_i^{\text{av}}(t)$	exogenous average monetary price for vehicle i
$D_{h,i}^{\text{use}}(t)$	unit demand of household h for using vehicles of type i
$V_{h,i}$	indirect utility of buying a vehicle of type i
\bar{P}_h	price index for aggregated vehicle purchases
$P_{h,i}^e$	effective price for each vehicle choice alternative i and each household h
$x_{h,i}$	vehicle attributes (range, engine power, fuel cost, maintenance cost, purchase price)
$\beta_{h,i}$	vector of shadow prices (marginal utilities) of each of vehicle attributes
$\alpha_{h,i}$	alternative (i.e. technology) specific constant
$\mathbb{P}_{h,i}$	probability of agent h to choose alternative i , given the prior decision to purchase any vehicle at all
$\theta_{h,i}$	share of purchases of vehicle i in total vehicle purchases of household h
\bar{V}_h	logsum of all vehicle types
$\Theta_h^{\text{pur}}(t)$	share of expenditures on vehicle purchases in total expenditures for individual transportation for household h in period t
$\theta_{h,i}^{\text{st}}(t)$	share of the size of the stock of vehicles of type i in the total stock of vehicles owned by household h
$e_{h,i}^{\text{pur}}(t)$	volume of expenditures on purchases of vehicles
$e_{h,i}^{\text{use}}(t)$	volume of expenditures on fuel and services
$\bar{D}_h(t)$	unit demand for purchases of any kind of vehicle
$D_h^{\text{IT}}(t)$	overall demand for IT
$D_{h,i}^{\text{pur}}(t)$	unit demand for purchases of vehicles of type i

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