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Simulating the effects of tax exemptions for plug-in electric vehicles in Norway

Paul Pfaffenbichler[1*], Nils Fearnley[2], Erik Figenbaum[2] and Günter Emberger[3]

Abstract

For many years Norway has been in the forefront of promoting electromobility. Today, Norway has the world's highest per capita fleet of plug-in electric cars. In 2021, 1.6% of the cars in the EU fleet were plug-in electric vehicles, whereas their share was 21% in Norway. Part of the successful market take-up rate is due to wide-ranging tax exemptions. Increasing plug-in electric vehicles numbers causes tax revenue losses, making exemptions unsustainable. Norway has the ambitious goal that from 2025, all newly registered cars shall be zero-emission vehicles. Keeping tax exemptions in place might be crucial for this goal. The objective of this paper is to provide information to solve this dilemma. Tax exemption reduction and abolition paths which offer a compromise between minimal effects on the development of zero-emission vehicles and tax revenues have been identified. An updated and re-calibrated version of the stock-flow-model SERAPIS was used to simulate and assess different scenarios. Results show that a controlled tax phase-in allows Norway to reach its environmental targets of 100% zero emission vehicles by 2025 and a 55% decrease of CO_2-emissions in 2030 relative to 2005 while simultaneously increasing public revenues significantly.

Keywords Passenger car, Battery electric vehicle, Plug-in hybrid electric vehicle, Carbon emissions, Incentives

1 Introduction

Comprehensive decarbonisation of the transport sector is crucial to keeping the global temperature rise within an acceptable range. Key strategies to achieve this goal are policies supporting a mode shift towards public transit and active travel modes and improved urban planning, efficient and intelligent operations, vehicle electrification and low- or zero-carbon fuels, e.g. sustainable biofuels or hydrogen based synthetic fuels [15]. EIT Urban Mobility, an initiative of the European Institute of Innovation and Technology (EIT) with more than 300 member organisations, formulated a vision for a green urban mobility transition (Tsavachidis & Petit, 25). Among other policies, vehicle electrification is seen as essential for the transition to sustainable urban mobility, reducing greenhouse gases, pollutants, and noise emissions. On the vehicle side, EU's 'Fit for 55' ambition for passenger cars is a 55% CO_2 emission reduction in new cars by 2030 and 100% zero emission vehicles from 2035 onwards [6]. As shown by [24], this in itself is a brave goal and can also cause considerable emission spill overs, notably to the energy and battery manufacturing sectors. While battery electric vehicles (BEV) as well as fuel cell electric vehicles (FCEV) and hydrogen based synthetic fuels have the potential to decarbonise passenger cars, BEVs have a clear advantage concerning energy efficiency and local exhaust emissions [3]. Especially in the urban context, BEVs have the lower environmental impact than other alternatives [5].

While Norway is not part of the European Union, the country is associated via the European Economic Area (EEA) and share the 'Fit for 55' targets. As shown below, current BEV shares of sales are already well ahead of EU

*Correspondence:
Paul Pfaffenbichler
paul.pfaffenbichler@boku.ac.at
[1] Institute of Transport Studies, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Straße 82, Vienna 1190, Austria
[2] Institute of Transport Economics (TØI), Gaustadalléen 21, Oslo 0349, Norway
[3] Institute of Transportation, TU Wien, Karlsplatz 13, Vienna 1040, Austria

targets. Additionally, Norway's electricity production is almost entirely based on near zero emission hydropower [26] such that emissions spill overs to the energy sector resulting from the transition towards BEVs do not have to be a major concern.

Since more than a decade Norway has been the leading country in the market take-up of battery electric vehicles. Today, Norway has by far the highest per capita fleet of plug-in electric passenger vehicles (PEV) worldwide. In 2012, battery electric vehicles (BEV) in the passenger car segment (M1) had a market share of total registrations of only 0.1% in the EU 27 [7]. At the same time the market share in Norway was 3.1% [8]. Until 2021, BEV market shares of sales increased to 9.0% in the EU 27 and 64.5% in Norway. In 2022, the market share in Norway increased further to 79.3% while in the EU 27 it increased to 12.1%. These market shares resulted in a BEV fleet percentage of the total passenger car fleet (M1) of about 0.01% in EU 27 in 2012 and 1.2% in 2022. At the same points in time about 0.27% and 16.8% of the Norwegian passenger car fleet were BEVs. The market share of plug-in hybrid electric vehicles (PHEV) in the EU 27 exceeded that of BEVs in the years 2013, 2015 and 2016 and reached 9.5% in 2022 [7]. In Norway, the PHEV market share sharply dropped from 21.7% in 2021 to 9.1% in 2022 [8]. In 2022 PHEV fleet shares reached a level of 1.1% in EU 27 and 6.1% in Norway. The combined PEV market share in 2022 was about 21.6% in EU 27 and 88.6% in Norway. In 2022 the combined PEV fleet share in Norway was 22.9%, which is about ten times higher than in the EU 27 with 2.3%.

Part of the successful market take-up of PEVs in Norway is due to wide ranging tax exemptions including even an exemption from value added tax. With the increasing market share and fleet size, it became clear that these tax exemptions are fiscally not sustainable in the long run. The increasing share of PEVs on the one hand leads to losses in tax revenues which calls for an abolition of the tax exemptions. On the other hand, Norway has very ambitious goals concerning zero-emission vehicles (ZEV). In its National Transport Plan 2018–2029, the Norwegian government formulated the target of a market share of 100% ZEV for passenger cars and light van sales by 2025 [17] p. 30). This target remains unchanged in the current National Transport Plan 2022–2033 [18] p. 22). The target is a back calculation of what the Paris agreement target of a 40% reduction of national greenhouse gas emissions (GHG) means for the transport sector. Keeping BEV tax exemptions unchanged might be crucial to reach this goal. To solve this dilemma, decision makers require knowledge about the effects of different scenarios of an abolition or reduction of the tax exemptions. The contribution of this paper is, therefore, to analyse future scenarios for a truly mature ZEV market – Norway – and to combine the conflicting objectives of securing state fiscal revenues while at the same time reaching the goal of 100% ZEV sales from 2025. The objectives of the work presented here were the identification of prerequisites for replacing the sales of internal combustion engine passenger vehicles (ICEV) completely with BEVs by 2025 and the assessment of resulting short and long term consequences for public budgets. An economic modelling framework, based on the System Dynamics[1] based stock-flow model SERAPIS,[2] was used to forecast and analyse future economic and environmental impacts of a transition to ZEVs on a national and regional level, as well as the effect of different policies. The SERAPIS model is a regional aggregated discrete choice model of new passenger car acquisitions [10]. Simulation results were used to identify different tax exemption reduction and abolition paths which offer a feasible compromise between minimal effects on the development of BEV numbers and sufficient tax revenues.

A literature review identified only two papers dealing with the topic of reducing electric car purchase incentives [29, 14]. (Harvey, 2020) [14] present the argument that it would be more efficient to replace EV subsidies by overall limits on fleet-average CO_2 emissions. In [29] the powertrain technology transition market agent model (PTTMAM) was used to analyse the effect of changing purchase incentives. The simulations covered the period 2019 to 2025. One main conclusion was that it would be premature to remove electric car purchase subsidies in the period 2020 to 2025 and that incentives were still key to speed up market penetration or at least keep its pace. In the meantime, the BEV market, especially in Norway, has matured considerably, which calls for a reassessment of the impact of scaling back incentives for PEV purchases. Therefore, it can be concluded that the work presented here represents an important contribution to the literature.

The remainder of the paper is organized as follows: after this introduction, section 2 presents the methodological approach of the simulation model used for the analysis including relevant input data and assumptions. Section 3 defines four different taxation scenarios before

[1] A comprehensive description of the principles and methods of System Dynamics is given e.g. in [23].

[2] SERAPIS stands for "Simulating the Emergence of Relevant Alternative Propulsion technologies in the car and motorcycle fleet Including energy Supply".

