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Abstract

The transport sector is the only sector where carbon emissions continue to grow. This has led policy makers to propose ambitious policies to reduce emissions in the car sector, in particular fuel efficiency standards, portfolio mandates for Electric Vehicles and purchase taxes or subsidies. A portfolio mandate describes a minimum quota of annual electric vehicle sales. We use a two-period model for the car manufacturing sector to compare the cost efficiency of these policies. The model has gasoline fuelled cars (GV) compete with battery electric cars (EV). Both types of cars have endogenous technological progress that is triggered by environmental policies, including tradable fuel efficiency standards, portfolio mandates, carbon taxes, purchase taxes and R&D subsidies. EVs can serve as batteries that permit grid operators to shift off peak (renewable) electricity to peak hour supply. The model is calibrated to evaluate the EU policy to reduce average carbon emissions of cars by 37,5% in 2030. We assess the cost-efficiency of three types of policy instruments evaluating production costs, fuel costs, and externalities. We find that a fuel efficiency standard targeting gasoline cars achieves emission reductions at a much lower cost than a portfolio mandate for Electric cars.

JEL-Codes: Q540, Q580.

Keywords: electric vehicles, EU climate policy, climate change, portfolio mandate, R&D.

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1. Introduction

There is a clear gap in the EU's emissions reduction policy: transportation. While countries across the EU continue to decrease national emissions through the EU ETS and building and electric appliance regulations, transport emissions continue to grow. Road transport is responsible for 73% of the transport emissions and more specifically cars stand for 44.5 % of GHG emissions (EEA 2017). The EU relies on two instruments to reduce CO_2 emissions in the light vehicle segment. There is the CO_2 performance standard for passenger vehicles and there is the minimum share of renewable fuels in the car sector. In the last years, the car sector relied mainly on biofuels to reach the mandated share of 10% renewable power in the transport sector. However, the new directive on renewable energy in the EU (RED II), sets out new biofuel sustainability criteria that will be difficult to meet by the current biofuels. EVs can act as an important complement to the generalized use of renewable electricity. The battery of EVs, when connected to the grid can help to bridge the periods with low and high renewable production. In this way EVs can add flexibility to the increasingly renewable power sector by acting as storage medium and shifting supply from the renewable off-peak to the less renewable peak demand hours. In addition, EVs can save electricity generation capacity and help in balancing the power sector. EVs will be essential to reduce carbon emissions in the transport sector[1] and to satisfy the renewable transport objective.

In this paper, we compare how targeted consumer and supply chain policy instruments affect the share of EVs. The direct effects of regulations and price incentives on EV penetration have already been widely studied using consumer choice models. We offer three contributions to this literature. The first contribution is to include the lagged effects of policy instruments on future costs and performance via R&D and learning by doing. Second is to also include a reduced representation of the power sector and third is to include some external effects of car use in addition to climate impacts.

To include the learning by doing and the R&D effects, we adapt the renewable electricity model of Fisher and Newell (2008) to the passenger car market. EVs can become cheaper through two knowledge building effects: by learning by doing and by pure R&D. Also, the fuel efficiency of conventional gasoline cars can improve over time thanks to pure R&D. How much both technologies improve depends on the policies in place. Policies can incentivize car producers to

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[1] As the emissions in the EU electricity sector are capped by the tradable emission scheme (ETS), the net carbon emissions of an EV are zero. Since 2018, matters are more complicated as the EU-ETS has been turned into a hybrid system because the number of permits issued each year will be a function of the stock of unused allowances. See Perino (2018) and Bruninx., Ovaere, Delarue (2019).

produce more cars (learning by doing) but can also stimulate them to invest in R&D that reduces the costs of crucial car components. Consumers are differentiated in function of the number of days per year they make a short or long trip. As EVs still have a difficulty to cover the long trips, this will segment the consumers between EV adopters and gasoline car adopters. The number of days with short trips will also determine the availability of batteries for Vehicle to Grid (V2G) storage. The electricity production sector is simple and the V2G option is modelled as in Greaker et al. (2019).

We use the two-period model for a simplified dynamic cost comparison of three main types of policy instruments: fuel efficiency targets for gasoline cars, a portfolio mandate for electric vehicle sales, and high purchasing taxes or subsidies combined with charging network subsidies. This numerical comparison shows that the market share of EVs depends strongly on the type of policy instrument used but that the share of EVs is not necessarily a good indicator for a successful carbon policy. We find that the fuel efficiency standard for gasoline vehicles with a tradeable permit scheme achieves the emissions reduction goals at the lowest cost.

Our paper is organized as follows: In section 2, we provide a review of the existing literature on policies for EV adoption. In section 3, we survey the existing policy instruments with a focus on the EU and in particular on Germany. In section 4, we present the formal model and in section 5, we derive the effects of different policy instruments in the theoretical model. In section 6, we discuss the calibration of our numerical model using data for the German and European EV market. We present the policy results in section 7 and section 8 concludes.

2. Literature review

There are several strands of literature that are significant to our research. We begin by reviewing the existing methods for modelling the impacts of climate policy on the development of the transport sector. This is followed by an outline of the research on EVs and the electricity grid. Next, we examine the literature on policy intervention in the transport sector and we conclude with the literature on the infrastructure challenges of widespread EV adoption.

