Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria—A model based analysis 2010–2050

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This paper investigates the effects of policy, fuel prices and technological progress on the Austrian passenger car fleet in terms of energy consumption and greenhouse gas (GHG) emissions. To analyse these effects a simulation model is used. We model the car fleet from a bottom-up perspective, with a detailed coverage of vehicle specifications and propulsion technologies. The model focuses on the technological trend toward electrified propulsion systems and their potential effects on the fleet's energy consumption and GHG emissions. To represent the impact of prices and income on the development of the fleet, we combine the fleet model with top-down demand models. We developed two scenarios for the time frame 2010–2050, using two different sets of assumptions for regulatory development and conditions of increasing fossil fuel prices and continuous technological progress in vehicle propulsion technologies.

The results indicate that material cuts in energy consumption and GHG emissions can be achieved with changes to the political framework for passenger cars. Appropriate taxation of fuels and cars can stabilise demand for individual motorised transport and lead to an improvement in vehicle efficiency by fostering the adoption of efficient vehicle propulsion technologies and low carbon fuels.

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1. Introduction

Low efficient cars, dependence on fossil fuels and emissions of pollutants and greenhouse gases (GHG) are some of the serious challenges passenger car transport is facing today. Even though efficiency of cars has improved in the last years (Meyer and Wessely, 2009; Pötscher, 2009), GHG emissions of the entire fleet kept growing in Austria (Schneider et al., 2010). Emissions of some pollutants could be reduced in the last years (e.g. CO and SO2) while others, e.g. particular matter and nitrogen oxides, are still a major issue (Pazdernik et al., 2010).

There are legitimate expectations that alternative vehicle propulsion technologies together with alternative fuels could alleviate these problems. The European Union is driving an effort to enforce the use of biofuels in order to reduce emissions and dependence on fossil fuels (Directive 2009/28/EC, 2009). However, the potential for substitution is limited with today’s biofuels (Kavlov, 2004) and advanced second generation biofuels are not available in a large scale yet (WBCSD, 2007). Also there are concerns, that the use of fertile land for the production of fuels for low efficient motor vehicles is not justified (Braun, 2008).

This analysis will focus on another approach, which is the electrification of the vehicle propulsion system. Hybrid electric vehicles (HEV), plug-hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) are in the spotlight today. Some car manufacturers already offer HEVs in their portfolio and several others are expected to follow within the next years. Furthermore, there is an increasing number of small car manufacturers trying to enter the market with BEVs. Even some of the leading carmakers are announcing the introduction of PHEVs and BEVs in the years to come (Brunner et al., 2010). It remains to be seen whether the promise of these cars will be converted into commercial success on a large scale. Electric cars are known to be superior to conventional ones in terms of energy efficiency and they produce no local pollutant emissions. When supplied with electricity from state of the art natural gas-fired gas and steam plants or even renewable electricity they cut total GHG emissions considerably (Kloess et al., 2009; Thiel et al., 2010).

Apart from their technical and environmental benefits electric cars have to struggle with some serious disadvantages associated with their limited driving range and long recharging time. These limitations and their high upfront costs are major barriers that could hold consumers to buy such cars (Cowan and Hultén, 1996; Sovacool and Hirsh, 2009). Hybrid cars have better prospects in...
this sense, but their economic success is still highly dependent on the specific framework conditions (Thiel et al., 2010).

By affecting the cost of transport political framework conditions have considerable impact on the car fleet in terms of vehicle characteristics and fuel efficiency (CBO, 2008; Bonilla, 2009) as well as driving distance per year (Johansson and Shipper, 1997; CBO, 2008). Furthermore, they also affect the spread of efficient propulsion technologies (Diamond, 2009). In this paper we analyse the policies regulation and fuel prices which would drive the uptake of electrified vehicle propulsion technologies in Austria. Secondly, we evaluate the effects on energy consumption and GHG emissions that such an uptake would have. In pursuit of those objectives, the paper will address the following questions:

- Which factors most influence the spread of hybrid and electric cars?
- What role can policy play to encourage the spread of these cars and to improve the efficiency of the sector as a whole?
- Within what time frames can hybrid and electric cars attain material market shares?
- How will large scale introduction of hybrid and electric vehicles influence the energy demand of the car fleet?
- What is their potential to reduce GHG emissions within the transport sector?

To answer these questions a model based analysis is performed using a simulation model for the Austrian passenger car fleet. The model has been developed starting in 2007 in the course of two research projects (Haas et al., 2008a; Kloess et al., 2009) funded by the Austrian Federal Ministry of Transport, innovation and technology.

It combines a bottom-up model of the Austrian passenger car fleet, including detailed coverage of vehicle specifications, technologies and user behaviour, with a top-down model of passenger car transport demand and service level. The effects of changing political, economic and technological framework conditions on the passenger car fleet can be simulated with the model. The impact of different fossil fuel price levels and different levels of fuel- and vehicle taxation on the passenger car fleet in terms of fleet size, vehicle specifications, efficiency, vehicle use and diffusion of technologies can be analysed with the help of different scenarios. The effects on energy consumption and GHG emissions can be illustrated on a well-to-wheel (WTW) basis. The model helps identify the main driving forces for the diffusion of efficient cars and can help policy makers to find strategies that support them.

One innovative aspect of the model is the detailed coverage of the recent technological trend toward electrified propulsion systems. It considers all relevant types of propulsion technologies with different degrees of electrification extending from conventional drive cars, HEVs to PHEVs and BEVs.

The remaining paper is structured in the following manner: Section 2 gives a brief overview on the current policy framework for passenger cars in Austria and explains the policy framework assumed in the scenarios for 2010–2050. Section 3 presents the propulsion technologies that are considered in the analysis and describes how their cost development is modelled. Section 4 describes the methodology of the scenario model including the general approach and a closer view on some key elements. Section 5 discusses the results of the analysed scenarios. Section 6 draws conclusions.

2. Taxes on transport fuels and passenger cars in Austria

In Austria taxes on transport fuels and cars account for a considerable part of total cost of transport. Fig. 1 depicts the total cost per kilometre for a middle class gasoline car in 2010 (left column). There are three main taxation instruments that affect the costs of passenger car transport which are: tax on acquisition, tax on ownership and taxes on fuels. This section will explain the mechanisms and rates of each of these taxes in Austria for the status of 2010. It also analyse their effectiveness to improve efficiency in passenger car transport and to promote the adoption of alternative propulsion technologies. After that the scenario assumptions will be presented.

2.1. Tax on acquisition

Tax on acquisition or registration tax is a policy instrument that can affect energy demand in two ways. By increasing fixed costs it can slow down fleet growth (see Section 4.3.1) and it can also improve the efficiency of cars sold if appropriate mechanisms are
applied (Giblin and McNabola, 2009). Within the European Union not all countries have registration taxes and the applied schemes differ strongly in height and functioning (ACEA, 2009; Mandell, 2009).