Table 1 Basic model structure SERAPIS

Elements	SERAPIS
New car registration	Discrete choice model (multinominal logit model)
Vehicle segments	Total: 9 • 3 ICEV incl. HEV (compact, family, luxury) • 3 PHEV (compact, family, luxury) • 3 BEV (compact, family, luxury)
# age classes	Not applicable (uniform survival rate)
Role of car in household	Two (1st car, 2nd + car)

Table 2 Elements taken into account in the utilities of SERAPIS

Utility elements SERAPIS
• Gross investment costs (car, wall box) incl. value added tax and purchase tax • Operating costs (fuel/energy, parking charge, road charge) • Variety of makes and models[a] • Density of service stations • Range • Time savings (e.g. due to bus lane access or preferential parking)

[a] Customers value diversity. Having only a limited choice reduces their perceived utility of a car and propulsion technology segments. The term makes refers to the car brand, e.g. Volkswagen, Tesla, etc. The term model refers to concrete product differentiated by vehicle's trim level, body style, engine size, etc., e.g. Volkswagen iD3 Pro Performance Go 150 kW, Volkswagen iD3 Pro S Go 150 kW, Tesla Model 3 Standard Range, Tesla Model 3 Long Range, Tesla Model 3 Long Range AWD, Tesla Model 3 Performance AWD, etc

presenting and discussing the simulation results. Section 4 concludes the paper and highlights the trade-offs in future policy making.

2 Methodological approach

2.1 Basic principles of the model SERAPIS

A first version of the System Dynamics based stock-flow model SERAPIS (Simulating the Emergence of Relevant Alternative Propulsion technologies in the car and motorcycle fleet Including energy Supply) was developed and utilised in 2009 [20]. Since then, SERAPIS was adapted for and used in several projects for different clients [22, 13, 21, 12, 19, 10, 11]. In the work presented in this paper a modified, updated and re-calibrated version of SERAPIS was used for the simulation and assessment of different tax reduction and abolition scenarios.

SERAPIS is a dynamic passenger car fleet and propulsion technology choice model. Table 1 summarises some basic information about the structure of the SERAPIS model. SERAPIS utilises the concept of stocks and flows to model and to simulate the fleet development in combination with a multinominal logit model for the choice of propulsion technology. As a dynamic model SERAPIS simulates the path towards a future target year in discrete time steps of one year. The base year of the model is 2008 and simulations cover the whole time period up to 2050. SERAPIS uses nine aggregated vehicle segments and a uniform survival rate (i.e. number of years to scrapping). The propulsion technology choice set p consists of internal combustion engine vehicles incl. non-plug in hybrids, e.g. the conventional Prius (ICEV), plug in hybrid and range extender vehicles, e.g. Prius Plug In or Volt (PHEV) and battery electric vehicles (BEV). SERAPIS models the fleet of passenger cars (M1) subdivided by vehicle category t (compact, e.g. Fiat 500, Renault Clio, Volkswagen Polo, etc., family, e.g. Volkswagen Golf, Ford Focus, BMW 3, Mercedes C, etc. and luxury, e.g. BMW 5 and 7, Audi A6, A7 and A8, Mercedes E and S, Ferrari, Lamborghini, BMW X series, Jeep Wrangler, etc.) and its role in the household n (first and second + car).

Table 2 gives an overview of the elements which are taken into account in the utility of the multinominal logit model. In SERAPIS the utility is defined by six elements of which some are direct vehicle characteristics while others are describing infrastructure elements, e.g. costs for wall boxes or the density of public charging stations, charges for parking and road use or exemptions from other regulations.

Figure 1 shows a screenshot of the core stock flow model of SERAPIS. The stock of cars (*Car fleet ntp*) in each iteration t is defined by the stock of cars in the base year 2005 (*car fleet ntp T = 0 xls*) and the inflow (*inflow cars ntp*) and outflow (*outflow cars ntp*) of iteration *t-1*. The outflow is defined by the average survival rate of the car stock (*years until disposal n*).The total inflow (*inflow cars nt*) is defined by the total outflow plus total growth from a scenario variable. In each iteration a multinominal logit model is used to calculate the probability that a certain propulsion technology is chosen (see equation in Fig. 1). The probability $P_{p,n,t}$ that propulsion technology p is chosen for a car of role n (first or second +) in category t (compact, family, luxury) is the exponential function of the utility $U_{p,n,t}$ of the propulsion technology p divided by the sum over the exponential functions of all alternatives.

The utility U_p of a propulsion technology p is a function of investment costs I_p, operating costs O_p, variety of makes and models M_p, density of service stations D_p, range with a single tank/battery content R_p and time saved due to exemptions from traffic regulations T_p. In the current definition the utility elements image and comfort are not taken into account.

$$U_p = f\left(I_p, O_p, M_p, D_p, R_p, T_p\right)$$

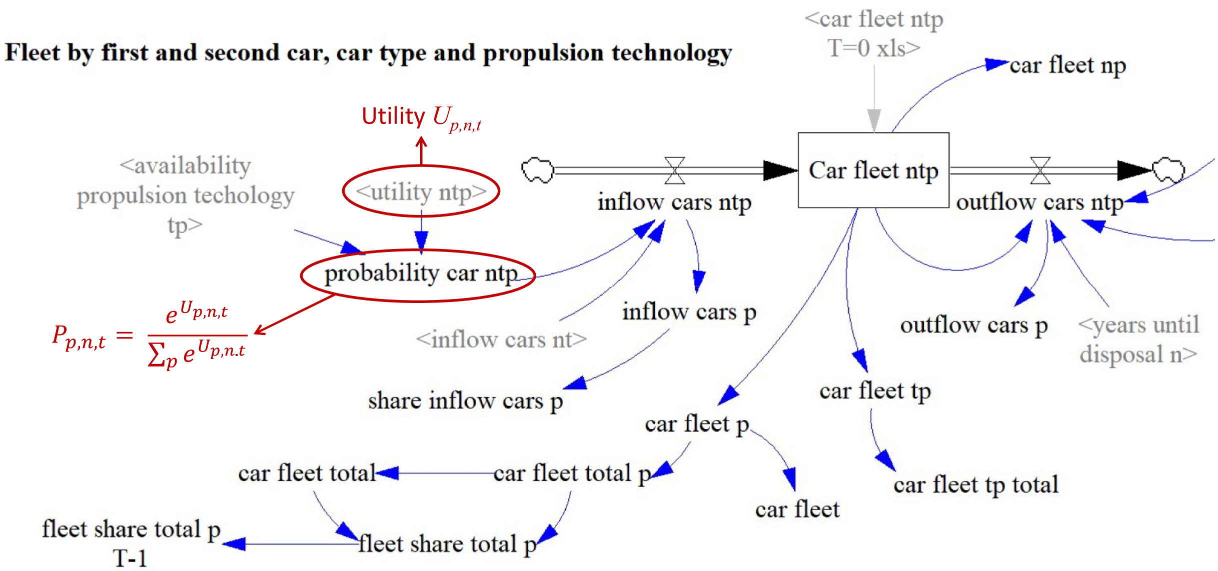

Fig. 1 Vensim screenshot core SERAPIS stock flow model

Equation 1: General form utility of the choice of a propulsion technology.

The utility U_p of propulsion technology p is the marginal utility price μ_P multiplied by the sum of the generalised costs $C_p{}^e$, where e are the utility elements defined in Eq. 1 (Eq. 2).

$$U_p = \mu_P * \sum_e C_p^e$$

Equation 2: Utility and generalised costs.

All generalised costs are calculated as discounted total costs per average lifespan of a car. Generalized costs from investments $C_p{}^I$ are calculated as a weighting parameter $\alpha_I{}^v$ multiplied by the vehicle investment costs $I_p{}^v$ plus a weighting parameter $\alpha_I{}^{ch}$ multiplied by the investment costs for a private home charging station $I_p{}^{ch}$ (Eq. 3).

$$C_p^I = \alpha_I^v * I_p^v + a_I^{ch} * I_p^{ch}$$

Equation 3: Generalised costs from investment costs.