To accurately account for the role of new technologies in climate policy, there are two approaches: an aggregate economy wide approach and a sectoral approach. Within the aggregate approach, one method is to take an existing CGE model and build out the transport sector in more detail to differentiate between a limited number of vehicle classes (see Paltsev et al. (2018) , Zhang et al (2017)). Another method within the aggregate model approach is to use an integrated assessment model which offers a detailed breakdown of the energy sector and then add a more detailed transport-energy demand function (see Pietzcker et al (2013), Tattini et al (2013), van der Zwaan et al (2013)). In the aggregate approach, technological progress is usually taken on board via a learning curve. The learning curve relates the future costs of a given technology to the number of installations. These models excel in trading off efforts in different sectors but fall short in the selection of policy instruments. In addition, the use of the learning curve approach tends to overstate the technological progress effects of additional installations (Nordhaus (2014)). The second, sectoral approach, can focus much better on the effects of policy instruments.

In this paper, we employ a partial equilibrium model of the car transport market. In his recent survey of technological progress Popp (2019) stresses the importance of integrating endogenous technological progress in the assessment of policies. For the integration of endogenous technological progress we follow a similar approach as Fischer and Newell (2008). They use a stylized model of the electricity sector with two subsectors (a representative fossil fuel firm and renewable firm) which incorporates learning by doing and R&D investment for renewables with two stages to allow time for innovation. Using this simple model, they assess various policy options for reducing carbon emissions. In our model, consumers demand car transportation services that they can buy from gasoline car producers and electric car producers. We allow for endogenous technical progress for EVs but also for fossil fueled cars. Endogenous technological progress has been modelled in a similar way for biofuels and their use in cars by Eggert and Greaker (2014).

The literature on Electric Vehicles (EV) focuses mainly on the speed of penetration of EV's as a new technology and on the possible barriers. The penetration is a function of the cost decrease over time and depends on the importance of car attributes such as the range and the refueling network. See Brownstone, Bunch and Train (2000) for one of the first studies. Li, Long, Xing, and Zhou (2017) and Coffman, Bernstein, and Wee (2017) are recent reviews of the consumer behavior towards EVs. Van Biesebroeck & Verboven (2018) provide a survey on the barriers to the large scale production and market penetration of EVs.

There are several papers focused on identifying the various types of policy intervention for emissions reductions in the transportation sector. Van der Steen et al. (2015) provide a general overview of government policy intervention strategies and differentiate the type and effect of policies implemented upstream on the producers, downstream on the consumers, and system-wide on the network. Hardman, Chandan, Tal, and Turrentine (2017) find in their review that financial purchase incentives have been effective in increasing the sales of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Maciuli, Konstantinaviciute, and Pilinkiene (2018) examine the different opportunities for local and national governments to stimulate EV adoption.

In our paper we assess the effectiveness of policies aimed at both the supply and demand sides of the EV market. An important assumption in our paper is that both consumer and producers act in a rational way. Policy makers in the EU and US often rely on a stream of literature that states car buyers are behaving myopically: consumers underestimate future fuel savings (see Brown (2001), Greene (2010)). Recent econometric evidence for the European car market contradicts this assumption and shows that consumers take into account approx. 90% of future fuel consumption costs (Grigolon, Reynaert & Verboven (2018)). Reynaert (2017) contends EU car manufacturers behave as rational producers in their non-compliance to the current fuel emission standard. According to Reynaert, the compliance costs of the fuel efficiency standard are too high compared to the current car fuel prices. In the absence of strict enforcement, the producers offer cars that minimize the total user costs of cars which results in less efficient cars than required by the standard.

Richardson (2012) reviews the literature regarding the ability of EVs to improve the integration of renewable energy sources into the existing electric grid. Further, Dallinger, Gerda, and Wietschel(2012) state that in a future with high renewable energy penetration in the electricity sector, EVs can store excess renewable energy produced in the off peak periods and use it in the peak period where there is less renewable production. While we do not model the electricity sector explicitly, we do differentiate between renewable-generated electricity and fossil fuel electricity and consider the impacts of shifting electricity demand from off-peak to peak periods.

There is limited literature concerned with the infrastructure challenges of EV adoption. Consumers with a garage can charge their car at home but those without a garage or on a long trip have to rely on the public charging infrastructure. Charging infrastructure for cars is a well-defined network good and therefore exhibits network effects. Greaker and Midttømme (2017) assert that a failure to account for network effects can hinder the adoption of existing clean technologies. Further, Greaker and Kristoffersen (2017) argue that the lack of charging technology harmonization contributes to negative network externalities and impedes widespread EV adoption. Springel (2017) studied the Norwegian EV market, where penetration of EVs in new car sales is high (>30% in Oslo). Her estimates find that consumers are more likely to purchase EVs when the network is denser and that charging stations are more likely to enter when there is a larger stock of EVs. Li et al.(2017) study the US market where penetration is much lower. They also find that diverting some of the subsidies for the purchase of EVs to the development of the charging network could be more effective in terms of EV penetration. Zhou and Li (2018) focus on the critical mass problem in the deployment of charging station deployment where the low adoption equilibrium may be the outcome in more than half of the U.S. Metropolitan Statistical Areas. We emphasize the production side of EVs and GVs but we include a simplified version of the charging station network effects via an average charging cost that is decreasing in the share of EVs. The passenger car sector is an important source of carbon emissions but is also characterized by several other externalities, including congestion, non-carbon air pollution, noise and accidents. The existing set of policy instruments to stimulate the adoption of EVs carries the risk of making these externalities worse. Wangsness et al. (2018) show that the Norwegian EV policy mix, that which guarantees a low nominal cost to EV users guarantees to the EV users a very low user cost, induces a significant increase in car use and a decrease of Public Transport use in Oslo. This emphasizes the importance of including these externalities in the EV promotion policy.

