Open Access

Advances in Environmental and Engineering Research

LIDSEN Publishing Inc.

Original Research

Energy Policy Scenarios for Carbon Emissions in Road Passenger Transport in Austria up to 2050

Marina Maier, Amela Ajanovic, Reinhard Haas *

Energy Economics Group, Vienna University of Technology, Gußhausstraße 25-29, 1040 Vienna, Austria; E-Mails: siebenhofer@eeg.tuwien.ac.at; ajanovic@eeg.tuwien.ac.at; haas@eeg.tuwien.ac.at

* **Correspondence:** Reinhard Haas; E-Mail: haas@eeg.tuwien.ac.at

Academic Editor: Joana Sousa

Special Issue: Energy Policies and Strategies for Achieving Sustainability

Adv Environ Eng Res
2024, volume 5, issue 4
doi:10.21926/aeer.2404026

Received: June 23, 2024
Accepted: November 18, 2024
Published: December 06, 2024

Abstract

The transport sector accounts for approximately 25% of CO_2-emissions in the EU and Austria, primarily due to passenger car transport powered by fossil fuels. Replacing conventional cars with sustainable alternatives is crucial for reducing emissions, improving air quality, and mitigating climate change while decreasing vehicle kilometers driven. This study analyzes policy strategies for Austria's road passenger transport sector up to 2050 to determine their potential for significant CO_2 reduction. Four scenarios were modeled: Business-as-usual (current policies without major changes), phase-out of fossil fuels, tax-scenario (financial measures to reduce high-emission vehicles), and a green-policy-scenario (promotion of public transport, active mobility, and vehicle efficiency). The scenarios were modeled using a dynamic approach, considering key factors such as income, vehicle kilometers driven, vehicle power, fuel intensity, and specific CO_2-emission factors. This methodology allowed for a comprehensive analysis of flow and embedded CO_2-emissions. Under the green-policy scenario, CO_2 emissions could be reduced by over 85%, from 17 million tons in 2019 to approximately 2.5 million tons by 2050, alongside a 65% reduction in vehicle stock. The major conclusions are: (i) The total vehicle kilometers traveled and overall vehicle stock must be reduced. (ii) Focusing solely on BEVs is insufficient; a modal shift toward public transport and active mobility is essential. (iii) Public transport and active mobility must become more attractive options to foster sustainability. These steps reduce emissions and promote long-term sustainability by shifting toward greener transportation modes. By implementing these integrated strategies, Austria can make significant progress toward meeting its climate targets and creating cleaner, more sustainable environments.

Keywords
CO_2 emissions; greenhouse gas emissions; road passenger transport; passenger car transport; electric vehicles; green mobility; public transport; transport scenarios; transport policies

1. Introduction

Climate change is a challenge for humanity and requires sustainable action in all areas of society. The transport sector is responsible for 25% of the total CO_2-emissions in the European Union (EU) and Austria, among other contributors. The road transport sector is responsible for 72% of the total emissions of the transport sector. Individual car transport accounts for 61% of these emissions, mainly due to the continuing dependence on fossil fuels. Passenger cars, therefore, offer the most significant opportunity to reduce overall CO_2-emissions. Specific policy interventions in road passenger transport can reduce these emissions. The decarbonization of road transport is an urgent priority in tackling climate change [1, 2].

The EU has established a cornerstone of its environmental policy framework with the European Climate Law. This law sets out a clear and ambitious roadmap for achieving climate neutrality by 2050 and reducing CO_2-emissions by at least 55% by 2030 compared to 1990 levels [1]. Achieving these goals will require a comprehensive strategy that includes a legal framework, technological innovations, and behavioral changes towards more sustainable mobility.

The push towards an increase in BEV adoption and improving the efficiency of the entire vehicle fleet are seen as pivotal steps forward. Supporting this transition, recommendations from the International Energy Agency emphasize the importance of discontinuing incentives for fossil fuel cars, increasing fuel taxation, and reinforcing fuel economy targets. Along with advocating for zero-emission vehicle sales and encouraging vehicle size and weight optimization, these measures outline a clear direction for progress [3, 4]. In parallel, a shift in mobility patterns is recognized as equally important. Transitioning from individual car use to public transport, walking, and bicycling is not just about reducing CO_2-emissions but also about creating healthier, more sustainable environments [5].

Scenario development plays a crucial role in exploring potential future trends in the transport sector. It allows for identifying various possible outcomes and pathways the industry may take.

The extensive literature on transport-related emissions and scenario development highlights various strategies for reducing the carbon footprint in the transport sector, many of which inform the scenarios in our study. Siebenhofer (Maier) et al. [6, 7] emphasize the need to reduce travel activity, increase public transport attractiveness, and ensure that BEVs are powered by renewable energy sources (RES) to cut emissions effectively. Eisenkopf et al. [8] and Barisa et al. [9] stress that improving vehicle efficiency through technological advancements is critical to achieving CO_2 reductions. Dugan et al. [10] and Zhang et al. [11] highlight that while BEVs have the potential to reduce emissions, they alone are insufficient. These studies argue that policies must also promote walking, cycling, and public transport to achieve substantial reductions in CO_2-emissions. Broadbent et al. [12] further emphasize the importance of rapidly transitioning to 100% BEVs in new car sales to achieve climate neutrality by 2050. Shared mobility solutions are seen as a critical component of sustainable transport strategies. Gerboni et al. [13] and Danielis et al. [14] highlight the importance of the diffusion of alternative fuel vehicles like EVs for reducing emissions. Tsemekidi Tzeiranaki et al. [15] focus on the difficulty of decoupling economic growth from increasing transport emissions, concluding that economic growth tends to drive higher energy consumption and emissions despite technological advancements. Lam et al. [16] support this by showing that promoting BEV attractiveness while disadvantaging internal combustion engine vehicles through taxation effectively reduces emissions. The Avoid-Shift-Improve (ASI) framework [17] remains central to the literature, advocating for reducing travel demand, shifting to more energy-efficient modes of transport, and improving vehicle efficiency. Finally, Jaehn and Meissner [18] warn of potential rebound effects where increased adoption of BEVs may not lead to lower overall emissions if total vehicle kilometers are not reduced.

While the existing literature provides valuable insights into the decarbonization of the transport sector, it often needs to integrate a comprehensive approach that considers both flow and embedded CO_2-emissions within different policy scenarios. Most studies have focused on technological advancements, such as the adoption of BEVs, or on promoting public and active transport modes. However, there is a clear need for a more holistic approach that accounts for all significant factors influencing CO_2-emissions, including vehicle power, fuel intensity, income levels, and the attractiveness of public and active transport modes. Moreover, while some studies have explored the impact of policies on modal split and vehicle efficiency, few have examined the potential rebound effects of shifting to alternative fuel vehicles without a corresponding reduction in vehicle kilometers traveled (vkm) [18].

This study addresses key gaps by developing an integrated model incorporating flow and embedded CO_2-emissions in road passenger transport scenarios up to 2050. The model evaluates various variables, including fuel and investment costs, vehicle efficiency, income, stock remaining factor, specific CO_2-emission factors and the attractiveness of public and active transport modes. This approach allows for a more accurate projection of the impacts of policy measures, such as higher registration taxes, a CO_2 tax, and the phase-out of internal combustion engine vehicles. Additionally, the model captures changes in the modal split, demonstrating how a shift toward public transport and active mobility, combined with adopting BEVs, can lead to significant reductions in CO_2-emissions. To the best of our knowledge, this comprehensive approach to modeling specific policy impacts on flow and embedded emissions in road passenger transport has not been previously explored, closing a crucial gap in the literature.

The primary objective of this study is to evaluate which policy strategies in road passenger transport can lead to significant CO_2-emission reductions in Austria by 2050. To achieve this, four scenarios are modeled: Business-as-usual (BAU), representing the continuation of current policies without significant changes; Phase-out, which targets a transition from internal combustion engines (ICEs) to battery electric vehicles (BEVs) in newly registered vehicles by 2035; Tax-scenario, focusing on financial incentives to discourage high-emission vehicles; and the green-policy-scenario, which emphasizes a shift towards public transport and active mobility alongside reductions in vehicle kilometers traveled. These scenarios represented a broad spectrum of potential policy interventions, from maintaining the status quo to implementing aggressive measures to transform the transport sector.

The study considers various vehicle types, including cars, motorbikes, light vehicles, and public transport buses, categorized by fuel type. The expected outcomes of these scenarios vary significantly. The bau-scenario serves as a baseline, showing the limited impact of minor changes, while the phase-out and tax-scenario focus on accelerating the shift towards BEVs and FCVs with moderate emission reductions. The green-policy-scenario, combining both technological and behavioral changes, is expected to achieve the largest CO_2 reduction, demonstrating that integrated strategies are essential for meeting Austria's climate targets. Each scenario provides insights into the long-term effects on emissions, modal split, and vehicle stock, highlighting the importance of transitioning from private motorized transport to more sustainable modes like public transport and active mobility.

The focus of this study on the Avoid-Shift-Improve (ASI) [17, 19] framework aligns with global best practices in sustainable transport planning. This study particularly emphasizes the "shift" and "improve" aspects. The shift strategy encourages a transition to more sustainable transport modes such as public transport and active mobility (walking and cycling). The "improve" element focuses on advancing vehicle technology, including improving vehicle power, fuel efficiency, and engine types. While shifting road transport to technologies like BEVs is key, this could trigger a rebound effect, where higher efficiency might lead to increased vehicle kilometers traveled (vkm) [18]. Therefore, reducing the overall number of vehicles and the vkm remains essential. The ASI framework shows that combining monetary and non-monetary policies is crucial for lowering passenger transport energy consumption and CO_2-emissions. Key measures include a phase-out of fossil fuel vehicles, promoting BEVs, a modal shift to public transport and active mobility, and reducing total vkm. Implementing these measures requires appropriate policies, such as taxes on ICEs (registration taxes, CO_2-taxes), fuel prices, and subsidies for purchasing BEVs. Additionally, making public and active transport more attractive through investments and expansions is necessary to maintain transport demand while reducing emissions.

The article is structured as follows: Chapter 2 provides an overview of the historical progress in road passenger transport in Austria. Chapter 3 describes the methodology and approach used to construct the model and the scenario development. Chapter 4 presents the findings within the developed scenario framework. Chapter 5 discusses the results, delving into the implications and the broader context of the study. Chapter 6 concludes the paper by offering policy recommendations based on the findings, addressing the limitations of the model and highlighting directions for future research.

2. Historical Developments of CO_2-Emissions in Road Passenger Transport and Politically Set Target Values in Austria

This section provides an overview of historical developments in the road passenger transport sector and its CO_2-emissions, as well as politically set targets, as the developed model is applied to Austria as a case study.

Figure 1 presents the cumulative CO_2-emissions (flow and embedded) from road passenger transport in Austria from 2000 to 2023. The emissions peaked at 17 million tons in 2018, then reduced to 13 million tons in 2020. This decrease is attributed mainly to the COVID-19 pandemic during 2020 and 2022, which led to reduced travel and mobility. By 2023, diesel vehicles were the main source of these CO_2-emissions at 58%, followed by gasoline vehicles at 33%.

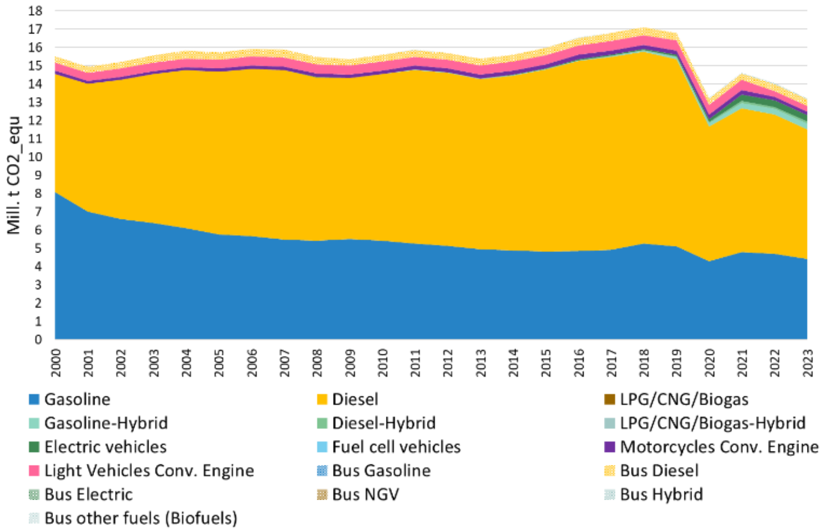

Figure 1 Total CO_2-emissions of flow and embedded CO_2-emissions from road passenger transport in Austria from 2000-2023 (own calculations).

When analyzing the mix of flow and embedded CO_2-emissions from road passenger transport in Austria between 2000 and 2023, as shown in Figure 2, it is apparent that most CO_2-emissions are attributed to flow emissions, which are generated from fuel combustion during vehicle operation. While embedded emissions arise once from the vehicle's lifecycle (manufacture, transport, maintenance, disposal), flow emissions are continuous and increase with vehicle usage.

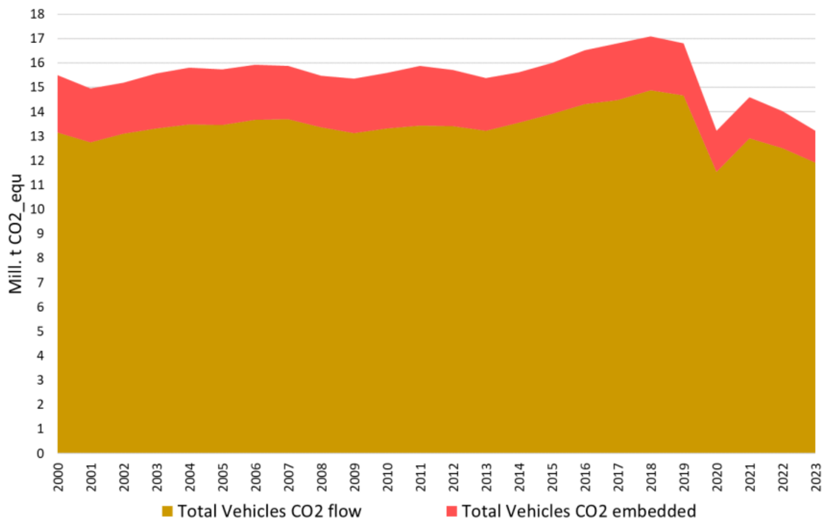

Figure 2 Flow and embedded CO_2-emissions from road passenger transport in Austria from 2000-2023 (own calculations).

The energy consumption from road passenger transport in Austria from 2000-2023 is highlighted in Figure 3. Since 2001, the energy consumption slowly increased until 2018, when the energy consumption amounted to 170 PJ. In 2022, a low due to COVID-19 is visible, with a total energy consumption of 130 PJ. The increase in energy consumption from diesel vehicles is primarily due to their high market share. Most recently, the total energy consumption was 140 PJ, 33% due to gasoline and 58% to diesel cars in 2023. Light vehicles, such as mopeds and motorized tricycles, produced an amount of CO_2-emissions that is nearly equivalent to that of public transport buses, with both contributing approximately 3.5 PJ in 2023. Despite the steady increase in alternative-fuelled vehicles, primarily BEVs, since 2000, they still accounted for only 1% of total energy consumption in 2023, reflecting their relatively small share in the overall vehicle stock. The last two charts have shown that, at least since 2021, low energy consumption and the corresponding CO_2-emissions have been slowly decreasing.

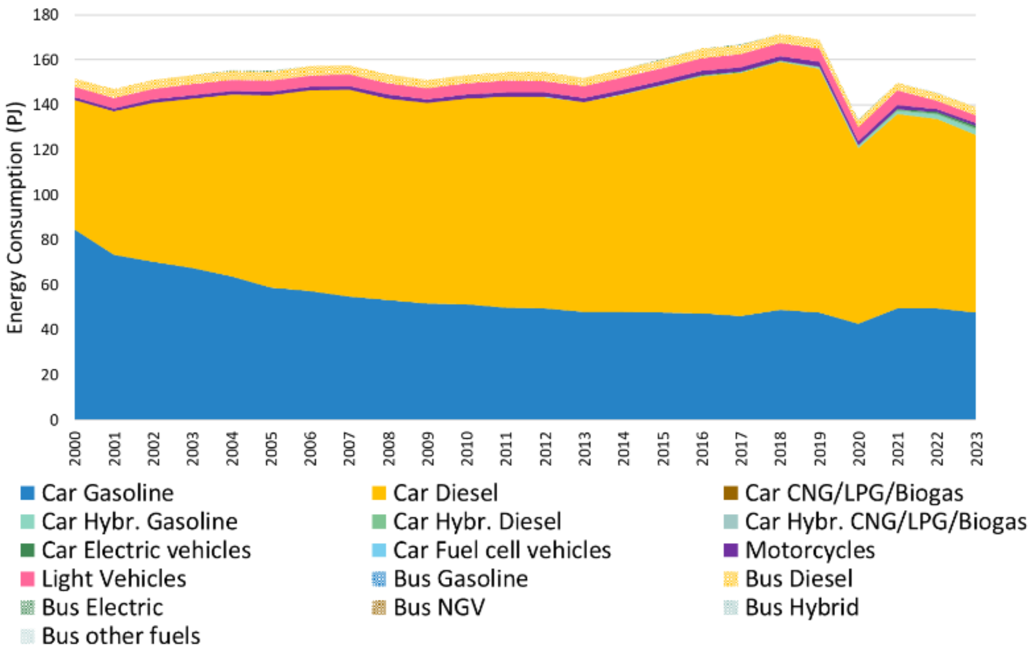

Figure 3 Energy consumption from road passenger transport in Austria from 2000-2023 (own calculations).

