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The Road to a Low Emission Society: Costs of Interacting Climate Regulations

Brita Bye[1] · **Kevin R. Kaushal**[1] · **Orvika Rosnes**[2] · **Karen Turner**[3] · **Hidemichi Yonezawa**[1]

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Abstract

Transportation is one of the main contributors to greenhouse gas emissions. Climate regulations on transportation are often a mix of sector-specific regulations and economy-wide measures (such as emission pricing). In this paper we consider how different and partly overlapping climate regulations interact and what are the effects on economic welfare, abatement costs and emissions? Our focus is on Norway, a nation where high taxation of conventional fossil-fuelled cars has paved the floor for another pillar of climate policies: promotion of electric vehicles (EVs) in private transport. Our contribution to the literature is two-fold. First, we analyse the costs and impacts of the partly overlapping climate regulations in transportation—the cap on domestic non-ETS emissions and the goal of all new cars for private households being EVs—focussing on the outcome in 2030. Second, we respond to a gap in the literature through a methodological development in economy-wide computable general equilibrium (CGE) approaches for climate policy by introducing EV technologies as an explicit transport equipment choice for private households. We find that, for the case of Norway, combining a specific EV target with policy to cap emissions through a uniform carbon price more than doubles the welfare costs.

Keywords Climate policy · Carbon pricing · Zero-emission transport policies · Overlapping regulations · Modelling electric vehicles · CGE-model

✉ Brita Bye
brita.bye@ssb.no

Kevin R. Kaushal
kevin.kaushal@ssb.no

Orvika Rosnes
orvika.rosnes@vista-analyse.no

Karen Turner
karen.turner@strath.ac.uk

Hidemichi Yonezawa
hidemichi.yonezawa@ssb.no

[1] Research Department, Statistics Norway, Oslo, Norway

[2] Vista Analyse, Oslo, Norway

[3] Centre for Energy Policy, Department of Government and Public Policy, University of Strathclyde, Glasgow, UK

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1 Introduction

Transportation is one of the main contributors to greenhouse gas emissions, accounting for almost one quarter of global energy-related greenhouse gas (GHG) emissions (IEA 2020a), with a similar proportion applying across the European Union (EU). Hence, policies to reduce emissions from transportation are an important part of climate policies in many countries. While many other large emitters (such as energy and metal industries) are part of the European emission trading system (EU ETS), transportation is not. Climate policies that target transportation are the domain of national authorities alone.[1] The climate regulations on transportation are often a mix of sector-specific regulations and economy-wide measures (such as emission pricing), where the EU and Norway are examples. In this paper we consider how different and partly overlapping climate regulations interact and what are the effects on economic welfare, abatement costs and emissions. We use an applied general equilibrium model that enables tracking and analysis of a broad range of interactions and responses.

Our focus is on Norway, a nation that is characterised by many interacting, and partly overlapping, climate regulations in the transportation sector. In Norway, transportation activities account for a third of GHG emissions.[2] Road transport is responsible for just over half of these (17%) and almost 35% of the non-ETS emissions.[3] Norway, in a similar manner to the EU, has newly submitted more ambitious targets for GHG emission reductions under the Paris agreement (2015): 50–55% reduction in 2030 and the long-term goal of 90–95% reductions in 2050, both compared to 1990 (Ministry of Climate and Environment 2021). About half of Norway's emissions are included in EU ETS. The domestic targets of 45–50% reductions in non-ETS sectors are more challenging to achieve.

Transportation activities face extensive climate regulations in Norway (Ministry of Finance 2020; Fridstrøm 2021). High taxation of conventional fossil-fuelled cars has paved the floor for another pillar of the Norwegian climate regulations, involving promotion of electric vehicles (EVs) in private transport. In 2021, more than 60% of all new private cars sold were EVs. Although the original target for the favourable EV policy (50,000 EVs on road) was reached in 2015, the current policy documents include another target for the transportation sector: all new private vehicles should be EVs in 2025 (Ministry of Climate and Environment 2021). More details about the Norwegian EV policies are provided in Sect. 2 below.

Our contribution to the literature is two-fold. First, in terms of applied policy we analyse the impact of interacting and partly overlapping climate regulations in transportation, specifically the consequences of two policies: the cap on domestic non-ETS emissions and the goal of all new cars for private households being EVs. In serving one primary objective,

[1] The climate policies in the EU allow for flexible mechanisms also in the non-ETS sectors and there are some examples of common policy in the EU, for instance CO_2 emission performance standards for new cars, https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en. The newly launched EU fit for 55 has high ambitions for emission reductions in private transportation with a specific target of 100% new zero-emission cars in 2035 and suggests establishing a quota market for transport and building sectors from 2026, https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541.

[2] https://www.ssb.no/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft.

[3] https://miljostatus.miljodirektoratet.no.

the use of multiple policy instruments can create expensive overlaps (Tinbergen 1952). The use of multiple instruments is justified in the presence of multiple externalities or imperfections (Bennear and Stavins 2007; Goulder and Parry 2008; Bjertnæs 2021). For example, if the consumers are myopic or there are considerable uncertainties regarding future climate externalities and regulations, current market signals alone may lead to limited development and adoption of climate-friendly technologies (Lehman and Gawel 2013). There may also be positive spillover effects, such as technology spillovers in battery and car technologies, or network and learning effects in the markets for new technologies as EVs, that support the argument for subsidies for new technologies (Acemoglu et al. 2012; Greaker and Midttømme 2016). However, simply piling multiple instruments does not guarantee that they will achieve the intended goals, and the costs of layering policy actions can be excessive (Böhringer et al. 2009, 2016; Fankhauser et al. 2010; Karplus et al. 2013a). Moreover, the use of multiple instruments is usually driven by political realities more than by purely economic considerations (Fankhauser et al. 2010). Here we demonstrate that layering different policy actions can potentially increase the welfare costs of each individual action through a range of direct and indirect routes.

Second, we respond to a gap in the economy-wide modelling literature through a methodological development that involves including the EV technologies as an explicit transport equipment choice for private households in a top-down disaggregated computable general equilibrium (CGE) single nation model designed particularly for climate policy analyses. This introduces country-specific detail relative to recent works such as that of Ghandi and Paltsev (2020), which study the global emission impacts of EVs in private transportation in a global CGE model. The CGE model developments made here ensure that we bring focus on how the economy-wide impacts of the electrification of private transport are transmitted through prices and will influence electricity demand in other industries and stimulate investments in new electricity production and grid capacity. Such generic development in CGE specification is crucial given that, to date, EVs constitute a relatively new and not yet a wide-spread technological option, with the implication that their deployment has not been thoroughly studied in economy-wide models.

Some top-down models have attempted to include more detail about specific transport technologies. For example, Li et al. (2017) and Zhang et al. (2018) use CGE models augmented with transport choice mode and other transport technology details to investigate the role and contribution of the transport sector to emission reduction. Li et al. (2017) and Zhang and Fujimori (2020) model EVs as an exogenous transport technology, and study interaction effects of introducing EVs and decarbonization of the electricity sector for future emission reductions. Li et al. (2017) find that the combination of policies promoting EVs in private transport and Carbon Capture and Storage (CCS) technologies in electricity production reduces emissions by reducing consumption of coal and oil, but at the cost of reduced GDP. Zhang et al. (2018) show, by coupling a detailed transport sector model with different technologies with a global CGE model, that new technologies have significant contributions to emission reduction while also lowering the mitigation costs. Zhang and Fujimori (2020) find that global mitigation costs are nearly halved when transport electrification is available. Others, for example Alabi et al. (2020), study the wider economy impacts of electrification of the transport sector in a CGE model, focussing on implementing and recovering the costs of investment needs in the electricity industry that are necessary to deliver enough electricity for the EV rollout in the UK. There the EV rollout in the CGE model is modelled by applying a soft-linking approach to an energy system model (UK TIMES).

A generic outcome of all these applied analyses is to show the importance of incorporating electrification of transport in a macroeconomic model framework when analyzing mitigation costs of reaching ambitious future carbon policy goals. Despite variation in approaches to linking transport models with electrification technologies to macroeconomic models, all tend to solve recursively. However, none of these studies model the consumers' choice between EVs and conventional cars with internal combustion engines (ICE), or the subsidies and other benefits that are necessary to obtain 100 per cent EV share (as noted by Zhang and Fujimori 2020). Thus, we contribute to this literature by fully integrating the electric transport choice in the CGE model that incorporates all the interactions and simultaneous market effects that are present in the economy, and showing how this impacts the costs of the carbon policies and in particular the costs of specific EV diffusion goals.

Specifically, our approach is to model the transport options available to the households (EVs and ICEs) as quite imperfect substitutes since the technologies have not been considered as highly substitutable. This is in contrast to those earlier approaches (e.g., Karplus et al. 2010, 2013b; Chen et al. 2017) that model plug-in hybrid electric vehicles (PHEV) or PHEVs and EVs combined as approximately perfect substitutes to ICEs.[4] The improvement of EV technologies and the larger market shares that we see in some countries now were unanticipated 5–10 years ago.

Our contribution is to combine the modelling and features of increasingly ambitious EV and climate policies (exemplified by the Norwegian policy), detailed modelling of EV technologies in private transportation and overall electrification of the economy, in an economy-wide consistent framework. Our contributions emerge through our study of the outcomes of two climate policy scenarios in 2030, relative to a baseline scenario, using the CGE model SNOW.[5] First, a *cap-only scenario,* where a cap on emissions induces a uniform emission price in non-ETS sectors. Second, a *cap and EV target scenario* where the emission cap in the non-ETS sectors is *supplemented* with the specific EV target, requiring that all new cars sold to private households are EVs by 2030. In both cases, we bring focus on consequences in terms of how abatement costs interact with economy-wide welfare costs (measured by equivalent variation or change in income).

Our main findings are as follows. We show that in the case of Norway, the interacting and partly overlapping policies more than double the welfare costs, compared to only capping emissions by a uniform carbon price. As the total cap for emissions from the non-ETS sectors is the same in both cases, less abatement is needed from other non-ETS sectors when households contribute more to emission reduction through increased use of EVs. Hence, the most expensive abatements in other sectors can be avoided in the cap and EV target scenario, and this transforms into a lower emission price for the whole non-ETS segment: the carbon price is about half of that in the cap-only scenario. In short, the lower emission price benefits all other non-ETS sectors at the expense of households. Yet, the total costs to the society are greater due to high costs in private transport, even though the most expensive emission abatements in the non-ETS production sectors are avoided. The welfare cost more than doubles and the GDP loss is twice as large as that observed in the cap-only scenario. This implies that the economy becomes less efficient in reducing the emissions with overlapping policies.

We note that the increased roll-out of EVs (due to the goal of all new cars being EVs) is achieved by an implicit subsidy (shadow price) to EVs, doubling the shadow price in the

[4] Dugan et al. (2022) and Miess et al. (2022) are very recent CGE model studies for Austria, but their modelling of EV consumption lacks real data.

[5] Fæhn et al. (2020) gives a recent model description and presents an analysis of a carbon cap.

baseline and in the cap-only scenario. This reflects the very high costs for the consumer of being effectively forced to purchase only EVs. This also implies that stronger EV policies (in the form of more benefits to EVs and higher taxes or restrictions on conventional vehicles) are needed to reach the EV sales target of 100%. This is confirmed by our cap-only scenario, which demonstrates that an EV target of 100% is not reached, despite the high CO_2 price (which is seven times higher than in the baseline).

The remainder of the paper is organised as follows: Sect. 2 gives an overview of the Norwegian case regarding EV outreach and electrification of the economy and compares it to other countries. Section 3 describes the numerical CGE model SNOW, including the modelling of EVs. Section 4 presents the scenarios and policy analyses, Sect. 5 studies the robustness of the results by some sensitivity analyses, while Sect. 6 concludes.