Compared to the literature, this paper offers several contributions. First, it endogenizes the progress in the costs and performance of EVs and of GVs by making technological progress a function of the policy instruments that are used. Second, it considers the role of the batteries in the EV to increase the share of renewable energy in the transport sector. Further, we consider the different car use externalities as well as the network externality that arises in the development of EV charging infrastructure Finally, it assesses a wide range of policy options to stimulate the penetration of EV.

3. Current policy incentives for the adoption of EVs

In the EU, there are two policy directives for the car manufacturers. First, there is the carbon efficiency standard for cars that requires a maximum emission rate of 95 g/vehicle-km by 2021 and the decision[1] is to decrease the emission rate by 37,5 % in 2030. Second, there is the portfolio standard requiring a minimum of renewable energy in the transport sector, which was mainly geared to be renewable biofuels. However the new RED II policy package that is being adopted by the European Parliament is now much more demanding on the sustainability of the biofuels than in the RED I package. As this implies that the role of biofuels will decrease, the role of electricity has to increase.

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[1] http://www.europarl.europa.eu/news/en/press-room/20190321IPR32112/parliament-backs-new-CO$_2$-emissions-limits-for-cars-and-vans

The EU also requires national governments to support the achievement of the policy objectives for the manufacturers by using additional policies at the level of the carbon intensity of the fuel used, at the level of the refueling infrastructures and at the level of the adoption of EV by car buyers. Enactment and enforcement of these initiatives are left to the member states. Some member states have added a strict target for the share of EVs.

The member state policies have been surveyed in IEA (2018) and they have almost all adopted a combination of reduced purchase taxes (or higher subsidies) and subsidized recharging points. As this paper focuses on Germany we limit ourselves to present the most important EV policies for this country.

In addition to motor vehicle tax exemption and purchase subsidies, Germany offers parking privileges to EV drivers.[1] While many countries implement consumer-targeted policies, few enact R&D policies for producers.

In our paper, the baseline scenario will assume that the main EU-policy that is implemented is a 37,5% reduction of the average fuel efficiency of new cars by 2030. We implement this requirement at the aggregate sales level for cars. The EVs are considered as zero carbon emission vehicles. This is correct in the case of the EU where the electricity sector is covered under the EU ETS. As the EU-ETS uses a global cap for industry and electricity sector emissions, adding the electricity demand of an EV does not affect the cap and therefore emissions of an EV can be counted as 0.

Present market shares (2016-2020) for BEV are of the order of 2% in Germany.

4. Building the model

4.1. The range of policy instruments

In this paper, we estimate the impacts of different policy instruments, which can be used in isolation or in parallel. First, we evaluate an aggregate tradable fuel efficiency target. The second major instrument we discuss is a portfolio mandate for electric cars. Next, we discuss the effects of an EV purchase subsidy and a subsidy for for en-route charging equipment. Finally, we assess a high purchase tax for GVs.

These instruments are always combined with a subsidy for R&D and the current tax on motorfuels. In Europe, the major instrument for fuel efficiency is the high gasoline tax, it acts as a carbon tax and is important in raising tax revenues and keeps other externalities like

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[1] The tax exemption is valid for 10 years after the purchase date of the EV.

congestion under control, be it inefficiently. In Germany, the gasoline tax accounts for nearly 60% of the total fuel price..

4.2. The choice of cars by consumers

We consider only two technologies: gasoline vehicle (GV) and battery electric vehicle (EV). There are two periods t=1,2 , each representing a number of years n_t. Vehicle users are differentiated by the number of days with long trips that they make in a year. This characteristic is important for two reasons. First long trips with an EV are more difficult when one must recharge en-route. Second, days with short trips allow EVs to be used as storage for the grid. We assume that we have *M* vehicle owners that are uniformly distributed[1] over the number of long trip days. The number of vehicle owners and the length of the short and long trips are given. This means that the mileage of each type of individual and of the total population are fixed This condensed model generates the shares of electric and gasoline vehicles for given vehicle prices, fuel costs and taxes.

Let l_m be the number of days with long trips for user *m* and $(365 - l_m)$ the number of days with short trips for user *m*. The total rental cost of a gasoline vehicle in period t is the annuity of the purchase price plus the cost of use. The purchase price of a gasoline vehicle is P_t^G, the producer price on an annual basis, plus the annual vehicle ownership tax, τ_t^G. As we use costs on an annual basis and as total vehicle ownership as well as annual mileage is fixed for each population segment, car purchase taxes and ownership taxes have the same effect. The usage cost U_t^G is a function of the variable cost per km driven, v_{tg}, and a tax per unit distance, t_{td}^G . This distance tax corrects for driving externalities such as noise, non-carbon emissions, accidents and traffic congestion. As gasoline vehicles may also make progress in fuel efficiency over time, we introduce the fuel consumption per unit distance, f_t.