In Austrian tax on acquisition has to be paid once when the car is registered for the first time in the country. It is paid as a percentage of the purchase price. The percentage depends on the fuel consumption of the vehicle and is capped at 16%. Also, there is an additional bonus/malus system linked to GHG emissions. When the cars' emissions are below or above a certain threshold, the acquisition tax is reduced or increased by 25 €/gCO₂. In 2010, the upper threshold for the bonus was 160 g/km and the lower threshold for the malus was 120 g/km (see Table 1). Moreover, there are special deductions for cars that use an alternative propulsion system (−500€) while zero emission vehicles pay no acquisition tax at all (BMF, 2010).

It is evident that the mechanism of this tax gives incentives to purchase fuel efficient cars. However, the comparison of total cost of different propulsion systems (Fig. 6 in Section 3) shows that the reduced tax rates for fuel efficient and alternative technologies cannot offset their higher upfront costs.

2.2. Tax on ownership

Tax on ownership or circulation tax is a tax that has to be paid on a monthly or yearly basis by car owners regardless of the intensity the car is used. The tax usually depends on engine power, cylinder capacity or fuel consumption respectively GHG emissions (ACEA, 2009; Mandell, 2009).

In Austria it depends on the engine power of the car and is paid on an annual basis (BMF, 2010). Since vehicles with higher power are usually less fuel efficient the tax has some kind of regulative effect on the efficiency of vehicles in the fleet, but when it comes to comparing systems with the same power there is no differentiating between high and low efficiency. Therefore, the current tax on ownership in Austria has only limited effectiveness in promoting fuel economy, as it gives no direct incentive to choose fuel efficient technologies.

2.3. Tax on fuels

Fuel taxes are seen as an effective regulatory instrument to restrain growth in energy consumption of road transport (Sterner, 2007). By affecting the fuel price it also affects the consumers' choice of cars (Bonilla, 2009), as well as the way they use it (CBO, 2008). An increasing fuel price as a result of higher fuel taxes would induce consumers to either switch to more efficient cars or to reduce their yearly driving distance. A more detailed view on the theoretical background of this relationship will be given in Section 4.

Fuel tax in Austria was 0.447 €/l on gasoline and 0.347 €/l on diesel in 2010. Biofuels and compressed natural gas (CNG) are excluded from the fuel tax so far (see Table 2). With this rated Austria finds itself in the midfield of EU member states, however the most big neighbour countries as well as most other western European countries have higher fuel tax rates (European Commission, 2010).

Apart from these taxes there is also the value added tax (VAT) on both cars and fuels which is 20% in Austria.

2.4. Scenarios for policy framework

To analyse the effects of different policies on energy consumption, energy carriers and GHG emissions of the passenger car fleet, two policy scenarios are developed for the time frame 2010–2050. This scenario time frame was chosen in order to be able to analyse the long term effects of the assumed policies.

2.4.1. Business-as-usual scenario—BAU-scenario

In this scenario the policy framework remains substantially unchanged from that of 2010. The only change is an adjustment of the fuel tax taking into account that CNG will be taxed at the same rate as diesel fuels from 2015. The BAU scenario forecasts the outcome if the present policy framework is retained and no ambitious policies are adopted to reduce energy consumption and GHG emissions.

2.4.2. Policy scenario

The policy scenario proves how the political framework can help reduce GHG emissions of the passenger car fleet in order to
3. Characteristics and costs of powertrain technologies

3.1. Description of powertrain systems

This section gives an overview on the vehicle propulsion technologies that are considered in the analysis. With the selection it was tried to consider all major steps of vehicle powertrain electrification capturing the entire spectrum from conventional drive cars to full electric cars.

**Conventional drive (CD):** This term is used for powertrain systems that are solely based on internal combustion engines (ICE) without additional electric traction motors. In the analysis this includes cars with gasoline, diesel and CNG engines.

**Micro-HEV:** These types of HEVs are closely related to conventional cars. That is why they are often considered not as real hybrids. The powertrain is only slightly modified with a stronger, combined starter-alternator instead of conventional separate starter and alternator. This configuration allows the vehicle to turn-off the ICE when the vehicle is standing and to recuperate some of the braking energy.

**Mild HEV:** Mild HEVs have an electric traction motor mounted between the ICE and the transmission that supports the engine during vehicle acceleration and recovers braking energy. A hybrid is called mild hybrid when the electric motor has significantly lower power than the ICE and the car cannot be propelled by the electric motor alone.

**Full HEV:** Full HEVs have more powerful electric motors than mild HEVs and usually also more complex powertrain architectures. This allows better support of the ICE and better recuperation of energy during braking, which makes the vehicle more efficient. Theoretically, a full hybrid can run in pure electric mode, but only for very short distances because of its small battery capacity.

**PHEV with 40 km electric driving range (PHEV 40):**

The PHEV 40 has a similar powertrain as the full HEV, but with higher battery capacity that allows electric driving at longer distances and the car can be recharged from the grid. In this particular case we consider a PHEV with 40 km driving range that is capable to operate 50% of its yearly driving distance in electric mode.

**PHEV with 80 km electric driving range (PHEV 80):**

The PHEV in the analysis is a series hybrid, which means that only the electric motors propel the car and the ICE only drives a generator that produces the required electricity on board. The 80 km driving range are considered to be sufficient to drive the car in electric mode at 80% of the yearly driving distance.

**BEV:** The BEVs run purely on electricity provided by its traction batteries that are charged from the grid.

To make the different powertrain systems comparable they are all based on reference specifications of the respective vehicle class. The detailed specifications of different powertrain systems in the middle class segment are presented in Table 3. We selected these based on the consensus among automotive experts for the propulsion systems that are most promising and feasible for the time frame 2010–2050. A more detailed description of the powertrain options as well as their characteristics is given in Kloess et al. (2009).

### 3.2. Investment costs of passenger cars

Investment costs are the most important cost category within the specific service costs of passenger cars (see Fig. 6). For electrified vehicles they represent a major barrier to introduction to the market. To identify the main cost drivers and to assess their potential for cost reduction, the cars are divided into their main components. The capital cost have been analysed on a component basis. The component groups are defined as follows:

**Vehicle basis:** This component group includes all components of the car that don’t belong to the propulsion system. The cost of the vehicle is determined from Austrian market statistics and prices considering data from Statistics Austria (2009) and Autorevue (2009).