Generalised costs from operating costs $C_p{}^O$ are calculated as the weighted sum of discounted costs $o_p{}^n$ for fuel f, road charges r, parking charges p and annual vehicle tax a (Eq. 4), where $\alpha_O{}^n$ are the weights of the different cost components, r is the discount rate, t future years and Θ the lifespan of the vehicle.

Equation 4: Generalised costs from operating costs.

Generalized costs for the variety of makes and models $C_p{}^M$ are calculated as the ratio of a weighting parameter α_M divided by the coefficient for the marginal utility price μ_P multiplied by the natural logarithm of the ratio of the number of makes and models n_p for propulsion technology p to the total number of makes and models N available on the market (Eq. 5).

$$C_p^M = \frac{a_M}{\mu_P} * ln\left(\frac{n_P}{N}\right)$$

Equation 5: Generalised costs variety of makes and models.

Generalised costs of range and density of public charging stations $C_p{}^{R,D}$ are calculated as the willingness to pay for range/density equal to the maximum available on the market $C_{r,p}$, $C_{d,p}$ multiplied by the exponential function of an elasticity parameter $b_{r,p}$, $b_{d,p}$ multiplied by the ratio of range/density of charging stations of a propulsion technology r_p, d_p to maximum range/density of charging stations r_{max}, d_{max} (Eq. 6), where $\alpha_{R,D}$ is a weighting factor.

$$C_p^{R,D} = a_{R,D} * \left(C_{r,p} * e^{b_{rp} * r_p / r_{max}} + C_{d,p} * e^{b_{dp} * d_p / d_{max}}\right)$$

$$C_p^o = \alpha_o^f * \sum_{t=0}^{\theta} \frac{o_p^f(t)}{(1+r)^t} + \alpha_o^r * \sum_{t=0}^{\theta} \frac{o_p^r(t)}{(1+r)^t} + a_o^p * \sum_{t=0}^{\theta} \frac{o_p^p(t)}{(1+r)^t} + a_o^a * \sum_{t=0}^{\theta} \frac{o_p^a(t)}{(1+r)^t}$$

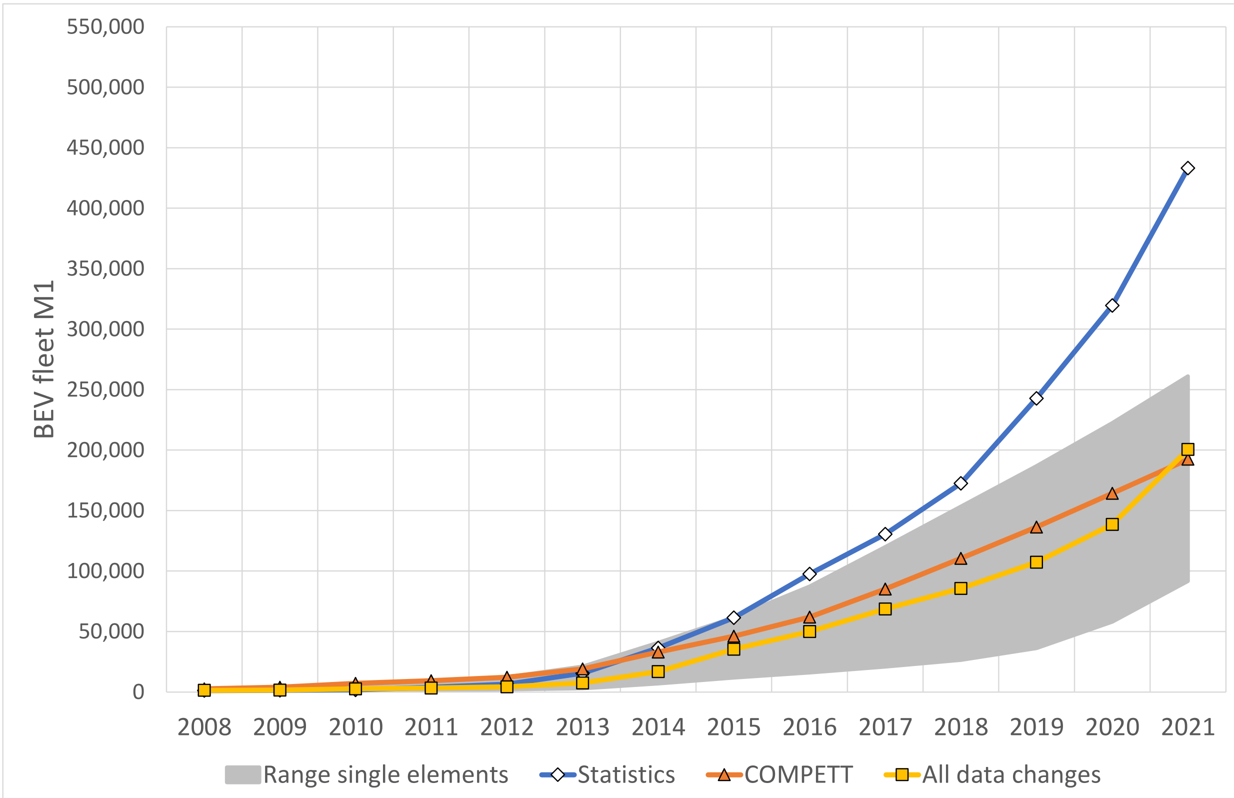

Fig. 2 Effect of data changes on the fit between model results and statistics. Source: [10, 8], own simulations

Equation 6: Generalised costs range and density of public charging stations.

Generalised costs from time savings due to exemptions from regulations $C_p{}^T$ are calculated as the discounted monetized time savings (Eq. 7), where α_T is a weighting factor, *VOT* is the value of time, $\Delta t_p(t)$ are the time savings in year *t*, *r* is the discount rate and Θ the lifespan of the vehicle.

$$C_p^T = a_T * \sum_{t=0}^{\theta} \frac{VOT * \Delta t_p(t)}{(1+r)^t}$$

Equation 7: Generalised costs from time savings due to exemptions from regulations.

The description of the structure and mathematical formulation of the model SERAPIS is based on previous work [10].

2.2 Model validation, data update and re-calibration

A previous SERAPIS version from a European project with partners from Norway, Austria and Denmark formed the basis for the work presented here [11]. The time period 2015 to 2021 was used to evaluate the quality of the forecasts of the scenarios defined in the preceding project. Even in the most optimistic scenario, called "Electromobility Delight", the BEV take-up observed in the real world was underestimated significantly. In this scenario, a BEV fleet of about 192,000 vehicles in 2021 was predicted (orange line with triangles in Fig. 2). In reality, Norway had a BEV fleet of about 433,000 vehicles in that year [8], i.e. more than twice the value as predicted by SERAPIS (blue line with diamonds in Fig. 2). Therefore, there was a strong need for an analysis of causes, a data update and a re-calibration of the model. The first step was to check the consistency between real world data and scenario assumptions concerning the development of net purchase price before taxes, availability of makes and models, range, life span, total car fleet, vehicle kilometres per car and year, fuel costs, parking and road charges, time savings, value of time and discount rate. The result of this process was that for several of the scenario variables, the assumptions made in 2015 were significantly off their real development.