2 Electrification and EV policies: The Case of Norway

2.1 Substantial EV Policy Development and Uptake

Conventional fossil-fuelled cars with internal combustion engines (ICEs) are heavily taxed in Norway: there is a carbon tax of 55 EUR/ton CO_2 on fossil fuels, in addition to an extensive CO_2 component in the registry tax (Ministry of Finance 2020). Moreover, the annual traffic insurance fees and excise taxation on fossil fuels include local externality costs (Fridstrøm 2021). Complementing this, policies promoting EV uptake and use have been in place for more than 20 years in Norway, see Table 1. Support schemes to EVs involve both fiscal instruments (e.g., exemption from VAT on purchase, registration tax and annual vehicle tax) and non-fiscal support instruments (such as exemptions from road tolls, no user fees on roads, use of bus lanes, free or reduced parking fees, free domestic car ferries and access to free or low-cost charging). In short, there are clear disincentives for continued reliance on fossil-fuelled vehicles. All these taxes on ICEs, as well as tax exemptions and other benefits for EVs, are represented in our numerical model and kept the same in all simulations.

There are almost 460,000 EVs and 184,000 PHEVs (plug-in hybrid EVs) on the road in Norway now, more than 20% of the total private car stock.[6] In 2020, the sales of EVs and PHEVs in Norway amounted to 106,000 cars, more than 3% of the global sales.[7] From the start in 1996, with very limited choice of EVs at the market, to 2021, with EVs constituting over 60% of the new private car sale, makes a tremendous difference. The initial high taxation of ICEs has made it easy to promote EV sales by exempting EVs from most or even all of the ICE taxation, instead of offering direct subsidies to EVs, and contributed to this development. The fiscal effects of these exemptions were insignificant for the first 15–18 years, but with a market share approaching 50%, the revenue loss amounts to 19.2 billion NOK in 2019 (Ministry of Finance 2020), more than 20% of the revenue from all taxation of ICEs in 2019.

Indeed, to date Norway has been at forefront with its generous support schemes and relatively high share of EVs. Yet, as EV technologies become mature, other countries are likely to consider policies related to EVs (Ghandi and Paltsev 2020). The CO_2 emission performance standards for new passenger cars and new vans from 2020 onwards in

6 https://www.ssb.no/transport-og-reiseliv/landtransport/statistikk/bilparken.

7 https://elbil.no/elbilstatistikk/; https://www.theguardian.com/environment/2021/jan/19/global-sales-of-electric-cars-accelerate-fast-in-2020-despite-covid-pandemic; https://www.ev-volumes.com/.

Table 1 Norwegian EV policy measures

Incentive	Trial period	Permanent
Temporary exemption from on–off registration tax	1990–1995	1996
Exemption from annual vehicle tax**		1996
Exemption from road tolls*		1997
Exemption from parking fees on municipally owned parking facilities*		1999
Reduced company car tax		2000
Exemption from VAT		2001
Use of transit lanes*	2003–2005	2005
Further reduction in company car tax		2009
Exemption from car ferry fees*		2009

Source: Aasness and Odeck (2015), Ministry of Finance (2017, 2020)

*In recent years these exemptions have been modified, e.g., in large cities as Oslo and Bergen EVs now pay (reduced) fees at toll roads, the availability of free parking and charging is reduced all over the country, car ferry fees and restrictions on the use of bus lanes during rush hours have been introduced, etc

**From 2021 all EVs pay an annual insurance fee, as the ICEs (Ministry of Finance 2020)

EU (EU 2019) is an example.[8] Denmark has newly established a strategy for electrification of private transport that builds on temporary subsidies to EV purchases and a goal of 100% new EVs in 2030 (Kommisionen for grøn transport 2020).[9] In several EU countries (France, Netherlands, Sweden, Germany), Canada and parts of US, a buyer's premium (a direct subsidy) of around 6000–9000 EUR has been offered to purchasers of new EVs, and in most EU countries EVs pay no registration fee.[10] Even with such promotion policies, the market penetration is still quite limited with EV market shares of 1–5% of new cars in most of these countries. The Netherlands has been an exception for several years, though, with more benefits for EV buyers compared to other EU countries and reaching a market share of more than 20% for new EVs in 2020. The introduction of new low- and medium cost EV models with wider driving range in 2020 may also contribute to the increased market share.

2.2 The Broader Electrification, Infrastructure and Industrial Landscape

When considering the effects of the policies and the interaction of the policies with Norway's climate policy regulations in general, it is important to keep in mind that these depend on a range of factors and conditions prevailing in the Norwegian context that may

[8] https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en.

[9] https://www.ft.dk/samling/20201/lovforslag/l129/index.htm.

[10] https://www.reuters.com/article/uk-germany-autos-subsidy-idUKKBN27W2FT. https://electrek.co/2021/01/08/the-netherlands-69-all-electric-market-share/. https://www.rvo.nl/sites/default/files/2021/03/Statistics%20Electric%20Vehicles%20and%20Charging%20in%20The%20Netherlands%20up%20to%20and%20including%20January%202021.pdf. https://iea.blob.core.windows.net/assets/af46e012-18c2-44d6-becd-bad21fa844fd/Global_EV_Outlook_2020.pdf, https://easyelectriclife.groupe.renault.com/en/outlook/cities-planning/subsidies-in-germany-how-do-they-work/.

not be present (at this point in time) in other nations but may emerge over time. Indeed, there could be some general lessons learned from the Norwegian case for increased electrification in other policy domains.

First, the Norwegian electricity market is characterised by the majority of households using electricity for heating and other domestic energy purposes: about 90% of residential energy demand (incl. heating) is met by electricity. The *additional* electricity demand that stems from EV charging is therefore relatively small.[11] Hence, the need for additional electricity production capacity development to support further EV rollout is limited. The electricity market with flexible prices, production and trade, accommodates this increase in demand. Also, the need for additional investments in electricity grids is smaller in Norway than in most other countries (NVE 2020). In other nations, such as the UK, extensive network investment and cost recovery through user bills constrains household consumption for an extended timeframe, as shown by Alabi et al. (2020). Kühnbach et al. (2020), on the other hand, find that increased EV rollout may reduce electricity prices for households in Germany since the additional electricity demand increases the overall utilization of the grid. This result is based on an analysis combining four energy system models.

Second, the housing and settlement pattern in Norway is different from many other countries, with implications for charging infrastructure: more than 75% of households live in detached or semi-detached houses and can charge EVs at home, so that a decentralised load requirement prevails. On the other hand, sparsely populated areas and large distances imply that driving range is an issue that may limit how easily the households adopt EVs. Hence, investments in infrastructure for charging EVs are needed to promote the uptake of EVs, especially outside large cities. In more densely populated countries, investing in charging infrastructure may be easier and cheaper.

Third, the Norwegian electricity production is almost exclusively renewable (about 98% from hydropower and wind power). Hence, electrification of transportation will not increase emissions related to domestic electricity production, as would be the case in countries that are more reliant on fossil-fuelled electricity production and/or at a less advanced stage of deploying renewables, again such as the UK. However, Norway is connected to the European electricity market, with the implication that the electricity mix may involve higher indirect emissions. In short, increasing electricity import or reducing exports may change the total emissions from European electricity production. Nevertheless, electricity production is part of EU ETS, so any change in emissions is within the ETS quota (but would influence the EU ETS price).

Fourth, Norway has no domestic car industry. Consequently, the EVs must be imported, and these costs depend to a large extent on the technological developments in the rest of the world. Positive productivity impacts on car and technology industries would accrue both to importing and exporting countries. However, there could also be short- and medium-term transitional benefits and costs for the car industry and the wider economy. Countries with domestic car or battery production are likely to experience higher benefits (which might be counterbalanced by losses in conventional vehicle production). For example, Alabi et al. (2020) and Turner et al. (2018) find potentially offsetting losses in the UK manufacture of petrol and/or diesel-powered vehicles, with a risk of net contraction in wider industry if sufficient EV production does not locate within that nation. On the other hand, both studies show that more substantial wider economy gains may emerge from expansion in the electricity industry, where domestic supply chain content is significantly higher than in the production and

[11] The total electricity consumption for charging EVs with the 100% EV target has been estimated to be less than 4 TWh in 2030, which is less than 3% of Norway's total electricity consumption (NVE 2017).

distribution of petrol and diesel. The German car industry, which is the major supplier to the EU market, launched an ambitious EV strategy in 2019, presenting new EV models in 2019 and an ambitious plan for EV development towards 2025.

Fifth, high initial taxation of ICEs has made it easier to use tax exemptions for EVs in Norway, instead of direct subsidies/payments. Since the political cost of direct subsidies is likely to be higher than the cost of using tax exemptions, countries opting for subsidizing EVs rather than taxation of substitutes may find it more difficult to implement costly EV policies. On the other hand, Norway has made significant progress in the uptake of EVs already, with the implication that our baseline includes a high share of new EVs. Our results suggest that the costs of reaching 100% EV share are high at the margin, since policies that bring even more EVs into the car fleet increase the welfare loss of the initial taxation of ICEs. This implies that the costs of electrification of transport through EVs could be lower in other countries that are starting from a lower base (as long as they do not push to 100% target). For example, the Danish government's earlier policies towards promoting EVs have been characterised by an on-and-off-strategy, as direct subsidies and registration fee exemptions have changed from one year to another, resulting in a low market share for new EVs. The recently launched strategy has a clear plan of phasing out the subsidies towards 2030 (Kommisionen for grøn transport 2020).

These specific Norwegian features are all incorporated in our CGE model and play decisive roles for the analysis. Modelling EVs as a technology choice in private transportation and including all the favourable policies are pivotal for the policy analysis, in combination with the detailed modelling of Norway's ambitious climate policies and diverse policy instruments. Electrification of private transport cannot be separated from the characteristics of supply and demand for electricity in the rest of the economy, and all features of such interactions are modelled, in addition to the specific characteristics of Norway as a small, open economy with a trade-intensive, specialised industrial structure. There are a few studies of the Norwegian experience in partial models; see Aasness and Odeck (2015), Bjertnæs et al. (2011), Holtsmark and Skonhoft (2014), Aurland-Bredesen (2017). However, none of these allow for treatment that combines the features of Norway's ambitious EV goals and climate policies, a highly electrified economy and the imperfect substitutability between different technologies in private transportation, in an economy-wide consistent framework as a CGE-model.

In short, the implications of EV policies and lessons emerging from the analyses presented below are likely to be characterised by a combination of country-specific and more generic effects. Generally, our findings suggest that the cost of interacting and partly overlapping regulations in electrification of Norwegian private transportation is high, but elucidation of the drivers of these findings is intended to inform investigation as to the extent to which costs may be even higher or potentially lower in another national context.

3 Method: The CGE-Model SNOW

We use the CGE-model SNOW to analyse the impact of the interacting climate policies. SNOW is a multi-sector CGE model for the Norwegian economy (Rosnes et al. 2019; Bye et al. 2018; Fæhn et al. 2020), programmed in GAMS/MPSGE (GAMS 2020; Rutherford 1999). This type of model incorporates the interaction of all agents in the economy (consumers, producers and the government), and is particularly suitable for studying the impacts of a policy that affects several markets and creates repercussions in the whole economy (as opposed to a partial equilibrium model). The model assumes optimising agents: a representative household maximising utility and profit-maximising producers that interact in several markets. The model finds equilibrium prices and quantities by simultaneously solving the set of equations that satisfy the profit-maximisation and utility-maximisation conditions. The solution determines production, consumption, export and import levels for all goods, input use in each industry, relative prices of all goods and input factors (labour, capital and energy resources), and emissions to air. The consumer price index is numeraire. A stylized version of the model is presented in Appendix 2.

Labour and capital are perfectly mobile between industries, implying that firms' investments can take place incrementally and instantaneously, and the labour market is always in equilibrium. Total capital inflow is given in the base year and then endogenized in line with domestic investment, which in turn is determined by household saving in each period, since the representative household receives all income in the model.[12] Total capital is distributed to domestic sectors equalising the real rate of return between sectors within the Norwegian economy. In focussing the analysis on overlapping climate regulations, we follow a standard national CGE modelling assumption that total labour supply is exogenous and fixed in each time period.