Therefore the total annual cost is:

$$C_t^G(m,f) = \mathrm{P}_t^G(f_t) + \tau_t^G + d(m).\mathrm{U}_t^G \tag{1}$$

where total distance $d(m) = l_m \cdot d_l + (365 - l_m) \cdot d_s$. Where d_s and d_l are the distances covered during a short and long trip day. The user cost is $U_s^G = (f_t \cdot v_{tg} + t^G_{td})$ where the variable cost $v_{tg} = r_{tg} + t_{tg}$, with t_{tg} the gasoline tax and r_{tg} the gasoline resource cost. As there is a direct

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[1] In the simulations we use triangular distribution of the number of long days per car.

proportionality between the consumption of gasoline and the emission of carbon, the gasoline tax is a de facto carbon tax.

We can calculate total annual carbon emissions per gasoline vehicle X_{tm}^{G} with the carbon emissions intensity factor per unit fuel consumed x_{g}^{cl} .

$$X_{tm}^{G} = d(m).f_t.x_g^{cl}$$

We will make use of the damage for carbon emissions, and define this as dam^{cl} in € per unit emissions, therefore we have the annual damage of emissions for a GV

$$C(X_{tm}^{G}) = X_{tm}^{G}.dam^{cl}$$

We measure the non-climate annual external costs of gasoline vehicle operation $C(Y_m^G)$ in € per unit distance using y^G as the sum of several externalities: $y^G = y_A + y_{OP}^G + y_N^G$ where y_A represents externalities due to accidents and congestion, y_{OP}^G represents non-carbon air pollution, and y_N^G represents noise pollution. These additional external costs vary with the length of the trip, so we have y_l^G and y_s^G for the non-climate external costs incurred during long trips and short trips, respectively. For instance, the cost of accidents and congestion increases in the length of the trip.

$$C(Y_m^G) = l_m \cdot d_l \cdot y_l^G + (365 - l_m) \cdot d_s \cdot y_s^G \tag{2}$$

The external costs of climate and other externalities do not enter the user cost, but they are included in the social welfare calculation.

The purchase price of an electric vehicle is the producer price on an annual basis $P_t^E(B)$ plus the annual vehicle ownership tax (or subsidy), τ_t^E. The purchase cost of an electric vehicle is increasing in its battery capacity B. The usage cost depends on the length of the trip and is decreasing in the capacity of the battery. For one short trip, the usage cost is

$$U_{ts}(B) = \mathrm{d}_s(e.p_{off} + t_{td}^E) - (\mathrm{B} - \mathrm{d}_s .e)(\mathrm{p}_{peak} - p_{off})$$

where e is the energy efficiency of the EV. This is the cost of electricity used to travel d_s km, assuming the battery was charged during off-peak hours, plus the tax per unit distance t^E_{td}, minus the savings realized by using the car for storage, i.e. selling back the unused energy to the grid, during peak hours. For long trips the user incurs, instead of savings, additional electricity and disutility costs of en-route charging. For one long trip, the usage cost is

$$U_{tl}(B) = \mathrm{d}_l .t_{td}^E + \mathrm{B}.p_{off} + (p_{ch} + z - P^P\, \mathrm{q}_t^E)(\mathrm{d}_l .e - B) \tag{3}$$

where p_{ch} is the price of electricity at the charging station, and z is the user's disutility from en-route charging in terms of time lost and P^Pq^E is the benefit of a wider recharging network where P^P is the recharging access cost reduction of an extra EV and q^E is the total number of electric vehicles. The user cost of charging stations decreases as the total amount of EVs sold increases (Li et al. 2017 and Springel (2017)). In the simple model, we assume that all EVs use the same charging technology, such that we have technology harmonization avoiding the harmonization issue. Following Greaker, et al (2019), we posit first that the cost of charging en-route is sufficiently high so that for a short trip, there is never a need to recharge the EV, so $B > d_s \cdot e$. Secondly, we assume that the battery cost in a car is higher than the cost of a fixed stand-alone battery $B < d_l \cdot e$. In this way, we have lower and upper bounds for the size of the car battery.

For a given electric vehicle user, the total annual cost is

$$C_t^E(m,B) = P_t^E(B) + \tau_t^E + (365 - \mathrm{l}_m).U_{ts} + \mathrm{l}_m .U_{tl} + CHE_t \tag{4}$$

where $CHE_t = k - s_{t,ch}$ and k is the total annuity cost of home charging equipment for the user. This may be subsidized by an amount $s_{t,ch}$.

There can be CO_2 emissions generated by charging EVs with fossil fuel electricity. We measure the carbon emissions intensity of the peak electricity per kWh with x_e^{cl}. We assume that off-peak electricity is generated with renewable sources, therefore it has negligible emissions. In this way we can calculate total annual emissions per vehicle, X_m^E.

$$X_m^E(B) = \left[l_m(d_l.e - B) - (365 - l_m)(B - d_s.e)\right]x_e^{cl} \tag{5}$$

The emissions generated on long trips by re-charging the battery during peak hours can be offset by discharging excess off-peak renewable electricity to the grid on short trips.

As to the total carbon emissions of an EV, we can take two stands. We can use the argument that the Electricity sector is part of the EU-ETS system and that an EV has therefore 0 carbon emissions. A second stand is to count explicitly the carbon emissions generated by the electricity sector for the EVs. In our calculations, we take this second stand as this makes the direct effects of an EV more transparent. We assume that the off-peak electricity is renewable while the peak electricity is not. Note that the substitution of peak electricity by renewable electricity made possible by the use of spare battery capacity during short trips leads to a decrease of total carbon emissions.