Figure 4 depicts the distribution of the Modal Split by distance traveled in Austria over the period from 2000 to 2023. In 2003, private motorized transport (cars, motorcycles, and light vehicles) accounted for 62% of the total distance traveled, while public transport contributed 21%. Public transport, which includes trains, buses, trams, and the metro, was used for 21% of the total distance traveled. Bicycles accounted for 12%, and walking for 5%. The development shows how people's travel habits have evolved. Shifts between the transport modes are due to many reasons, such as new policies that make alternative modes of transport more attractive, new infrastructure, raising awareness of sustainable transport, and changing transport behavior in general.

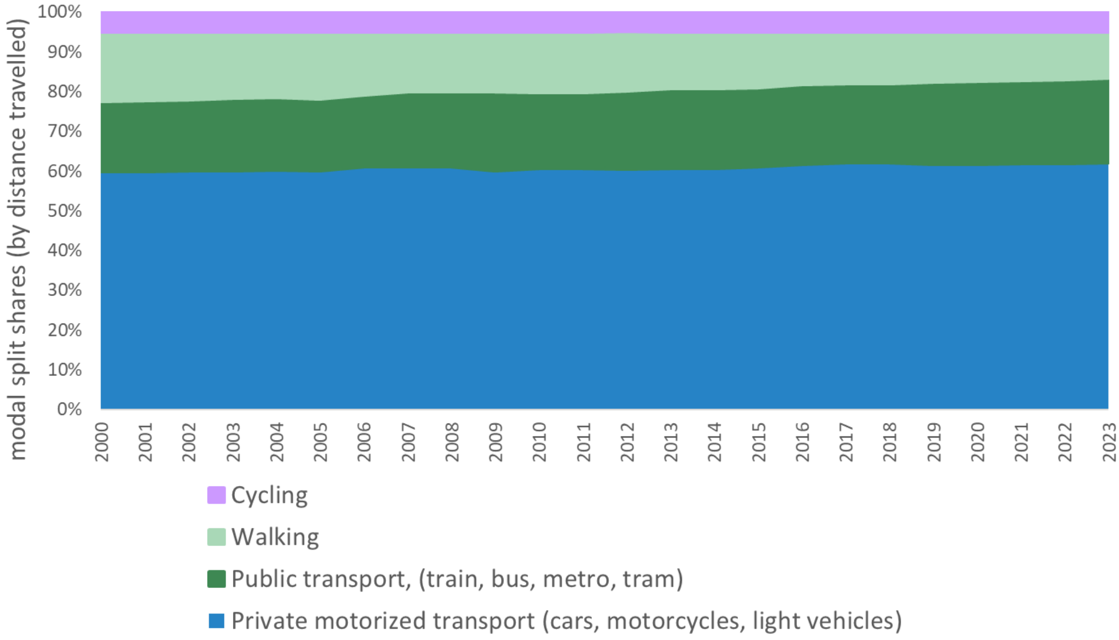

Figure 4 Modal Split in Austria from 2000-2023 (based on [20, 21]).

Figure 5 depicts CO_2-emissions from total transport in Austria from 1990 to 2021, with a projection towards 2030. The chart shows a general decrease in CO_2-emissions over the years. Emissions peaked before 2005 and then gradually declined, with a significant drop observed by 2021. This downward trend is expected to continue. The red dotted line in the graph represents Austria's commitment to the EU's climate goals, targeting a 55% reduction in CO_2-emissions by 2030 compared to 1990 levels. These targets are part of Austria's broader strategy to meet EU environmental objectives, with the ultimate goal of achieving climate neutrality by 2050 [5, 22-24].

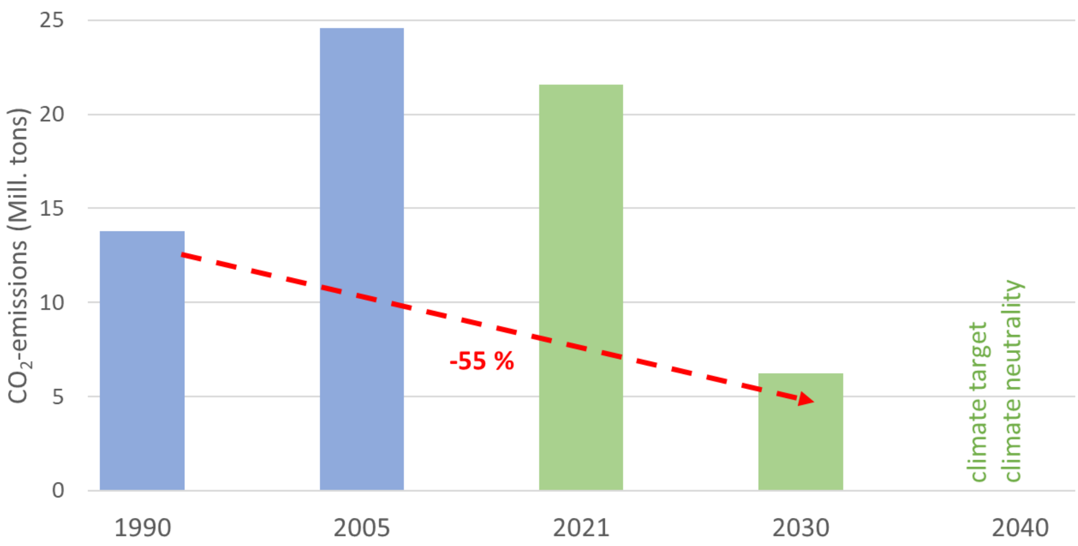

Figure 5 CO_2-emissions from total transport in Austria, 1990, 2005, 2021 and target (based on [5, 22-24]).

In recent years, Austria has implemented various regulatory policies to reduce CO_2-emissions in road passenger transport. A key element in these efforts is the introduction of CO_2 taxation as part of the 2022 eco-social tax reform [25], which places a price on carbon emissions [26] to incentivize lower fossil fuel consumption. Additionally, Austria's registration tax (Normverbrauchsabgabe (NoVA) [27]) is based on vehicle emissions, making high-emission vehicles more expensive to register, thereby encouraging the purchase of cleaner alternatives. These regulatory policies are complemented by fuel economy standards [28] and are aligned with EU directives, which set strict limits on CO_2-emissions for newly registered vehicles.

Austria's current transport policies, such as the klimaaktiv mobil initiative, promote sustainable mobility through compact settlement structures, mixed land use, and increased reliance on public transport, cycling, and walking. Public transport usage has grown, reaching 21% of the modal share, while active mobility has risen to around 17% in 2023. However, private motorized transport remains dominant at 62%, underscoring the need for continued interventions to reduce car dependence and support a modal shift. Programs like the KlimaTicket [29] make public transport more affordable, and subsidies for EV purchases and home charging infrastructure [30] foster a shift to electromobility. At the local level, cities like Vienna are expanding cycling infrastructure and pedestrian-friendly designs, which align with Austria's sustainable mobility goals [31].

3. Methodology

This chapter explains the methodology behind the model and relevant equations for the data stock and the development of the scenarios. Furthermore, the assumptions for the development of the scenarios are described.

3.1 Model and Equations

The following text outlines the methodology and essential equations applied to analyze historical data concerning road passenger transport, including cars, motorcycles, light vehicles, and buses, and project future scenarios. The primary analytical tool utilized in this research is derived from a European project named 'Alter-Motive' from 2011 [32]. This tool integrates various quantifiable factors that affect CO_2-emission and is instrumental in modeling regulatory policies for CO_2-emission mitigation and forecasting future trends in road passenger transport. This model has been further expanded and refined in the current study.

The model allows the integration of various policy measures, such as subsidies for BEVs, fuel efficiency standards, taxes on ICEs, or a strategic phase-out of ICEs. The model illustrates how targeted policies influence energy consumption, resulting in flow, and embedded CO_2-emissions. From these results, recommendations for policymakers to decrease CO_2-emissions in road passenger transport can be derived.

Figure 6 illustrates the correlations of the model variables and the output variables. The model is a dynamic tool that considers annual historical data (from 2000-2023) obtained mainly from statistical databases from 2000 to 2023 (blue boxes). The historical data is obtained from the following sources: vehicle km driven (vkm): Statistik Austria [33], Odyssee Mure [34], Winkelbauer et al. [35], Statistisches Bundesamt DIW Berlin [36]; service km (skm): Statistik Austria [33], Odyssee Mure [34], Winkelbauer et al. [35], Statistisches Bundesamt DIW Berlin [36]; newly registered vehicles (Vnew): Statistik Austria [37]; vehicle stock (Vstock): Statistik Austria [38]; fuel intensity of newly registered vehicles (FInew): Statistik Austria [33], Ivkovic et al. [39], Amt der NÖ Landesregierung [40]; fuel intensity of the vehicle stock (FIstock): Statistik Austria [33], Ivkovic et al.

[39], Amt der NÖ Landesregierung [40]; fuel prices (PF): Statistik Austria [41]; tax on fuels (τ_F): Statistik Austria [41]; CO_2-tax (CO_{2_tax}): Bundesministerium für Finanzen [42], Bundesministerium für Klimaschutz [26]; Registration taxes (τ_{reg}): Bundesministerium für Finanzen [42]; Subsidies on BEVs: Bundeskanzleramt Österreich [30]; Standards on fuel efficiency: Bundesministerium für Klimaschutz [43]; Income (Y): Statistik Austria [44]. The most important policies that can be modeled are taxes on fuel (τ_F), a CO_2-tax (CO_{2_tax}), registration taxes (τ_{reg}), subsidies on BEVs and standards on fuel efficiency (see green boxes). Furthermore, the income (Y), stock remaining factor (Φ), the attractiveness of public transport (A_{PT}), and active mobility (A_{AM}) are considered. The most important results of the calculations are energy consumption (E_{flow}) and resulting CO_2-emissions (CO_{2_flow} and CO_{2_emb}) for road passenger transport for the historical period (2000-2023) and the coming years (2024-2050) (see orange boxes). Individual road passenger transport (cars, motorbikes, and light vehicles) is modeled according to this principle. Public transport buses are modeled as a passive variable, as no fuel and investment costs are considered here (Figure 7). Finally, based on these results, recommendations for policymakers can be derived.

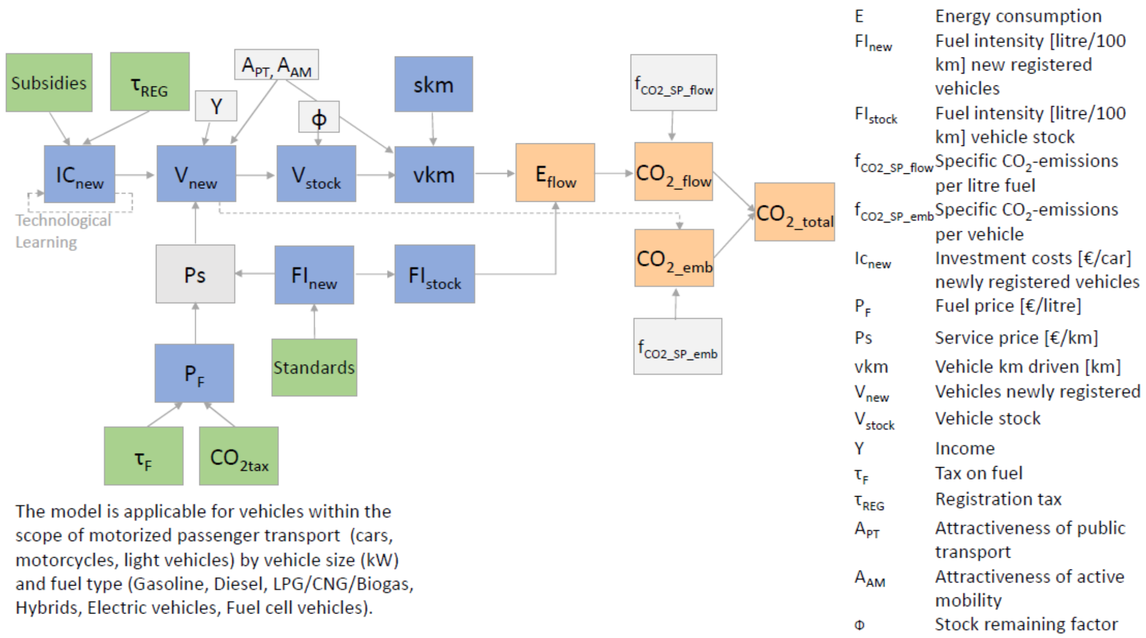

Figure 6 Formal framework of the yearly dynamic model (cars, motorcycles and light vehicles) (based on own calculations and framework [32]).

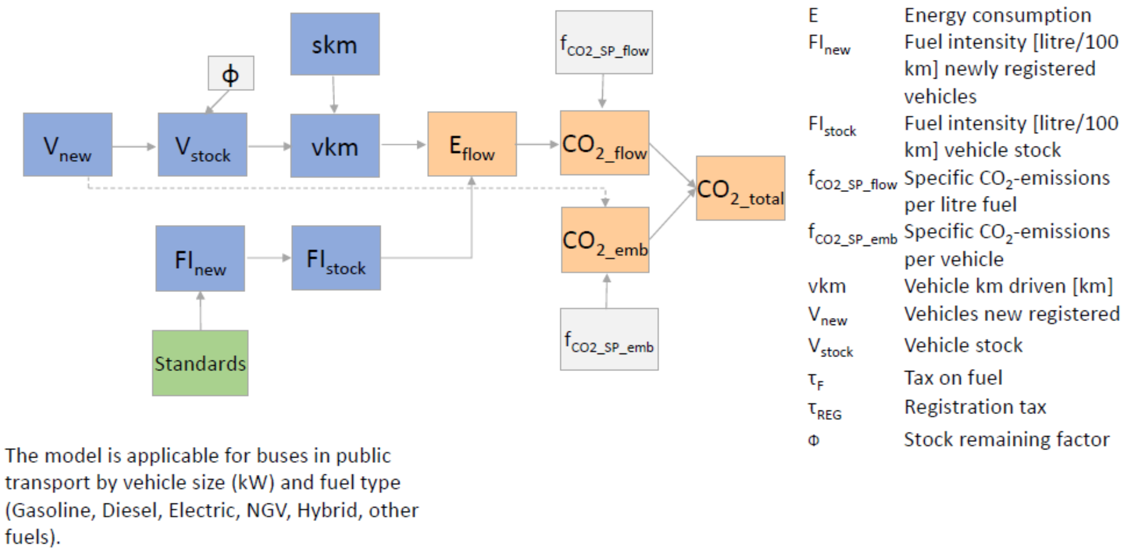

Figure 7 Formal framework of the yearly dynamic model (buses in public transport) (based on own calculations and framework [32]).

The equations used in the model are explained in more detail as follows:

The total CO_2-emissions are computed by adding the flow and embedded CO_2-emissions, and multiplying their respective specific CO_2-emission coefficients. Flow CO_2-emissions, categorized as operational emissions, originate from fuel consumption during vehicle usage. They are derived from flow energy consumption. Embedded CO_2-emissions are emitted during the manufacturing process, transportation, maintenance, and disposal and are derived from newly registered vehicles.

$$CO_{2\_total} = (E_{flow\_ijt} * f_{CO_{2}\_sp\_flow}) + (V_{new\_ijt} * f_{CO_{2}\_sp\_emb})(\text{mill tons CO}_2) \qquad (1)$$

where:

CO_{2_total}	Total CO_2-emissions
E_{flow}	Flow energy consumption
$f_{CO_{2}\_sp\_flow}$	Specific CO_2-emission coefficients by fuel type (flow)
$f_{CO_{2}\_sp\_emb}$	Specific CO_2-emission coefficients by fuel type (embedded)
V_{new}	Newly registered vehicles
i	Vehicle size
j	Vehicle type by fuel type
t	Year

Table 1 shows the specific CO_2-emission coefficients (f_{CO2}) for vehicle flow and embedded emissions. The coefficients for these calculations are fixed but expected to evolve over time due to improved fuel ecological characteristics, increased use of RES electricity, and reductions in embedded CO_2-emissions.

Table 1 CO_2-emission coefficients of fuels (flow) and of vehicles by fuel type (embedded) [3, 32, 45-48].