**ICE & transmission:** This includes the ICE the transmission and the fuel tank. The component costs are taken from EUCA r et al. (2006)

**Electric drive components:** the electric drive includes the electric motors and generators including controllers, the vehicle on-board charger as well as the necessary upgrade for hybrid power trains. The costs of electric motors and hybrid powertrain

<table>
<thead>
<tr>
<th>Specifications of middle class vehicles with different propulsion systems.</th>
<th>Electric range (km)</th>
<th>Overall range (km)</th>
<th>Power Engine (kW)</th>
<th>e-Motor (kW)</th>
<th>Battery capacity (useable) (kWh)</th>
<th>2010</th>
<th>2030</th>
<th>Fuel consumption (l; kg; kWh /100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-Gasoline</td>
<td>700</td>
<td>75</td>
<td></td>
<td></td>
<td>7.5</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD-Diesel</td>
<td>700</td>
<td>75</td>
<td></td>
<td></td>
<td>6.0</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD-CNG</td>
<td>700</td>
<td>75</td>
<td></td>
<td></td>
<td>5.2</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-HEV</td>
<td>700</td>
<td>75</td>
<td></td>
<td></td>
<td>6.9</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild HEV</td>
<td>700</td>
<td>65</td>
<td>20</td>
<td></td>
<td>6.4</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full HEV</td>
<td>700</td>
<td>50</td>
<td>50</td>
<td></td>
<td>5.9</td>
<td>5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHEV-40</td>
<td>40</td>
<td>700</td>
<td>50</td>
<td>50</td>
<td>10</td>
<td>10</td>
<td>5.9</td>
<td>5.2/20.4</td>
</tr>
<tr>
<td>PHEV-80</td>
<td>80</td>
<td>700</td>
<td>40</td>
<td>75</td>
<td>20</td>
<td>20</td>
<td>5.5</td>
<td>4.7/20.4</td>
</tr>
<tr>
<td>BEV</td>
<td>200</td>
<td>200</td>
<td>75</td>
<td>40</td>
<td>40</td>
<td>22.2</td>
<td>20.4</td>
<td></td>
</tr>
</tbody>
</table>
upgrade are taken from EUCAR et al. (2006) and the cost of the charger is taken from Williams and Kurani (2007).

Battery system: this component group includes batteries for the on board grid as well as traction batteries of electrified powertrain systems. For the traction batteries the use of Lithium Ion (Li Ion) batteries is assumed. Li Ion batteries are broadly seen as the best option for all types of electrified cars, but they also imply high cost. Their specific costs in 2010 were set at 700 €/kWh according to Passier et al. (2007). In literature cost estimation with considerably lower costs can be found, e.g. Kalhammer et al. (2007). However, these estimations refer to high production volumes and cannot be applied for the introduction phase of this technology.

The total investment cost of all powertrain systems is illustrated in Fig. 2. The figures are in the range of cost estimations found in comparable analysis, e.g. van Vliet et al. (2010) and Thiel et al. (2010). They point out that batteries are the main cost driver for PHEVs and BEVs and reduction of cost will be a major challenge for their future development.

3.2.1. Technological learning

We use technological learning to estimate the cost development of Li Ion batteries. The cost of the other, more mature, car components have been assumed to remain constant. This implies that learning effects are outweighed by the required improvements of these components in the time frame 2010–2050 (e.g. higher comfort and security requirements, lightweight materials, stricter emission standards, etc.)

In technological learning theory, future costs C are a function of the costs of the first unit built a, the cumulative production x and the learning index b (Grübler, 1998)

\[ C(x) = ax^{-b} \]  

(1)

To estimate the global cumulative production of automotive batteries we assume that we are at the beginning of the technological substitution process where electrified drive systems (HEVs, PHEVs and BEVs) are slowly but steadily substituted for internal combustion engines on a global level. Thereby, the diffusion of electric propulsion systems follows the classical S-shaped curve of technological life cycles. The technology is currently in an early phase, the so-called "introduction" or "childhood phase". The increasing market share of HEVs and the emergence of PHEVs and BEVs are evidence of this development (IEA, 2009). The next step is the steep growth phase, which leads to a great shift in automotive development with production focusing on electric machines and electricity storage systems. This change will be strongly reflected in the development of cumulative global production of these components. The growth of cumulative production of batteries has been derived from this development. The other critical factor for the cost estimation is the learning index b that can also be expressed by the so called progress ratio p, or the learning rate LR.

\[ p = 2^{-b} \]  

(2)

\[ LR = 1 - 2^{-b} \]  

(3)

The range of learning rates for energy-related technologies extends from 5% to 25%, with an average of around 16–17% (McDonald and Schrattenholzer, 2001). Every technology has a base cost that arises from raw material and energy consumption, which can be considered as a lower boundary for future cost reductions. In the applied approach costs are separated in a fixed part \( C_{fix} \) and variable part that is affected by learning effects \( C_{learn} \):

\[ C = C_{fix} + C_{learn} \]  

(4)

This approach aims for a better coverage of technology-specific characteristics in the cost estimations and has also been applied in other models (Fulton et al., 2009). To determine the fixed costs, the results of bottom-up analysis are used. For Li Ion batteries base costs of 100 €/kWh are used which correspond to the long term goals of battery developers (USABC, 2010).

A learning rate of 15% is utilised for the variable part of the cost. The sensitivity of the model’s results to changes in the learning parameter is verified by analysing different learning rates (see Section 5). Fig. 3 illustrates the derived reductions of specific Li Ion battery cost in the time frame 2020–2050.

The effects of battery cost reduction on total investment cost of propulsion systems is displayed in Fig. 4 for the year 2030. In spite of the reduction, batteries remain a strong cost driver and PHEVs and BEVs remain more expensive than conventional vehicles even in the long term (see Table 4).

3.3. Fuel costs

The fuel costs of the cars are determined by their fuel consumption and fuel prices.
Fuel efficiency of all propulsion technologies was analysed by experts of AVL, an Austrian company specialised in automotive research and development. They determined fuel consumption of passenger cars at technology status 2010 and estimated the potentials of the technologies up to 2050 (Kloess et al., 2009) (see Table 3).

The fuel price is mainly determined by two factors: net fuel price and fuel taxes. The net price development of energy carriers in the time frame 2010–2050 is assumed in line with the European Energy and Transport Price Scenario PRIMES-High (Kapros et al., 2008). The crude oil price is increases from 76 $/bbl in the base year 2010 to 109 $/bbl in 2030 and up to 148 $/bbl in 2050. Fig. 5 shows the gross prices development of gasoline, diesel and electricity up to 2050 in the scenarios, considering the increase of fossil fuel prices as well as the increase in fuel tax. The electricity price also implies the costs of charging infrastructure.

3.4. Calculation of total cost

Total cost of transport is an important criterion for the assessment of propulsion technologies and it will also be a key factor in the model described in Section 4.