Some examples are: For the net purchase price before taxes, significant reductions were assumed in all three vehicle size categories. In reality, prices increased due to the higher quality and performance of the new

Length	3,143 mm	3,475 mm	3,632 mm
Width	1,658 mm	1,475 mm	1,683 mm
Height	1,596 mm	1,610 mm	1,527 mm
Load	202 kg	315 kg	325 kg
Range	100-160 km	150 km	250-300 km
Power	30 kW	49 kW	87 kW
Torque	90 Nm	180 Nm	220 Nm

Fig. 3 Comparison of key performance characteristics of selected pre and post 2015 battery electric compact cars. Source: [4, 27, 16, 1, 2]

models. In 2021, real world net purchase prices of BEVs before taxes were + 15% (luxury cars) to + 231% (compact cars) higher than what was assumed in the original scenarios.[3] The analysis of the development of the available makes and models gives a differentiated picture. The total number of available makes and models was overestimated in the period up to 2019 and significantly underestimated in the years 2020 and 2021.[4] In 2021, the number of available makes and models was overestimated by 85% for compact cars and underestimated by 70% and 26% for family and luxury cars. The assumption that small cars will be dominant in the BEV segment was outright wrong. The battery range of BEVs was overestimated by about 21% for luxury cars and underestimated by 24% and 41% for compact and family cars.

The assumptions regarding the scenario variables mentioned above were adjusted for the period 2015–2021 according to their real developments. All data changes were tested one by one and in combination. The grey area in Fig. 2 shows the bandwidth of the effect of the data changes for single variables. Some data updates led to higher estimates will others led to lower estimates. The yellow line with rectangles shows the effect of the combination of all data updates. The model with updated data still significantly underestimates real world fleet data. The crucial difference and improvement compared to the 2015 assumptions is that the basic profile of the curve is much more consistent with real world developments, i.e. resulting in a strongly increasing gradient in the later years.

Our interpretation of the results of the evaluation is as follows: Vehicle characteristics and vehicle owners' perceptions changed significantly between pre and post 2015. While pre 2015 vehicles like the Norwegian Think or the Mitsubishi i-MiEV dominated in the compact segment, post 2015 vehicles like the Volkswagen E-Up, Fiat 500e or the Mini became typical cars of this segment. The quality and performance of pre 2015 vehicles is not at all comparable with that of the post 2015 ones. Figure 3 shows a comparison of some key characteristics of selected pre and post 2015 passenger cars in the vehicle segment compact. The post 2015 model Fiat 500e is about 20% bigger than the pre 2015 models Think City and Mitsubishi i-MiEV. The payload of the Fiat 500e is about 60% higher than that of the Think City. The range of the post 2015 model Fiat 500e is roughly two times that of the pre 2015 models Think City and Mitsubishi i-MiEV. The engine power of the post-2015 Fiat 500e model is 80% to 190% higher than that of the pre-2015 models. The torque is about 20% to 150% higher. In addition to the differences in the examined performance

[3] Data sources: Registration numbers: https://elbilstatistikk.no/, Prices: https://www.vegvesen.no/kjoretoy/kjop-og-salg/nybilvelger/ and range: OEM web pages. Data collected by Erik Figenbaum, TØI.

[4] Data source: (ÖAMTC, n.d.). Data collected and analysed by Paul Pfaffenbichler, BOKU.

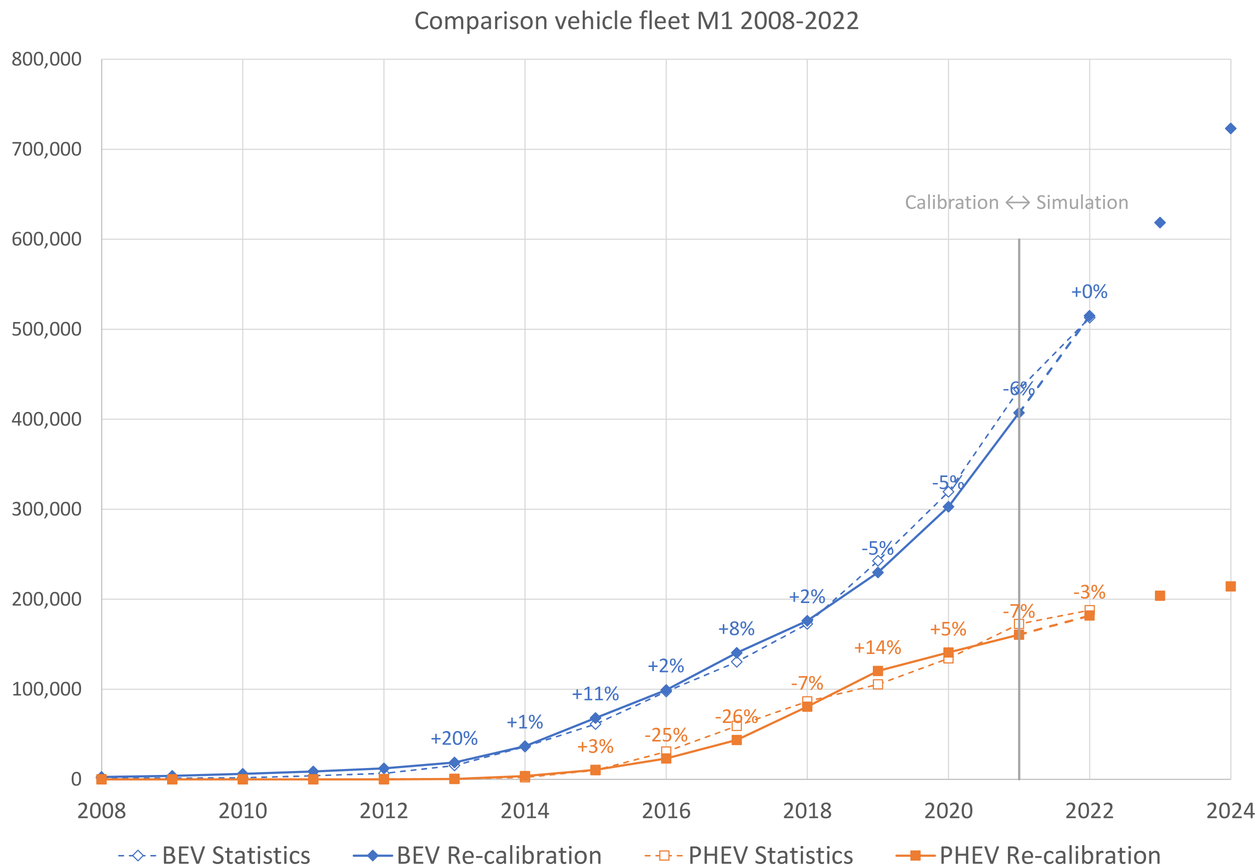

Fig. 4 Calibration and validation results BEV and PHEV fleet

characteristics, there are also substantial qualitative differences. E.g. Think City's plastic body does not meet the quality standards expected by the majority of car buyers. The Mitsubishi i-MiEV was too narrow and had too small tires to be accepted by the majority as a fully-fledged car. The sum of these facts led to the abovementioned price increases but also to a widespread change in customer perception of BEVs.

In the preceding project the utility parameters were calibrated based on the pre 2015 perception which does not fit to the post 2015 situation anymore. Apart from range none of the abovementioned performance characteristics is directly represented in the utility definition of the SERAPIS model. A need for recalibration is the natural consequence of these facts and the newly estimated parameters represent the changes in performance characteristics which are not part of the utility function. The resulting parameters of the utility function are summarised in the Appendix 1 and 2. A near perfect fit could be reached with the newly estimated utility parameters (Fig. 4). For the BEV fleet the difference between simulation and statistics is constantly in the range of -6% to + 8% during the period 2016 to 2021. For the PHEV fleet the difference between simulation and statistics in the same period is less good but still in the range of -26% to + 14%. Notably the difference becomes smaller over the years. Since the time of the calibration new data about the car fleet in 2022 become available. The model calibrated to the period 2008 to 2021 forecasts the fleet size in 2022 with high accuracy. The size of the predicted BEV fleet is less than 0.5% higher than data from the registration statistics. The size of the PHEV fleet is under predicted by only 3%. It can be concluded that the quality of the re-calibrated model is satisfying.