Fuel type	CO_2-TTW (Tank-to-Wheel) kg/kWh final energy f_{CO_2}	tons CO_2/new vehicle (80 kW)
Gasoline	0.309	6
Diesel	0.315	6.6
CNG/LPG	0.253	6.3
Bioethanol	0.175	6.3
Biodiesel	0.169	6.3
Biogas	0.087	6.3
Electricity RES	0.000	10.5
Electricity UCTE Mix	0.000	10.5
Hydrogen RES	0.050	9
Hydrogen Natural Gas	0.403	9
Motorcycles		2.9
Light Vehicles		1.45
Bus Gasoline		64.0
Bus Diesel		64.0
Bus Electricity		100.0
Bus NGV		64.0
Bus Hybrid		70.0
Bus other fuels (Biofuels)		64.0

CO_2-emission coefficients represent emissions from fuel combustion during operation (flow). These values are based on fuel-specific factors commonly used in European studies and reflect Austria's energy mix. CO_2-emission coefficients of vehicles by fuel type (embedded) were calculated using lifecycle assessment (LCA) methodologies, covering emissions from material extraction, manufacturing, transportation, maintenance, and end-of-life disposal. These coefficients align with general ranges reported in studies referencing the Handbook Emission Factors for Road Transport (HBEFA) [49] and data from the European Environment Agency (EEA) [50]. Calibrated for Austria's transport sector, these values ensure relevance and applicability for this study. The differentiation between smaller vehicles (e.g., cars at 6–10.5 tons CO_2 per new vehicle) and larger vehicles (e.g., buses at 64 tons CO_2 per new vehicle) reflects scaling factors based on size, power, and material usage.

Flow energy consumption depends on two main factors: vehicle kilometers driven and the fuel intensity of the vehicle stock. These are calculated separately for each type of fuel. Flow energy consumption can be achieved by improving the technical implementation of the vehicles (lower energy consumption per km driven and per kW), smaller vehicles (less kW) and fewer km driven (utilizing reduced vehicle use or a modal shift to other transport modes).

$$E_{flow} = vkm_{ijt} * FI_{stock\_ijt} (\mathrm{PJ}) \quad (2)$$

where:

vkm Vehicle kilometers driven

FI_{stock} Fuel Intensity of vehicle stock by fuel type

Vehicle kilometers driven are computed from the service km driven (km/vehicle/year) and the vehicle stock. The factors for Public Transport Attractiveness and Active Mobility Attractiveness are included to reflect how attractive and convenient public and active transport are, influencing people's choice to drive less. The factors provide insight into how people's transportation choices might change in response to public and active transport options improvements.

$$vkm_{ijt} = skm_{ijt} * V_{stock_{ijt}} * A_{PT} * A_{AM} \text{ (mill km)} \tag{3}$$

where:

skm Service kilometers driven (km/vehicle/year)

V_{stock} Vehicle stock

A_{PT} Factor of Public Transport Attractiveness

A_{AM} Factor of Active Mobility Attractiveness

Fuel intensity is calculated for the existing vehicle stock, (excluding newly registered vehicles) and newly registered vehicles. For the newly registered vehicles, the fuel intensity is calculated using the set standards for fuel intensity.

$$FI_{stock_{ijt}} = \frac{FI_{stock_{t-1_{ijt}}} * \left(V_{stock_{ijt}} - V_{new_{ijt}}\right) + FI_{new_{ijt}} * V_{new_{ijt}}}{V_{stock_{ijt}}} \text{ (litre or kg/100 km)} \tag{4}$$

where:

FI_{new} Fuel intensities of newly registered vehicles (Standards)

V_{stock} Vehicle stock

The vehicle stock is calculated by the stock remaining factor and the vehicle stock of newly registered vehicles.

$$V_{stock_{ijt}} = \varphi_j * V_{stock_{ijt-1}} + V_{new_{ijt}} \text{ (1000)} \tag{5}$$

where:

φ PHI - stock remaining factor

The newly registered vehicles are the key variable in the model because the policies and attractiveness of public transport and active mobility directly impact the vehicle stock (purchase decision and choice of transport mode). To predict new vehicle registrations, new registered vehicles by size, vehicle, and fuel type take into account the proportional changes in service prices, income, and investment costs. Factors that contribute to the attractiveness of public transport are also considered.

The elasticities are explained as follows: (1.) Alpha is the elasticity of new vehicle registrations concerning service price changes. It indicates how sensitive the registration of new vehicles is to changes in fuel prices from one period to the previous one. (2.) Beta represents the income elasticity of demand for new vehicles. It shows how registering new vehicles responds to changes in income from one period to the previous one. (3.) Gamma is the elasticity of new vehicle registrations concerning changes in investment costs. It measures how sensitive the new vehicle registrations are to changes in the investment costs of new vehicles from one year to the previous one [51-53].

$$V_{new_{ijt}} = V_{new_{t-1}} * (1 + \left(\left(\frac{P_{st} - P_{st_{t-1}}}{P_{st}}\right) * \alpha\right) + \left(\left(\frac{Y_t - Y_{t-1}}{Y_t}\right) * \beta\right) + $$
$$+ \left(\left(\frac{IC_t - IC_{t-1}}{IC_t}\right) * \gamma * \mathrm{A}_{PT} * \mathrm{A}_{AM}\right) (1000) \quad (6)$$

where:

P_{st}	Service price of the stock
γ	Income
IC	Investment costs
α	Service price elasticity
β	Income elasticity
γ	Investment costs elasticity

The CO_2-tax, fuel taxes, VAT and the net price of the fuel determine the fuel price (real).

$$PF_{ijt} = CO_{2\_tax} + \tau_F + VAT + PF_{net} \text{ (EUR/litre or kW or kg)} \quad (7)$$

where:

PF_{ijt}	Price of fuel
CO_{2_tax}	CO_2-tax
τ_F	Fuel tax
VAT	Valued Added Tax
PF_{net}	Price of fuel net

The fuel price and fuel intensity of newly registered vehicles comprise the service price.

$$PS_{ijt} = FI_{new\_ijt} * PF_{ijt} \text{ (EUR/100 km)} \quad (8)$$

where:

PS_{ijt}	Service Price

The investment costs for a vehicle are calculated by the registration tax, the subsidies and the net investment costs.

$$IC_{ijt} = \tau_{REG} + \sigma + IC_{net} \text{ (EUR)} \quad (9)$$

where:

IC	Investment costs
τ_{REG}	Registration tax
σ	Subsidies
IC_{net}	Investment costs net

The total investment costs are the sum of the investment costs for the conventional part of vehicles and the investment costs for the new technology part of the vehicles. The latter part, IC_{new}, is expected to decrease due to a learning curve.

$$IC = IC_{conv} + IC_{new} \text{ (EUR)} \quad (10)$$

where:

IC_{conv} Conventional part of vehicles investment costs

IC_{new} Investment costs for the part of the new technology of vehicles (exist at BEVs, FCVs, hybrids)

The investment costs for the part of the new technology of vehicles (BEVs, FCVs, hybrids) are expected to decrease over time due to technological learning. In this model, the investment costs fall as the cumulative number of vehicles produced increases.

$$IC_{new} = IC_0 * {Y_t}^{-b} \text{ (EUR)} \quad (11)$$

where:

IC_0 Investment costs first unit

Y Cumulative output (vehicles produced)

b Parameter used to measure the extent of learning

The exponent −b describes the learning effect and can be used to calculate the learning rate. The learning rate captures how much the cost decreases with each doubling of cumulative production. If the cumulative production doubles, the cost will decrease by a percentage.

$$LR = 1 * 2^{-b} \quad (12)$$

where:

LR Learning rate

Figure 8 illustrates the expected investment costs for an 80 kW standard model of the VW Golf for various new technologies: Hybrids, Fuell-cell-Vehicles (FCVs) and EVs. As production increases, technological advances lead to cost reductions, known as technological learning. For example, the cost of an FCV in 2024 is estimated at 55,800 euros, excluding taxes and without adjustment for inflation. By 2050, the cost is estimated to drop to 37,000 euros due to a technological learning rate of 12% and a parameter of 0.18. On the other hand, the purchase cost of an EV in 2024 is estimated at EUR 32,400, which is expected to fall to EUR 25,200 by 2050, reflecting the impact of ongoing improvements and efficiency gains in EV technology. For a hybrid car, the cheapest option is EUR 15,400 in 2024, and costs are expected to fall slightly to EUR 14,200 in 2050. This cost trajectory underlines the impact of technological learning on reducing the costs associated with vehicle production over time [54].

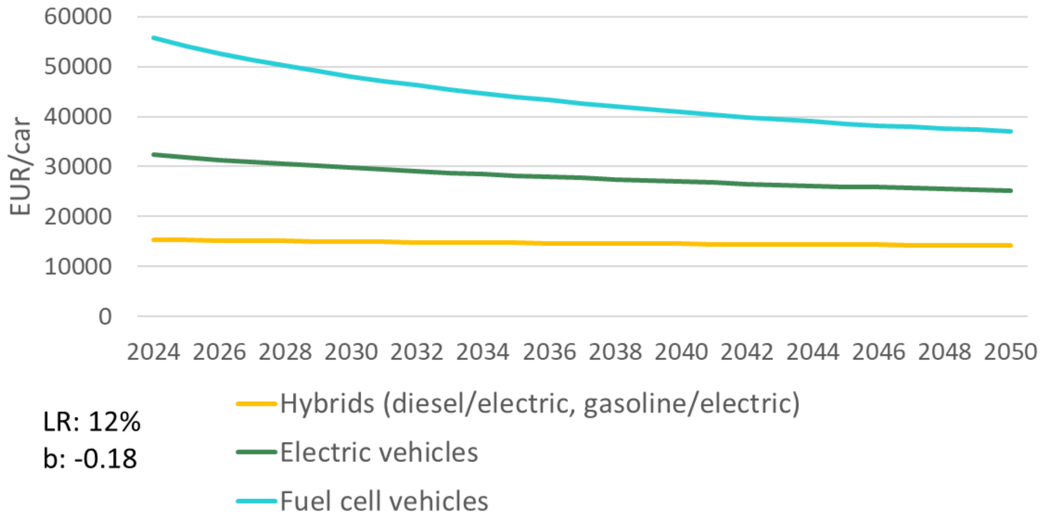

Figure 8 Development of technological learning for an exemplary 80 kW VW Golf from 2024 until 2050 (own calculations).

3.2 Assumptions for Scenario Building

This chapter describes the assumptions for the scenarios. Four scenarios were created to demonstrate possible developments in road passenger transport up to 2050: (1) a business-as-usual-scenario (bau-scenario), (2) a fossil phase-out-scenario (phase-out-scenario), (3) a tax-scenario and (4) a green-policy-scenario (green-scenario). The focus is on the results of flow energy consumption and related CO_2-emissions and which policies can positively influence these factors. In this study, the model was applied to Austria.

Table 2 shows the assumptions for four distinct scenarios in the development of road passenger transport for Austria from 2024 to 2050, each aimed at reducing CO_2-emissions but under varying policy frameworks. The bau-scenario illustrates how CO_2-emissions will develop if policies remain as they are. The phase-out-scenario describe what would happen if no more ICEs were permitted from 2035 onwards. In addition, the phase-out-scenario is based on the current EU-policy, and the other has a 'purely green' focus (transport shift to public transport and active mobility). Furthermore, the tax-scenario focuses on increasing CO_2-tax and registration taxes for conventional vehicles.

Table 2 Assumptions for energy policies in different scenarios in road passenger transport for Austria (2024-2050).

Effect on		BAU-Scenario	Phase-Out-Scenario	TAX-Scenario	Green-Policy-Scenario
Investment costs	Registration tax/year	As of 2023;	As of 2023;	+10%/year (exempt. FCV, BEV);	+6%/year (exempt. FCV, BEV);
	Subsidy increase/year	As of 2023;	As of 2023; as of 2035, no more subs.;	As of 2023;	2024-2030: +4%/year

	Technological learning (Hybrids, BEVs, FCVs) [54]	Learning rate: 12% b: - 0.18	Learning rate: 12% b: - 0.18	Learning rate: 12% b: - 0.18	Learning rate: 12% b: - 0.18
Fuel prices	CO_2-tax	As of 2023	2022-2025 (set); 2026+ (as of 2025)	2022-2025 (set) 2026+ (linear increase)	2022-2025 (set) 2026+ (linear increase)
	Fuel tax	As of 2023	As of 2023	As of 2023	As of 2023
Fuel Intensities	Standards	As of 2023	As of 2023	As of 2023	As of 2023
Newly reg. cars	Elasticities [51-53]	α (Ownership service price elasticity) = -0.50; β (Ownership investment costs elasticity) = -0.50; γ (Income elasticity) = 1.10			
	ICEs (inkl. hybrids)	Up to 2050 -1%/year	Up to 2034 +1%/year; 2035: No ICEs (phase-out)	Up to 2034 -2%/year	Up to 2050 -2%/year;
	BEVs, FCVs	Up to 2050 -> +1%/year	Up to 2034 -> +2%/year	Up to 2034 -> +2%/year	Up to 2050 -> +2%/year
	Motorcycles, light vehicles	No data available for fuel types; assumption: 2% of total motorcycles/light vehicles are electrically powered;			
Newly reg. cars, vehicle kilometers driven	Factor of attractiveness of public transport and active mobility	1	1	1	gradual annual decrease of 0.2% from 2024-2050

The investment costs are influenced by policies such as registration taxes on ICEs or subsidies for BEVs. Additionally, a CO_2-tax and fuel tax impact the fuel price, and standards are set to address fuel intensity. The attractiveness factors for public transport and active mobility are also vital, representing policies that influence public behavior and choices in ways that are not directly quantifiable (e.g., through awareness-raising and information campaigns). Furthermore, the scenarios assume that BEVs will be powered by 100% RES by 2050. Without clean energy, the benefits of BEVs could be undermined if fossil fuels continue to dominate electricity generation, as emphasized by Ajanovic et al. [55]. This assumption is critical, as it ensures that the shift to BEVs contributes to substantial CO_2 reductions; however, achieving 100% RES will require significant advancements in energy infrastructure and policy commitments. If RES targets are not fully met, emissions will be higher than projected. This underscores the need for parallel investments in renewable energy, though this study does not consider alternative scenarios without 100% RES.

3.2.1 BAU-Scenario

Under the bau-scenario, past developments (2000-2023) were used to predict future developments. Registration taxes and subsidies for BEVs and FCVs are in place as of 2023, and no further increases are projected. Technological learning continues steadily, with the learning rate for hybrids, BEVs, and FCVs set at 12% and the b-factor at -0.18, indicating ongoing technological improvements that will lower investment costs over time. Fuel prices are impacted by a CO_2-tax and fuel tax as of 2023. The elasticities affecting new vehicle registrations are grounded in ownership service price, investment costs, and income, with specific values assigned to each parameter. It is assumed that -2% of new ICEs will be registered annually until 2024. BEVs and FCVs, on the other hand, are expected to be newly registered at a rate of +2%/year.

3.2.2 Fossil Phase-Out-Scenario

The scenario is based on current EU policy. Starting in 2023, no new fossil-fuelled vehicles will be allowed to be registered. Different assumptions were made for the scenario creation, emphasizing a phase-out of fossil-fueled vehicles. From 2035, BEVs and FCVs will no longer receive subsidies. Similar to the bau-scenario, it includes a CO_2-tax affecting fuel prices and technological learning that reduces investment costs. New vehicle registrations are influenced by similar elasticities as in the bau-scenario, with ownership service price and investment costs playing significant roles. It is assumed that 1% of new ICEs will be registered annually until 2034. This is intended to compensate for the upcoming phase-out of fossil-fueled vehicles in 2035. In addition, the number of newly registered BEVs and FCVs will increase by 2% per year until 2034

3.2.3 Tax-Scenario

The tax-scenario focuses on increasing registration taxes and CO_2-taxes. There is no mandatory fossil phase-out. Under the tax-scenario, the registration tax for newly registered ICEs (including hybrids) will rise by 10% annually until 2050. Fuel prices will include a CO_2-tax that increases linearly in 2026 after a politically determined increase in 2022-2025. It is assumed that -2%/year ICEs (incl. hybrids) will be registered up to 2050. 2% more BEVs and FCVs will be registered each year.

3.2.4 Green-Policy-Scenario

The same historical database was used as in the other three scenarios. Assumptions developed for the scenario focus on 'pure green' developments. This means shifting transport to more sustainable modes such as public transport and active mobility. The registration tax for ICEs will rise by 6%/year up to 2050. Subsidies for BEVs and FCVs will increase by 4%/year until 2030, after which they fall by 4%/year. There will be no more subsidies from 2035. The CO_2 tax will be based on EU policy until 2025 and will increase linearly from 2026. The number of newly registered ICEs (incl. hybrids) is set to fall by 2%/year until 2050. A significant emphasis is placed on public transport and active mobility attractiveness, with a yearly 0.2% decrease from 2024 to 2050. With this assumption, the consumer's preferences should shift significantly towards more sustainable modes of transport, such as public transport and active mobility, which will strongly influence the number of newly registered vehicles and kilometers driven.

Together, these scenarios represent a roadmap with various political drivers, each of which impacts the introduction of vehicle technologies, consumer behavior (towards the choice of transport mode and choice of vehicle technology) and ultimately, the CO_2-emissions emitted by road passenger transport.