In this paper total cost of transport will be denominated service costs $C_{ij}$ corresponding to energy economics terminology. Service costs of each vehicle of the vehicle class $i$, with the technology $j$ are determined by their fuel costs $FC$, their capital costs $CC$ and tax on ownership $TO$. Other cost categories that contribute to total cost of ownership (e.g. maintenance and insurance) are not considered in this analysis.

\[
SC_{ij} = CC_{ij} + FC_{ijh} + TO_{ij} \quad (\text{€/year})
\]

Yearly fuel costs of cars are determined by fuel consumption $EC$, the price $FP$ of the fuel $h$ used and the distance driven per year $D$ by user category $u$

\[
FC_{ijh} = EC_{ijh}FP_{ih}D_{ih} \quad (\text{€/year})
\]
Capital costs are calculated using capital recovery factor $CRF$ with a standard depreciation time $DT$ of 10 years and an interest rate $r$ of 5%. They include net investment cost of cars $IC$, tax on acquisition $TA$ and valued added tax $VAT$.

$$CC_{ij} = (CRF(IC_{ij} + TA_{ij})(1+VAT)D_u^{-1}(€/km)$$

$$CRF = \frac{r(1+r)^{DT}}{(1+r)^{DT}-1}$$

Service costs of all propulsion technologies are calculated dynamically for the time frame 2010–2050, considering shifts in fuel prices, technological costs and taxation. Fig. 6 depicts total cost of powertrain system in the middle class at yearly driving distance of 15,000 km. It shows that conventional diesel cars are still the least cost option in 2010. Micro-hybridisation is a cost effective measure to cut fuel consumption. If applied to a diesel engine, it would become the least cost option. Mild HEVs are already close to economic competitiveness, while more complex hybrid systems like full HEVs and fully electric drivetrains (PHEVs and BEVs) have significantly higher costs due to their high capital costs. Fig. 7 gives the total cost of the same propulsion systems in 2030 in the policy scenario. The figures show impressively how increasing fossil fuel prices and the changed policy framework together with reduction of battery costs affect the cost ranking among technologies. Now BEVs and PHEVs are the least cost options with considerably lower cost than conventional cars.

4. Scenario model of the passenger car fleet

The focuses of the model is on new vehicle propulsion technologies. The model can develop scenarios with different political and economic framework conditions to analyse the effects on diffusion of new propulsion technologies as well as the effects on energy demand and greenhouse gas emissions. However, the model also captures other effects of changing framework conditions that have an impact on these parameters. This includes fleet growth, yearly driving distance of cars as well as characteristics of new cars in terms of mass and engine power. Unlike other transport models as described in Zachariadis (2005), Fulton et al. (2009) or Ceuster et al. (2007) where the passenger car is one transport mode amongst others in a global model of the transport sector, this model only covers the passenger car fleet. Thereby it focuses on the specific relevant policies and new propulsion technologies for cars. Thus, policy instruments and technological aspects of propulsion technologies are covered in more detail than in other models. In the model powertrain systems with different degrees of electrification, covering the
The one presented by Christidis et al. (2003). In addition, it considers highly developed and are a real alternative to the use of cars. Alternative transport modes like railways and public transport are transport increases. For the case of Austria, this is admissible since they can switch to other modes if the cost of passenger car transport increases. For the case of Austria, this is admissible since alternative transport modes like railways and public transport are highly developed and are a real alternative to the use of cars.

The core of the model is a bottom-up fleet model comparable to the one presented by Christidis et al. (2003). In addition, it considers the impact of prices and income on the overall passenger car transport demand. A further strength of the model is its detailed coverage of the energy supply of the sector including WTW energy and GHG balances of conventional and alternative conversion chains. This is of particular relevance for future scenarios where a broader variety of energy carriers is expected to be involved.

4.1. Principle and structure of the model

To model energy demand a systematic energy economic approach is followed. As for any other energy service, energy demand \( E \) of transport can be expressed as a function of transport service demand \( S \) and the efficiency \( \eta \) the service is provided (Haas et al., 2008b)

\[
E = f(S, \eta)
\]  

In the model passenger car transport service demand is defined by the number of cars in the fleet \( CAP \) and the kilometres they drive per year \( D \)

\[
S = f(CAP, D)
\]  

The efficiency of cars in the fleet is a function of the technology \( j \) they use and their transport service level \( F \). The transport service level defines the quality the transport service is provided (e.g. comfort level, driving performance). In the given approach transport service level is expressed by mass and power of cars

\[
\eta = f(j, F)
\]  

The following sections will explain how all these parameters are considered in the model.

Fig. 8 illustrates the global structure of the model. It consists of four main modules:

Module 1: The first module is the vehicle technology model where different vehicle powertrain options are modelled bottom-up to analyse the influence of technological progress on their costs (see Section 3).

Module 2: The second module derives market shares of technologies based on their specific service costs considering different levels of willingness to pay. The heterogeneity in consumer preferences has been modelled using a logit model approach with specific service costs as the main decision criterion (see Section 4.2). To consider the specific competitive disadvantages of alternative propulsion technologies that might arise from limitations in performance characteristics or lack of availability, diffusion barriers are used (see Section 4.2).

Module 3: The third module covers the influences of income, fuel prices and fixed cost on transport demand and transport service level. Transport demand is represented by fleet size and average annual driving distance. Transport service level is represented by characteristics of cars sold in terms of curb weight and engine power.

Module 4: The fourth module is a bottom-up fleet model of the Austrian passenger car fleet. The fleet is modelled in detail considering age structure, user categories and main specifications of the cars (e.g. engine power, curb weight, propulsion technology, specific fuel consumption, GHG emissions, etc.). The settings are based on a data pool including detailed information about the fleet today and time series of historic developments between 1980 and 2008 (Statistics Austria, 2009).

4.2. Market shares of technologies

The applied approach focuses on the economics of propulsion technologies as the main decision criteria of consumers. This implies that the purchase decision for a vehicle propulsion system is based on the specific costs, especially when different options offer the same service level. However, this brings the need to incorporate different levels of willingness-to-pay (WTP) or information deficits in the model. For example, there are consumer groups who are willing to pay for an advanced vehicle technology, which is environmentally benign even if it is not the best economic option.
In the model market shares $z$ of technologies $j$ are determined on a yearly basis $t$ using a multi-nominal logit-model, which is a common instrument for this types of problems in energy models (Train, 2009; Erdmann and Zweifel, 2008; Assen et al., 2009). Eqs. (12)-(14) describe how market share of a technology is derived. It is defined by the technologies’ service costs $SC$, by the service costs of a reference technology $SC_{ref}$ and of competing technologies (quantity: $k$), as well as by technology-specific diffusion barriers $a$. The reference technology is defined as the technology with the highest market share in the previous year. The parameter $b_i$ defines the slope of the logit-function and is determined by using historic data of the Austrian car market (1990–2008) (see Appendix A)

$$
z_{jt}(\%) = f \left( \sum_{j=1}^{k} w SC_{jt} SC_{ref} \left( b_i \right) \right)$$ (12)

$$
\tau_{jt}(\%) = \frac{w SC_{jt} SC_{ref} \left( b_i \right)}{\sum_{j=1}^{k} w SC_{jt} SC_{ref} \left( b_i \right)}$$ (13)

$$
w_{jt} = \left( 1 - \frac{1}{1 + e^{-6 \left( SC_{jt} - SC_{ref}\right)}} \right)$$ (14)