There are non-climate external costs $C(Y_m^E)$ from operating an electric vehicle, which we estimate in € per unit distance with y^E. As with GVs, y^E is the sum of accident and traffic congestion (y_A), non-carbon air pollution ($y_{OP}{}^E$), and noise pollution ($y_N{}^E$). Further, these external costs vary with trip length, so we have y_s^E and y_l^E and we can express the total non-carbon external costs as a function of trip length:

$$C(Y_m^E) = l_m \cdot d_l \cdot y_l^E + (365 - l_m) \cdot d_s \cdot y_s^E \tag{6}$$

We assume that vehicles contribute equally to congestion and accidents whether they are GVs or EVs, so y_A is constant across vehicle types. Further, we posit that EVs are quieter than GVs, therefore $y_N^E < y_N^G$, and EVs produce less non-climate emissions than GVs such that $y_{OP}^E < y_{OP}^G$.

We normalize the distribution of m users with the maximum number of long trips $m(l \leq l^{max}) = 1$ and the number of m users with the minimum number of long trips $m(l \leq l^{min}) = 0$. Let l^o be the number of long trip days from which it becomes interesting to have a GV, then we have the total number of EVs given by

$$q_t{}^E = m(l \leq l^o) \cdot M$$

$$q_t^G = \left[1 - m(l \leq l^o)\right] \cdot M$$

4.3. *Gasoline vehicle production*

The producers of GVs maximize profits under perfect competition. There is only one standard type of gasoline vehicle and we assume users are not myopic. We consider two cases for the cost functions for gasoline cars. In the first case the fuel efficiency is not constrained. Then each producer wants to offer a vehicle with a fuel consumption per mile f that minimizes users' costs and this implies that the fuel efficiency is a function of the fuel cost and an average mileage. In the second case, the minimum fuel efficiency is constrained by the government. In the EU, the second case is more realistic as producers tend to underperform compared to the fuel efficiency standard (Reynaert, 2017). Producers of gasoline vehicles can however buy fuel efficiency credits fec_t from producers of EVs at a price $pfec_t$. We assume that there is good monitoring of the realized minimum fuel efficiency (here maximum fuel consumption per vehicle km f^{max}) and that the fine is sufficiently high to make all car manufacturers comply.

Following the Fisher & Newell (2008) technique to introduce endogenous technological progress, we assume that the gasoline car producers can, in the first period, invest in a better knowledge base that helps to reduce the costs of vehicles in the second period. The knowledge base is produced by two factors: learning by doing as well as by pure R&D. Learning by doing decreases costs by drawing on the accumulated production, also known as the experience curve approach. Learning by doing is used in many long term simulation models but is biased because it forgets the learning by pure R&D (Nordhaus(2014)). The pure R&D is the second way to increase the knowledge base. It is difficult to separate the effects of learning by doing and pure R&D. Aghion et al.(2016) in their study of the patents firm-level panel data on auto industry innovation distinguishing between “dirty” internal combustion engine and “clean” e.g., electric, hybrid, and hydrogen patents across 80 countries, show that both factors matter. They showed that the innovation activities of all automobile producers react to fuel price incentives, that gasoline firms specialize in fuel efficiency patents and greener car producers specialize in patents bringing down the costs of electric vehicles. They also show that there are important localized spillovers. In our formulation, we limit the effect of the knowledge base of gasoline cars to the costs that are specific to the fuel efficiency efforts of gasoline cars. This is in line with the separation in Aghion et al between dirty patents and grey patents, where the grey patents are the ones that are related to the reactions of the fossil fueled cars to fuel price changes. The total investment in R&D for fuel efficiency and the learning by doing will then reduce the fuel efficiency related costs in the second period.

The total knowledge base in the first period is $K^G{}_1$, in second period $K^G{}_2$ and is defined by the following expressions:

$$\begin{aligned} K_1^G &= 1 \\ K_2^G &= \left(\frac{H_2^G}{1}\right)^{\eta^h} \left(\frac{Q_2^G}{1}\right)^{\eta^Q} \\ H_2^G &= n_1 h_1^G \\ Q_2^G &= n_1 q_1^G \end{aligned} \tag{7}$$

The total knowledge build up via investments h^G in R&D for gasoline cars and the accumulated production Q^G both contribute to the knowledge stock, where n stands for the length of the period in years and q stands for the production per year. R&D and learning-by-doing can be complements or substitutes.

We now discuss the model equations assuming a tradable fuel efficiency policy. The GV firm profit equals total sales times the producer price for GV, P_t^G, minus a production tax on GV, φ_t, minus total production costs for GV, $G(q_{G_t})$ minus the expenses for R&D and minus the costs of the necessary fuel efficiency credits when it does not meet the fuel efficiency target. The firm maximizes the sum of profits in the first period, made up of n_1 years, and discounted profits from the second period, made up of n_2 years. $R(h^G)$ is subsidized by the government at a rate σ_G.

$$\begin{aligned}\Pi_G &= n_1 \left\{ (\mathrm{P}_1^G - \phi_1) q_1^G - G(K_1^G, q_1^G) - (1-\sigma_G) R(h_G) - \left(\frac{1}{f_1^{\text{target}}} - \frac{1}{f_1}\right).pefc_1.q_1^G \right\} \\ &+ \delta n_2 \left\{ (\mathrm{P}_2^G - \phi_2) q_2^G - G(K_2^G, q_2^G) - \left(\frac{1}{f_2^{\text{target}}} - \frac{1}{f_2}\right).pefc_2.q_2^G \right\}\end{aligned} \tag{8}$$