The model is of a small, open economy; thus, the world market prices are considered as exogenous. Domestic and imported goods are considered imperfect substitutes and goods used in the domestic market correspond to a constant elasticity of substitution (CES) aggregate of domestically and imported goods in line with Armington (1969) modelling. Similarly, production in each sector consists of goods sold to the domestic and international market with a constant elasticity of transformation (CET) function.

Emissions of seven GHGs (CO_2, CH_4, N_2O, HFK, PFK, SF_6, NF_3) are included, in addition to other pollutant compounds (NO_x, SO_2, NH_3, NMVOC, PM_{10}, $PM_{2,5}$), see Sect. 3.3 for more details. The model includes a detailed module of consumers' choice between EVs and conventional ICEs cars (incl. vintages), see Sect. 3.1.1.

The model is calibrated to the Norwegian national accounts and environmental accounts from Statistics Norway.[13] The input–output tables are prepared by Statistics Norway.[14]

As the analysis focuses on policies targeted in 2030, we use a dynamic recursive version of the model to make a projection of the Norwegian economy in 2030. In the dynamic recursive model, investments depend on previous year's prices, implying "backward-looking" expectations. Recursive models provide greater flexibility in details of the modelling and policies that can be analysed, compared to forward-looking models, see Babiker et al. (2009). Details of the modelling of households' savings and firms' investments are given below, see also the stylized model in Appendix 2.

Besides parameters (elasticities) describing behavioural characteristics, the main exogenous factors driving the sectoral and macroeconomics results are demographic development, international market prices, government policies including taxes and subsidies, and sector- and factor-specific productivity growth rates. The productivity growth rates and emission coefficients can be exogenously adjusted to represent technological improvements. Our baseline projection is described in Sect. 4.1.

[12] We also include the imported and exported capital on top of the domestic capital. The share of capital import and export is, however, small.

[13] The base year of the model is 2013.

[14] https://www.ssb.no/en/nasjonalregnskap-og-konjunkturer/metoder-og-dokumentasjon/supply-and-use-and-input-output-tables.

3.1 Households

SNOW features a representative household that owns and receives net-of-tax income from labour, capital and natural resources as well as transfers from the government. Tax revenue (net of subsidies) is collected by the government, but reallocated to the household sector, so that all tax revenue eventually goes to the household. The representative household maximises utility subject to the income constraint, while labour supply is exogenous in this model version.[15] Household savings are determined endogenously by a Cobb–Douglas function of consumption and savings, see Appendix 2 for more details.

Households' utility maximisation determines total consumption demand. The consumption demand system is determined by a nested Constant Elasticity of Substitution (CES) function as depicted in Fig. 1.[16] The CES-function includes all the necessary information of demand for all goods: relative end user prices (including relevant taxes and subsidies) of the goods and the degree of substitutability between them, reflecting the consumers' preferences.

At the top level, CES-aggregates of housing services, transport services and other goods and services are combined (and can substitute each other) to give total material consumption. At the second level, the CES function describes the three main aggregates as combinations of dwellings and energy use (in housing services), public and private transport (in transport services), and all other goods and services (see Table 10 in Appendix 1 for the complete list of all goods for final consumption). The third level in the energy-in-housing aggregate specifies substitutable energy sources. The consumer can choose between the following sources for residential heating: electricity, district heating, gas, paraffin and heating oil, coal, fuel wood and pellets. The expenditure share for electricity is about 90%.[17] In the transport nest, there are substitution possibilities between public and private transport, between new and old cars, and between electric vehicles and conventional cars.[18] Section 3.1.1 describes the private transportation in detail.

3.1.1 Private Transport and EVs

The representative household's demand for transport services is modelled in detail, see Fig. 1. At the second level in the consumer demand system, transport services model substitution between private and public transport. In *public transport*, road, rail, air, and sea

[15] The annual labour supply is based on population projections from Statistics Norway and employment rate projections from the Ministry of Finance.

[16] The nested CES function (see Varian 1992) is common in CGE models. The functions nest commodities and quantify their use according to values for share parameters and substitution elasticities. It is possible to specify different substitution elasticities at all levels in the nested CES function. At the outset, the elasticities are set in accordance with estimates from relevant econometric literature (Aasness and Holtsmark 1993; Hertel et al. 2012; Reimer and Hertel 2004; Narayanan et al. 2012); however, the model user can set the substitution elasticities that are considered relevant. For example, in fields with rapid technological change, new substitution possibilities may emerge or old ones become less relevant, see e.g. Bye et al. (2018) and further discussion in Sect. 3.1.1. Table 12 in Appendix 1 lists values of the elasticities used in this analysis.

[17] Fuel wood constitutes the largest part of the remaining residential energy consumption. Gas distributed through networks and district heating are very limited in Norway, while use of heating oil is forbidden from 2020.

[18] Other examples of nested CES functions modelling new transport technologies include e.g., Karplus et al. (2010). See also Bye et al. (2018) for more details and an example of how a CES function can encompass technological improvements.

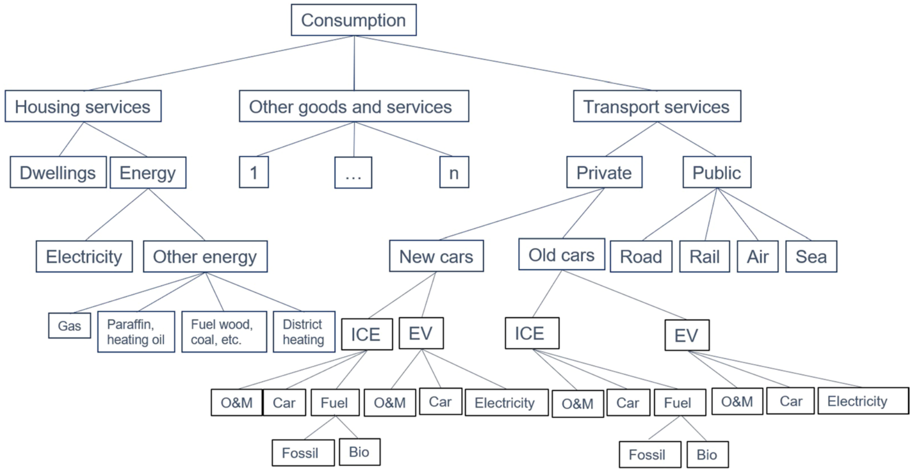

Fig. 1 The CES function of private material consumption in SNOW. See Table 12 in Appendix 1 for elasticities in the consumption function

transport are specified as substitutable choices. *Private transport* is split into use of old and new cars, tracking annual policy changes and purchase shares of new cars that changes rapidly (in contrast to Karplus et al. (2013a) that use five-year vintages of PHEVs and ICEs). *Old and new cars* are further split into electric vehicles (EV) and conventional vehicles with internal combustion engines (ICE), to keep track of the development of the stock of each car technology and the resulting emission effects.[19]

In the following we describe the CES cost functions in the model of private transport in more detail. In all the cost functions the parameters θ represent the value share of corresponding input in the composite good in the benchmark. Note that the benchmark values are represented with bar (e.g., $\overline{P}_{PRV}$). The parameters σ represent elasticities of substitution in the CES functions.

For the representative household, the choice between services from new and old cars at the top level of the private transport composite is described by:

$$\frac{P_{PRV}}{\overline{P}_{PRV}} = \left[\theta_{NCAR}\left(\frac{P_{NCAR}}{\overline{P}_{NCAR}}\right)^{1-\sigma_{on}} + \theta_{OCAR}\left(\frac{P_{OCAR}}{\overline{P}_{OCAR}}\right)^{1-\sigma_{on}}\right]^{\frac{1}{1-\sigma_{on}}} \tag{1}$$

where P_{NCAR} and P_{OCAR} are the prices of the composite of the services of new and old cars, respectively. The elasticity of substitution between old and new cars is 10, which implies that old and new cars are considered as very close substitutes.

At the next level, when buying a new car, the representative household can choose between an EV and an ICE:

[19] Ordinary hybrid cars are classified as ICE as they use only petrol/diesel, and thus they are simply more efficient ICEs. Plug-in hybrids (PHEV) are currently grouped together with ICEs in the model, since they constitute only a small share of new cars in Norway.

$$\frac{P_{NCAR}}{\overline{P}_{NCAR}} = \left[\theta_{NEV} \left(\frac{P_{EV}^{new}\left(1 - s_{EV}\right)}{\overline{P}_{EV}^{new}\left(1 - \bar{s}_{EV}\right)} \right)^{1-\sigma_{trpr}} + \theta_{NICE} \left(\frac{P_{ICE}^{new}\left(1 + t_{ICE}\right)}{\overline{P}_{ICE}^{new}\left(1 + \bar{t}_{ICE}\right)} \right)^{1-\sigma_{trpr}} \right]^{\frac{1}{1-\sigma_{trpr}}} \tag{2}$$

P_{EV}^{new} is the price of services of new EVs and P_{ICE}^{new} is the price of services of new ICEs, see Eqs. (4) and (5) below. The parameters s_{EV} and t_{ICE} represent implicit subsidies and taxes on EVs and ICEs. We come back to the interpretation and calibration of these below. There is a similar choice between EVs and ICEs when choosing between the services of old cars:

$$\frac{P_{OCAR}}{\overline{P}_{OCAR}} = \left[\theta_{OEV} \left(\frac{P_{EV}^{old}\left(1 - s_{EV}\right)}{\overline{P}_{EV}^{old}\left(1 - \bar{s}_{EV}\right)} \right)^{1-\sigma_{trpr}} + \theta_{OICE} \left(\frac{P_{ICE}^{old}\left(1 + t_{ICE}\right)}{\overline{P}_{ICE}^{old}\left(1 + \bar{t}_{ICE}\right)} \right)^{1-\sigma_{trpr}} \right]^{\frac{1}{1-\sigma_{trpr}}} \tag{3}$$

The price of services of EVs (P_{EV}^{r}) consists of the annual rental value (user cost of capital) of EV (P_{EV}^{cap}), the price of electricity consumption (P_{ELE}) and other costs as service and maintenance costs ($P_{i,EV}$). t_{EV}^{r} is the combined registration tax and VAT on car purchase, which are both zero for EVs in the present car tax system (see Table 1). The set *r* represents old or new vehicles and the set *i* represents the good or service.

$$\frac{P_{EV}^{r}}{\overline{P}_{EV}^{r}} = \left[\theta_{ceev}^{r} \left(\frac{P_{ELE}}{\overline{P}_{ELE}} \right)^{1-\sigma_{ceev}} + \left(1 - \theta_{ceev}^{r}\right) \left(\theta_{evcar}^{r} \left(\frac{P_{EV}^{cap}\left(1 + t_{EV}^{r}\right)}{\overline{P}_{EV}^{cap}\left(1 + \bar{t}_{EV}^{r}\right)} \right) + \sum_{i} \theta_{i,EV}^{r} \left(\frac{P_{i,EV}}{\overline{P}_{i,EV}} \right) \right)^{1-\sigma_{ceev}} \right]^{\frac{1}{1-\sigma_{ceev}}} \tag{4}$$

Similarly, the price of services of ICEs (P_{ICE}^{r}) consists of the rental value of ICE (P_{ICE}^{cap}), petrol/diesel consumption (P_{CPAD}), and other costs ($P_{i,ICE}$):

$$\frac{P_{ICE}^{r}}{\overline{P}_{ICE}^{r}} = \left[\theta_{cpad}^{r} \left(\frac{P_{CPAD}}{\overline{P}_{\mathrm{CPAD}}} \right)^{1-\sigma_{cpad}} + \left(1 - \theta_{cpad}^{r}\right) \left(\theta_{icecar}^{r} \left(\frac{P_{ICE}^{cap}\left(1 + t_{ICE}^{r}\right)}{\overline{P}_{ICE}^{cap}\left(1 + \bar{t}_{ICE}^{r}\right)} \right) + \sum_{i} \theta_{i,ICE}^{r} \left(\frac{P_{i,ICE}}{\overline{P}_{i,ICE}} \right) \right)^{1-\sigma_{cpad}} \right]^{\frac{1}{1-\sigma_{cpad}}} \tag{5}$$

The service prices of the EVs and ICEs include all relevant taxes and fees, i.e. the registry tax on purchase of new cars, the electricity tax that is included in the purchaser price of electricity and the road use tax and the CO_2 tax that are included in the purchaser price of gas/diesel. All purchaser prices include VAT. Hence, the total costs of choosing an EV or ICE are modelled including taxes, subsidies and the non-fiscal advantages.