Furthermore, the market share in the previous year has an influence on the technology’s market share and diffusion barriers are summarised with the variable $a_j$. In the case of vehicle powertrain technologies, these barriers can have different causes, e.g., an incomplete infrastructure for a certain type of fuel. Lock-in and lock-out phenomena are often a reason why new technologies have difficulties entering the market even if they offer clear advantages compared to the established options (Erdmann and Zweifel, 2008). It is also possible that the range of car models available with the desired propulsion technology is very small, driving customers to choose other options. All these barriers represent a competitive handicap for certain technologies and have been considered in the model. Another diffusion limitation is the simple fact that the majority of consumers tend to be conservative in their decisions, especially when it comes to large investments as it is required when buying a new car. This means that they would rather buy technologies, proven to be reliable and efficient in the past. That is why new technologies are only slowly increasing their market share even after becoming cost efficient. Together these barriers constrain the potential growth rates in market shares of a technology. This limitation can be represented by the classical S-shaped curves of technological diffusion (Griibler, 1998).

Past experience with innovation in the automobile industry showed that their diffusion can vary strongly depending on the technology (Jutila and Jutila, 1986). The shape of the curve used in the model is technology specific, and has been determined through evaluation of the specific diffusion barriers for the considered technologies. Fig. 9 gives a schematic view on the
4.3.3. Demand for passenger cars

The parameters that are typically used to determine demand for transport in transport models are income, price, price of alternative modes and taste (Button, 2010). We apply a simplified approach that only considers income and price. As described in Section 4.1 transport is expressed by user intensity \( D \) of cars and by the size of the fleet \( CAP \) (see Eq. (15)). Fleet growth is determined by income (gross domestic product—GDP), fuel price and fixed costs. In the scenarios GDP growth is assumed to decrease steadily from 2% to 1% between 2010 and 2050 and fixed costs. In the scenarios GDP growth is assumed to decrease steadily from 2% to 1% between 2010 and 2050 which is in the range of assumption made by Kratena and Wüger (2005).

4.3.1. Demand for passenger cars

The development of annual vehicle demand is given by the elasticity of fuel price \( \varepsilon_{FP} \), vehicle price \( \varepsilon_{VC} \) and income \( \varepsilon_{IC} \) (see Eqs. (2) and (3)).

The elasticity of vehicle stock with respect to income has been set to 0.5 for the scenario time frame 2010–2050 in the model. Deriving elasticities for future scenarios always incorporates uncertainties as they are influenced by many factors, e.g. a strong influence of absolute income level on the income elasticity of vehicle ownership. The ratio of car ownership to income growth as well as the income elasticity of vehicle ownership is highly dependent on the absolute income level of the country. This correlation can be described by the Gompertz function (Dargay and Gately, 1999). In countries with high income levels like Austria the car fleet is already in saturation and therefore the income elasticity is decreasing. This means that lower income elasticity has to be used. It has to be mentioned at this point that car ownership is also as well as driving distance of cars will also be affected by other parameters like developments in settlement structure, availability and quality of public transport infrastructure (Dargay, 2002). However, taking all these factors into account would go beyond the scope of this model, which is primarily designed to energy related questions.

For Austria we use an elasticity of car ownership with respect to income of 0.5. This is within the range of values found by Goodwin et al. (2004) who analysed data from UK and comparable countries and showed that vehicle stock elasticity with respect to income lies between 0.32 (short term—ST) and 0.81 (long-term—LT) in developed countries.

Calibration of the model based on historic data on the Austrian vehicle fleet (1990–2009) results in an elasticity of car stock versus fuel price of —0.2 and of —0.5 with respect to car purchase price. These values are within the range of results from the international analysis performed by Goodwin et al. (2004), who found elasticity of the car stock with respect to fuel price ranging from —0.25 (LT) to —0.08 (ST) and with respect to capital cost ranging from —0.49 (LT) to —0.24 (ST).

\[
\frac{CAP_t}{CAP_{t-1}} = \left( \frac{FP_t}{FP_{t-1}} \right)^{\varepsilon_{FP}} \left( \frac{CC_t}{CC_{t-1}} \right)^{\varepsilon_{VC}} \left( \frac{GDP_t}{GDP_{t-1}} \right)^{\varepsilon_{IC}}
\]  

\( \varepsilon_{FP} \) is the fuel price elasticity and equals —0.2; \( \varepsilon_{VC} \) is the elasticity on fixed costs and equals —0.5; \( \varepsilon_{IC} \) is the income elasticity and equals 0.5; \( CAP \) is the vehicle registration per year; \( CC \) is the capital costs (fixed costs); \( FP \) is the fuel price; \( GDP \) is the gross domestic product; \( t \) is the time (year).

4.3.2. Driving distance

Shifts in economic framework conditions influence the behaviour of consumers. Car owners react to changes in the cost of energy by adapting their use intensity expressed in kilometres travelled per year. The cost of energy is affected by the fuel price and by the efficiency of cars. Therefore, efficiency improvements of cars lead to higher yearly driving distances, offsetting part of the energy savings of new technologies. This rebound effect has been analysed by Schipper et al. (2002) for the case of switching from gasoline to diesel cars in Europe. They found that a considerable proportion of fuel savings have been offset by the increased travel distance.
This correlation is modelled using elasticities of fuel price and income. The calibration runs of the model are based on statistic data (1990–2008) and showed an elasticity of driving distance with respect to income of 0.3 and of −0.3 with respect to fuel price. This corresponds to the results found by (Johansson and Shipper, 1997), where elasticity of mean driving distance with respect to fuel price ranges from −0.35 to −0.05. The more recent analysis of Goodwin et al., 2004) underlines the validity of the elasticity with respect to fuel price (−0.3 for LT).

\[
\frac{D_t}{D_{t-1}} = \left( \frac{FP_t}{FP_{t-1}} \right)^{\omega_{FP}} \left( \frac{GDP_t}{GDP_{t-1}} \right)^{\omega_{GDP}}
\]

(16)

\(\omega_{FP}\) is the price elasticity and equals −0.3; \(\omega_{GDP}\) is the income elasticity and equals 0.3; \(D\) is the distance travelled by year; \(FP\) is the fuel price; \(GDP\) is the gross domestic product; \(t\) is the time (year).