The production cost of GVs has constant returns to scale and consists of a part that is non fuel efficiency related (NFP) and a part that is fuel efficiency related. The fuel efficiency related costs will decrease when the knowledge level K^G increases. The cost of increasing fuel efficiency is quadratic in 1/f. The knowledge level K is a function of learning by doing Q and investments in knowledge H for gasoline cars. At the start of the first period, the knowledge level is set to 1 but in the second period, the accumulation of knowledge decreases the costs of more fuel efficiency.

$$G(K_t^G, q_t^G) = q_t^G \left[NFP + \frac{1}{K_t^G} (\mathrm{i}_g + 0.5 j_g . f_t^{-1}) f_t^{-1} \right] \tag{9}$$

We assume perfect competition in the production of cars, so every manufacturer takes prices of cars as given. Maximizing profits generates equilibrium market prices for GV in the first and second period as well as firm optimal investments in R&D and a firm optimal fuel efficiency:

$$\begin{aligned}
\frac{\delta\Pi^G}{\delta q_1^G} &= n_1\left[(\mathrm{P}_1^G - \phi_1) - G_{q_1^G}(K_1^G, q_1^G) - (\frac{1}{f_1^{\text{target}}} - \frac{1}{f_1}).pefc_1\right] - \delta\rho n_2\left[G_{Q_2^G}(K_2^G, q_2^G).n_1.\frac{\delta K_2^G}{\delta Q_2^G}\right] = 0 \\
\frac{\delta\Pi^G}{\delta q_2^G} &= \left[(\mathrm{P}_2^G - \phi_2) - G_{q_2^G}(K_2^G, q_2^G) - (\frac{1}{f_2^{\text{target}}} - \frac{1}{f_2}).pefc_2\right] = 0 \\
\frac{\delta\Pi^G}{\delta h_1^G} &= -n_1(1-\sigma_G)R_h(h_G) - \delta n_2\rho G_{K_2^G}(K_2^G, q_2^G).n_1.\frac{\delta K_2^G}{\delta H_2^G} = 0 \\
\frac{\delta\Pi^G}{\delta(\frac{1}{f_t})^{-1}} &= 0 \Rightarrow i + j(\frac{1}{f_t})^{-1} = pefc_t
\end{aligned} \tag{10}$$

The first equation in (10) shows that the price of a GV will equal the marginal production cost in the first period plus the efficiency credits it will need per car minus the cost decrease it can realize in the second period thanks to learning by doing in the first period. Of the knowledge the firm did build up in the first period, only a share ρ ≤ 1 can be captured by the firm due to spillovers that cannot be valorized by patents.

The investment in pure R&D also helps to reduce the cost of more fuel efficient vehicles in the second period, again only a share ρ is captured by the firm. The level of fuel efficiency of cars is, in each period, pushed until the marginal cost of more fuel efficiency equals the price of a fuel efficiency credit. Note that knowledge efforts are directed mainly to reduce the cost of making cars more fuel efficient: the stricter the fuel efficiency target, the higher the price of fuel efficiency credits , the higher the payoff of knowledge building and the higher the optimal marginal cost of fuel efficiency efforts .

We will also model other policy instruments. A popular policy contender is the portfolio obligation by which the car market has to reach a market share of minimum α EVs. This can be implemented via a tradable portfolio credit with a value *prport* that will be received by EV manufacturers for every EV they sell and by making the GV producers buy a proportion α/(1- α) of the portfolio credit for each GV they sell. The portfolio credit obligation is then added to the marginal cost of the GV. Prices of GV will be increased and EV prices decreased until the desired portfolio is reached.

4.4. Electric vehicle production

Similarly, EV producers maximize the sum of the discounted profits in the first period and second period. The total cost in the first period consists of production costs, $G(K^E_t, q^E_t)$ and the R&D investment made by the firm, $(1 - \sigma_E)R(h^E_t)$ and the sales of fuel efficiency credits to the GV industry. Where q_t^E is the production of EVs in period t and K^E_t is the knowledge stock for EVs. As the main challenge in terms of technological progress is to make batteries cheaper (and lighter), we assume that the knowledge stock serves to decrease the cost of the battery component of EVs. The knowledge stock $K(H^E{}_t, Q^E{}_t)$ allows to decrease the costs of batteries in the second period. $q^E{}_t$ is the number of EVs produced in period t and σ_E is share of R&D expenditure that is paid by the government. Production costs are proportional in output, and decreasing and convex in knowledge stock. The knowledge stock is built up in the first period by the total sales of EVs (learning by doing) and by the total investment in pure R&D.

EV producers maximize profits:

$$\begin{aligned}\Pi_E &= n_1 \left\{ (\mathrm{P}_1^E - \nu_1) q_1^E - G(K_1^E, q_1^E) - (1-\sigma_E) R(h_E) + \left(\frac{1}{f_1^{\text{target}}}\right).pefc_1.q_1^E \right\} \\ &+ \delta n_2 \left\{ (\mathrm{P}_2^E - \phi_2) q_2^E - G(K_2^E, q_2^E) + \left(\frac{1}{f_2^{\text{target}}}\right).pefc_2.q_2^E \right\}\end{aligned} \tag{11}$$

Where ν_t is the production tax (or subsidy) for EVs.