Consumption of fossil fuel (petrol/diesel) and electricity is based on the stock of old and new cars. The electricity consumption per EV is based on an exogenous efficiency parameter. The model accounts for the increase in total household electricity consumption associated with electric vehicles as the number of EVs increases as part of the electricity market. As both electricity prices and petrol and diesel prices are endogenous, climate policies that alter the relative prices will influence both the households' choice of vehicle and the level of driving activity, and, ultimately, through households' demand also the energy markets and the production of electricity and petrol and diesel.

3.1.2 Calibration of the EVs in the Base Year and in the Baseline to 2030

The modelling of private vehicles is calibrated to tally with the 2018 stock of EVs and ICEs. For calibration purposes, we use 2014 figures to account for households' electricity consumption for charging EVs and the sales share of EVs. The reason for using 2014 data (and not data from the base year 2013) is that it is difficult to calibrate the nested CES structure when the share is very small, as is the case for EVs in 2013.[20]

The EV projections for 2020–2030 in the baseline are fitted to match the official projections for EV shares in Norwegian Environmental Agency (2020). The exogenous world market price of imported EVs falls 20% from 2014 to 2018 and is assumed to fall 5% annually in 2019–2023 and further 2.5% annually in 2024–2030, based on technology projections from Zamorano (2017). Overall, the real import price of EVs falls approximately 50% from 2020 to 2030, while the real import price of ICEs remains nearly the same in this period. The real import price of EVs was about 20% higher than that of ICEs in 2020; hence, the price development implies that new EVs are relatively cheaper to purchase than ICEs in 2030.[21] The phase-in rate of EVs, EV prices and substitution elasticity are exogenous.

We use the implicit subsidy and tax parameters s_{EV} and t_{ICE} to capture the non-fiscal advantages of EVs as the calibration instruments. The non-fiscal advantages to EV users, e.g., free parking, access to bus lanes, lower road toll etc., are assumed to be extended to 2030, aligning with the official projections in Norwegian Environmental Agency (2020).

The elasticity of substitution between EVs and ICEs (σ_{trpr} for new cars in Eq. 2) reflects the consumers' preferences about the two types of cars and hence captures the substitutability between EVs and ICEs. The higher the elasticity, the more similar are the attributes of EVs and conventional cars. This substitutability will be higher as the EV technology improves, in particular with increased driving range and better access to charging facilities. Technological development of EVs is also captured by a falling real price of EVs at the world market.

The EV technologies and available EV models have developed substantially over the last few years and are, thus, considered to be much closer substitutes to conventional cars in 2020 than just a few years ago, with substitutability expected to increase further over the next years. In the calibration of the baseline to 2030, the elasticity of substitution increases from 0.5 in 2013 (base year) to 4 in 2020 and to 8 in 2030, as in Fæhn et al. (2020). The choice of 0.5 in the base year mirrors the attributes of the available EV models in 2014: a small car with short driving range and low driving comfort, mostly suitable for short distance commuting, as charging possibilities were scarce. As such, it was often a second car in a household (i.e., complemented the family's first car, an ICE). A recent study of Norwegian car ownership finds that EVs are becoming closer substitutes to ICEs and households now are more likely to sell their old car when they buy an EV than was the case 5–10 years ago (Fevang et al. 2021). Increasing the elasticity of substitution between EVs and conventional cars to 8 in 2030 indicates that they will become almost perfect substitutes. The literature of relevant elasticities seems to be very scarce, however, some recent contributions support our assumptions: Fridstrøm and Østli (2021) estimate a cross-price elasticity of 0.36 for EVs and gasoline-driven ICEs, and 0.48 for EVs and diesel-driven ICEs, based on Norwegian data. This corresponds to a CES elasticity of substitution of around 0.5–0.7

[20] EVs counted for 6% of purchases of new private cars in 2013, and for 13% in 2014 (https://elbil.no/elbilstatistikk/).

[21] The observed price difference in 2020 is consistent with our model. The import prices of an average ICE and EV were 392,500 NOK and 480,000 NOK, respectively, in 2020, according to the Norwegian Environmental Agency (2020).

in 2018 and 7.2–9.6 in 2030 (assuming increased market share of EVs).[22] Johansen (2021) estimates, also based on Norwegian data, a cross-price elasticity of EVs of 0.71. Both studies emphasize that the cross-price elasticities are highly context-specific, as they depend crucially on market shares.

Combined with the knowledge that EVs are becoming closer substitutes to ICEs (Fevang et al. 2021), we conclude that EVs are substitutes to public transport in the same way as conventional cars in Norway. Transport in Norway is characterised by the country being scarcely populated, hilly and with a quite rough climate for at least 4–6 winter months. The largest share of the absolute number of trips taken is by private car, while public transport counts for 10%, cycling for 4%, and walking for the remainder.[23] These shares have been fairly stable over the last years.[24] However, note that these shares are for the number of trips; if measured in kilometres, the share of biking would be much smaller.

3.2 Production

The model specifies 47 production sectors, producing one good each, with one representative producer in each sector. The sectoral disaggregation enables us to study climate policies and emissions from different industries in detail. There are five energy-producing industries: coal, oil and gas extraction, refined coal and oil products, gas distribution, and electricity. Other emission-intensive industries (such as basic metals, cement, etc.) are also modelled as separate industries, as well as three different transport sectors (land, air and water transport), see Table 9 in Appendix 1 for the full list of industries. In addition, there are 24 final consumption goods (see the list in Table 10 in Appendix 1).

The production technologies are described by nested CES functions, where combinations of capital, labour, energy, and intermediate products are inputs in production.[25] Figure 2 shows the separability structure of the production functions. Substitution among inputs is possible at all levels, except in the nests marked with L (Leontief) on Fig. 2. See Table 11 in Appendix 1 for other elasticities.

3.3 Emissions

The SNOW model features a more detailed modelling of emissions than most CGE models. Emissions from both energy use and industrial processes are modelled. In particular process emissions are absent in most CGE studies, Bednar-Friedl et al. (2012) and Bye et al. (2018) being notable exceptions.

Energy-related emissions are linked to the use of fossil fuels with coefficients differentiated by the specific carbon contents of the fuels, see Fig. 2. The disaggregation of energy goods into coal, crude oil, natural gas, refined oil products and electricity is essential to

[22] See Berck and Sydsæter (1995) ch. 4 for the relationship between price elasticities and substitution elasticities.

[23] In the main city Oslo the pattern deviates to some extent, with private driving and public transport account for 25% each, while cycling is around 8%, so that about 40% of trips (by absolute number) involve walking (https://www.oslo.kommune.no/statistikk/miljostatus/reisemiddelfordeling/#gref).

[24] https://syklistforeningen.no/aktuelt/4-prosent-sykkelandel-i-2020/.

[25] The quantifications differ among commodities and are based on conventional estimations, see Andreassen and Bjertnæs (2006), in addition to other pertinent literature as collected in the GTAP database, see Narayanan et al. (2012). See Table 11 in Appendix 1 for the values of the elasticities used in the model.

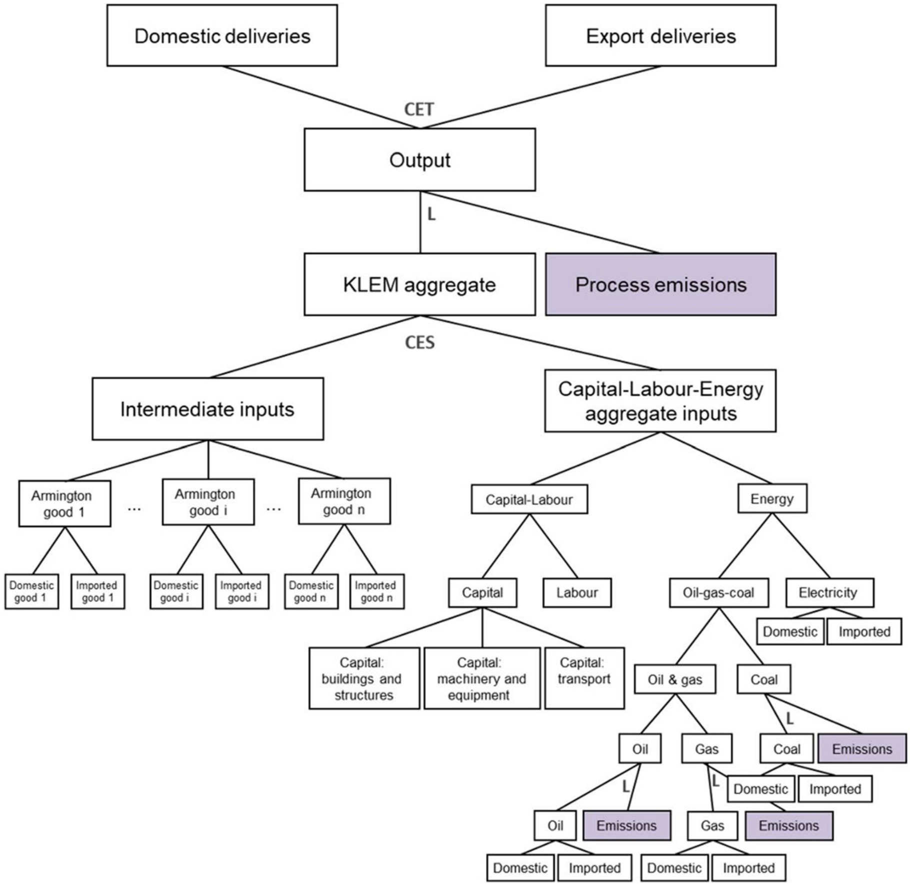

Fig. 2 Nested CES production function in SNOW, with emissions highlighted. L on the figure notes Leontief (substitution elasticity equals zero). See Table 11 in Appendix 1 for other elasticity values

differentiate energy goods by emission intensity and degree of substitutability. Similarly, the final consumption goods are disaggregated into petrol and diesel and electricity in transport, and into various fuels in housing (see Fig. 1). Abatement of the energy-related emissions can be achieved by substitution between the energy goods, substitution of capital or other goods for energy (i.e., investing in technologies with higher energy efficiency), or reducing production in industries and/or final consumption.

Emissions from industrial processes are linked to output level, see 'process emissions' in Fig. 2. These emissions are not related to energy use, but stem from chemical processes, for instance in the production processes of aluminium and cement, and from animal husbandry in agriculture. Abatement of process emissions can be achieved by reducing output (endogenously) or by introducing new technologies (exogenously).

The sectoral distribution of emissions is shown in Fig. 3. ETS covers emissions from industry and energy, oil and gas extraction, and most of air transport, while other transport, in particular road transport, and agriculture are important for non-ETS emissions.

3.4 Government

The government collects taxes, purchases goods and services from domestic sectors and abroad to provide public services and distributes subsidies and transfers to the representative household. Overall government expenditure is exogenous and increases at a constant rate as the general economy grows. The revenue from all taxes accrues to the government, which can use the tax revenues on public goods and services, as deposits in the Government Pension Fund Global or as transfers.[26] Surplus tax revenue over that required to fund (exogenous) government consumption and investment is reallocated to the household sector, so that all tax revenue eventually services households.