4.4. Transport service level—shares of vehicle classes

The specific service costs not only affect the annual car sales but also the service level of the cars sold which is defined by their average characteristics (e.g. average vehicle weight and engine power). For example, at high service cost levels, as a consequence is the fuel price; \(C_0\) recent analysis of Goodwin et al., 2004) underlines the validity of Shipper, 1997), where elasticity of mean driving distance with respect to income of 0.3 and of \(C_0\) data (1990–2008) and showed an elasticity of driving distance with respect to the service parameter \(\gamma\) (Meyer and Wessely, 2009). Thus changes in framework conditions that are affecting the specific service costs also affect consumers’ choices of a vehicle category.

The model defines three categories of vehicles: compact class, middle class, upper class, and consumers are choosing one of those three options when purchasing a car (see Table 5). The specifications have been set in such a way as to represent the Austrian stock of vehicles. Each vehicle class is defined by mass and engine power. Current consumer preferences concerning vehicle categories were identified from historical data (Statistics Austria, 2009) and are used as a basis for the model settings.

To model the effect of fuel price and income on the mean vehicle specifications, we introduced a service factor \(F\) representing average mass and engine power of cars sold. It is assumed that the specifications of cars sold are distributed around the mean value \(\overline{F}\) in a distribution with positive skew. From that distribution the shares of the three vehicle classes are derived (for a detailed description see Appendix B). In the model the development of the service parameter \(F\) is determined by Income and fuel prices

\[
\frac{F_t}{F_{t-1}} = \left( \frac{FP_t}{FP_{t-1}} \right)^{\beta_{FP}} \left( \frac{GDP_t}{GDP_{t-1}} \right)^{\beta_{GDP}}
\]

(17)

\(\beta_{FP}\) is the price elasticity that equals −0.3; \(\beta_{GDP}\) is the income elasticity that equals 0.3; \(\overline{F}\) is the mean vehicle service factor; \(FP\) is the fuel price; \(GDP\) is the gross domestic product; \(t\) is the time (year).

The corresponding elasticities have been determined through calibration runs comparing the model results with historic data on Austrian passenger car sales in the time frame 1990–2008. In the last two decades there has been a continuous increase in both weight and power of passenger cars in Austria (Meyer and Wessely, 2009) which indicates the influence of income on the these parameters. However, the higher prices between 2003 and 2009 have led to a saturation of the average weight which is an indicator of considerable price sensitivity of this parameter.

There is hardly any historic analysis covering the effects of price and income on vehicle characteristics. Most studies only capture the fuel intensity of the cars in the fleet (e.g. Johansson and Shipper, 1997). Even though there is certainly a correlation between vehicle size or engine power and fuel consumption, the parameter is not applicable in the model because the model separately captures technological improvements. These are implicit in the fuel consumption parameter (see Section 4.2).

4.5. Bottom-up fleet model

There is considerable inertia in the regeneration of the car fleet which delays the response of the car fleet to shifts in policy, regulation, fuel prices and costs. Once registered a car usually remains in the fleet from 10 to 15 years. To represent this time lag accurately a detailed fleet model has been created using data on the Austrian fleet (Statistics Austria, 2009). In the model the fleet is divided into three vehicle categories and three user groups, each with a specific user pattern represented by the annual kilometrage driven (see Table 5). Moreover, there is a detailed coverage of vehicle efficiency and technologies in the fleet.

The actual fleet \(CAP\) is determined by the surviving cars of all the previous 30 generations. The fleet structure can be expressed as follows:

\[
CAP_t = \sum_{n=0}^{n=30} S_{Zn}
\]

(18)

\(CAP\) is the car fleet; \(SZ\) is the survivors of a car cohort; \(t\) is the time (year); \(n\) is the car cohort.

The annual decommission of cars is determined by the likelihood of mechanical failure modelled through a Weibull distribution. Similar approaches were used in other models to represent the scrapping of vehicles in the fleet (Zachariadis, 2005; Christidis et al., 2003).

4.6. Energy and greenhouse gas balances considered in the analysis

Based on the fleet model the total energy consumption and the GHG emissions are determined. An important aspect is the differentiation between tank-to-wheel (TTW) and WTW energy balances and emissions. Usually, energy consumption and GHG-emissions of vehicles are expressed in the TTW view in litres per 100 km and gram CO₂ per kilometre. However, for a reliable analysis it is necessary to consider the entire energy conversion pathway represented in the WTW balances.

The necessary data was provided by JOANNEUM Research who determined the WTW energy and emission balance of all fuels based on life cycle analysis (LCA) (Kloess et al., 2009). The Life-Cycle-Data includes production of the fuel (respectively generation of electricity), transport and conversion into kinetic energy in the car as well as the embodied energy of the car (Cherubini et al., 2009).

For the WTW balances the sources of the fuels are of crucial importance. In the model there are four main fuel types linked to specific vehicle technologies that can be chosen by consumers. Those fuels are gasoline, diesel, CNG and electricity. These four fuels can be produced from traditional fossil sources such as crude oil or natural gas, but they can also have fractions of alternative fuels based on renewable sources added. In Austria there are obligatory rates for biofuel blending following the EU biofuel directive (Directive 2003/30/EC, 2003). The rate of 5.75%
determined by this guideline has been met in Austria since 2008 by blending diesel with biodiesel and gasoline with first generation bioethanol (Winter, 2008). It is to be expected that following the EU directive, the 2010 level of biofuel blending would be extended to 10% by 2020 (Winter, 2008).

As illustrated in Table 6 biofuels and electricity can be obtained from various sources. To obtain a detailed view of the cumulated energy consumption and of GHG emissions it is necessary to consider their source. For example first generation ethanol, which is the standard option for blending of gasoline, is produced from three different sources with different proportions in Austria. In long-term scenarios, e.g. 2010–2050 the sources for fuels are likely to change due to economic and technological developments as well as political directives. The sources of the blends are assumed to continuously shift to more advanced options, e.g. first generation biofuels like Biodiesel and first generation ethanol (Ethanol 1) are substituted by second generation biofuels like Fischer-Tropsch Diesel (FT-Diesel) and second generation ethanol (Ethanol 2) (see Table 6). For second generation biofuels the entire plant instead of only seeds or fruits can be used to produce fuel which makes them more efficient and environmentally compatible. In the case of CNG, the fuel will be blended with biogas and synthetic natural gas (SNG).

In the case of electricity the generation source has an even greater impact on the primary energy demand and the GHG emissions of the conversion chain. For the first years as the required additional capacity is practically negligible, the current Austrian supply mix has been used. In the mid to long term the electricity demand of the increasing number of electric vehicles will have to be covered by additional capacities that can either be based on fossil or renewable sources. To this extent two supply scenarios have been established:

**Electricity “Fossil”:** In this scenario the electricity supply is based on the Austrian mix first and, with increasing demand, it is complemented exclusively with fossil electricity from natural gas fired gas and steam plants.