The assumptions for the scenarios were derived from established literature, supplemented by previous projects conducted by the Energy Economics Group at TU Wien (as project manager or project participant). Notable contributions include the Alter-Motive project [32], the ODYSSEE-MURE project [34], and the TransLoc project [56]. Further aspects were derived from the following studies: FCVs are not seen as having any more extensive prospects in road passenger transport. They cannot compete economically with ICEs, which was derived from several studies by Lam et al. [16], Ajanovic et al. [55, 57], and Zhang et al. [58]. The green-policy-scenario is especially examined from studies with a focus on the shift to more sustainable transportation modes such as public transport and active mobility by Barisa et al. [9], Hahn et al. [59], Stepniak et al. [60], and Christidis et al. [61]. In the scenarios developed within this study, it was assumed that the electricity mix for BEVs comes from 100% RES. This is a necessary condition to pave the way to a low-carbon future. This importance was emphasized by Ajanovic et al. [55], and Siebenhofer (Maier) et al. [7].

The model was developed, and the assumptions for the scenarios were applied to Austria as a case study in our paper. The model for predicting the development of passenger road transport can be applied to any country/city.

4. Results

This chapter presents the results of the bau-scenario and the three policy scenarios (fossil phase-out-scenario, tax-scenario, and green-policy-scenario) developed. The focus is always on energy consumption and the resulting CO_2-emissions and how these change with the implementation of proper policies. The biggest levers are the newly registered vehicles and, as a result, the vehicle stock on the road.

4.1 Newly Registered Cars

Figure 9 illustrates the bau-scenario for the development of newly registered vehicles in road passenger transport in Austria up to 2050. Beginning in 2016, there was a sharp drop in new registrations from 370 thousand vehicles to 200 thousand in 2024, primarily among conventional gasoline and diesel vehicles. The sharp decline in the number of newly registered vehicles between these years is mainly due to the impact of the COVID-19 pandemic from 2020 to 2022, which led to a decline in travel and mobility. As a result, the number of new vehicles registered by the population was significantly lower than in previous years. The pandemic significantly influenced consumer behavior, as lockdowns and restrictions led to a temporary decline in personal vehicle use, while economic uncertainty prompted many to delay vehicle purchases. As a result, overall demand for transportation temporarily dropped during this period. From 2024, the number of fossil-fuelled vehicles will slowly decline, while the number of BEVs will slowly increase. In 2050, 240 thousand new vehicles will be registered in this scenario. Furthermore, the landscape of new vehicle registrations has transformed, with gasoline and diesel vehicles comprising only a tiny fraction of the total. At the same time, BEVs appear to emerge as the predominant choice for new vehicle buyers.

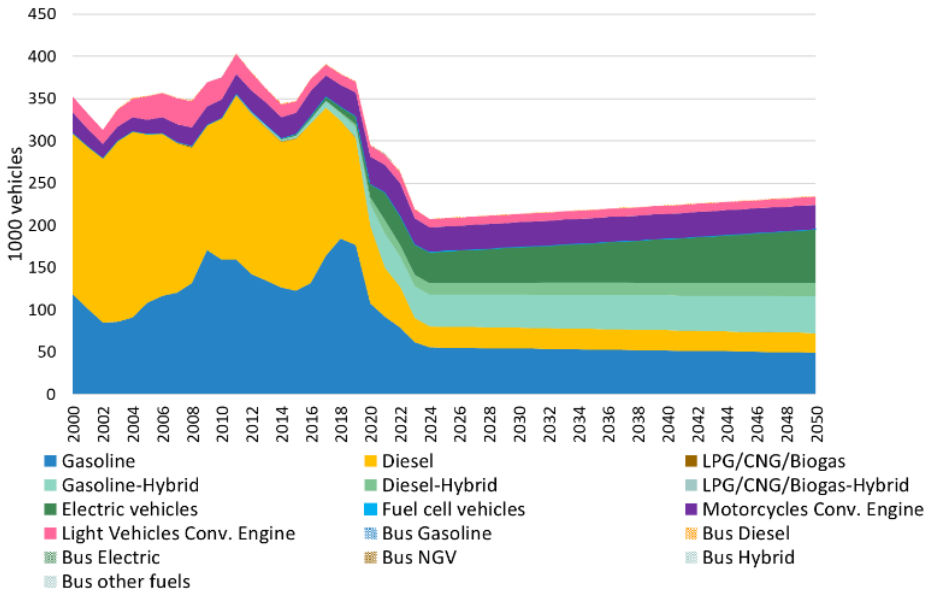

Figure 9 Bau-scenario: Development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [37], from 2024 own modeling).

Figure 10 shows the projected trends in new vehicle registrations by fuel type from 2000 to 2050 in the phase-out-scenario. In this scenario, ICEs are not permitted to be registered from 2035. It is assumed that newly registered ICEs will increase by 2035. From 2035, only BEVs will be registered. By 2050, the transition towards sustainable fuel types is clear, with BEVs leading the market, reflecting shifts towards reducing carbon emissions and fossil fuel dependency. In 2050, the total number of newly registered vehicles will amount to 60 thousand vehicles.

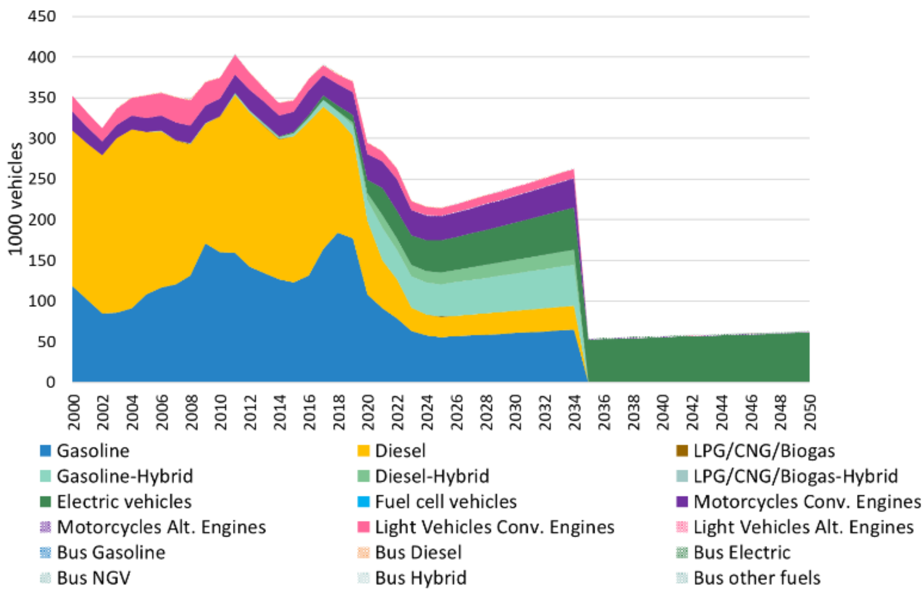

Figure 10 Phase-out-scenario: Development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [37], from 2024 own modeling).

Figure 11 illustrates the development of newly registered vehicles in road passenger transport in Austria extending to the year 2050 in the tax-scenario. The graph shows that by 2020, new registrations for ICEs have substantially decreased, with alternative fuel types like BEVs and hybrids taking a larger share. The sharp reduction in newly registered vehicles after 2020 and more sharply from 2024 reflects several policies favoring higher prices for ICEs and fuels. By 2050, the graph indicates that the total number of new vehicle registrations, with 160 thousand vehicles, is much lower than the peak with 400 thousand vehicles observed in 2011. The data in this tax-scenario suggests a transition to a more sustainable and less car-dependent mobility culture.

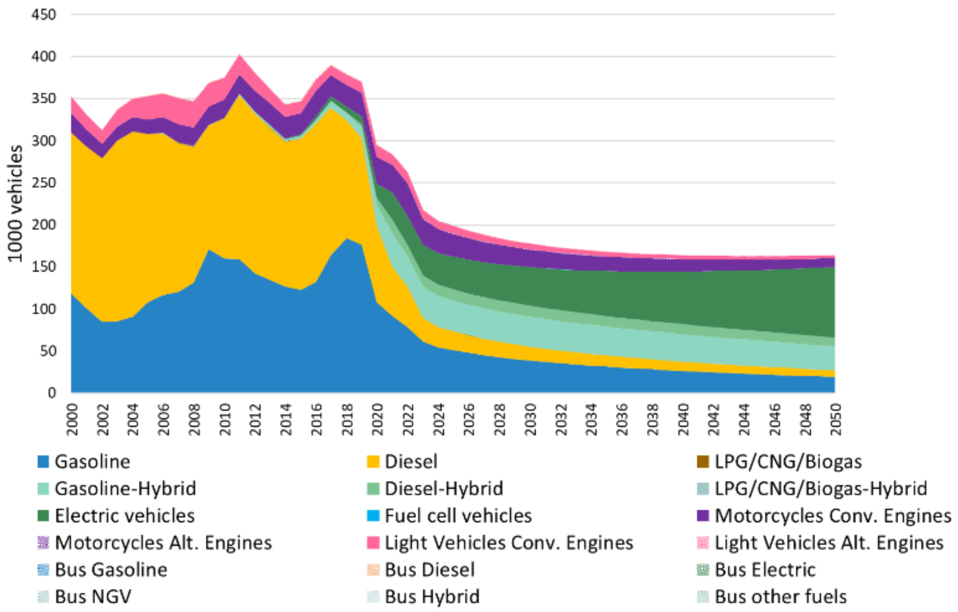

Figure 11 Tax-scenario: Development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [37], from 2024 own modeling).

Figure 12 shows the development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 in the green-policy-scenario. ICEs dominated the early years, peaking at approximately 400 thousand around 2011. Post-2019, these registrations decline sharply, nearing zero by 2050. BEVs will decrease from 2020 to around 8 thousand by 2050. By 2050, new vehicle registrations across all types reduce significantly, indicating a transition towards sustainable transport in Austria. These developments are reflected in various strategies that favor green policies. Particular focus is placed on the general reduction of individual road transport and, thus, a shift to other modes of transport, such as public transport and active mobility.

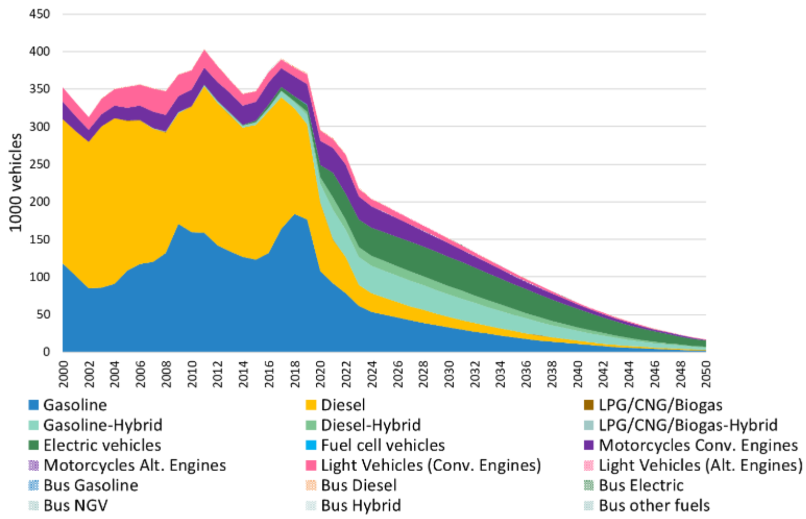

Figure 12 Green-policy-scenario: Development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [37], from 2024 own modeling).

Figure 13 illustrates the development of the total number of newly registered cars in Austria's bau- and policy scenarios from 2000 to 2050. The graphs of the bau-scenario depict a slight increase in the total amount of newly registered cars until 2050. The phase-out-scenario shows, at first, a harsh increase in the total number of newly registered vehicles and, after 2035, a strong fall in the total number, followed by a slight increase. The tax-scenario highlights a relatively constant development in newly registered vehicles, supported by higher taxes for fossil-fueled vehicles. In contrast, the green-policy-scenario indicates a significant and continuous decline in new vehicle registrations after 2024. This scenario suggests aggressive measures to reduce the overall number of vehicles. The green-policy-scenario points to a comprehensive strategy for sustainable transport, significantly decreasing private vehicle registrations, indicating a strong commitment to environmental goals and a transformative change in mobility patterns and infrastructure.

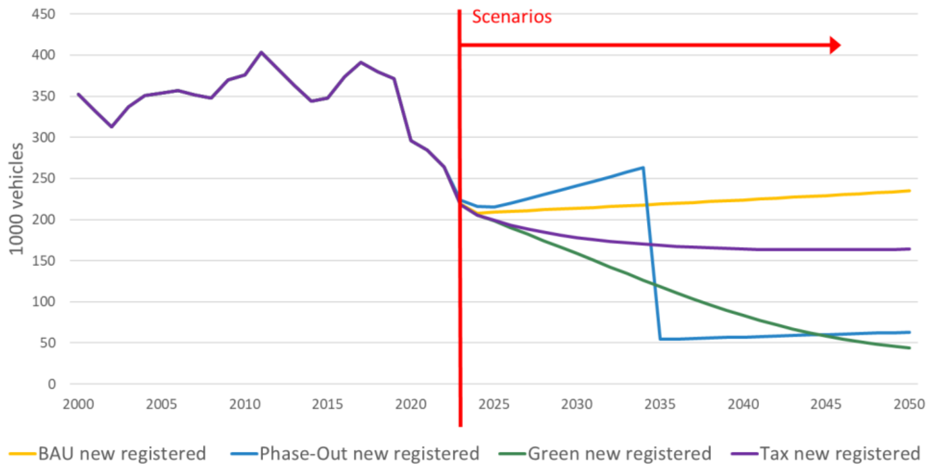

Figure 13 Comparison bau- and policy-scenarios: Development of newly registered vehicles in road passenger transport by fuel type in Austria up to 2050 (based on own calculations).

4.2 Vehicle Stock

Figure 14 shows the development of vehicle stock in road passenger transport by fuel type in Austria from 2000 to 2050 in the bau-scenario. Over the years, gasoline and diesel vehicles were the most common, with 5 million vehicles in 2023. By 2022, the total number of vehicles, including all types, peaked at 6 million. A significant shift will occur from 2020 onwards as alternative fuel vehicles such as BEVs become more prevalent. Hybrid gasoline and diesel vehicles make noticeable entries. BEVs are increasing after 2022. By 2050, BEVs will dominate the total vehicle stock, but the proportion of gas, diesel, and hybrid vehicles is also high. The total vehicle stock in this scenario is 4.6 million vehicles in 2050. Light vehicles, such as motorcycles and various types of buses, including standard, hybrid, and those using other fuels, are also represented. Although their numbers change over the years, they take up a relatively more minor portion of the total vehicle stock than cars. The graph indicates a transformative shift in Austria's vehicle composition, with a steep decline in traditional gasoline and diesel vehicles by 2050, primarily replaced by BEVs and hybrids.

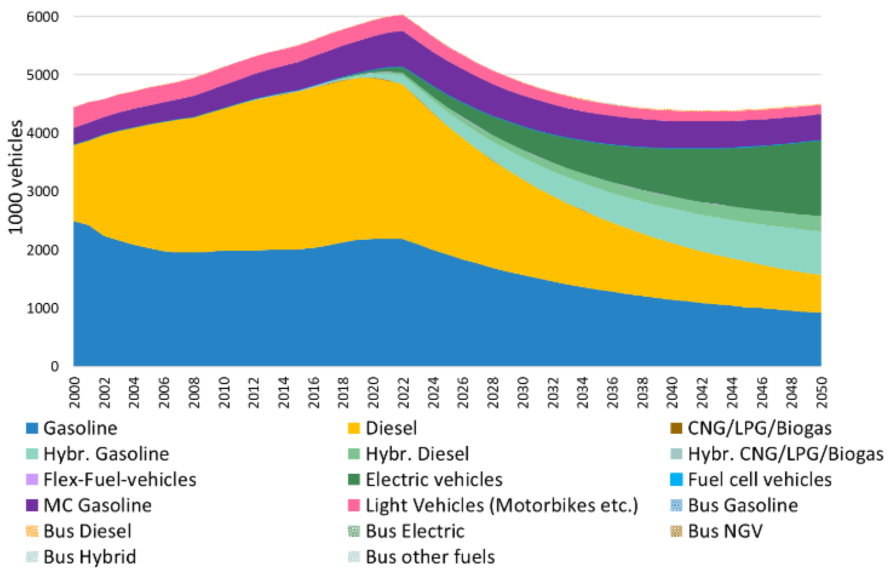

Figure 14 Bau-scenario: Development of vehicle stock in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [38], from 2024 own modeling).

Figure 15 illustrates the phase-out-scenario, which predicts the development of vehicle stock in passenger road transport by fuel type in Austria up to the year 2050. Notable changes occur with the introduction and growth of BEVs and hybrids. A remarkable transition is visible from 2022 onwards, where BEVs rise in numbers, overtaking other fuel types by 2050. In 2050, there will still be many vehicles on the road, a total of 2.9 million. Motorcycles and light vehicles with both conventional and alternative engines maintain a steadily smaller fraction of the vehicle fleet throughout the period. Buses show variation but remain a minor component compared to cars. Overall, the development of the vehicle stock shows a shift away from fossil fuels towards more sustainable and environmentally friendly vehicle technologies by 2050, with BEVs taking the forefront in the national effort to reduce carbon emissions in transport.