The model incorporates a detailed account of government revenue and expenditure. The government revenues in SNOW are from income tax, product and production taxes, taxes related to emissions and labour costs including employers' taxes. All taxes and fees are included as percentage (ad valorem) rates in the model, and all taxes are net taxes (taxes minus subsidies).[27]

4 Analysis: Costs of Overlapping Climate Policies

4.1 The Scenarios

Our scenarios are based on the Norwegian climate policy goals for 2030, which are part of Norway's road to a low emission society. Norway's climate policy is linked to that of the EU, and Norway participates in the EU emission trading system EU ETS (Ministry of Climate and the Environment, 2022). In the updated National Determined Contributions to the Paris Agreement (NDC 2021), Norway commits to reduce the total GHG emissions 50–55% in 2030, compared to 1990. For the non-ETS sectors, the ambition is to reduce the domestic emissions 50% by 2030, compared to 2005.[28]

We analyse two interacting and partly overlapping climate regulations in transportation and the consequences for the abatement costs in the non-ETS sectors and for economy-wide welfare costs in 2030: the 50% cap on GHG emissions in the non-ETS sectors in 2030 compared to 2005 level (Norwegian Environmental Agency 2020) and the 100% market share of new EVs for private households in 2030 (Ministry of Climate and Environment 2021).

[26] The fiscal policy rule is adhered to in each year by assumption.

[27] All quantity-based taxes, such as taxes on alcohol, petrol etc., are transformed to average ad valorem tax rates by using base year tax income divided by base year tax base, see Rosnes et al. (2019) for more details. This is standard procedure in MSPGE-based CGE models, Rutherford (1999).

[28] The non-ETS ambition is 50% reduction from 2005, but since the emissions in 2005 are almost identical to the emissions in 1990, this goal is in line with Norway's NDCs.

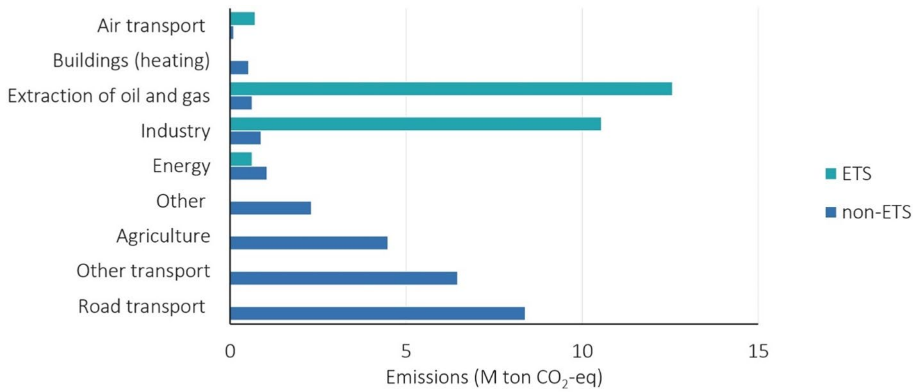

Fig. 3 Emissions from ETS and non-ETS industries, 2020, mill. ton CO_2-eq. Source: Norwegian Environmental Agency and Statistics Norway, https://miljostatus.miljodirektoratet.no/tema/klima/norske-utslipp-av-klimagasser/klimagassutslipp-og-kvoteplikt/

4.1.1 Baseline

We analyse the effects of the climate policies as compared to a *baseline*. Our baseline is based on the government's projection prepared for Klimakur 2030 (Fæhn et al. 2020; Norwegian Environmental Agency 2020). This is a business-as-usual path, based on standard assumptions about demographic and technology development and current climate policies in Norway (see e.g., Ministry of Finance 2017b). The rest of the world (most importantly the trade partners and the EU) are supposed to follow a similar path, with no additional climate policies. The EV projections in the baseline are fitted to match the official projections for EV shares in 2030 in Norwegian Environmental Agency (2020), as described in Sect. 3.1.1. The existing taxes on ICEs and tax exemptions for EVs (as described in Sect. 2.1), are included in the numerical model and kept unaltered in all scenarios.

With these assumptions, Norwegian GHG emissions are projected to approximately 47.3 M ton CO_2-eq in total in 2030, distributed on 20.3 M ton in non-ETS sectors and 27 M ton in ETS sectors. A 50% reduction of GHG emissions in the non-ETS sectors relative to 2005 implies a cap on non-ETS emissions of 14.8 M ton CO_2-eq in 2030. The baseline projected emissions in 2030 are approximately 5.6 M tons CO_2-eq higher and this gives the emission reduction target in the non-ETS sectors.[29]

4.1.2 Climate Policy Scenarios

We implement the climate policy scenarios in the model as follows:

- *Cap-only scenario*: the exogenous cap on GHG emissions in non-ETS sectors (amounting to approximately 14.8 M ton CO_2-eq in non-ETS sectors in 2030) determines a uniform carbon price in the non-ETS sectors. The uniform carbon price replaces today's differentiated CO_2 taxes. The carbon price applies to all GHG emissions and is measured in EUR/ton CO_2-eq.

[29] The ETS-industries are subject to the cap in the EU ETS market.

- *Cap and EV target scenario*: The emission cap in the non-ETS sectors is *supplemented* with the specific EV target, requiring that all new cars sold to private households are EVs by 2030.[30] The exogenous emission cap and EV target determine the uniform carbon price and the new (implicit) subsidy to EVs that is necessary to reach the EV target (see Sect. 3.1.1).

We also analyse the effects of the *EV target only*, to isolate the effects of an EV target without emission cap. In this case, all new cars sold to private households are EVs by 2030.[31] Since there are no additional regulations in the other non-ETS sectors, the emission reduction in this scenario is much smaller.

Note that some abatements in commercial transportation and agriculture are implemented exogenously in the policy scenarios. In line with Fæhn et al. (2020) and Norwegian Environmental Agency (2020) that our baseline builds on, we include emission reduction measures that have costs well below the endogenously calculated non-ETS emission prices.[32] These exogenous emission reductions in agriculture and commercial transportation are the same in both policy scenarios.

The nominal deficit and real government spending are required to follow the same path in the policy scenarios as in the reference scenario, implying revenue neutrality in each period. The excess tax revenue (negative or positive) from the emission pricing and changes in other governmental revenues in the policy scenarios are distributed as lump-sum transfers to the representative household. Household savings are exogenous, equal to the savings in the baseline, in the policy scenarios.

In addition to the policy scenarios, we perform several sensitivity analyses. These are discussed in Sect. 5.

4.2 Macroeconomic Effects

Since the climate policies are defined and targeted for 2030, we concentrate our analysis on the effects in this year. By using the dynamic recursive version of the model, we can calculate the results in 2030 for the different scenarios, even though 2030 is not necessarily characterised as a long run steady state solution, but rather as a point on the path to a new, long run equilibrium.[33] We measure the effects in the scenarios as relative (percentage) changes from the baseline. The relative changes are not sensitive to the number of periods in the simulations.

[30] The target is implemented as 99.9% in the simulations to solve the model.

[31] The initial CO_2 taxes are kept at the same level as in the baseline.

[32] This includes measures such as transition from red meat to plant-based diet and reduced food-waste in agriculture. In commercial transportation emissions are reduced by introduction of biofuels and electric/hydrogen trucks and city buses. Fæhn et al. (2020) provides more details of the modelling of these measures.

[33] We have tested the stability of the results in the baseline by extending the simulation period. The results are robust to the number of periods.

4.2.1 Cap-Only Scenario

In the cap-only scenario, the carbon price that is necessary to close the emission gap in non-ETS sectors reaches 419 EUR/ton CO_2-eq in 2030.[34] This is almost seven times higher than the current carbon tax that most non-ETS sectors pay in the baseline.[35] The higher carbon costs imply higher production costs in all non-ETS industries. Higher costs lead to lower production in many industries, and to lower demand for labour and capital in these industries. Labour and capital are reallocated to other industries and real wage rate and the real rate of return to capital fall by 1.7% and 2.2%, respectively (see Table 2, first column of results).

Lower labour and capital prices benefit labour and capital-intensive industries. Capital-intensive non-ETS industries, such as production of machinery and metal products and other manufacturing (leather goods, textiles and food products), expand. Likewise, labour-intensive industries, such as business services, expand. For these industries, lower capital and labour costs outweigh the increase in emission costs.

The ETS-industries (aluminium, iron and steel and cement) also benefit from lower capital and labour prices. (Recall that carbon prices in the EU ETS market are the same in all scenarios.) They substitute labour and capital for intermediates and energy, while their output level is approximately unaltered, suggesting that they become relatively more capital and labour intensive. Output of energy-producing industries (refineries and oil/gas extraction) declines, as a response to lower demand for fossil fuels from other industries.

GDP falls by 0.2%. The exchange rate appreciates to adjust to the fixed current account, benefitting especially industries that import intermediates.

The household sector ultimately receives all income in the economy and this income falls, with consequent reductions in consumption of all goods and services. Price increase is substantial for transport activities, following the sevenfold increase of the carbon price, and this leads to large substitution effects in consumption. The consumer price of petrol and diesel increases more than 50% because of the carbon price increase, and there is a large substitution from ICEs to EVs in households. Use of petrol and diesel for transport purposes by households falls by 31% while electricity used for EVs increases by almost 10% (Table 3). The market share of new EVs to households increases to 88% (from 75% in the baseline), see Table 4. Consumption of housing and residential energy use are reduced, including households' demand for electricity for housing purposes, which falls by 1.9%. The cap-only policy leads also to substitution from public transport to private EV transport. The price of public transport increases (except air transport) and consumption of both road, rail, and water transport is reduced by 0.5 to 1.2%.

Overall, total welfare, measured as the equivalent variation, falls by 1.0% (Table 2). This is the welfare cost of the cap-only scenario. The carbon price interacts with other policies and distortions in the economy which are represented in our model, so the welfare cost is a mix of the direct abatement costs of the carbon cap and the carbon price's interaction effects with other policies and distortions. Fæhn et al. (2020) identify that the direct abatement costs make up approximately 40% of the total welfare cost of the cap, and the

[34] The EU ETS price is exogenous and equal in all scenarios, 42 EUR/ton CO_2-eq in 2030 (increasing from 28 EUR/ton CO_2-eq in 2020). Exchange rate of 0.128 EUR/NOK is used (2013 value). Sensitivities of the ETS price are provided in Sect. 5.4.

[35] Note that since the original carbon tax was not equal, some industries experience relatively larger cost increase than others.

Table 2 Main macroeconomic results, 2030. Change (%) from baseline; absolute values for carbon price

	Cap-only	Cap and EV target	EV target only
Carbon price for non-ETS industries (EUR/ton CO_2-eq)[a]	419	228	Same as in baseline [b]
GDP	−0.2	−0.4	−0.3
Welfare[c]	−1.0	−2.5	−2.0
Real wage rate	−1.7	−0.3	0.7
Real return to capital	−2.2	−1.2	0.2
Capital use	−0.1	−0.2	−0.2
Exchange rate (NOK/foreign currency)	−0.3	0.2	0.4

[a]The EU ETS price is exogenous and equal in all scenarios

[b]All industries have the same non-uniform CO_2 tax as in the baseline

[c]Measured as the equivalent variation (percentage change relative to the benchmark income)

favourable EV policy as one of two other main sources for interaction effects with the carbon pricing that causes welfare loss.[36] A rule of thumb is that increasing consumption of goods that are heavily taxed initially (as ICEs and petrol and diesel) contributes positively to welfare, while increasing consumption of goods that are heavily subsidised initially (as purchase and use of EVs) will contribute negatively to welfare, as is confirmed in this scenario with increased purchases and use of EVs and a substantial reduction in purchases and use of ICEs.

4.2.2 Cap and EV Target Scenario

When the cap and EV target are combined the carbon price is 228 EUR/ton CO_2-eq, about half of that in the cap-only scenario. As the total cap for emissions from the non-ETS sectors is the same in all scenarios, less abatement is needed from other non-ETS sectors when households replace the rest of their new fossil-fuelled cars with EVs. Hence, the most expensive abatements in other sectors can be avoided, and this transforms into a lower emission price for the whole non-ETS segment.

The lower emission price benefits all other non-ETS sectors by reducing production costs, and the decline in output level in most industries is smaller than in the cap-only scenario. The fall in demand for labour and capital is smaller than in the cap-only scenario, consequently, wage rate and return to capital are reduced less than in the cap-only scenario (Table 2).