Where the production cost of EVs has constant returns to scale and consists of a non-battery part (NBP) and a battery part (B). The battery part decreases with additional knowledge but is linear in the battery power per car.

$$\begin{aligned} G(K_t^E, q_t^E) &= q_t^E \left[NBP + \frac{a}{K_t^E} \mathrm{B} \right] \\ K_1^E &= 1 \\ K_2^E &= \left(\frac{H_2^E}{1} \right)^{\eta^h} \left(\frac{Q_2^E}{1} \right)^{\eta^Q} \\ H_2^E &= n_1.h_1^E \\ Q_2^E &= n_1.q_1^E \end{aligned} \tag{12}$$

The optimal production level of electric vehicles in the two periods and the investment in pure R&D in the first period are determined by the first order conditions:

$$\begin{aligned}
&\frac{\delta\Pi^E}{\delta q_1^E} = n_1\left[(\mathrm{P}_1^E - \nu_1) - G_{q_1^E}(K_1^E, q_1^E) - (\frac{1}{f_1^{\text{target}}}).pefc_1\right] \\
&-\delta\rho n_2\left[G_{Q_2^E}(K_2^E, q_2^{sE}).n_1.\frac{\delta K_2^E}{\delta Q_2^E}\right] = 0 \\
&\frac{\delta\Pi^E}{\delta q_2^E} = \left[(\mathrm{P}_2^E - \nu_2) - G_{q_2^E}(K_2^E, q_2^E) - (\frac{1}{f_2^{\text{target}}}).pefc_2\right] = 0 \\
&\frac{\delta\Pi^E}{\delta h_1^E} = -n_1(1-\sigma_E)R_h(h_E) - \delta n_2\rho G_{H_2^E}(K_2^E, q_2^E).n_1.\frac{\delta K_2^E}{\delta H_2^E} = 0
\end{aligned} \tag{13}$$

4.5. *The electricity market*

In this stylized model, the electricity market has two types of production: peak fossil fuel production and off-peak renewable production. To represent the different costs of the peak and off-peak electricity, we have one peak electricity production technology and one renewable production technology. Using peak load pricing theory, the marginal cost of peak electricity (excluding climate permits) equals p_{peak} and is equal to the variable fossil energy cost plus the capacity cost divided by the length of the peak period. For the off-peak electricity we have a cost p_{off}. As we assume that the fossil fuel plant is only used in the peak period and as we assume that there is no peak shifting in the total electricity demand, we take the peak and off-peak prices of electricity as given and these can be considered as the opportunity costs of peak and off-peak power. We can include in the model two types of electricity demand during the peak and off-peak: demand by the vehicle sector and demand by all other sectors. The demand for electricity by the car sector is determined by the share of EVs and the annual distance that they travel. Demand for electricity by all other sectors is given by a representative demand function. But as long as the prices of electricity do not change, we do not have to consider the demand for electricity of the other sectors.

4.6. *Social welfare function*

In this welfare optimization problem, we maximize the sum of total consumer surplus and producer surplus in the vehicle market and in the electricity market plus the government surplus, represented by respectively CS_V, PS_V, CS^{ot}_{EL}, PS_{EL} and GS . And we minimize the sum of the other external and carbon emissions damage costs produced by the gasoline and electric vehicles, C^E_Y, C^G_Y, C^E_X and C^G_X.

$$W = CS_V + PS_V + GS + CS_{EL}^{ot} + PS_{EL} - C_Y^E - C_Y^G - C_X^E - C_X^G$$

In the set up of the model, we assume that peak and off-peak electricity prices are fixed in both periods, therefore we do not need to include electricity market surplus in the welfare maximization problem.

$$W = CS_V + PS_V + GS - C_Y^E - C_Y^G - C_X^E - C_X^G \tag{14}$$

The total government surplus is given by the gasoline and electric vehicle producer and consumer taxes,

$$\begin{aligned}
GS = {} & n_1\left[(\phi_1 + \tau_1^G)q_1^G + (\nu_1 + \tau_1^E - s_{ch})q_1^E - \sigma_G R^G(h_1) - \sigma_E R^E(h_1)\right] \\
& + M\left[\sum_{m=0}^{m(l_1{}^\circ)} d(m)\,\mathrm{t}_1^E + \sum_{m=m(l_1{}^\circ)}^{M} d(m)(\mathrm{t}_1^G + f_1.\,\mathrm{t}_1^g)\right] \\
& + \delta n_2\left[(\phi_2 + \tau_2^G)q_2^G + (\nu_2 + \tau_2^E - s_{ch})q_2^E\right] \\
& + M\left[\sum_{m=0}^{m(l_2{}^\circ)} d(m)\,\mathrm{t}_2^E + \sum_{m=m(l_2{}^\circ)}^{M} d(m)(\mathrm{t}_2^G + f_2.\,\mathrm{t}_2^g)\right]
\end{aligned} \tag{15}$$

Where we have included both the production and consumer taxes, summed over the total distance travelled for each mode for each user.

5. Solving the model

5.1. Market equilibrium

In our model, the car ownership and the car use is given. The only equilibrium value of interest is therefore the market share of GVs and EVs.