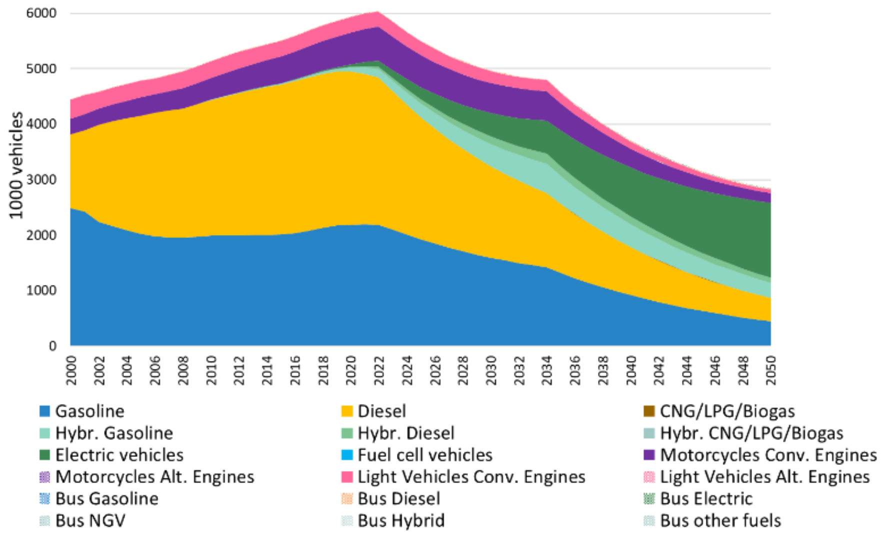

Figure 15 Phase-out-scenario: Development of vehicle stock in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [38], from 2024 own modeling).

Figure 16 highlights the development of vehicle stock in road passenger transport by fuel type in Austria from 2000 to 2050 in the tax-scenario. Conventional powered vehicles dominate the stock initially, peaking around 2022 at nearly 5 million vehicles. Post-2022, these numbers decline sharply, with diesel and gasoline vehicles almost phased out by 2050. BEVs and hybrid vehicles show significant growth from 2022 onwards, peaking around 2050, with BEVs reaching about 1.2 million. By 2050, the vehicle stock will transition heavily towards electric and hybrid vehicles, aligning with policies favoring higher vehicle prices and reliance on conventional fuels.

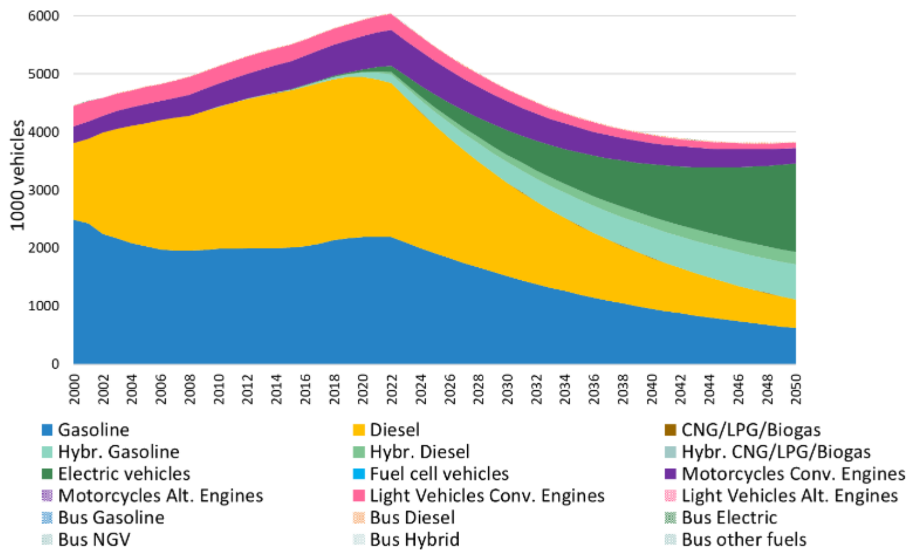

Figure 16 Tax-scenario: Development of vehicle stock in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [38], from 2024 own modeling).

Figure 17 illustrates the development of the vehicle stock in road passenger transport under the green-policy-scenario in Austria from 2000 to 2050. The scenario anticipates a significant increase in BEVs, accelerating around 2024. By 2050, the number of BEVs will expand significantly, indicating a strong push towards electric mobility. Around 2.3 million vehicles will be on the road in 2050 in this green-policy-scenario, compared to 6 million vehicles in 2022. Buses, including diesel, hybrid, and electric, along with motorcycles and light vehicles with conventional engines and alternative engines, indicate a smaller share in the total vehicle fleet than cars. The green-policy-scenario underlines a significant move towards greener, more sustainable transport modes, aligning with global trends and targets for reducing carbon emissions in the transport sector.

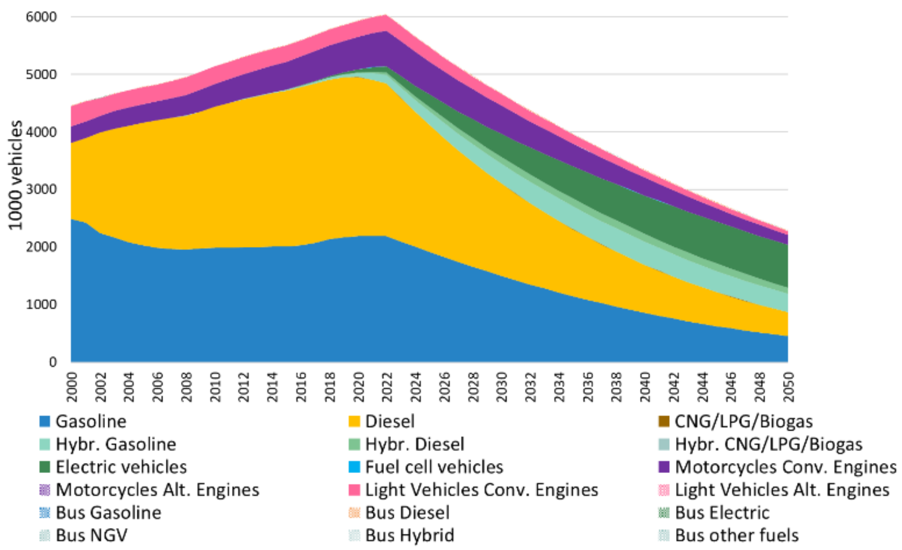

Figure 17 Green-policy-scenario: Development of vehicle stock in road passenger transport by fuel type in Austria up to 2050 (data 2000-2023 [38], from 2024 own modeling).

Figure 18 presents the development of vehicle stock in road passenger transport in Austria up to 2050 for the four scenarios. The bau-scenario shows a steady increase in vehicle stock, peaking at around 6 million vehicles in 2022, followed by a slight decline, which ends up in a slight rise, maintaining approximately 4.5 million vehicles by 2050. In comparison, the vehicle stock in the phase-out-scenario slightly increased until 2034 and afterward sharply declined to around 3 million by 2050, indicating aggressive reduction policies like a Phase-Out of ICEs. The tax-scenario gradually decline to 3.9 million by 2050, suggesting a moderate reduction through financial incentives. The green-policy-scenario declines to about 2.7 million by 2050. Overall, the scenarios illustrate varying degrees of policy intervention impacting the vehicle stock reduction in Austria. When comparing these scenarios, it is evident that the future of vehicle stock is highly dependent on the interplay of policy decisions, technological advancements, and social behavior toward sustainability. The green-policy-scenario is the most favorable scenario with the lowest vehicle stock, with 2.7 million in 2050, compared to the bau-scenario, with the most tremendous total amount of vehicles, with around 4.6 million in 2050.

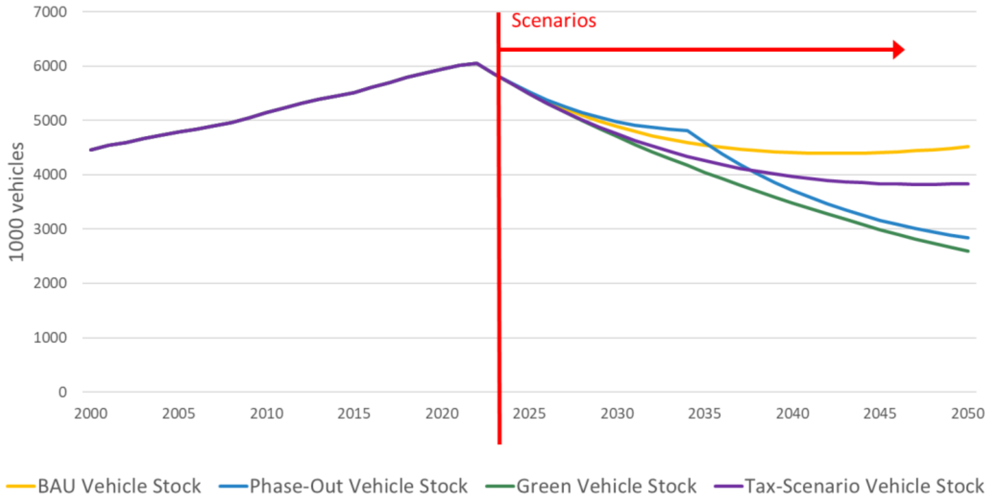

Figure 18 Comparison bau- and policy-scenarios: Development of vehicle stock in road passenger transport in Austria up to 2050 (based on own calculations).

4.3 Modal Split

Figure 19 presents a comparative analysis of modal split shares in road passenger transport in Austria, projecting up to the year 2050 across four different scenarios. The modal split is measured in percentage shares of distance traveled, showing the contribution of each transport mode to the total distance traveled by vehicles or passengers.

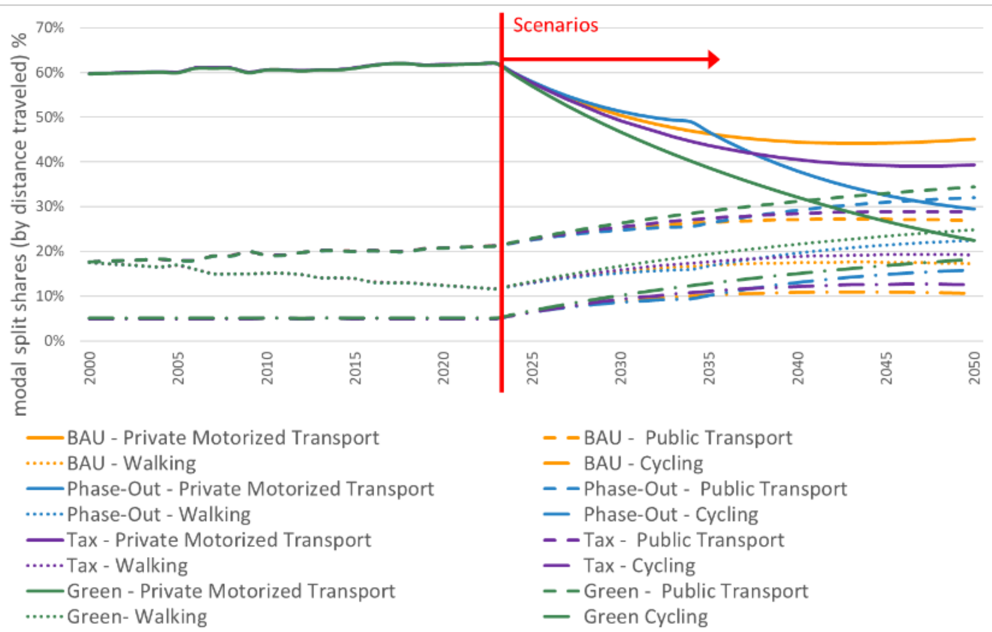

Figure 19 Comparison of the development of modal split shares in road passenger transport in Austria up to 2050 (2000-2019 [20, 21], from 2020, the data points were extrapolated and modeled for the scenarios).

4.3.1 BAU-Scenario

The share of private motorized transport remains relatively stable until around 2025 when it begins to decline slowly. By 2035, the share of private motorized transport falls to about 52% and continues to increase gradually, reaching approximately 55% by 2050. This decline suggests a gradual shift away from conventional vehicles, likely influenced by ongoing but moderate policy changes and advancements in vehicle technology. Public transport usage shows a modest increase, rising from around 22% in 2025 to approximately 24% by 2050. Walking and cycling modes maintain a consistent share throughout, stabilizing at around 14% for walking and 8% for cycling by 2050. Compared to the other scenarios, the bau-scenario depicts the least aggressive shift towards sustainable transport modes, reflecting a slower introduction of proper policies.

4.3.2 Phase-Out-Scenario

Private motorized transport experiences a significant reduction. From 2024, its share drops below 60% and continues to decline, reaching about 34% by 2050, making it the second lowest among the scenarios. The share of public transport increases substantially, from approximately 22% in 2024 to around 30% by 2050. Walking and cycling also see notable growth, with their combined share rising to about 35% by 2050. This scenario reflects strong policies aimed at phasing- out conventional vehicles and promoting sustainable alternatives, resulting in a marked decrease in private motorized transport and significant increases in public and active transport modes.

4.3.3 Tax-Scenario

In the tax-scenario, private motorized transport shows a notable decline due to the implementation of higher taxes designed to decrease the price of fuel and corresponding vehicle usage. Starting from 2024, its share falls steadily, reaching about 48% by 2035 and approximately 47% by 2050. The share of public transport will rise considerably during this period, increasing from around 22% in 2024 to about 26% by 2050. Walking and cycling also experience significant growth, with their combined share approaching 27% by 2050. This scenario highlights the effectiveness of tax policies in promoting sustainable and active modes of transport, showing a pronounced shift compared to the bau-scenario but less aggressive than the green- or the phase-out-scenario.

4.3.4 Green-Policy-Scenario

A significant reduction in the share of private motorized transport is visible, dropping to levels comparable with public transport by 2050. Public transport sees a considerable increase in its share, potentially doubling compared to current levels. Walking and cycling also increase noticeably, suggesting proper policies promoting these modes over private vehicle use. The share of private motorized transport is substantially lower, at 24% in 2050. In 2024, the private motorized share was 60%. Public transport share increase from 22% in 2024 to approximately 26% in 2050, and walking and cycling might collectively make up roughly 42% of the modal split.

In summary, each scenario offers different protections for the future of transport in Austria. The green-policy-scenario provides the most significant reduction in reliance on private vehicles, followed by the tax and phase-out scenarios. The bau-scenario shows the least change, with a continued reliance on private motorized transport.

4.4 Total CO_2-Emissions and Energy Consumption

Figure 20 shows the development of CO_2-emissions from road passenger transport in Austria from 2000 to 2050 in the bau-scenario. The most significant share of CO_2-emissions over time is from vehicles powered by diesel, followed by gasoline. Since 2019, the total CO_2-emissions in passenger road transport have decreased from 17 million tons CO_2 to 5.8 million tons CO_2 in 2050. Especially CO_2-emissions emitted by ICEs are constantly falling, and CO_2-emissions emitted by alternative fuels are slowly increasing. In 2050, the total CO_2-emissions will only be 1/3 of the emissions of 2019.

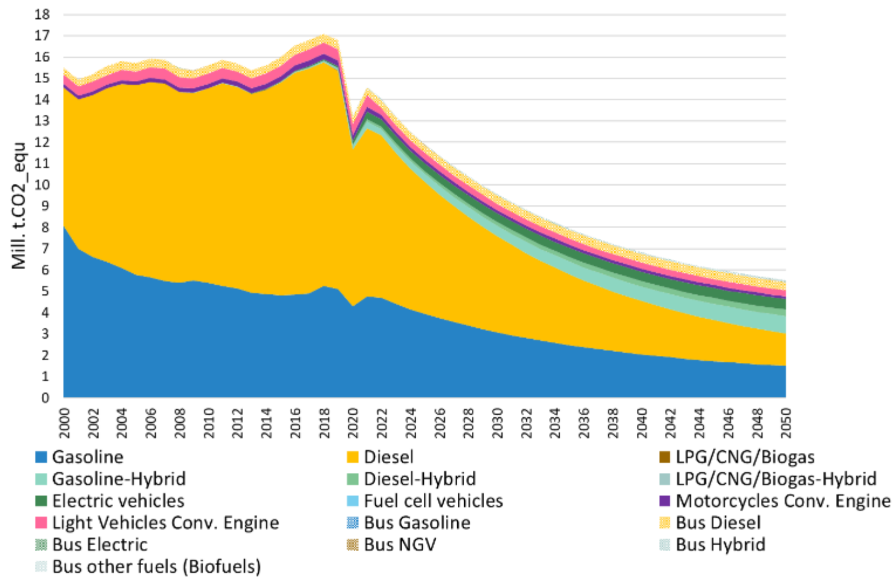

Figure 20 Bau-scenario: Development of CO_2-emissions from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 21 highlights the development of CO_2-emissions from road passenger transport by fuel type in Austria from 2000 to 2050 under the phase-out-scenario. Initially, CO_2-emissions are dominated by diesel and gasoline vehicles, peaking around 2020 at approximately 17 million tons. Post-2020, there has been a significant decline in CO_2-emissions from ICEs, reflecting a shift towards more sustainable transport. By 2050, emissions from diesel and gasoline vehicles are almost negligible compared to 2020. The share of CO_2-emissions from BEVs and hybrids increases initially but then decreases. By 2050, overall CO_2-emissions from road passenger transport reduce to around 4 million tons, indicating a successful transition to lower-emission vehicles and alternative fuels. This scenario reflects the effectiveness of phasing-out conventional vehicles in reducing CO_2-emissions.