3 Scenario simulation

3.1 Scenario definition

Four main scenarios have been defined to analyse the potential economic and environmental impacts of policies for the continued electrification of the Norwegian passenger car fleet. For ICEVs and PHEVs it was assumed that all taxes and charges remain as they were in 2020. For BEVs the assumptions described in Table 3 were used. In the scenario "Continuing BEV taxation exemptions" it was assumed that nearly all exemptions are kept in place until 2050. This is the scenario most supportive for a

Table 3 Tax and charge assumptions

Element	Continuing BEV taxation exemptions	Constant tax revenues 2020 level	Rebound to tax revenues from 2005–2010	Tax shock 2023
VAT	No VAT	Phase in by type 2024–2030	Phase in 2024–2030	Full VAT from 2023 on
Purchase tax	No purchase tax	No purchase tax	Phase in 2024–2040 to 40% ICEV level	Full tax from 2023 on
Road charges	Lower than ICEV level	Lower than ICEV level	Phase in 2024–2030 to ICEV level	Full charge from 2023 on
Parking charges	50% ICEV level	50% ICEV level	Phase in 2024–2030 to ICEV level	Full charge from 2023 on

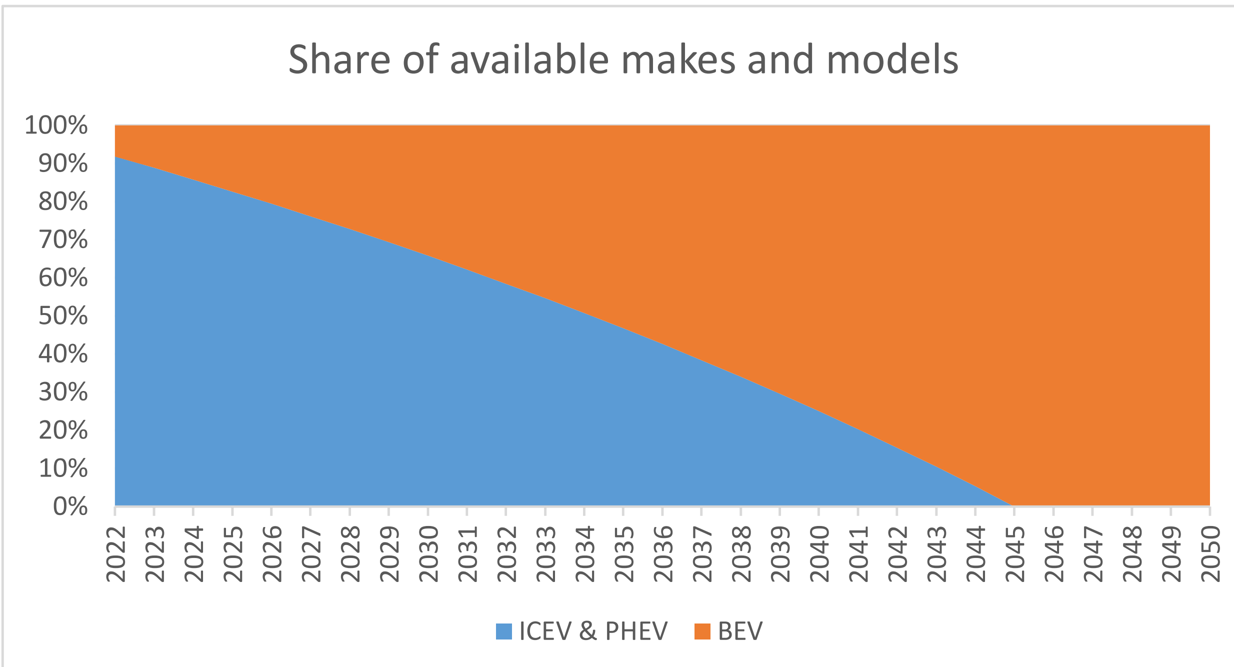

Fig. 5 Exogenous scenario development available share of makes and models

continuation of a fast BEV take-up. There are two scenarios "Constant tax revenues 2020 level" and "Rebound to tax revenues from 2005–2010" in which a gradual phase in of taxes and charges takes place on two different paths. As the names already imply, one was designed in a way to keep public revenues from taxes and charges at about the level of 2022, just over 40 billion NOK (NOK) annually, and the other was designed in a way to rebound public revenues from taxes and charges to about the same level as before a significant uptake of BEVs, i.e. about the level in 2005 to 2010 (around 60 billion NOK annually). In the fourth scenario, a shock implementation of all taxes and charges in 2023 to 2024 was tested.

In all scenarios it was uniformly assumed that benefits from time savings due to bus lane exemptions would be fully phased out in the next five to ten years. Technological development influencing purchase prices, range, charging time, etc. was assumed to be the same in all four scenarios too, as these are exogenous to Norway. The development of the number of available makes models is also assumed to be exogenous (Fig. 5). Their development is based on the target of the "Fit for 55" package of European Union to reach a share of 100% zero emission vehicles from 2035 onwards [6]. We assumed that this ban of non carbon free propulsion technologies will cause a continuous decline of available ICEV and PHEV models. It was assumed that, with a time lag of ten years, i.e. by 2045, no such models will be available in Norway anymore. Fossil fuel price is assumed to increase between 2022 and 2040 by about 50% (Fig. 6). In the same period fuel efficiency is assumed to increase by about 6%. As a result, ICEV fuel costs per kilometre will increase by about 40%. The average annual mileage per car is assumed to decline from about 15,800 kms in 2020 to about 13,700 kms in 2040. Only direct emissions are used to assess climate effects of the scenarios. The reason is that upstream chain emission are already allocated to the industry sector in the emissions balance. The average carbon content of one litre ICEV fuel is estimated with 2.485 kg CO_2. The average fuel consumption of an ICEV in 2020 is estimated to be 6.7 L per 100 kms. Biofuels that are blended in are considered climate-neutral. As Norway's electricity production is almost entirely based on near zero emission hydropower BEVs are assumed to be carbon neutral.

3.2 Results and discussion

Simulation results show that an abolishment of tax and parking and road charge exemptions in form of a shock in 2023 would have some significant adverse effects. In the first years after implementation of full taxes and charges the share of new PEV registrations will drop from about 92% to 59% (Fig. 7). In contrast, the market share in the scenarios tax exemptions and phase in continues to increase to about 99% by 2025. Even in the long run the effect of the tax phase in scenario on market shares is marginal. Over time the magnitude of the tax shock effect decreases due to a shift of the number of available makes and models towards BEVs, technological improvements increasing BEV range and an increasing number of charging points. Thus, financial benefits are becoming less and less relevant (Fig. 8). The significant drop in market shares in the tax shock scenario in 2023 translates into a decrease of the fleet share in 2024 from about 33% in the tax exemptions scenario to about 31%. Over the whole evaluation period the fleet share of the tax shock scenario is about two to four percentage points lower than that of the tax exemption and tax phase in scenarios. In the final simulation year 2050 the BEV fleet is only about 4% smaller than in the scenario with continuing tax exemptions. In absolute numbers, the difference is about 178,000 BEVs in 2030 and 106,000 BEVs in 2050. The adverse effects of the phase-in scenarios are quite limited. The number of annual BEV registrations drops only by up to around 1%. Also, the stock of registered BEVs is only reduced by up to about 1%. In the final simulation year 2050 the BEV fleet is nearly the same in the scenario with continuing tax exemptions. Depending on the level and