However, GDP declines 0.4% compared to baseline, twice as much as in the cap-only scenario. This illustrates that the economy is less efficient in reducing the emissions when such overlapping policies are present. Even though the most expensive emission abatements in the non-ETS production sectors are avoided, the total costs to the society are higher. In particular welfare is reduced by 2.5% compared to the baseline. In other words, the additional target on new EVs comes at a cost. As welfare falls two and a half

[36] The other wedge is taxes that influence the real wage rate, interfering with the labour-leisure choice. With exogenous labour supply this effect is absent from our analysis. The wedges and imperfections in the current version of the SNOW model in climate policy analysis are thoroughly discussed in Fæhn et al. (2020).

Table 3 Household consumption of energy and transport goods, electricity production and trade, 2030. Change (%) from baseline

	Cap-only	Cap and EV target	EV target only
Electricity production	−4.5	−4.7	0.0
Electricity net import	14.6	14.2	2.3
Household consumption:			
Purchases of EVs	18.6	57.0	55.0
Purchases of ICEs	−53.1	−98.0	−98.0
Petrol and diesel	−30.9	−49.8	−42.9
Electricity use for EV charging	9.6	22.7	22.6
Electricity use for residential purposes	−1.9	−3.5	−1.9
Public road and rail transport	−1.2	−3.1	−2.9

Table 4 EVs in private transport, 2030

	Baseline	Cap-only	Cap and EV target	EV target only
EV sales (share of total car sales for households)	75	88	100	100
EV stock (share of total private vehicle stock)	59	64	69	69
Shadow price of EVs to households (rate)	23	23	34	36

times more than in the cap-only scenario, this leads to a considerable negative income effect on consumption of all goods and services. The only exception is the increase in the number of EVs and accordingly also consumption of electricity used for charging EVs, which is almost 23% higher than in the baseline (compared to the 10% increase in the cap-only scenario), see Table 3. Households' spending on EVs is nearly 60% higher than in the baseline and 30% higher than in the cap-only scenario.

Net imports of electricity increase to meet the higher demand for charging EVs. The exchange rate depreciates to keep the current account fixed, making imports, including more import of EVs, more expensive.

The increased roll-out of EVs is achieved by an implicit subsidy to EVs (see Sect. 3.1.1 for more details on modelling). This subsidy represents a shadow price on EVs to households. The shadow price of increasing the market share of new EVs to 100% amounts to 34%, an increase of 50% compared to the baseline and cap-only scenario where the shadow price is 23% (Table 4). This illustrates that more incentives (in the form of more benefits to EVs and higher GHG price or restrictions on ICEs) are needed to reach the EV sales target of 100%. This is also confirmed by our cap-only scenario, which demonstrated that an EV market share of 100% new EVs in 2030 was not reached with the carbon price of 419 Euro/ton CO_2-eq (see Table 4). We find that the 100% market share of new EVs comes at a considerable welfare cost—the welfare loss is more than doubled (i.e., 250% higher) in the cap-and-EV target scenario compared to the cap-only scenario. Thus, policy actions that bring even more EVs into the car fleet increase the welfare loss of the initial taxation of ICEs.

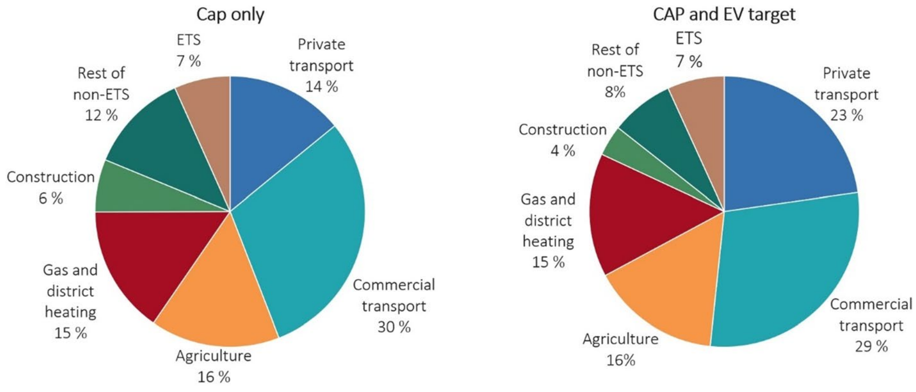

Fig. 4 Emission reduction (as share of total CO_2 emission reduction in scenarios)

4.3 Emissions

The cap on emissions in the non-ETS sectors implies a nearly 15% reduction in emissions from the baseline in 2030. In the cap-only scenario, transportation contributes most to the emission reduction, followed by gas and district heating, agriculture and forestry, and construction industries (see Fig. 4).[37] Emissions from commercial transport are reduced by 85%, while emissions from private transport are reduced by 31%, compared to baseline (Table 5). However, the share of emission reductions is approximately 30% in both scenarios for commercial transport (Fig. 4).

In the cap-and-EV target scenario emissions from private transport are 30% (0.5 M ton) lower than in the cap-only scenario, while emissions from the other industries are 0.5 M ton higher (particularly emissions from commercial transport, construction, water transport, food products and fisheries). The cap, combined with the EV target, implies that households take a larger share of the emissions reductions compared to the cap-only scenario.

4.4 Decomposition of the Effects: EV Target Only

In this scenario we study the effects of only imposing the EV target of a 100% market share of new EVs in 2030, without the cap and uniform emission pricing in the non-ETS sectors. Rather, the CO_2 taxes are kept as in the baseline, which implies that there are non-uniform CO_2 taxes. This scenario highlights the effects of imposing a specific regulation on private transport without regulating carbon emissions by an additional cap.

Some interesting results emerge as we consider the results in the tables. Firstly, the emission reduction goal is not reached in this scenario: emissions are only reduced by 1 M ton CO_2, not 5.6 ton, as is the goal for non-ETS sectors. Emissions from private transport fall, but, with no cap on non-ETS emissions, the other industries have no incentives to

[37] Recall that abatements in commercial transportation and agriculture are implemented exogenously in the analysis, as explained in Sect. 4.1.2.

Table 5 Emissions from non-ETS sectors, 2030. Change from baseline

	Cap-only	Cap and EV target	EV target only
Emissions (relative change from baseline, %)			
Total emissions in non-ETS sectors	−27.5	−27.5	−5.7
Private transport	−31	−50	−43
Commercial road and rail transport	−85	−82	3
Road transport in total	−54	−63	−23
Emissions (change from baseline, M ton CO_2)			
Total emissions in non-ETS sectors	−5.6	−5.6	−1
Private transport	−0.9	−1.4	−1.2
Commercial road and rail transport	−1.8	−1.7	0.1

reduce emissions. Second, private consumption is 2% lower than in the baseline, a slightly smaller reduction than in the cap-and-EV-target scenario (see Table 2).

The crucial conclusion is that the welfare costs of the 100% EV target are large, and the emission reductions are small. Subsidising EVs to such an extent, without pricing carbon emissions to reach a more stringent emission cap, is a very costly policy. The non-ETS sectors benefit from insufficient emission pricing, however, higher real wage and capital costs outweigh the lower carbon cost and GDP falls by 0.3%, see Table 2.[38]

5 Sensitivity Analyses

The results of the policy analyses rest particularly on the assumptions about EV technologies in the future. We test the robustness of the costs of the climate policies to these assumptions in sensitivity analyses. First, we test how the costs of the policies depend on EV technology development, particularly the price of the EVs at the world market (Sect. 5.1). Second, we look at the importance of the assumptions of the relative attributes of EVs and ICEs, i.e., the extent to which households perceive EVs and ICEs to be close substitutes (Sect. 5.2). Third, we test the sensitivity of the additional costs of pursuing a very strict EV target (Sect. 5.3). Fourth, we test how increased annual driving distance for EVs, approaching the average driving distance for ICEs, will impact the electricity market (Sect. 5.4). Finally, we test the robustness of our results for emission reduction possibilities in agriculture and the carbon price in EU ETS (Sect. 5.5).

5.1 EV Technology Development and World Market Prices

The first sensitivity exercise analyses how the costs of the policies depend on EV technology development: how much cheaper or more expensive it would be to reach the same emission reduction target with different technological development of EVs. Norway has

[38] We have tested the sensitivity of the results with a share of new EVs of 95% in this scenario. We find that the welfare effect for EV target only scenario then is −0.7% compared to BAU, less than half of the loss with 100% EV target. Recall that the share of new EVs in the baseline is 75%. We discuss the impact of pushing a very strict EV target in Sect. 5.3 below.

no car production, so EVs are all imported. The prices of EVs at the world market are sensitive to technology development and world market demand effects. As other countries are considering EV policies, this will also influence world market demand and technology development.

The world market price development of EVs in our baseline closely follows the projection of Bloomberg (Zamorano 2017) suggesting a price fall of more than 50% from 2020 to 2030. The prices of EVs have declined substantially in the past, even more than the projections by Bloomberg, see e.g., IEA (2020b); Kittner et al. (2020); Norwegian Environmental Agency (2020). On the other hand, Ghandi and Paltsev (2019) also show battery cost projections with lower reduction rate over time. Hence, we test the robustness of the results by performing two sensitivities for world market prices for EVs: a more moderate price development, implying 50% higher price for EVs in 2030, and an even more optimistic price development, leading to 50% lower price for EVs in 2030.

We implement these alternative EV price assumptions in the *cap-only* and *cap and EV target* scenarios discussed above. Table 6 summarises the key results (measured as relative change from the relevant main policy scenario, that is, change from c*ap-only* and c*ap and EV target* scenarios, respectively).

In the cap-only scenario**,** with 50% higher EV price, there is now less substitution from ICEs to EVs than in the main scenario. Emissions from private transport are higher, and the carbon price that is necessary to reach the emission cap is 3% higher than with the baseline EV price projections (Table 6). The welfare cost is 0.4%. The GDP effect is also slightly negative since other non-ETS sectors than households must take a larger share of the emission reduction at a higher cost (higher carbon price). This includes commercial road transport where production and emissions are lower than in the main cap-only scenario.

The effects in the cap-only scenario with lower EV prices are symmetric, but with opposite signs: there are more EVs and less ICEs and the households take a larger share of the emission reduction, at a lower carbon price.

In the cap and EV target scenario, world market prices of EVs have a different effect. With the 50% higher EV price, the costs of reaching the 100% market share of new EVs in 2030 increases. Consumption of private transport falls. Purchases of both EVs and ICEs fall by 3.3%, following the higher costs of private transport and the negative household income effect, while GDP is only 0.04% lower. The carbon price is almost 2% lower than in the main policy scenario, reflecting lower consumption and production activity. The welfare costs of reaching the additional EV target, measured by change in welfare, are especially sensitive for the technological development of EVs.

On the other hand, when the world market price of EVs is 50% lower, the costs of private transport fall considerably, and purchases of both EVs and ICEs increase by 3.1%.[39] Household income increases, giving a positive income effect for all goods and services. Consumption of all energy goods increases, especially electricity for charging EVs, but also petrol and diesel. This results in higher emissions from private transport. Production of commercial road transport also increases, contributing to higher emissions.

From this sensitivity exercise, it is especially interesting to note that with the additional EV target, the improved (cheaper) EV technologies stimulate private transport activities of both EVs and ICEs, and the emissions from private transport increase. The carbon price

[39] Note that the EV target is implemented as 99.9% requirement in 2030; hence, there are a few new ICEs also in the cap and EV target scenario.