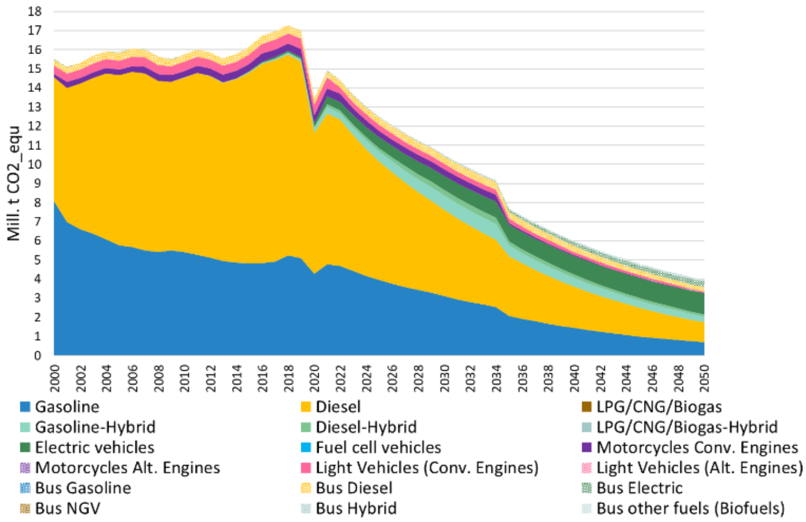

Figure 21 Phase-out-scenario: Development of CO_2-emissions from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 22 shows the projected trends in CO_2-emissions from various fuel types in Austria from 2000 to 2050 under the tax-scenario. Again, CO_2-emissions are strongly influenced by ICEs, reaching a peak around 2020 at approximately 17 million tons per year. However, after introducing policies influencing the amount of taxes around 2024, CO_2-emissions from ICEs begin a notable decline. Concurrently, CO_2-emissions from BEVs and hybrid vehicles show an initial rise as their adoption increases. By 2050, total CO_2-emissions from passenger transport will drop to about 5 million tons, indicating a significant shift towards lower-emission and alternative fuel vehicles. This scenario underscores the effectiveness of tax policies in driving substantial reductions in greenhouse gas emissions from the transport sector.

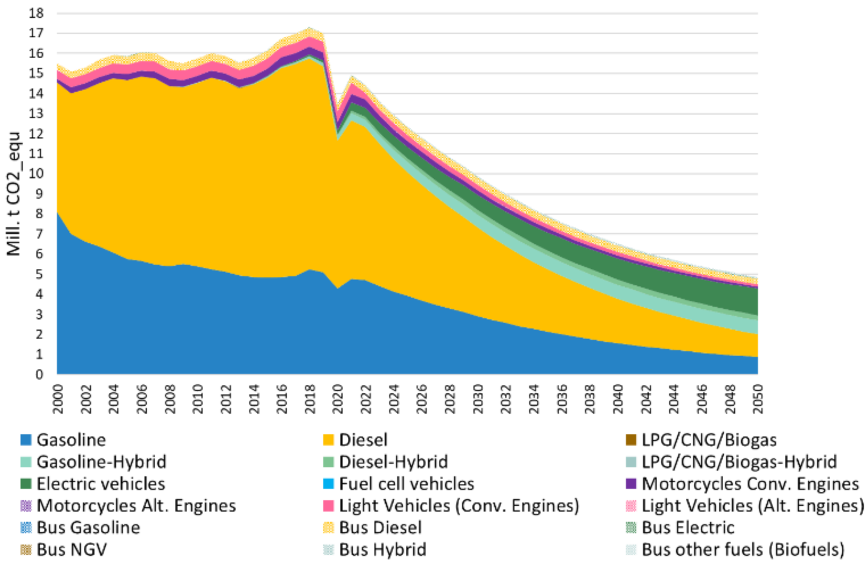

Figure 22 Tax-scenario: Development of CO_2-emissions from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 23 illustrates the green-scenario for CO_2-emissions from road passenger transport by fuel type in Austria, showing a significant decline from 2024 to 2050. Starting in 2024, emissions from gasoline and diesel vehicles begin a steep decline from around 12 million tons to 2.5 million tons in 2050. Alternatively-fueled vehicles will develop relatively constantly until 2050. This scenario highlights the substantial potential for CO_2-reduction by adopting cleaner technologies and effective transport policies.

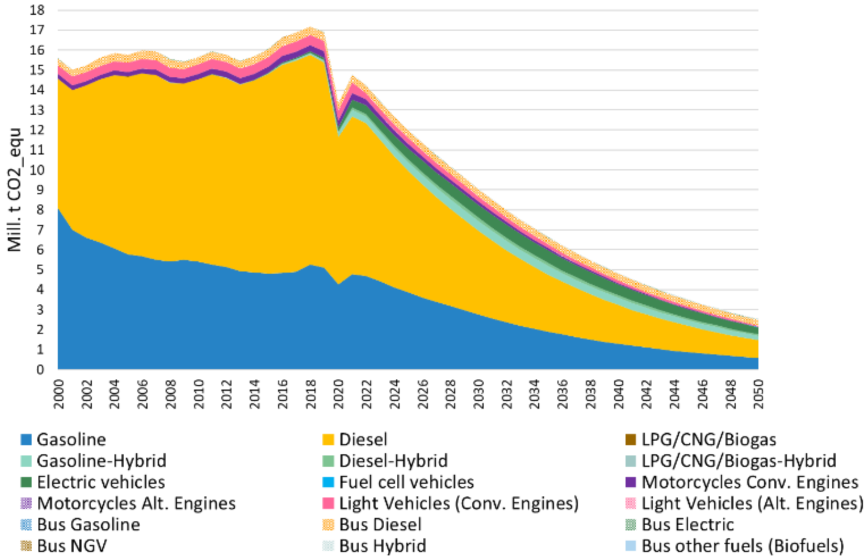

Figure 23 Green-scenario: Development of CO_2-emissions from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 24 presents the development of CO_2-emissions from road passenger transport in Austria from 2000 to 2050 across all four scenarios. Overall, the graph illustrates that while all scenarios predict a decline in CO_2-emissions, the green-policy-scenario shows the most significant reduction in flow and embedded CO_2-emissions, signalling a potential path towards achieving more ambitious environmental targets. The distinction between flow and embedded emissions indicates that flow emissions can be reduced more quickly with changes in the number of vehicles, vehicle km driven, vehicle technology and fuel types. Embedded emissions from vehicle production and end-of-life processes require different strategies and more time to decrease. Again, the most favorable scenario is the green-policy-scenario, followed by the phase-out, the tax-scenario, and the bau-scenario. In the green-policy-scenario CO_2-emissions from flow energy decreased from around 15 million tons of CO_2 in 2019 to 2.7 million tons in 2050.

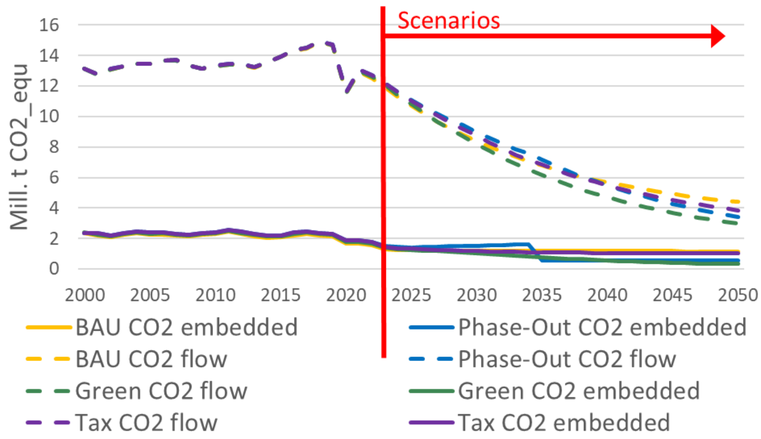

Figure 24 Comparison development of CO_2-emissions in all scenarios (own calculations).

Figure 25 shows the development of energy consumption from road passenger transport by fuel type in Austria up to 2050 in the bau-scenario. Over time, most energy is consumed by diesel cars, followed by gasoline cars. In 2018, 50 PJ were emitted by gasoline, and 105 PJ were emitted by diesel-fueled vehicles. The energy consumed by alternative-powered vehicles has been rising slowly since 2019. In 2050, around 60 PJ will still be consumed by passenger road vehicles in Austria. The energy consumed by conventionally-fueled vehicles is slowly decreasing, while that of alternatively-fueled vehicles is gradually increasing over time.

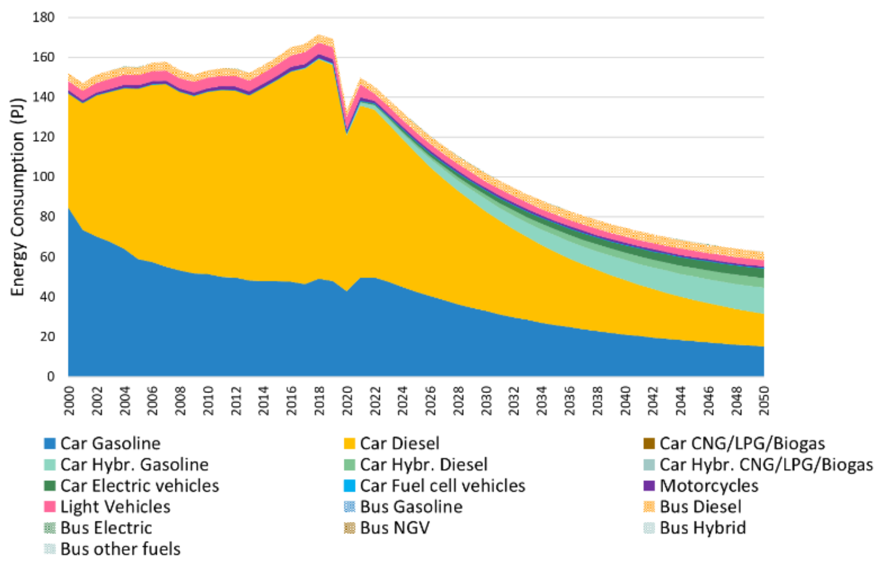

Figure 25 Bau-scenario: Development of Energy Consumption from road passenger transport by fuel type in Austria up to 2050 (own calculations).

In the phase-out-scenario, energy consumption from road passenger transport by fuel type in Austria until 2050 is significantly reduced, as shown in Figure 26. Total energy consumption is decreasing rapidly due to the decline in petrol and diesel vehicles because of the Phase-Out from 2035. An increase in the energy consumed by BEVs can be seen in this scenario. In 2050, only 38 PJ will be consumed in road passenger transport.

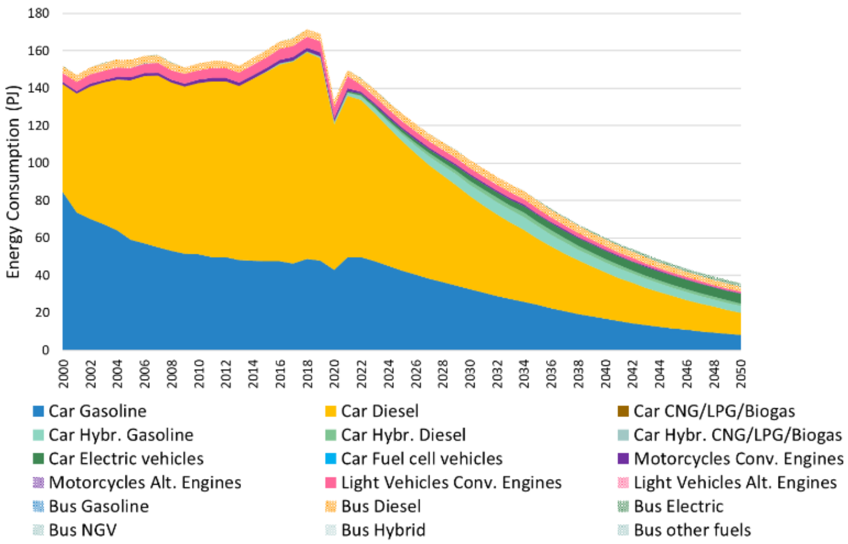

Figure 26 Phase-out-scenario: Development of Energy Consumption from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 27 depicts the projected trends in energy consumption from road passenger transport by various fuel types in Austria from 2000 to 2050 in the tax-scenario. Following the implementation of tax-related policies to reduce energy consumption and promote efficiency, there has been a significant decline in the energy use of diesel and gasoline vehicles. By 2050, energy consumption from these conventional fuel types will drop substantially. Conversely, energy consumption by EVs and hybrids initially increases as their adoption grows but eventually stabilizes and reduces as technology advances and efficiency improves. By 2050, overall energy consumption from road passenger transport will fall to around 40 PJ per year, illustrating the effectiveness of taxation policies in reducing energy use and encouraging a shift towards more energy-efficient and sustainable transport options.

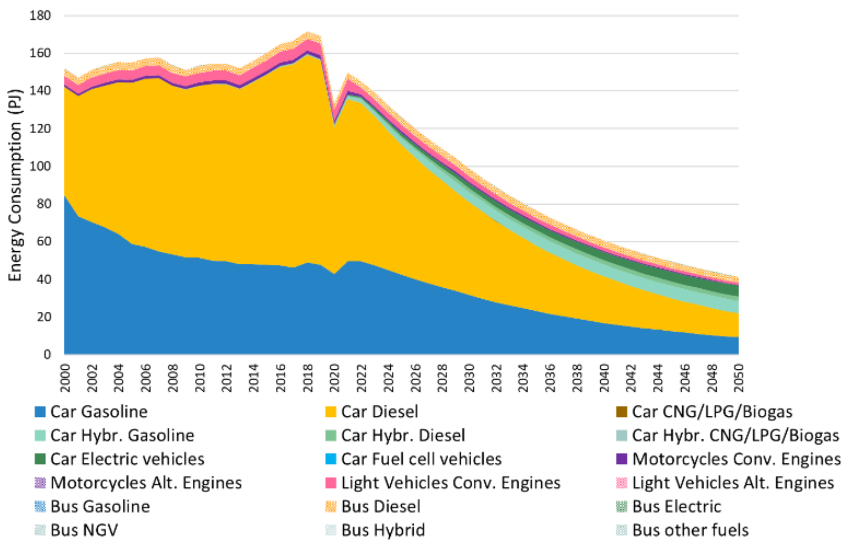

Figure 27 Tax-scenario: Development of Energy Consumption from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 28 shows the results for energy consumption from road passenger transport by fuel type in Austria up to 2050 in the green-policy-scenario. Starting around 2024, energy use from diesel and gasoline vehicles will drop significantly, nearing elimination by 2050. Concurrently, the energy consumption of electric and hybrid vehicles rises initially as adoption increases but eventually stabilizes and then declines with improved efficiency. By 2050, total energy consumption from road passenger transport will fall to about 30 PJ, driven by a shift towards public transport and active mobility. This scenario highlights the gradual and effective reduction of energy consumption through sustainable policies and technological advancements.

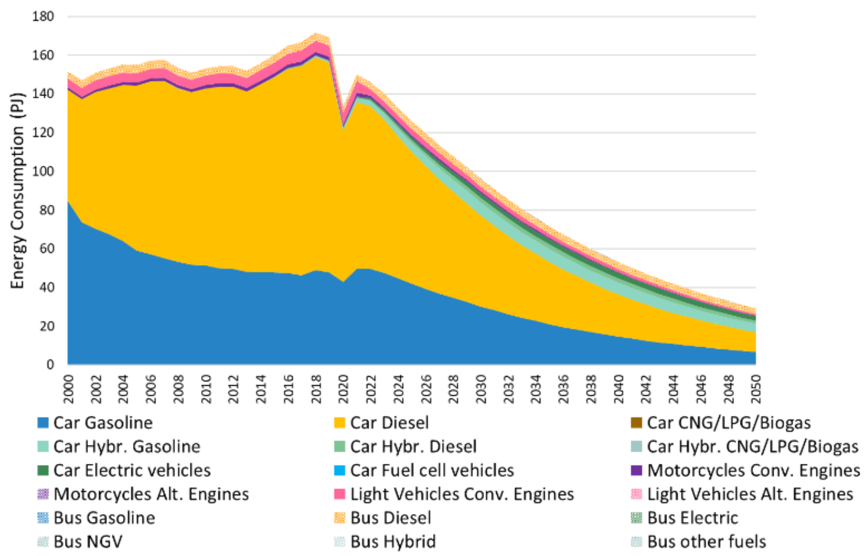

Figure 28 Green-policy-scenario: Development of Energy Consumption from road passenger transport by fuel type in Austria up to 2050 (own calculations).