**Electricity “Renewable”:** In this scenario the supply for EVs is shifted to a pure renewable mix, which implies a high share of decentralised supply with shares of photovoltaic, hydro-energy, wind and biomass (see Table 7).

Potential effects of the generation mix on the electricity price are not explicitly considered in the scenarios.

### 5. Results

The results indicate how different policy schemes affect energy consumption and GHG emissions of the car fleet, by affecting diffusion of efficient technologies, fleet growth, characteristics of cars and yearly driving distance.

The model provides data on the development of the fleet in terms of total growth, average characteristics of cars and diffusion of technologies. Energy consumption is displayed on a TTW-basis, broken down into energy carriers, and on WTW-basis broken down in fossil and renewable parts. GHG emissions are displayed on a WTW basis broken down into the WT section (fuel production/electricity generation) the TTW section (conversion of the fuel into kinetic energy) and production of the car. The figures for energy consumption and GHG emissions also illustrate the effect of variations in the learning parameter. In the following sections we discuss the results of the two scenarios separately.

#### 5.1. Business as usual BAU–scenario

The scenario indicates that the introduction of HEVs together with biofuel blending is not sufficient to achieve a reduction in GHG emissions. Furthermore, the car fleet remains highly dependent on crude oil based fuels.

In this scenario no considerable measures to promote efficient and alternative vehicle technologies are taken. Fig. 10 depicts the development of the car fleet up to 2050, showing a strong trend towards HEVs. This development is mainly driven by the improving economic competitiveness of these cars in an environment of increasing fuel prices. Also reduction in cost of key components contributes to this development that leads to a substitution of conventional powertrain systems by micro- and mild HEVs. Both technologies are closely related to conventional powertrain systems and can increase vehicle efficiency for a relatively low additional cost. In the medium- to long run technologies with a high degree of electrification, like PHEVs and BEVs, very slowly gain market shares in this scenario.

The figure also indicates that the car fleet is growing constantly throughout the time frame 2010–2050. In this price scenario the demand for transport keeps increasing as a result of the relatively low cost of the transport mode. The increasing crude oil price that has been considered in this scenario is offset by the improving efficiency of vehicles, keeping the overall price of transport low.

With the chosen approach cost reduction of batteries has an impact on the cost effectiveness of hybrid and electric powertrain systems and thus on their market shares. These cost reductions have been modelled using a technological learning curve and therefore depend on the learning parameter used (see Section 3.2.1). A sensitivity analysis with respect to the learning rate is performed in order to check for the resulting uncertainty.

### Table 6

Biofuel blending and biofuel types.

<table>
<thead>
<tr>
<th>Biofuel blending</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of biofuels (%)</td>
<td>5.75</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biofuel blends</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline blends</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol 1 (%)</td>
<td>10</td>
<td>75</td>
<td>50</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Ethanol 2 (%)</td>
<td>0</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Diesel blends</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel (%)</td>
<td>100</td>
<td>75</td>
<td>50</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>FT-diesel (%)</td>
<td>0</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>CNG-blends</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas (%)</td>
<td>100</td>
<td>95</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>SNG (%)</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table 7

Electricity supply scenarios.

<table>
<thead>
<tr>
<th>Electricity supply scenarios</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Fossil” supply scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity-Mix Austria of 2010 (%)</td>
<td>100</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>Additional source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas (gas and steam) (%)</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>“Renewable” supply scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity-Mix Austria of 2010 (%)</td>
<td>100</td>
<td>75</td>
<td>50</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Additional sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro (%)</td>
<td>0</td>
<td>10</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Wind (%)</td>
<td>0</td>
<td>7.5</td>
<td>10</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Photovoltaics (%)</td>
<td>0</td>
<td>2.5</td>
<td>10</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Biomass (%)</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td>25</td>
</tr>
</tbody>
</table>
The results indicate that the sensitivity of the market shares of technologies to variations in the learning rate is moderate (see Fig. 11). While the effect on the rate of adoption of hybrid cars is insignificant, there is some long term effect on the adoption of electric cars. The scenario’s results show that this effect is marginal in comparison to the impact of policy measures. The uncertainty range which is caused by the learning parameter assumption is depicted in all scenario charts.

The diffusion of more efficient technologies, HEVs in particular, leads to a slight reduction in final energy consumption of the fleet in this scenario (see Fig. 12). The energy carrier mix remains dominated by gasoline and diesel fuels, while electricity gains importance only in the long term. When considering WTW energy consumption there is no reduction at all in this scenario (Fig. 13).

For GHG emissions it is important to use WTW balances to get an unbiased view of the development. The WTW balance can be split up in the well-to-tank (WTT) part covering the entire fuel supply chain and a tank-to-wheel part (TTW) considering the energy conversion in the car. For cars with internal combustion engines that use fossil fuels, 80–90% of GHG emissions occur in the TTW part (Kloess et al., 2009). This is why the WTT part is often neglected. For cars that are using alternative fuels the WTT part can actually be more important. A good example for this is the electric car that has no TTW emissions, since all emissions occur in the WTT part where the electricity is generated. Moreover, the production of the car must not be neglected in the WTW energy balance, as it usually accounts for around 10% of life-cycle emissions.

Fig. 14 depicts the WTW GHG emissions of the entire car fleet that are caused by burning of the fuel, fuel production and vehicle production. Altogether, there is only a slight reduction in GHG emissions.

5.2. Policy scenario

The results of the Policy Scenario give valuable insight on how policy can influence the development of the passenger car fleet in order to reduce GHG emissions. It demonstrates that a significant reduction of both fossil energy demand and GHG emissions is achievable through ambitious policy measures in the field.

In the Policy Scenario higher taxes on fuels combined with reduction in tax rates for efficient vehicles lead to an improvement in the competitiveness of electric propulsion technologies (see Fig. 7). The overall cost competitiveness of highly efficient cars causes major shifts in the market shares of vehicle technologies (see Fig. 15). In the short term diffusion of HEVs is similar as in the BAU scenario. Starting form 2020, the market share of BEVs grows steeply, reaching 50% in 2030 and PHEVs account for another 20% of the market. Higher taxes on cars and fuels cause raise overall transporta-

Fig. 10. Passenger car fleet (BAU-Scenario).