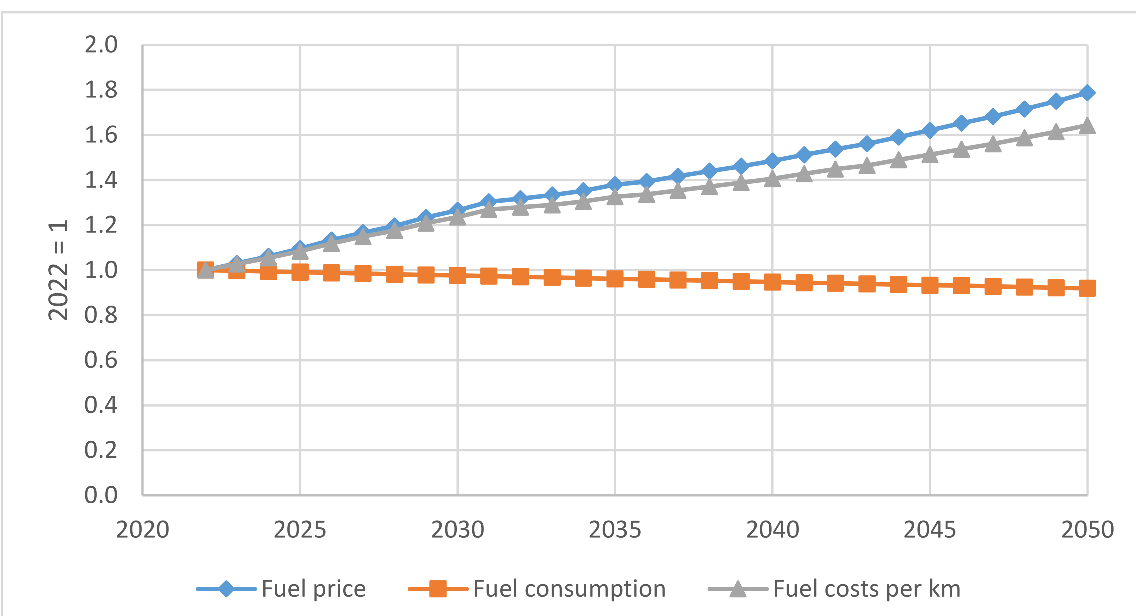

Fig. 6 Development of ICEV fuel price, specific fuel consumption and fuel costs per km

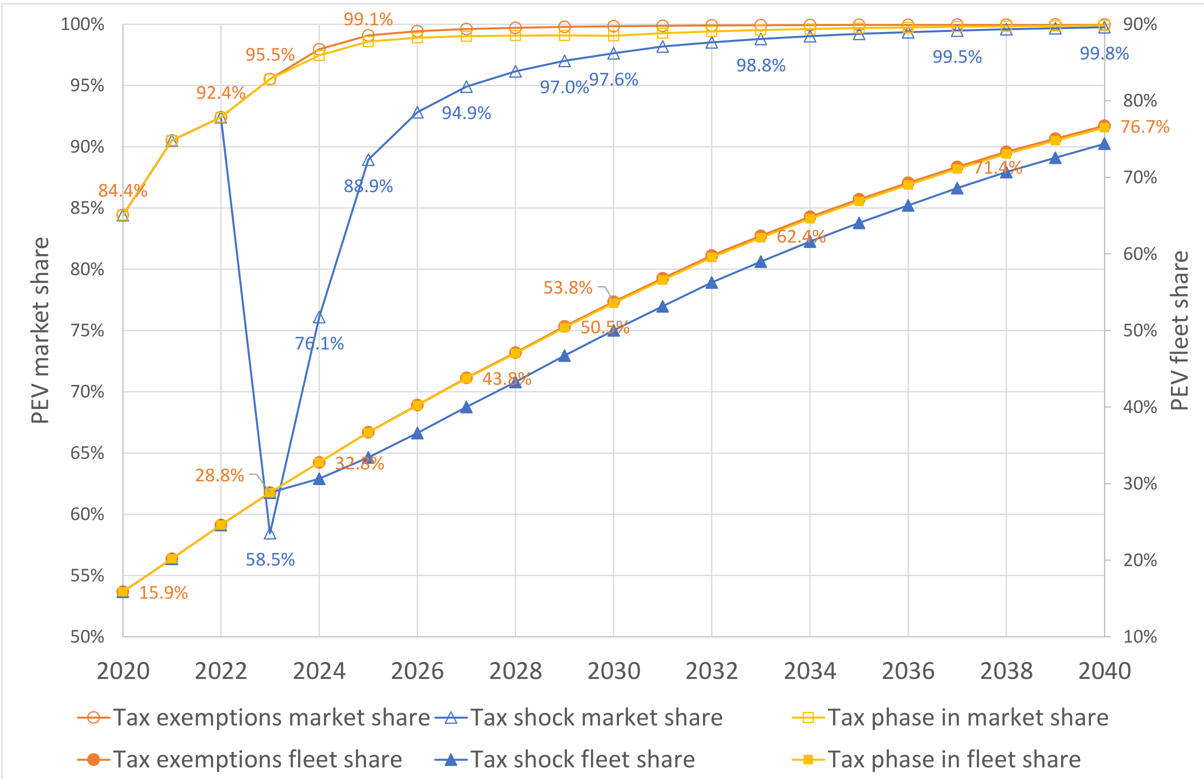

Fig. 7 Development of PEV market and fleet shares in the different scenarios

timing of the phase-in, the number of registered BEVs is only 3,000 to 7,000 vehicles and 11,000 to 19,000 vehicles lower in 2030 and 2050 respectively.

In 2022 the purchase of an average ICEV had a dis-utility of about 304,000 NOK (Fig. 8). In comparison with this value, the average BEV had a relative advantage of about 89,000 NOK from the disutility of the investment costs, which was caused mainly by the exemptions from VAT and purchase tax. The relative advantage caused by energy costs is about 126,000 NOK. Advantages from exemptions from parking and road charges and annual taxes are with 7,000 and 3,000 NOK respectively relatively small. In 2022, due to the higher number of ICEV makes and models BEVs had a relative disadvantage of about 47,000 NOK. The disadvantage resulting from BEV range and service station density amounted to a mere 2,000 NOK. The advantage from time savings amounted to slightly more than 1,000 NOK. By 2040, even in the tax shock scenario the relative ratio of utilities is expected to change further in favour of BEVs. Due to the decrease of available ICEV makes and models the dis-utility of an average ICEV increased to about 370,000 NOK. Due to the abolishment of tax exemptions the investment cost advantage of BEVs decreased by about 23,000 NOK to about 66,000 NOK. The relative advantage of energy costs increased to about 133,000 NOK. As the exemptions for parking fees, tolls and annual tax were further reduced, the advantage of BEVs in this area declined. The most significant change between 2022 and 2040 relates to the development of model variety. The dis-advantage in 2022 turned into an advantage of about 56,000 NOK in 2040. Differences concerning range and time savings are negligible in 2040.

While the variety of makes and models is a key driver for the future development of the Norwegian BEV fleet, our simulations also reveal that the Norwegian tax policy has been crucial in making Norway the world leader in BEV use and reducing its passenger transport GHG-emissions. To analyse the policy effects, the Norwegian policies and utility parameters have been replaced with values from Austria, which lags several years behind in the development of its BEV fleet. In contrast to Norway, there was no exemption from VAT or parking charges in Austria, nor was there a shared use of bus lanes. Austria, on the other hand, relied on subsidising the purchase price. Utility parameters, representing the perception of BEVs from the perspective of Austrian customers, are available from a recently calibrated SERAPIS model. In a simulation with Norwegian policy and calibration parameters, the share of BEVs in the passenger car fleet increases from 0.1% in