Figure 29 compares the developments of total energy consumption in the bau- and policy-scenarios in road passenger transport in Austria up to 2050. From 2024, the bau-scenario shows a slower decline in energy consumption, maintaining higher levels than the other scenarios, reaching around 60 PJ by 2050. The green-policy-scenario demonstrates a more rapid reduction, with energy consumption dropping to approximately 37 PJ by 2050, reflecting strong environmental policies and a shift towards sustainable transport modes. The phase-out-scenario follows a similar trajectory to the green-policy-scenario, with a substantial decrease, reaching around 38 PJ by 2050, driven by the phase-out of conventional vehicles. The tax-scenario also shows significant reductions in energy consumption, falling to about 40 PJ by 2050, due to the impact of higher taxes. Overall, the green-policy-scenario achieves the most substantial reduction, followed closely by the phase-out and tax-scenarios, while the bau-scenario shows the least change.

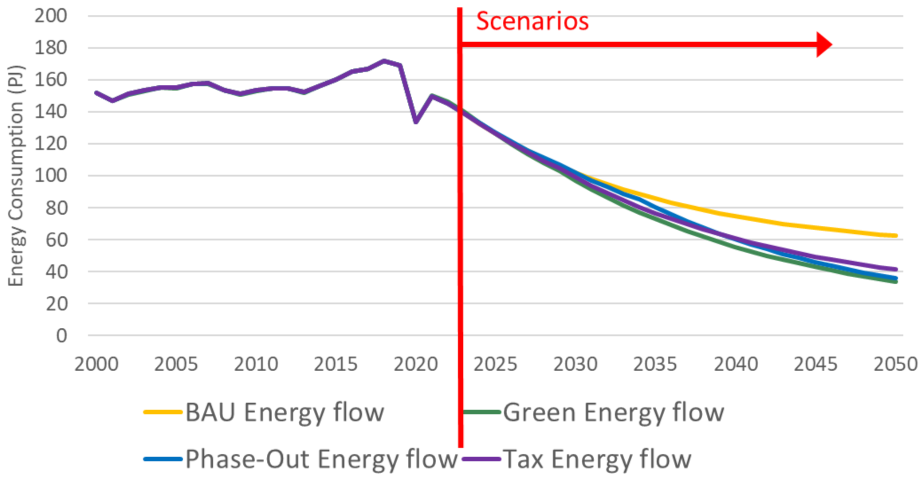

Figure 29 Comparison bau- and policy-scenarios: Development of total energy consumption from road passenger transport in Austria up to 2050 (own calculations).

4.5 Summary of the Results

This section summarizes the most important results. The distinct scenarios for road passenger transport in Austria from 2024 to 2050 reveal different levels of policy interventions and their impact on vehicle registrations, vehicle stock, flow and embedded CO_2-emissions, and energy consumption.

- Vehicle Stock and New Registrations
    - Bau-scenario: Projects a slight increase in vehicle stock and new registrations by 2050.
    - Phase-out-scenario: A marked decline in ICEs after 2035, with BEVs becoming predominant.
    - Tax-scenario: Results in moderate reductions, driven by increased fossil-fuel vehicle costs.
    - Green-policy-scenario: Largest reduction, with growth in public transport and active mobility.
- Modal Shift
    - Bau-scenario: Minimal change, private car use remains high.
    - Phase-out- and tax-scenario: Significant declines in private motorized transport.
    - Green-policy-scenario: Largest reduction, with growth in public transport and active mobility.
- CO_2-emissions and Energy Consumption
    - Overall Decline: All scenarios show reduced emissions and energy use.
    - Phase-out- and tax-scenario: Significant reductions, though less than in the green-policy-scenario.
    - Green-policy-scenario: Steepest reduction (down to 2.7 million tons CO_2, 37 PJ energy use by 2050).
- Key insight: The green-policy-scenario is the most effective, underscoring the need for a comprehensive approach that integrates electrification and modal shifts to public transport and active mobility.

5. Discussion

This chapter specifically discusses the results and the most important findings of CO_2-emission, energy consumption, and modal split changes and addresses each scenario's quantitative characteristics.

5.1 BAU-Scenario

The bau-scenario assumes that no significant technological progress or substantial changes in societal awareness occur regarding a shift towards alternative fuels or more sustainable transport modes. It anticipates that the patterns of behavior and policy observed over the past decade will continue without any significant new interventions beyond those already in place by 2023. Despite this, CO_2-emissions from passenger road transport are expected to decrease from 17 million tons in 2019 to 5.8 million tons by 2050. While this reduction indicates that the current policies are effective to some extent, there is still considerable room for improvement, particularly in reducing overall road transport activity.

In comparison, the green-policy-scenario suggests that emissions could be reduced even further, down to 2.5 million tons, with a stronger emphasis on public transport and active mobility. The relatively minor rebound effect seen in the bau-scenario is due to the absence of aggressive policy interventions, which leads to a slower shift in consumer behavior and vehicle usage.

This outcome aligns with the findings of Siebenhofer (Maier) et al. [6], who noted that without significant shifts in policy or behavior, emission reductions are likely but insufficient to meet international climate targets. Similarly, Tsemekidi Tzeiranaki et al. [15] emphasize that, even with improved vehicle efficiency, the gains in the bau-scenario are limited as economic growth tends to increase transport demand, offsetting the technological improvements.

The lack of more robust policy measures suggests a need for more targeted interventions, such as higher taxes or stricter fuel efficiency standards. Furthermore, the relatively small rebound effect contrasts with studies like those by Jaehn and Meissner [18], which warn that improved vehicle efficiency could lead to increased vehicle use, underlining the need for a comprehensive strategy that also includes a modal shift toward more sustainable forms of transport.

5.2 Phase-Out-Scenario

The phase-out-scenario predicts a considerable reduction in CO_2-emissions, driven primarily by policies encouraging a shift towards BEVs, especially after 2035, when the phase-out of ICEs begins. By 2050, CO_2-emissions are expected to decrease to approximately 4 million tons, a notable improvement over the bau-scenario.

Under this scenario, the share of private motorized transport decreases significantly, dropping from 60% in 2024 to around 30% by 2050, marking the second-lowest reduction among all scenarios. Public transport use will grow from about 22% to 35%, while walking and cycling will experience considerable growth, reaching a combined share of roughly 35% by 2050.

Studies like those of Broadbent et al. [12] support the findings of this scenario, showing that a rapid shift to 100% BEVs is essential for substantial emission reductions. However, the focus of the scenario on the electrification of vehicles without sufficient emphasis on modal shifts may pose a challenge. While BEVs can reduce emissions, solely relying on them without addressing other factors, such as public transport and active mobility, could result in continued traffic congestion and strain on infrastructure, as suggested by Danielis et al. [14]. Compared to the more comprehensive green-policy-scenario, the limited focus of the phase-out-scenario on public transport is a potential shortcoming. Zhang et al. [11] argue that relying solely on technology, without significant behavioral changes in transport habits, risks limiting the sustainability of such policies.

5.3 Tax-Scenario

The tax-scenario projects a significant reduction in private motorized transport due to introducing higher taxes to reduce vehicle and fuel usage. Starting from 2024, with private transport accounting for 60%, the share steadily declines to about 40% by 2050. During the same period, the use of public transport rises notably from 22% in 2024 to approximately 26% by 2050. Walking and cycling also grow considerably, with their combined share reaching around 34% by 2050. This scenario highlights the potential effectiveness of tax policies in promoting more sustainable and active transport modes. However, the shift is less aggressive than in the green-policy or phase-out scenarios.

This scenario emphasizes the importance of financial disincentives, such as higher taxes on ICEs and fossil fuels, to encourage the adoption of greener alternatives. The results show the impact of these fiscal measures on consumer behavior. Lam et al. [16] support this, arguing that policies like fuel taxation and higher vehicle registration taxes effectively reduce the purchase of ICEs and encourage the uptake of EVs.

However, while taxes can indeed drive a shift towards greener technologies, studies such as Enoch et al. [62] indicate that without complementary measures—like improvements in public transport accessibility—tax-related policies alone may not fully achieve the necessary modal shift for long-term sustainability. Without these supporting policies, tax measures risk leaving gaps in the transition to a more sustainable transport system.

Compared to the green-scenario, which combines financial and non-financial interventions to promote broader changes in transportation habits, the tax-scenario appears less robust in bringing about broad behavioral changes.

5.4 Green-Scenario

The green-scenario represents the most ambitious pathway for reducing CO_2-emissions, with a projected decrease to around 2.7 million tons by 2050. This scenario focuses on shifting away from ICEs to other modes, such as public transport and active mobility. This scenario shows the most significant reduction in the reliance on private vehicles, with the share dropping to just 24% by 2050. Public transport usage grows to approximately 34%, and walking and cycling combined make up around 42% of the total modal share. The green-scenario, therefore, achieves a more sustainable and balanced transport system, focusing not only on technology shifts but also on changing mobility behavior towards more sustainable transport modes.

Studies such as Barisa et al. [9] and Christidis et al. [61] support the findings of this scenario, indicating that a combination of technological advancements and shifts in mobility habits is essential to achieving the desired reductions in emissions. The ASI framework in this scenario also aligns with global best practices for sustainable transport planning. This framework emphasizes reducing unnecessary travel (avoid), encouraging a shift to more sustainable transport modes (shift), and improving vehicle technologies to maximize efficiency (improve), as highlighted by Martensson et al. [63].

Compared to other scenarios, the green-scenario stands out because of its comprehensive approach. It addresses the need for technological innovation and behavioral changes in transport patterns. This comprehensive strategy is critical to achieving long-term sustainability goals, as demonstrated in studies by Siebenhofer (Maier) et al. [6] and Enoch et al. [62].

5.5 Comparison of the Scenarios

Each scenario presents a distinct outlook on the future of the transport system in Austria, with varying levels of policy interventions. The green-scenario is the most effective, offering the largest reduction in private vehicle usage and CO_2-emissions. This scenario integrates technological advancements and shifts in mobility behavior, emphasizing public and active mobility, leading to a balanced and sustainable transport system. The tax-scenario and phase-out-scenario also achieve substantial reductions, though they rely more heavily on financial measures and vehicle electrification. The bau-scenario, on the other hand, shows the least change, reflecting limited progress in reducing private vehicle reliance and emissions.

5.6 Economic and Social Implications

The economic and social implications of the proposed scenarios are significant and must be considered when evaluating their feasibility and impact. The green-policy-scenario and phase-out-scenario involve extensive investments in public transport infrastructure, alternative fuel technologies, and active mobility, which could lead to economic benefits such as job creation in these sectors. However, the initial costs of such investments are high, and ensuring public acceptance will be crucial. Studies such as those by Gerboni et al. [13] suggest that improving access to sustainable transport modes can enhance social equity by providing affordable mobility options, especially for lower-income groups.

In contrast, the tax-scenario might face more excellent resistance from consumers and industries, particularly in rural areas where public transport infrastructure is less developed and reliance on private vehicles is higher. Higher fuel and vehicle ownership taxes could disproportionately affect lower-income households, raising concerns about social equity. Lam et al. [16] argue that while tax-based policies can drive significant behavioral changes, they must be coupled with subsidies or compensation mechanisms to mitigate adverse impacts on vulnerable populations.

Moreover, the potential for public resistance to specific policies, such as higher taxes or the phasing out of ICEs, could pose social and political challenges. Resistance from stakeholders, including consumers, industry, and political entities, may delay or reduce the effectiveness of these measures. Therefore, addressing public acceptance and ensuring fair distribution of costs and benefits across different socio-economic groups is essential for the success of any scenario.

5.7 Integration of Alternative Fuel Vehicles (AFVs)

The integration of AFVs, particularly BEVs, remains a challenge. Issues such as limited driving range, high battery costs, and inadequate charging infrastructure continue to hinder widespread adoption. A lack of fast-charging stations, especially in rural areas, presents significant obstacles. In addition, grid capacity will require considerable investment to accommodate the increased demand for BEV charging, as highlighted by Broadbent et al. [12]. Consumer perception also plays a crucial role. Misconceptions about the reliability and efficiency of BEVs persist, limiting broader adoption. Danielis et al. [14] argue that policy measures must support technological innovation and address public confidence and awareness to ensure a smooth transition to AFVs.

Austria and other European countries have introduced various initiatives and programs to overcome the challenges of integrating AFVs. Notable among these is Austria's klimaaktiv mobil initiative [31], which plays a significant role in supporting e-mobility through targeted infrastructure investments and incentive programs. On a broader scale, the European Union's Green Deal [64] encompasses funding mechanisms like the Connecting Europe Facility (CEF) [65], aimed at enhancing cross-border charging infrastructure and the development of hydrogen refueling stations to facilitate seamless long-distance travel. Coordinated policy measures that foster private sector participation and regional collaboration are essential to scale these efforts and effectively reduce adoption barriers. Moreover, city-level pilot projects focusing on expanding charging networks and practical EV trials can provide valuable insights into addressing consumer concerns and logistical challenges, fostering wider public acceptance and paving the way for more comprehensive infrastructure solutions.

5.8 Sensitivity Analysis

While certain key variables, such as elasticities and technological learning, can be found in literature, other variables, such as the spread of EVs and ICEs or the attractiveness of public transport, must be assumed to build the scenarios. A sensitivity analysis could provide further insight into how variations in these assumptions might affect the results but was not performed in this study. Future studies could improve the robustness of these projections by examining the impact of different key assumptions to provide a more comprehensive understanding of the uncertainties and potential outcomes.

6. Conclusions

The exploration within the road passenger transport sector in Austria delineates the nuanced interplay between policy frameworks and their resultant impact on transport modal choices and resulting CO_2-emissions, towards a sustainable transport pathway. Four main scenarios have been investigated: the bau-scenario, the phase-out-scenario, the tax-scenario, and most important, the green-policy-scenario. These scenarios provide a detailed understanding of potential development paths and policy implications.

The green-scenario, proposes a comprehensive package of policy measures ranging from an increased registration tax for ICEs to increased subsidies for BEVs and FCVs. The most critical assumptions, however, are the shift from motorized private transport to public transport and active mobility. By 2050, CO_2-emissions could decrease from 17 million tons in 2019 to approximately 2.5 million tons. This scenario projects a marked reduction in private motorized transport, dropping from 60% to 24% by 2050, with active mobility (walking and cycling) and public transport accounting for 76% of the modal split.

In contrast, the phase-out-scenario, focused primarily on electrification, foresees emissions falling to 4 million tons by 2050. However, without significant behavioral change, the modal shift is less pronounced than in the green-policy-scenario. Private motorized transport will still account for 34% by 2050, compared to 24% in the green-policy-scenario. Through financial incentives and disincentives, the tax-scenario could reduce emissions to around 5 million tons by 2050 but lacks the robust modal shift seen in the green-policy-scenario. Private motorized transport remains at 47% by 2050. Assuming minimal policy intervention, the bau-scenario sees emissions decline but only to 5.8 million tons by 2050, with private motorized transport still accounting for 55% of the modal split.

Scenarios assume BEV electricity will be 100% renewable by 2050, a key factor for meaningful CO_2 reduction. The study examines the importance of including public transport and active mobility (factors for the attractiveness of public transport and active mobility) in modeling road passenger transport. These factors are crucial for consumers' choice of transport mode. In this discourse, it becomes clear that the policies in the green-policy-scenario, which include both technological changes and modal shifts, are an effective approach to reducing CO_2-emission in road passenger transport while also initiating a paradigm shift towards sustainable mobility. It reflects a fundamental understanding that addressing the environmental footprint of transport requires an approach that combines technological innovation and behavioral change - a scenario in which public transport and active mobility are not just alternatives but integral parts of the future mobility landscape.

The following recommendations for policymakers are derived:

1. Enhance Public Transport and Active Mobility: No single policy will sufficiently reduce energy consumption and CO_2-emissions. A diverse, adaptable policy portfolio is essential. Investment in public transport infrastructure and active mobility should be prioritized to make them attractive alternatives to private cars. This includes improving accessibility, coverage, frequency, and comfort alongside integrating user-friendly technologies. The green-policy-scenario shows that a strong focus on public transport and active mobility could reduce private motorized transport to 24% by 2050, contributing to an 8% reduction in CO_2-emissions.
2. Implement Comprehensive Policy Packages: A combined strategy—higher taxes on ICEs, increased subsidies for BEVs and FCVs, and promotion of public transport and active mobility—is essential. The green-policy-scenario, with its integrated approach, proved to be the most favorable, reducing CO_2-emissions to 3 million tons by 2050 while promoting sustainable transport and lowering energy consumption.
3. Regular Monitoring and Adjustments: Continuous monitoring of policies is necessary to ensure effectiveness. Strategies must be flexible to adapt to new trends, technological advancements, and scientific feedback. This adaptive approach will help maintain progress toward reducing emissions and energy consumption across all scenarios.
4. Set Ambitious Policies to Meet EU Targets: Strong, comprehensive policies are needed to meet EU climate goals. This includes phasing out ICEs, improving vehicle energy efficiency, and promoting sustainable transport modes. The green-policy-scenario underscores that achieving the EU's goals requires significant modal shifts, which reduce energy consumption to 37 PJ by 2050, and lower CO_2-emissions to 3 million tons in Austria.