Fig. 11. Sensitivity of the technology shares to the battery learning rate (BAU-Scenario).
cars. This effect together with the spread of highly efficient propulsion systems like PHEVs and BEVs lead to a reduction in average emissions (see Fig. 19). The emissions are compared on a WTW basis (without vehicle production), considering fossil pathways for both conventional cars (gasoline, diesel & CNG) and BEVs (electricity from natural-gas-fired gas and steam turbines). In the BAU Scenario the average GHG emissions of new cars decrease from 180 g/km in 2010 to 140 g/km in 2030. In the Policy Scenario a substantial reduction is achieved with average emissions of around 110 g/km in 2030 (Fig. 20). In the Policy-Scenario the spread PHEVs and BEVs lead to an increased importance of electricity as energy carrier. In 2050 electricity demand for the passenger car fleet reaches 7.5 TWh which is around 50% of total final energy consumption of the fleet. With these high shares of electricity in the energy carrier mix the WTW balance has to be taken into account in order to have an unbiased view on the energy consumption. Fig. 21 shows the WTW energy balance split into fossil and renewable fractions, for both the fossil and the renewable supply scenario (see Table 7). In the renewable supply scenario the demand for fossil energy of the passenger car fleet could be reduced by about 75%.

Also the short term effects of the increase of fuel tax are reflected in the energy consumption charts. In the years where the tax is increased the energy demand drops, because consumers react to the higher prices by reduction their yearly driving distance.

The better efficiency of cars and the use of less carbon intense fuels lead to a considerable reduction in GHG emissions in the Policy-Scenario. Fig. 22 shows the corresponding WTW GHG gas balance for the fossil supply scenario and the renewable supply scenario (100% RES electricity: see Table 7). Because of the growing demand for electricity, emissions from fuel production increase. Emissions from vehicle production also increase, since electric cars cause higher emissions in their production than conventional cars. Even with an electricity mix dominated by fossil source (natural gas fired gas & steam plant), the aggregate emissions can be significantly reduced by increasing the use of EVs and PHEVs. In this case a reduction of 40% up to 2030 and 50%
by 2050 can be achieved. When electricity generation is shifted to pure renewable source, the WTW GHG emissions can be reduced by two thirds up to 2050.

6. Conclusions

The results indicate that considerable reduction of energy demand and GHG emissions can be achieved through policy measures in a long run. An appropriate policy framework not only promotes the diffusion of efficient cars but can also slow down fleet growth and reduce yearly driving distance of cars.

Both scenarios share one major trend: a shift in the passenger car fleet towards hybrid vehicles. Even though hybridisation will improve the efficiency of the fleet, the results of the BAU-Scenario point out that energy demand and GHG emissions cannot be reduced by simply switching to HEVs since fleet keeps growing and driving distance of cars remains high.

In order to meet ambitious GHG reduction targets, countries like Austria need additional measures. Policy makers must set the appropriate conditions if there is to be any hope of achieving these targets. In the Policy-Scenario policies are set to support
efficient cars by adopting higher taxes on fuels and on low efficient cars. This drives the market share of PHEVs and BEVs sooner and also leads to a smaller fleet, with smaller cars and lower yearly odometer readings of each car. All these effects cause a considerable reduction in energy demand of the fleet and an increasing importance of electricity within fuel mix. This then requires a low carbon electricity generation base in order tap the full potential of electricity as an energy carrier for transport. A completely decarbonised electricity mix reduces the annual fossil fuel energy demand of the passenger car fleet by up to 75% and GHG emissions by almost 70% by 2050 in the Policy-scenario.

When taking a look at the time frame of the achieved reduction it shows that substantial reduction can only be achieved in a long term. This is mainly because of the generally slow modernisation of the car fleet and the fact that high efficient cars like PHEVs and BEVs won’t be available, or will still be too costly in the first years. Therefore, they cannot contribute much to the achievement of reductions up to 2020. To reduce energy consumption and GHG emission up to 2020, we will have to rely on reduction of fleet growth, driving distance as well as on the diffusion of more efficient conventional cars and HEVs. However, it shows that the policy framework implemented up to 2020 is crucial for the diffusion of electric propulsion technologies in the following decade (2020–2030). Up to 2020 technological progress will lead to a reduction in the cost of key components of PHEVs and BEVs and increasing fuel prices will further improve their competitiveness. Appropriate policy measures implemented between 2010 and 2020 will prepare the ground for their large scale uptake in the following years. The actual effects of this development on energy demand and GHG emission will only be seen the years and decades after, as indicated by the long-term development in the scenarios.

It is evident that the scenario time frame up to 2050 implicates uncertainties. However, it is important in this case to illustrate...
long-term consequences of decisions that have to be made in the upcoming years. Policy makers should have this in the back of their mind when setting the course of the future policy framework.

Appendix A. Market shares of technologies

We use historic market share of diesel cars in Austria between 1990 and 2008 to set the parameters of the logit-function. Starting in the 1990s there was a strong trend toward diesel cars. This was triggered by the emergence of turbo charge diesel engines, which made diesel cars equal to gasoline cars in terms of attractiveness. The main driver of the market diffusion of diesel cars was their better economic performance due to the higher efficiency of diesel engines as well as lower cost of diesel fuels (Schipper et al., 2002; Meyer and Wessely, 2009). This development gives quantitative information on how cost signals affect market share of a vehicle propulsion technology. Since this is the only large scale diffusion process of new propulsion technologies with sufficient data coverage, we used it to set the parameter \( b \) of the logit-model (see Section 4.2). Fig. A1 compares the historic market share with the market share derived from the model. More recent technologies such as HEVs or even BEVs could not be used since their numbers are still too small and time series are too short to get significant results.

Appendix B. Distribution of vehicle classes

To model the distribution of vehicle classes the transport service factor \( F \) is introduced. The transport service factor defines the quality the transport service is provided. In the model it is defined by the mass and power of cars (see Eq. (B.1)). It is assumed that the specifications of sold cars are distributed around the mean value in a distribution with positive skew (Fig. B1). The distribution \( \nu \) was defined based on statistic data on passenger car sales in Austrian (Salchenegger, 2006; Pötscher, 2009). In the model the distribution is used to derive the shares of the three vehicle classes (see Eq. (B.2))

\[
F_t = f(\overline{m}_t, \overline{P}_t)
\]

(B.1)

\[
z_i(t) = z_i^{-1} \int_{F_{i,.}}^{F_{i,U}} \nu(F; F_t) dF
\]

(B.2)

\( F \) is the mean vehicle service factor; \( \overline{m} \) is the mean vehicle mass; \( \overline{P} \) is the mean vehicle power; \( z_i \) is the share of the vehicle class \( i \); \( Z \) is the new cars registered per year; \( F_i \) is the specification of the vehicle class; \( F_{i,.} \) is the maximum service level of vehicle class \( i \); \( F_{i,.} \) is the minimum service level of vehicle class \( i \); \( \nu \) is the distribution of sold vehicles around the mean value (vehicle service factor); \( t \) is the time (year).

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Fig. A1. Share of diesel cars in Austrian passenger car sales: historic vs. model

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Fig. B1. Distribution of the service factor within car sales (schematic illustration).
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