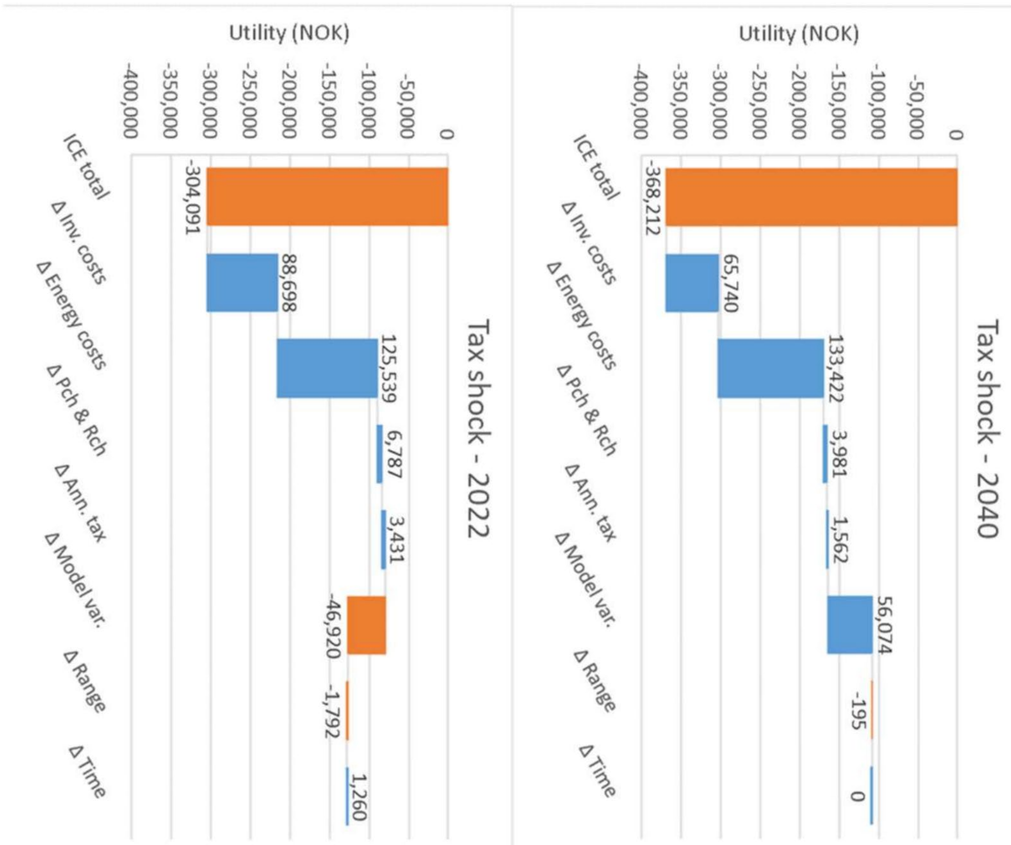

Fig. 8 Utility of average ICEVs and BEVs in 2022 and 2040 – Scenario tax shock

2005 to about 18% in 2022. Replacing the policy elements of VAT exemptions, parking charge exemptions and shared bus lane use with direct subsidies results in a 2022 BEV share of about 9%. Assuming that in this case customer perception would have remained at the same level as in Austria, i.e. using the utility parameters from the Austrian model, reduces the BEV share further to around 3% in 2022. This is only about one percentage point above the current Austrian BEV share of about 2% [9]. As the variety of makes models has developed in the same pattern in both countries, the simulations show that both the Norwegian policy and the related change in customer perception have been crucial success factors. In terms of BEV market shares the Norwegian policy clearly outperforms a policy of direct subsidies.

In the continuing BEV tax exemption scenario public revenues continue to decrease from about 44 billion NOK in 2020 to about 26 billion NOK in 2050 (Fig. 9). This corresponds to a 40% decline. As a positive effect of the tax shock scenario, annual public revenues roughly double to around 80 billion NOK immediately (Fig. 9). In the two different tax phase in scenarios annual public revenues stabilise from 2030 onwards at values of about 40 and 60 billion NOK respectively. Thus, it can be concluded that appropriate phasing in strategies can stabilize tax revenues without compromising fleet targets.

Figure 10 shows the development of the CO_2-emission resulting from the different scenarios in relation to the Norwegian reduction target for 2030. As the differences between the tax exemption and phase-in scenarios are hardly visible, only the phase-in scenario with a tax revenue rebound to 2005–2010 levels is shown in the diagram (yellow line with squares). In the tax phase-in and tax shock scenario it is assumed that liquid fuels contain a constant share of biofuels of 12%. In the tax shock scenario CO_2-emissions in 2030 are about 39% lower than in 2005, thus the reduction target is clearly missed. The tax exemption and phase-in scenarios result in a reduction of around 44%, still missing the target. In these scenarios, the target would be met with a delay of 3–4 years. The grey line with diamonds shows the resulting CO_2-emission for a scenario combining the phase-in with a tax revenue rebound to 2005–2010 levels with a gradual increase of the biofuel share from 12 to 30% by 2030. The results show that it is possible to reach Norway's GHG

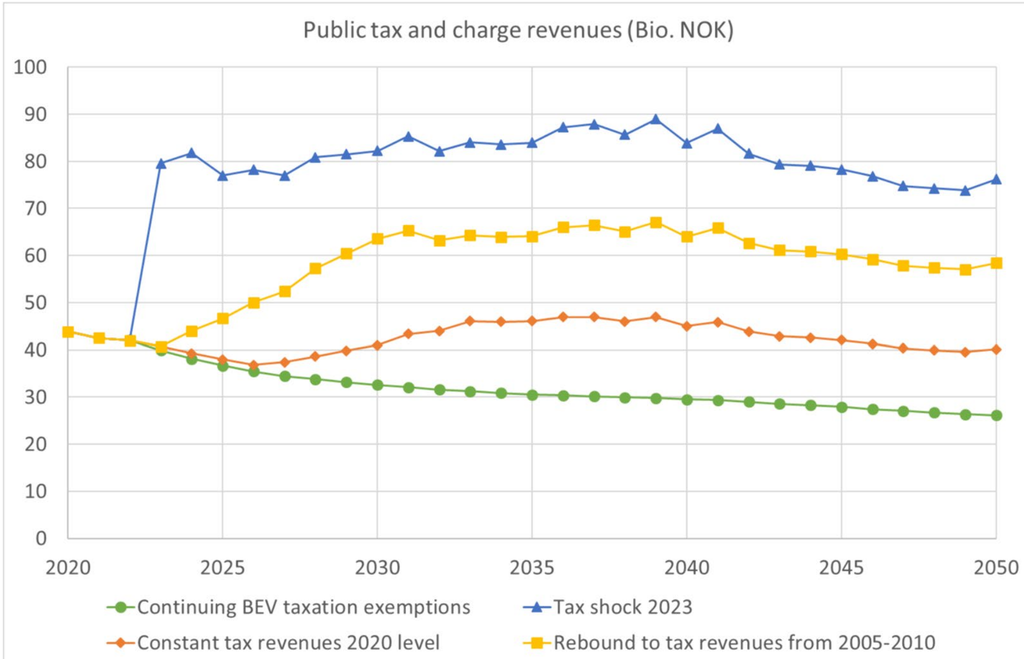

Fig. 9 Tax revues in the different scenarios

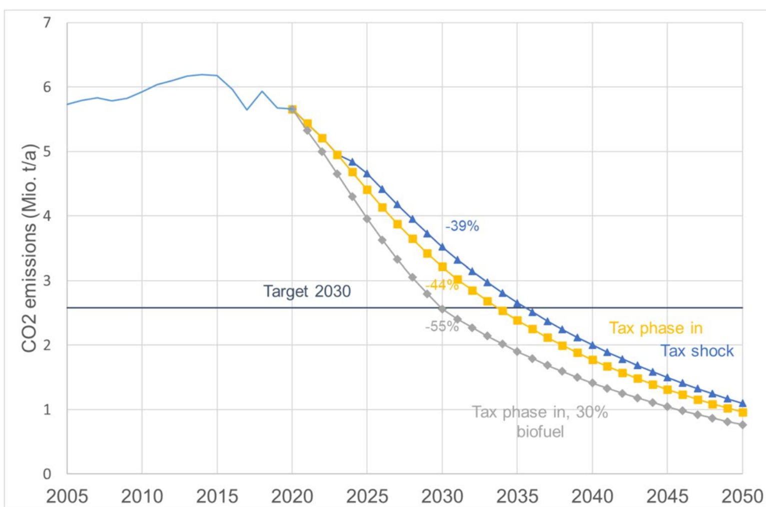

Fig. 10 CO_2-emission of different scenarios relative to target 2030

emission target for 2030 even with a tax phase-in, but a share of about 30% biofuels will be required.