The model's limitations primarily lie in the fact that although the study shows how important the focus on active mobility and public transport is, it does not show which specific policies influence the choice of transport mode or the expansion of the corresponding infrastructure to promote these modes. Here, we refer to other studies that have already dealt with these issues. For example, the Chatziioannou et al. [66] study focused on identifying and prioritizing specific policies to enhance sustainable urban mobility. Key strategies included transit-oriented development, parking policy reforms, and promotion of telecommuting. Strategies such as the development of comprehensive bus rapid transit (BRT) systems, creating exclusive lanes for public transport and bike lanes, and establishing robust public bicycle sharing systems. Peer et al. [67] identified policies such as creating safe bike storage and fast cycling lanes as practical strategies to encourage walking and cycling in rural and semi-rural areas. These measures and the implementation of reduced speed limits in cities were identified as critical factors in promoting active mobility.

For future research, it would be essential to facilitate the accessibility of statistical data to generate such models. Moreover, it is necessary to develop practical implementation plans. Strategies like phasing out ICEs and improving public transport infrastructure need clear timelines, concrete steps, and resource allocation. Future research should focus on specific actions, such as regulatory measures, investment needs, and technological development. Although this study centers on EV adoption, other emerging technologies—autonomous vehicles, shared mobility, and advanced public transport—also have transformative potential. These innovations could improve efficiency, reduce emissions, and support shifting from private vehicles. Exploring their integration into sustainable transport strategies and their impact on modal shifts, energy use, and CO_2-emissions will provide a broader perspective on the future of transport and its role in meeting climate goals. While the potential of these technologies is significant, given the rapid pace of technological advancements, their influence on the transport sector may occur sooner than anticipated. This could lead to earlier-than-expected impacts on policy and infrastructure needs. Policymakers should remain agile and ready to monitor and respond proactively to ensure these transitions align with sustainable practices.

Interdisciplinary approaches incorporating insights from different fields can improve understanding of the complexity of sustainable transport. Comparative analyses with other regions or countries can provide valuable insights. In addition, long-term impact studies are crucial to assess the sustainable effectiveness and social acceptance of policies, enabling continuous improvement and adaptation of policy frameworks to ensure they remain effective in promoting sustainable mobility.

Acknowledgments

I am grateful to TU Wien, especially the Energy Economics Group, for their technical support and for giving me the opportunity to conduct this research.

Author Contributions

All three authors (M.M., A.A., R.H.) contributed to the conceptualization, methodology, formal analysis, and resource allocation. M.M. conducted the investigation, data curation, original draft writing, and visualizations. Both M.M. and R.H. participated in the rewriting and editing process. Supervision was provided by R.H., while project administration was managed by R.H. and A.A.

Competing Interests

The authors have declared that no competing interests exist.

References

1. European Parliament and the Council of the European Union. European Climate Law [Internet]. Brussels, Belgium: European Union; [cited date 2024 December 2]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003L0030.
2. European Environment Agency. CO_2 Emissions from Cars: Facts and Figures (Infographics) [Internet]. Copenhagen, Denmark: European Environment Agency; 2023. Available from: https://www.europarl.europa.eu/topics/en/article/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics.
3. US Congressional Budget Office. Emissions of Carbon Dioxide in the Transportation Sector. At a Glance [Internet]. Washington, DC: US Congressional Budget Office; 2022. Available from: https://www.cbo.gov/system/files/2022-12/58566-co2-emissions-transportation.pdf.
4. International Energy Agency. Energy System—Transport [Internet]. Paris, France: IEA; [cited date 2024 May 4]. Available from: https://www.iea.org/energy-system/transport.
5. European Commission. Putting European Transport on Track for the Future [Internet]. Brussels, Belgium: European Commission; 2020. Available from: https://www.transport-community.org/wp-content/uploads/2021/01/Smart-and-Sustainable-Mobility-Strategy-presentation.pdf.
6. Siebenhofer M, Ajanovic A, Haas R. How policies affect the dissemination of electric passenger cars worldwide. Energies. 2021; 14: 2093.
7. Siebenhofer M, Ajanovic A, Haas R. On the future of passenger mobility and its greenhouse gas emissions in cities: Scenarios for different types of policies. J Sustain Dev Energy Water Environ Syst. 2022; 10: 1100424.
8. Eisenkopf A, Burgdorf C. Policy measures and their impact on transport performance, modal split and greenhouse gas emissions in German long-distance passenger transport. Transp Res Interdiscip Perspect. 2022; 14: 100615.
9. Barisa A, Rosa M. A system dynamics model for CO_2 emission mitigation policy design in road transport sector. Energy Procedia. 2018; 147: 419-427.
10. Dugan A, Mayer J, Thaller A, Bachner G, Steininger KW. Developing policy packages for low-carbon passenger transport: A mixed methods analysis of trade-offs and synergies. Ecol Econ. 2022; 193: 107304.
11. Zhang R, Long Y, Wu W, Li G. How do transport policies contribute to a low carbon city? An integrated assessment using an urban computable general equilibrium model. Energy Procedia. 2018; 152: 606-611.
12. Broadbent G, Allen C, Wiedmann T, Metternicht G. The role of electric vehicles in decarbonising Australia's road transport sector: Modelling ambitious scenarios. Energy Policy. 2022; 168: 113144.
13. Gerboni R, Grosso D, Carpignano A, Dalla Chiara B. Linking energy and transport models to support policy making. Energy Policy. 2017; 111: 336-345.
14. Danielis R, Scorrano M, Giansoldati M. Decarbonising transport in Europe: Trends, goals, policies and passenger car scenarios. Res Transp Econ. 2022; 91: 101068.
15. Tzeiranaki ST, Economidou M, Bertoldi P, Thiel C, Fontaras G, Clementi EL, et al. The impact of energy efficiency and decarbonisation policies on the European road transport sector. Transp Res A Policy Pract. 2023; 170: 103623.

16. Lam A, Mercure JF. Which policy mixes are best for decarbonising passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. Energy Res Soc Sci. 2021; 75: 101951.
17. Farzaneh H. Energy Systems Modeling. Singapore: Springer; 2019.
18. Jaehn F, Meissner F. The rebound effect in transportation. Omega. 2022; 108: 102563.
19. Interreg Europe. Sustainable Transport: Avoid-Shift–Improve [Internet]. Lille, France: Interreg Europe; 2019 [cited date 2023 September 6]. Available from: https://projects2014-2020.interregeurope.eu/innotrans/news/news-article/6151/sustainable-transport-avoid-shift-improve/.
20. Anderl M, Gangl M, Haider S, Ibesich N, Lampert C, Poupa S, et al. Bundesländer Luftschadstoff-Inventur 1990–2018. Wien: Umweltbundesamt; 2020.
21. Bundesministerium für Verkehr, Innovation und Technologie. Österreich Unterwegs 2013/2014: Ergebnisbericht Zur Österreichweiten Mobilitätserhebung. Wien: Bundesministerium für Verkehr, Innovation und Technologie; 2013.
22. Council of the European Union. Fit for 55: Reducing Emissions from Transport, Buildings, Agriculture and Waste [Internet]. Brussels, Belgium: Council of the European Union; 2024 [cited date 2023 August 10]. Available from: https://www.consilium.europa.eu/en/infographics/fit-for-55-effort-sharing-regulation/.
23. UBA-GmbH. Treibhausgas-Bilanz 2019 Nach Sektoren [Internet]. Vienna: Umweltbundesamt Gesellschaft mit beschränkter Haftung (UBA-GmbH); 2021 [cited date 2024 May 23]. Available from: https://www.umweltbundesamt.at/news210119/sektoren.
24. European Commission. European Climate Law [Internet]. Brussels, Belgium: European Commission; [cited date 2024 June 24]. Available from: https://climate.ec.europa.eu/eu-action/european-climate-law_en.
25. European Commission. Eco-Social Tax Reform Good for Climate, Households and Businesses [Internet]. Brussels, Belgium: European Commission; 2022 [cited date 2024 September 6]. Available from: https://commission.europa.eu/projects/eco-social-tax-reform-good-climate-households-and-businesses_en.
26. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. Ökosoziale Steuerreform [Internet]. Wien: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie; [cited date 2024 September 6]. Available from: https://www.bmk.gv.at/themen/klima_umwelt/klimabonus/oekosoziale-steuerreform.html.
27. Bundesministerium für Finanzen. NoVA Steuersatz [Internet]. Bundesministerium für Finanzen; 2024 [cited date 2024 September 6]. Available from: https://www.bmf.gv.at/themen/steuern/kraftfahrzeuge/Normverbrauchsabgabe-Übersicht/NoVA-Steuersatz.html.
28. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. Novelle Der Kraftstoffverordnung [Internet]. Wien: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie; 2022 [cited date 2024 September 6]. Available from: https://www.bmk.gv.at/service/presse/gewessler/2022/20221218_kraftstoffverordnung.html.
29. Bundeskanzleramt Österreich. Klimaticket [Internet]. Wien: Bundeskanzleramt Österreich; 2024 [cited date 2024 September 6]. Available from: https://www.oesterreich.gv.at/themen/mobilitaet/klimaticket.html.

30. Bundeskanzleramt Österreich. Elektroautos Und E-Mobilität – Förderungen und weiterführende Links [Internet]. Wien: Bundeskanzleramt Österreich; 2024 [cited date 2024 September 6]. Available from: https://www.oesterreich.gv.at/themen/mobilitaet/elektroautos_und_e_mobilitaet/Seite.4320020.html.
31. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. Klimaaktiv Mobil [Internet]. Wien: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie; 2022 [cited date 2024 September 6]. Available from: https://www.bmk.gv.at/themen/mobilitaet/klimaaktiv-mobil.html.
32. Ajanovic A, Haas R. ALTER-MOTIVE: An action plan for sustainable future European transport policies. Internationale Energiewirtschaftstagung an der TU Wien; 2011 Febrary 16-18; Wien, Osterreich. Available from: https://publik.tuwien.ac.at/files/PubDat_202234.pdf.
33. Statistik Austria. Fahrleistungen Und Treibstoffeinsatz Privater Personenkraftwagen (2000-2022), Ergebnisse Für Österreich 2022. Vienna: Statistik Austria; 2022.
34. Agence de L'environnement et de Lamaitrise de L'Energie. Odyssee-Mure, A decision support tool for energy efficiency policy evaluation [Internet]. Agence de L'environnement et de Lamaitrise de L'Energie; 2022 [cited date 2023 November 9]. Available from: https://cordis.europa.eu/project/id/696077.
35. Winkelbauer M, Pommer A. Fahrleistungen von Motorrädern in Österreich (Mileage of PTW in Austria). 2014. doi: 10.13140/2.1.2435.4568.
36. Statistisches Bundesamt, Deutsches Institut für Wirtschaftsforschung e.V., Das Kraftfahrt-Bundesamt, Durchschnittliche Fahrleistung von Mofas, Mokicks Und Mopeds in Deutschland. Available from: https://de.statista.com/statistik/daten/studie/250913/umfrage/durchschnittliche-fahrleistung-von-mofas-und-mopeds-in-deutschland/.
37. Statistik Austria. Kfz-Neuzulassungen - Statistik Austria - Die Informationsmanager [Internet]. Vienna: Statistik Austria; [cited date 2024 May 23]. Available from: https://www.statistik.at/statistiken/tourismus-und-verkehr/fahrzeuge/kfz-neuzulassungen.
38. Statistik Austria. Kfz-Bestand. Statistik Austria - Die Informationsmanager [Internet]. Vienna: Statistik Austria; [cited date 2024 May 23]. Available from: https://www.statistik.at/statistiken/tourismus-und-verkehr/fahrzeuge/kfz-bestand.
39. Ivković IS, Kaplanović SM, Milovanović BM. Influence of road and traffic conditions on fuel consumption and fuel cost for different bus technologies. Therm Sci. 2017; 21: 693-706.
40. Amt der NÖ Landesregierung. Marktübersicht Elektrobusse. St. Pölten: Amt der NÖ Landesregierung; 2018.
41. Statistik Austria. Energy Prices and Taxes (Q) Energy Products by Year and Values Counting: Net Price, Energy Fees and Taxes, VAT, Overall Taxes, Gross Price 2024. Vienna: Statistik Austria; 2024.
42. Bundesministerium für Finanzen. Offizieller NoVA Rechner [Internet]. Bundesministerium Für Finanzen; [cited date 2024 September 10]. Available from: https://onlinerechner.haude.at/BMF-NoVARechner.
43. Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. CO_2-Monitoring von Personenkraftwagen [Internet]. Wien: Bundesministerium für Klimaschutz,

Umwelt, Energie, Mobilität, Innovation und Technologie; 2022 [cited date 2024 September 10]. Available from: https://www.bmk.gv.at/themen/mobilitaet/co2_monitoring/pkw.html.

44. Statistik Austria. Volkswirtschaftliche Gesamtrechnungen: 1995/2022. Vienna: Statistik Austria; 2023.
45. Umweltbundesamt. CO_2-Emissionsfaktoren Für Fossile Brennstoffe. Dessau-Roßlau: Umweltbundesamt; 2022.
46. European Federation for Transport and Environment AISBL. CO_2 Emissions From Cars: The facts [Internet]. Brussels, Belgium: Transport & Environment; 2018. Available from: https://www.transportenvironment.org/articles/co2-emissions-cars-facts.
47. International Energy Agency. Emissions Factors - Data Product. Paris, France: IEA.
48. Concawe. Technology Scouting-Carbon Capture: From Today's to Novel Technologies. Brussels, Belgium: Concawe; 2020; no. 18/20.
49. HBEFA. The handbook emission factors for road transport. Berne, Switzerland: HBEFA; [cited date 2024 November 13]. Available from: https://www.hbefa.net/.
50. European Environment Agency. Analysis and Data [Internet]. Copenhagen, Denmark: European Environment Agency; [cited date 2024 November 13]. Available from: https://www.eea.europa.eu/en/analysis.
51. Fouquet R. Trends in income and price elasticities of transport demand (1850–2010). Energy Policy. 2012; 50: 62-71.
52. Ajanovic A, Haas R. The role of efficiency improvements vs. price effects for modeling passenger car transport demand and energy demand—Lessons from European countries. Energy Policy. 2012; 41: 36-46.
53. Litman T. Transport Elasticities: Impacts on Travel Behaviour: Understanding Transport Demand To Support Sustainable Travel Behavior. Eschborn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit; 2024; Sustainable Urban Transport Technical Document #11.
54. Haas R, Sayer M, Ajanovic A, Auer H. Technological learning: Lessons learned on energy technologies. Wiley Interdiscip Rev Energy Environ. 2023; 12: e463.
55. Ajanovic A, Haas R, Schrödl M. On the historical development and future prospects of various types of electric mobility. Energies. 2021; 14: 1070.
56. TU WIEN. B (TransLoc) Transformation von Städten in Eine Dekarbonatisierte Zukunft Und Deren Auswirkung Auf Den Urbanen Stoffhaushalt, Umwelt Und Gesellschaft [Internet]. Wien, Österreich: TU WIEN; 2022 [cited date 2023 November 9]. Available from: https://tiss.tuwien.ac.at/fpl/project/index.xhtml?id=1464033.
57. Ajanovic A. Electricity vs hydrogen in the transition towards sustainable mobility. Oxford Open Energy. 2023; 2: oiad013.
58. Zhang W, Fang X, Sun C. The alternative path for fossil oil: Electric vehicles or hydrogen fuel cell vehicles? J Environ Manag. 2023; 341: 118019.
59. Hahn A, Pakusch C, Stevens G. The impact of service expansion on modal shift from private car to public transport. A quantitative analysis in the Bonn/Rhein-Sieg area, Germany. J Urban Mobil. 2023; 4: 100064.
60. Stępniak M, Gkoumas K, dos Santos FM, Grosso M, Pekár F. Recent trends and progress in public transport innovation in the scope of European research projects. Transp Res Procedia. 2023; 72: 4295-4302.

61. Christidis P, Ulpiani G, Stepniak M, Vetters N. Research and innovation paving the way for climate neutrality in urban transport: Analysis of 362 cities on their journey to zero emissions. Transp Policy. 2024; 148: 107-123.
62. Enoch MP, Cross R, Potter N, Davidson C, Taylor S, Brown R, et al. Future local passenger transport system scenarios and implications for policy and practice. Transp Policy. 2020; 90: 52-67.
63. Mårtensson HB, Larsen K, Höjer M. Investigating potential effects of mobility and accessibility services using the avoid-shift-improve framework. Sustain Cities Soc. 2023; 96: 104676.
64. European Commission. The European Green Deal [Internet]. Brussels, Belgium: European Commission; [cited date 2024 July 24]. Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
65. Innovation and Networks Executive Agency. European Commission. Connecting Europe Facility. Brussels, Belgium: Innovation and Networks Executive Agency. Available from: https://ec.europa.eu/inea/en/connecting-europe-facility.
66. Chatziioannou I, Nikitas A, Tzouras PG, Bakogiannis E, Alvarez-Icaza L, Chias-Becerril L, et al. Ranking sustainable urban mobility indicators and their matching transport policies to support liveable city Futures: A MICMAC approach. Transp. Res. Interdiscip. Perspect. 2023; 18: 100788.
67. Peer S, Gangl K, Spitzer F, Van der Werff E. Which policy measures can motivate active mobility in rural and semi-rural areas? Trans Res D Transp Environ. 2023; 118: 103688.