Table 6 Sensitivity analyses with alternative EV world market price assumptions, 2030. Change (%) from the main policy scenarios

	Cap-only[a]		Cap and EV target[b]	
	50% higher EV price	50% lower EV price	50% higher EV price	50% lower EV price
Carbon price in non-ETS industries	3.0	−3.0	−1.9	2.0
Emissions from private transport	2.1	−2.1	−0.4	0.4
Emissions from commercial road and rail transport	−4.7	5.0	−2.1	2.1
GDP	−0.02	0.01	−0.04	0.04
Welfare	−0.4	0.4	−0.5	0.6
Electricity production	0.00	0.00	−0.02	0.02
Electricity net import	−0.7	0.7	−0.9	0.9
Household consumption:				
Purchases of EVs	−3.6	3.0	−3.3	3.1
Purchases of ICEs	10.8	−10.3	−3.3	3.1
Petrol and diesel	2.1	−2.1	−0.4	0.4
Electricity use in households for EV charging	−3.5	3.7	−1.7	1.8
Electricity use in households for other purposes	−0.2	0.3	−0.4	0.4

[a]Measured as relative change from the main cap-only scenario

[b]Measured as relative change from the main cap and EV target scenario

is higher and more of the emission reductions take place in other sectors than private and commercial road transport, at a higher emission reduction cost.

5.2 What if EVs and ICEs are not Perceived as Close Substitutes?

In the main scenarios, it is assumed that the attributes of the EVs and ICEs become more similar in the future and the consumers perceive them as close substitutes. This is reflected in the model by assuming a gradual increase of the substitution elasticity between ICE and EVs from 4 in 2020 to 8 in 2030 (as discussed in Sect. 3.1.1). In this sensitivity exercise, we test the effects of the ICEs and EVs *not* becoming as similar by assuming that the substitution elasticity remains constant at 4, and we simulate the two policy scenarios with this lower elasticity. We find that lower substitution elasticity impacts the two policy scenarios in different ways (see Table 7 for results, measured as relative change from the relevant main policy scenario, with baseline elasticity).

In the *cap-only scenario* purchases of EVs are reduced by 15.2%, while purchases of ICEs increases considerably (but from a very low level, since the majority of car sales is EVs). The market share of EVs (both of sales and of stock) is 1 percentage point lower. Consumption of electricity for charging EVs is reduced, while consumption of petrol and diesel for ICEs increases, leading to higher emissions from private transport.

Welfare increases by 0.5%, which may seem counterintuitive given that reduced options for substitution may be expected to reduce welfare. However, the welfare effects depend on initial tax wedges and imperfections in the economy, as discussed in Sect. 4.1. In this sensitivity exercise, purchase and use of EVs is reduced, while purchase of ICEs and petrol

Table 7 Sensitivity analysis with lower substitution elasticity between EVs and ICEs, 2030. Change (%) change from the main policy scenarios

	Cap-only[a]	Cap and EV target [b]
Carbon price in non-ETS industries	24.0	−27.6
Emissions from private transport	12.3	−14.8
Emissions from commercial road and rail transport	−17.5	3.2
GDP	0.1	0.01
Welfare	0.5	−0.3
Electricity production	0.1	0.0
Electricity net import	0.3	0.5
Household consumption:		
Purchases of EVs	−15.2	−0.6
Purchases of ICEs [c]	116.6	−0.6
Petrol and diesel	12.3	−14.9
Electricity use in households for EV charging	−13.4	−0.4
Electricity use in households for other purposes	0.9	0.1

[a]Measured as relative change from the main cap-only scenario

[b]Measured as relative change from the main cap and EV target scenario

[c]The share of ICE purchases is initially low in the baseline. The 116.6% increase in the Cap-only scenario is in fact the same sales share as in baseline

and diesel increase, and both effects contribute to increased welfare, since the favourable EV policy is identified as one of the major contributors to the welfare loss of the carbon policy. Since households abate less emissions, the carbon price increases and other industries (commercial transport and the other carbon-intensive industries in non-ETS) must contribute more to the emission reduction to reach the cap, but the higher carbon price is not enough to outweigh the welfare gain of less use of EVs.

In the *cap and EV target scenario* the EV target implies that the household cannot substitute away from EVs. Therefore, the lower substitutability implies higher costs of EVs and private transport for the household, and purchases of both EVs and ICEs are reduced. The reduction in consumption of ICEs and fuel for ICEs (petrol and diesel) contribute to a welfare loss that is not offset by the slight reduction in consumption of EVs. In total, welfare falls by 0.3%. Lower emissions from private transport contribute to lower the carbon price that is necessary to reach the emission cap, and less abatement take place outside the household sector. However, the lower carbon price is not enough to outweigh the welfare loss of even less use of ICEs.

5.3 Additional Costs of Pursuing a Very Strict EV Target

The goal that all new cars must be EVs in 2030 generates a corner solution and that may pose problem when working with CES functions, as we do here. We have tested the extent to which our results depend on this specific target by analysing how the economy-wide costs increase when increasing the EV target from 88% (as in cap-only scenario) to 100% in the cap and EV target scenario.

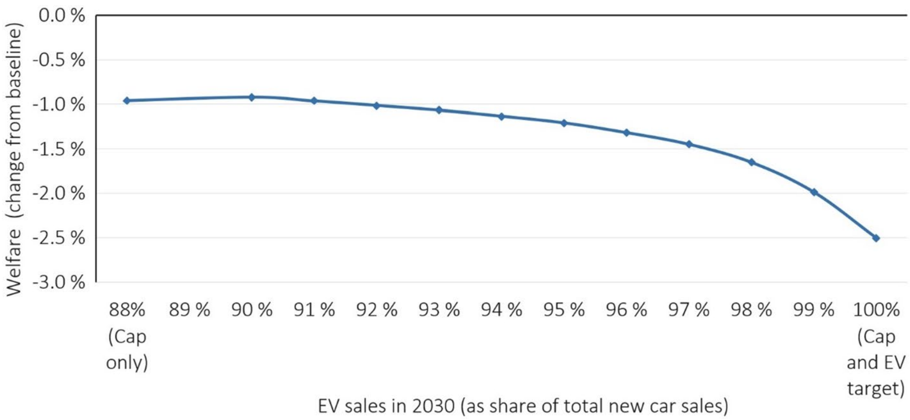

Fig. 5 Sensitivity of welfare loss to the EV target in the cap and EV target scenario

The results show that the costs (measured as welfare loss) increase steadily with the EV target, see Fig. 5. While the initial cap and EV target scenario, with all new cars being EVs, shows a welfare loss of 2.5%, reducing the EV target to 99% reduces the welfare loss to 2%, and an EV sales target of 95% results in a welfare loss of 1.2%. Recall that the cap-only scenario yielded an EV sales share of 88%, at a welfare loss of 0.9% (see Fig. 5). The doubling of the welfare loss when the EV sales share increases from 95 to 100% in the cap and EV target scenario, illustrates that it is significantly costlier to choose the corner solution. Note, however, that the costs do not increase exponentially for the last percentage point, even though it is the last two percentage points (increasing the share of EVs from 98 to 100%) that come at the largest cost. This is also illustrated by the increase in the shadow price on EVs as the increase in ratio of the EV price is rather modest (from 23% in the baseline to 34% shown in Table 5). The typical concern in corner solutions is that we need to have very large price wedges, but that is not the case in our EV target scenario.

This sensitivity illustrates the problem with pursuing very restrictive policy goals: the costs of pursuing a restrictive target (either zero emissions or a 100% EV target) will increase the costs considerably, compared to a slightly less strict goal.[40]

5.4 Increased Driving Distance of EVs

In our modelling of EVs we assume that the average driving distance is constant. However, over the last years we have seen a considerable increase in the annual average driving distance for EVs; it is reasonable to assume that the annual driving distance will continue to increase over time as EV batteries and the infrastructure for charging improves.[41] Hence,

[40] Note that the EV target does not imply that there are no ICEs available. The target applies to new car sales; it is possible to use the 'old' ICEs as long as they function (average life-time for a car has been 17 years in Norway), and the 'old' ICEs are available at second-hand market for several years to come. As our model keeps track of the stock of old and new cars, this feature is included in the model. The elasticity of substitution between old and new cars is 10, hence making them almost perfect substitutes.

[41] https://www.ssb.no/en/transport-og-reiseliv/statistikker/klreg (table 12577). See also: https://www.ssb.no/transport-og-reiseliv/artikler-og-publikasjoner/mindre-bilkjoring-i-koronaaret.

in this scenario we assume that the annual driving distance for each EV is doubled, to approximately the same driving distance as for ICEs, to investigate the effects of higher electricity demand.

The results of this sensitivity analysis, compared to the two main policy scenarios, are given in Table 8. The effects are largest in the electricity market as expected, while the macroeconomic effects are minor in both policy scenarios. With a longer driving distance, the households' electricity demand for charging the EVs is nearly doubled.[42] However, this doubling is from a very low absolute level, as electricity for charging accounts for a small share of total household electricity consumption. The total electricity consumption for charging EVs with the 100% EV target has been estimated to less than 4 TWh in 2030, which is less than 3% of Norway's total electricity consumption (NVE 2017). In our simulation, the electricity market effects are minor: production of electricity only increases by 0.1% and the electricity net import increases by 2–2.8% (Table 8). However, the initial level of electricity import to Norway is moderate, around 1% of total electricity consumption.

5.5 No abatement in Agriculture and Higher EU ETS price

The robustness of our results is also tested by two additional sensitivity analyses. First, we have tested for the importance of the exogenous abatements in the agricultural sector. With a given emission cap, more emission reductions must be carried out in the other non-ETS industries when the agricultural sector abates less. We find that in the cap-only scenario the carbon price in non-ETS is 717 EUR/ton CO_2-eq, while the welfare loss is approximately 0.5 percentage point higher than in our main scenarios (where abatements in agriculture were included exogenously). In the corresponding cap and EV target scenario, the carbon price is 535 EUR/ton CO_2-eq, while the welfare loss is 0.3 percentage point higher. This confirms that if no exogenous emission reduction possibilities are available in agriculture, the additional costs in the rest of the economy will be significant. Since relatively more abatement must be taken in private transport, there will be more EVs in the cap-only scenario when no exogenous abatement in agriculture is available (94% market share compared to 88%). The welfare loss in the cap and EV target scenario relative to the cap-only scenario is smaller (190% compared to 250%), but the difference is still large. Thus, our main results are robust.

Second, we have carried out sensitivity analyses by doubling and tripling the EU ETS price, to reflect recent developments of the EU ETS price (in March 2022 the EU ETS price was approximately 70 EUR/ton CO_2-eq). The results of the sensitivity analysis show that the welfare loss is higher with higher ETS price (compared to the main result), as expected, but the effect is limited. However, as the higher ETS price also will affect the costs in other European countries, it is difficult to subject the ETS price to sensitivity in a single nation model as we have tested here. It does not seem to be a key driver in our scenarios, but it is a factor that should be considered in models involving several countries.

[42] Since the shift results in slightly more driving, the cost of driving EVs increases for the household, and there is a small substitution effect towards ICEs.

Table 8 Sensitivity analysis with increased EV driving distance, 2030. Change (%) from the main policy scenarios

	Cap-only[a]	Cap and EV target[b]
Electricity use in households for EV charging	98.5	99.6
Electricity use in households for other purposes	−0.2	−0.3
Electricity production	0.1	0.1
Electricity net import	2	2.8

[a]Measured as relative change from the main cap-only scenario

[b]Measured as relative change from the main cap and EV target scenario

6 Concluding Remarks

We have analysed the abatement costs and economy-wide welfare effects of interacting and partly overlapping climate regulations in private transportation and in the non-ETS sectors in general. We show that the combination of policies—when the uniform carbon price is supplemented with a specific EV target—more than doubles the welfare costs (increasing by 250% compared to only capping emissions by a uniform carbon price). In doing so, we have also made important developments in how electrification of private transport is modelled by introducing EV uptake and use as an explicit and endogenous private transportation choice.

In terms of the headline results emerging, in our *cap-only* scenario, the high uniform carbon price (that is needed to reach to cap) implies that the emission-intensive non-ETS industries experience high costs. In our *cap and EV target* scenario, a lower carbon price is needed to reach the cap, since the larger number of EVs in private transportation reduces emissions from households (and hence the necessary emission reduction from other sectors). One key outcome is that all non-ETS industries benefit from the lower carbon price. Hence, for the non-ETS industries there are incentives for overlapping climate regulations, as the EV policies reduce the marginal carbon price for these industries. However, the trade-off is substantial welfare losses for Norwegian households as more EVs are brought into the car fleet. A sensitivity analysis also illustrates the problem with very restrictive policy goals: the costs of pursuing a restrictive target (either zero emissions or a 100% EV target) will increase the costs considerably, compared to a slightly more relaxed goal.