4 Conclusions

Decision makers in Norway and elsewhere face the dilemma that on the one hand, tax exemptions for ZEVs cause increasing losses in public revenues while on the other hand, they might be essential to reach GHG emission targets. The intention of the research presented in this paper was to analyse this problem and to identify potential solutions for the world's most mature market for BEVs. A literature review revealed a significant gap in relation to this subject, hence the work presented here represents an important contribution to the literature. One study, [30], analyses the effects of different taxation policies on market penetration and travel behaviour in the greater Oslo area. There findings show that while continuing policy of tax, toll and parking charge exemptions substantially reduces GHG-emissions, it also leads to more car traffic and congestion, and therefore higher social costs. Unlike this study, the research presented here adopts a national perspective and examines Norway as a whole.

A theoretical framework and data collected in a nationally funded Norwegian research project formed the basis for the analysis. An economic modelling framework based on an updated and modified version of the stock flow model SERAPIS of the Norwegian car fleet was established. SERAPIS is a dynamic regional aggregated discrete choice model of new passenger car acquisitions. SERAPIS was used to forecast future economic and environmental impacts of electromobility on a national and regional level, as well as the effect of different taxation policies. Four different scenarios concerning the future of tax and parking charge exemptions for BEVs and PHEVs have been defined. Simulation results clearly demonstrate the adverse effects of an abrupt abolition of the tax exemptions concerning the goal of a decarbonisation of the Norwegian passenger car fleet. Instead of the 55% reduction in GHG emissions aimed for in 2030, this scenario only achieves a reduction of 39%. Thus, the simulation results demonstrate that there is a clear need for a controlled phase-in of taxes and charges to minimize public revenue losses on the one hand while on the other hand maximising market shares of ZEVs. In the phase-in scenarios, a reduction in GHG emissions of at about 44% is achieved in 2030. In combination with an admixture of 30% carbon neutral biofuel or synthetic fuel Norway is on the one hand able to meet its 2030 target of 55% GHG emission reduction for the transport sector and on the other hand able to stabilise public revenue levels roughly at pre-BEV take up levels. Thus, these results provide decision-makers with essential information needed to balance the two opposing objectives reducing GHG emissions and generating of public revenues.

In addition to predicting future developments, the model was also used to analyse the effectiveness and efficiency of the Norwegian policy since 2005 in comparison to policies in other European countries. To this end, two hypothetical scenarios were analysed that represent the Austrian policy of the years 2005 to 2022. The first assumed that Norway would not have granted tax exemptions, but would have subsidised the purchase price directly, as Austria did. In the second scenario, it was additionally assumed that the customers' perception of BEVs would have stagnated at the current Austrian level. Whereby the latter was implemented by applying the calibration parameters of a current Austrian model version. The switch from the Norwegian tax exemptions to direct subsidies reduced the BEV fleet share in 2022 from 18 to 9%. The additional change in the customer perception further reduced the BEV fleet share to 3%. This value is only about one percentage point above the Austrian BEV share in 2022 [9]. It is therefore safe to conclude that the Norwegian tax policy was a key success factor. In terms of BEV market shares the Norwegian policy clearly outperforms a policy of direct subsidies. Compared to scenario without BEVs the Austrian strategy would have reduced cumulated GHG-emissions from 2005 to 2022 by a meagre -0.2%, while the Norwegian strategy has reduced them by around 13%. In 2030 the Austrian strategy would miss the Norwegian GHG target by 13 percentage points. For the period 2005 to 2030 revenue losses of the Austrian strategy would amount to about 17,400 NOK per ton CO_2 saved. For the Norwegian strategy revenue losses about 14% higher and amount to about 19,900 NOK per ton CO_2 saved.

The SEARPIS modelling framework is a policy-sensitive, strategic decision support tool that can be adapted to different case study areas with relatively little effort using publicly available data. Public authorities, planners and environmental organisations can use the tool to assess the effectiveness and efficiency of various policies and incentives with relatively little effort. Measures that can be influenced by the public sector, include direct subsidies, parking and road user charges and tax exemptions, but also the shared use of bus lanes or the density of public charging. Measures that can be influenced by technological progress and car manufacturers, are range and the variety of makes and models. Utilities and charging infrastructure operators can utilise the framework to estimate future demand scenarios.

Nevertheless, it has to be acknowledged that the applied method has some limitations. One of the limitations is the use of an average uniform survival rate for all vehicles in the fleet. Modelling the vehicle fleet in age cohorts with corresponding specific survival rates could improve the predictive quality of future versions of the model. Another weak point is the fact that, due to limited resources for data acquisition and preparation, the model SERAPIS was only calibrated to fit the total fleet by propulsion technology. A calibration towards the fleet development by propulsion technology and the vehicle categories compact, family and luxury is expected to improve the interpretation of the utility parameters and the predictive quality of the model. An additional limitation is the lack of performance characteristics such as engine power, torque, load space, etc. in the utility function. Due to the constant technical development of BEVs, however, it can be expected that the relevance of this restriction will be decreasing.

Appendix 1: Literature review

The literature review was carried out on Scopus using the following advanced query: (TITLE-ABS-KEY ("market share") OR TITLE-ABS-KEY ("take-up") OR TITLE-ABS-KEY ("take-up") OR TITLE-ABS-KEY ("forecast") OR TITLE-ABS-KEY ("prediction")) AND (TITLE-ABS-KEY (bev) OR TITLE-ABS-KEY ("electric car") OR TITLE-ABS-KEY ("electric cars") OR TITLE-ABS-KEY ("battery electric")) AND PUBYEAR> 2018 AND PUBYEAR < 2025 AND (EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA ,"COMP") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA ,"CHEM") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA ,"HEAL") OR EXCLUDE (SUBJAREA , "PHAR")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) This search resulted in 161 documents. A manual review of the abstracts identified 13 papers which covered different aspects of the work presented in this paper.

Appendix 2: Utility function parameters

Table 4 Utility function parameters after re-calibration 2022

Category	Compact		Family		Luxury	
Role	1st car	2nd car	1st car	2nd car	1st car	2nd car
Marginal utility price μ_P	-1.29E-05		-7.01E-06		-4.78E-06	
Investment costs vehicle α_I^V	1	1	1	1	1	1
Investment costs private charging α_I^{ch}	1.00	0.25	2.62	0.25	5.00	1.00
Operation costs fuel α_O^f	2.00	4.71	2.30	5.00	2.01	2.86
Operation costs parking α_O^p	1.00	0.25	4.84	1.67	0.25	1.00
Operation costs road charge α_O^r	1.00	0.25	2.53	1.08	0.25	1.00
Annual tax α_O^a	1.00	5.00	5.00	5.00	5.00	1.26
Range and charging station density $\alpha_{R,D}$	3.00	5.00	5.00	5.00	5.00	3.00
Variety of makes and models α_M	1.00	2.00	1.63	1.20	0.79	3.77
Time savings α_T	1.00	0.42	1.91	1.27	1.34	1.00

Abbreviations

BEV	Battery electric vehicle
EEA	European Economic Area
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine passenger vehicle
M1	Vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat (UNECE, 28)
NOK	Norwegian kroner
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
PTTMAM	Powetrain technology transition market agent model
SERAPIS	Stands for "Simulating the Emergence of Relevant Alternative Propulsion technologies in the car and motorcycle fleet Including energy Supply"
VAT	Value added tax
ZEV	Zero-emission vehicle

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Authors' contributions
PPF led the work on model update, recalibration and simulation and prepared the first draft of the paper. NF and EF lead the work on data collection and scenario definition. GE, NF and EF supervised the modelling work and provided feedback on the analyses and organisation of the content. All authors read and approved the final manuscript.

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Availability of data and materials
On request, the SERAPIS model including data can be made available in form of a Vensim Packaged Model. Models in this particular file format can be operated and analysed with the free Vensim Model Reader software.

Declarations

Competing interests
Not applicable.

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