Until now, Norway has been an international leader in decarbonising private transportation, with its generous support schemes and relatively high share of EVs. As EV technologies become mature, other countries are likely to introduce more policy focus on promoting, enabling and incentivising EV uptake. Our findings suggest that the cost of these policies is high in Norway but may be even higher in other countries. The effects of the interacting regulations and especially the EV policies depend on a range of factors and conditions prevailing in the national context: the degree of the initial electrification of the society, the share of electricity in household energy use, the electricity production and grid capacity and investment needs. Further, the economy-wide effects will also depend on whether it is a car-producing nation, potentially benefitting from new market options related to EVs, or whether these benefits accrue to foreign nations. Technological improvements and productivity effects will benefit both exporting and importing countries. Thus, the implications and lessons emerging are likely to be characterised by a combination of country-specific and more generic effects. Still, even though the magnitude of the effects depends on country-specific conditions, the key conclusion remains: a combination of partly overlapping policies increases the abatement costs, since the additional EV policy puts the most efficient emission abatement policy—uniform carbon price—partly out of action. Crucially, the novel CGE model developments introduced here enable investigation of the features of ambitious EV and climate policies, a highly electrified economy and EV technologies in private transportation in an economy-wide consistent framework.

Some caveats remain. Our model has one representative household. However, by drawing on other analyses we can add some comments on distributional aspects. Fæhn and Yonezawa (2021) find that a carbon policy in line with the cap-only scenario is progressive when interactions between changes in income from capital and labour and household income distribution are taken into account. Earlier analyses of the Norwegian EV support policies have found that wealthy households have benefitted most; see Fevang et al. (2021) and Halse et al. (2022). Pricing carbon combined with subsidies to EVs have less adverse distributional effects than only subsidizing EVs, which is also found in Johansen and Munk-Nielsen (2021). With more and cheaper EV models available in the market and a well-functioning second-hand market for EVs, the distributional effects of future EV policies may be less regressive.

The large improvements in EV technologies that have taken place the last few years will contribute to reduce the costs of electrification through EVs, as our sensitivity of technological development shows. Here we note a caveat in that our model does not include positive technology externalities, such as learning effects, technology spillovers, or network externalities, each of which may result in EV support turning out to be less expensive in reality than in our analyses. However, independent of the source or size of technology externalities, it is likely that support schemes for climate technologies should still be combined with sufficient carbon pricing to reach the emission reduction goals. To gain more knowledge of technology externalities, development of markets for new climate technologies and effects of policy instruments, with insights informing modelling economy-wide impacts thereof, should be at the research agenda in the years to come, given the myriad of policy instruments and technologies that are used.

Appendix 1: Industries, Final Consumption Goods and Elasticities in SNOW

Table 9 Industries in SNOW

Agriculture	AGR
Forestry	FRS
Fishing	FSH
Coal production	COA
Oil & gas extraction	CRU
Minerals nec	OMN
Food products—meat	MEA
Vegetable oils and fats	VOL
Dairy products	MIL
Food products nec	OFD
Beverages and tobacco products	B_T
Textiles	TEX
Wearing apparel	WAP
Leather products	LEA
Wood products	LUM
Paper products, publishing	PPP
Petroleum, coal products	OIL
Chemical, rubber, plastic products	CRP
Mineral products nec	NMM
Ferrous metals	I_S
Metals nec	NFM
Metal products	FMP
Motor vehicles and parts—conventional internal combustion engine (ICE) vehicles	MIE
Motor vehicles and parts—electric vehicles (EV)	MEV
Transport equipment nec	OTN
Machinery and equipment, incl. electronic equipment	MEE
Manufactures nec	OMF
Electricity	ELE
Gas manufacture, distribution	GAS
Water	WTR
Construction	CNS
Trade	TRD
Transport nec	OTP
Water transport	WTP
Air transport	ATP
Communication	CMN
Financial services nec	OFI
Insurance	ISR
Business services nec	OBS
Recreational and other services	ROS
Public sector (defence)	OSG
Dwellings	DWE
Public sector—central government (administration, education, health services, culture)	OSS
Public sector—local government (admin., education, health services, culture, water)	OSK
Private education and health services	OSP
Waste management (public)	AVK
Waste management (private)	AVP

Table 10 Final consumption goods in SNOW

Food and non-alcoholic beverages	CFAB
Alcoholic beverages and tobacco etc	CABT
Clothing and footwear	CCAC
Housing & water	CHAW
Electricity (for heating)	CELE
Gas (for heating)	CGAS
Paraffin and heating oil (for heating)	CPAH
Fuel wood, coal etc. (for heating)	CFAC
District heating	CDHE
Furnishings, household equipment and routine household maintenance	CFHR
Health	CHEA
Transport equipment—conventional internal combustion engine (ICE) vehicles	CTEQ
Transport equipment—electric vehicles (EV)	CTEV
Fuel in private transport—Petrol & diesel	CPAD
Fuel in private transport—Electricity for EVs	CEEV
Public transport (rail)	CRAI
Public transport (road)	CROA
Public transport (air)	CAIR
Public transport (boat)	CBOA
Communication	CCOM
Recreation and culture	CRAC
Education	CEDU
Restaurants and hotels	CRAH
Miscellaneous goods and services	CRAH
Final consumption expenditure of central government	GS
Final consumption expenditure of local government	GK
Final consumption expenditure of NPISHs	GF
Gross fixed capital formation—private	I
Gross fixed capital formation—central government	IG
Gross fixed capital formation—local government	IG
Changes in stocks and statistical discrepancies	ST

Table 11 Elasticities in the CES function for production and trade

Parameter	Explanation	Value
Elasticities in production function		
esub_kle_m	Elasticity of substitution between aggregate intermediate inputs (M) and other inputs (KLE)	0.5
esub_m	Elasticity of substitution between non-energy intermediate inputs (M)	0.25
esub_e_va	Elasticity of substitution between capital-labour aggregate (KL) and energy aggregate (E)	0.5
esub_va	Elasticity of substitution between capital (K) and labour (L)	0.75
esub_k	Elasticity of substitution across capital types	0.25
esub_elec	Elasticity of substitution between electric and non-electric energy in the energy aggregate	0.5
esub_c_go	Elasticity of substitution between coal and the oil–gas aggregate	0.5
esub_g_o	Elasticity of substitution between oil and gas	0.5
Elasticities in trade		
esub_dm	Armington elasticity—domestic versus imports	4
etrn	Elasticity of transformation	4
Elasticities for emissions		
	Elasticity between energy-related emissions and energy goods	0
	Elasticity between process emissions and output level	0

Source: Andreassen and Bjertnæs (2006), Narayanan et al. (2012)

Table 12 Elasticities in the CES function for final consumption

Parameter	Explanation	Value
esubh_nele	Substitution between non-electric energy inputs in housing	0.5
esubh_ele	Substitution between electricity and the non-electric energy aggregate in housing	0.5
esubh_hou	Substitution between energy and other inputs in housing	0.5
esubh_trnt	Substitution between public and private transportation in final consumption	0.75
esubh_trpu	Substitution between alternative public transportation in final consumption	0.5
esubh_on	Substitution between old and new cars in private transportation in final consumption	10
esubh_trpr	Substitution between EVs and ICEs in transportation in final consumption	0.5—8[a]
esubh_cpad	Substitution between fuel and the composite of car and O&M for conventional cars in transportation in final consumption	0.5
esubh_ceev	Substitution between electricity and the composite of car and O&M for electric cars in transportation in final consumption	0
esubh_m	Substitution between all other consumption goods (except those transportation and housing)	0.5

[a]Substitution elasticity between EVs and ICEs is 0.5 in 2013 (base year), increasing gradually to 4 in 2018 and to 8 in 2030, see Sect. 3.1.1

Source: Aasness and Holtsmark (1993), Bye et al. (2018), Fridstrøm and Østli (2021), Hertel et al. (2012), Johansen (2021), Reimer and Hertel (2004)

Appendix 2: A Stylized Version of the Recursive Dynamic Model SNOW

Assumptions: One representative firm that use labour and capital for input, we disregard other intermediates and natural resources. One household that receives all income, net taxes and transfers, and all imports, while all investments take place in the firm. Emissions are omitted in the stylized model.

Equations		Corresponding endogenous variable
(1)	$p^Y = c(w, r)$	p^Y
(2)	$p^Y = \left[\phi^{-\eta}\left(p^H\right)^{(1+\eta)} + (1-\phi)^{-\eta}\left(v\overline{p}^W\right)^{(1+\eta)}\right]^{1/(1+\eta)}$	p^H
(3)	$p = \left[\theta_A^{\sigma_A}(p^H)^{(1-\sigma_A)} + (1-\theta_A)^{\sigma_A}(v\overline{p}^W)^{(1-\sigma_A)}\right]^{1/(1-\sigma_A)}$	v (and p, but p is numeraire)
(4)	$K^D = \left(\frac{r}{\theta p^Y}\right)^{-\sigma} Y$	K^{D}
(5)	$L^D = \left(\frac{w}{\theta p^Y}\right)^{-\sigma} Y$	L^{D}
(6)	$M = \left(\frac{v\overline{p}^W}{\theta_A p}\right)^{-\sigma_A} C$	M
(7)	$A = \left(\frac{v\overline{p}^W}{\varphi p^Y}\right)^{\eta} Y$	A
(8)	$H = Y - \overline{G} - \overline{D}$	H
(9)	$Y + M = C + A + \overline{G} + I$	Y
(10)	$K = (1-\delta)\left(K_{-1} + I_{-1}\right)$	K
(11)	$L = \overline{L}$	L
(12)	$K^D = K$	r
(13)	$L^D = L$	w
(14)	$S = S(H, p)$	S
(15)	$C = C(H, p)$	C
(16)	$I = S$	I

Equation (1) is the first-order condition for the cost minimising firm. Equation (2) production is a CET-aggregate of domestic and foreign deliveries. Equation (3) consumer price is an Armington-aggregate of a domestic and foreign variety. Equations (4) and (5) are demand for capital and labour. Equations (6) and (7) denote demand for import and export. Equation (8) is consumer budget balance. The aggregate of savings and consumption H is determined residually in this dynamic, recursive model. Equation (9) is the equilibrium condition in this one product economy. From Eqs. (8) and (9) savings is determined by trade balance surplus: $\overline{D} = A - M$. Domestic savings and consumption are distributed by a CES-function, see Eqs. (14) and (15), and savings determines real investments, (Eq. (16)).

The stock of capital is given in the base year and develops along with domestic real investments, while labour supply is exogenous. There are 17 endogenous variables (p^Y, p^H, v, p, K^D, L^D, K^S, L^S, M, A, H, C, Y, r, w, S, I), and p is numeraire that determines the model. All prices are defined in real prices in terms of the consumer good. All variables with bar and parameters with Greek letters are exogenous.

Variables in the stylized model

w	Wage rate
r	Rate of return to capital (user cost)
$c\,(\cdot)$	Unit cost
p^Y	Unit income
p^H	Price of domestic delivery
$\overline{p}^W$	World market price (export and import) measures in foreign currency
v	Exchange rate
p	Consumer price
Y	Production
C	Consumption
M	Import
A	Export
K^D	Capital demand
L^D	Labour demand
K	Capital stock
L	Labour stock
G	Government consumption
$\overline{L}$	Exogenous labour supply
$\overline{D}$	Exogenous foreign savings
S	Savings (in real terms)
I	Private investments
H	CES-aggregate of S and C
$\theta, \theta_A, \varphi$	Share parameters
η, σ_A, σ	Transformation elasticity, Armington elasticity, factor substitution elasticity
δ	Depreciation rate

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