The major disadvantage of EVs compared to GVs is their limited range. So we can expect a user equilibrium where EVs are selected by consumers that make mainly short trips. So we look for $l°_t$, the number of long trips for user *m* where she is indifferent between using a gasoline vehicle and an electric vehicle. To do this we compare the total cost of both vehicles. The break-even point will be determined by the number of long trips where the consumer cost in the first period for GV and EV are equalized. In the second period, the threshold number of long trips can increase due to stronger technological progress for EVs. The equilibrium is influenced by the exogenous policy interventions.

The easiest way to determine, for a given set of policy parameters, the threshold number of long trips *l*°, is to use *l*° as a control variable and check the slope of total cost functions as a function of the number of long trips *l*.

Taking the derivative of the total annual cost (6) for the *m-th* EV user, $C^E(m)$, yields the following expression:

$$\frac{\delta C^E(m)}{\delta l_m} = (d_l - d_s)t_d^E + (B - d_s.e)p_{peak} + (p_{ch} + z - P^p q_t^E)(d_l.e - B)$$

Where the first term represents the additional distance charge for one extra day with a long trip, $(B - d_s \cdot e)p_{peak}$ represents the lost opportunity of storage and $(p_{ch} + z - P^p q^E_t)(d_l \cdot e - B)$ represents the total cost of charging en-route. This expression is constant and the slope will be higher for a small battery car than for a large battery car.

Taking the derivative of the total annual cost (1) for the *m-th* GV user, $C^G(m)$, yields the following expression:

$$\frac{\partial C^G(m)}{\partial l_m} = (d_l - d_s)\big[f \cdot v_g + t_d^G\big]$$

As both $\frac{\partial C^E(m)}{\partial l_m}$ and $\frac{\partial C^G(m)}{\partial l_m}$ return scalars, we know that $C^E(m)$ and $C^G(m)$ are linear in l_m.

We can represent the car market equilibrium graphically.

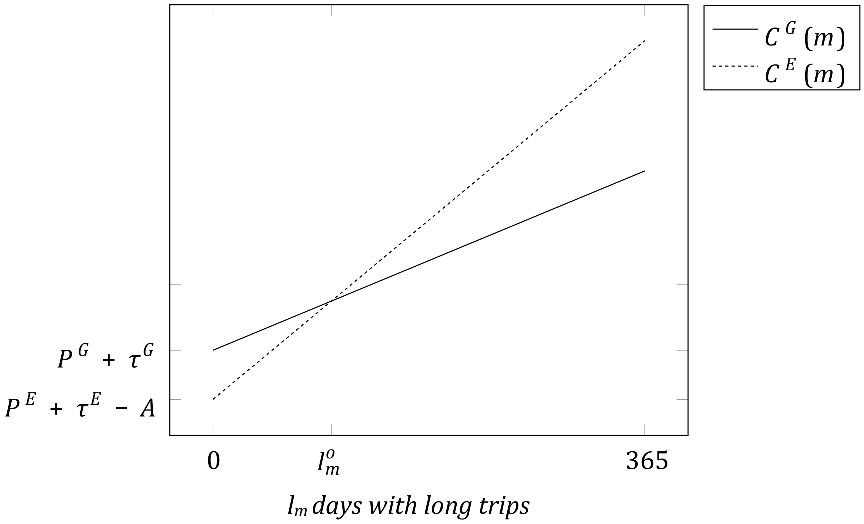

FIGURE 1 Illustration of the user equilibrium mechanism for one period

In the graph A represents the gains from storage :

$$A = 365(B - d_s \cdot e)(p_{peak} - p_{off})$$

which is the annual benefit of selling stored battery electricity during the peak. If $l_m = 0$, then all trips are short and every day the vehicle user can sell excess electricity to the grid. From this graph, it is clear that for $l_m < l_m^o$ users prefer electric vehicles, and for $l_m > l_m^o$ users prefer gasoline
vehicles.

5.2. *Comparative statics*

Equalizing $C^E(m^o) = C^G(m^o)$, we can solve for $l°$

$$l_m^o = \frac{P^E - P^G + \tau^E - \tau^G + CHE + 365(U_s - d_s \cdot U^G)}{(d_l - d_s)U^G - (U_l - U_s)}$$

Consider first an increase in the battery capacity B. This has two benefits: it decreases the costs of the long trips and allows to gain more storage credits on short trip days. This would lead to more EVs: the slope of the $C^E(l)$ would become flatter but it increases also the cost of an EV and this shifts the $C^E(l)$ upwards so that the end result is undetermined.

Lower costs for en route charging (denser network, faster charging) will of course lead to higher penetration of EVs:

$$\frac{\delta l_m^o}{\delta p_{ch}} < 0 \qquad \frac{\delta l_m^o}{\delta P^P} < 0$$

As EVs also can serve a storage function, lower costs of off-peak electricity (lower renewable costs in the off-peak) also increases the market share of EVs:

$$\frac{\partial l_m^o}{\partial p_{off}} < 0$$

Conversely, as we increase the price differential of peak and off-peak electricity, the potential benefit to EV users of selling excess power increases.

We can also prove that to decrease emissions via more storage of renewable off peak electricity, we must increase $l°$. First, we find the total emissions from our stylized vehicle model.

$$\begin{aligned}\Delta X_V &= X_G - X_E \\ &= \left[l_m \cdot d_l + (365 - l_m) \cdot d_s\right] \cdot f \cdot x_g^{cl} - \left[l_m(d_l \cdot e - B) - (365 - l_m)(B - d_s \cdot e)\right] x_e^{cl}\end{aligned}$$

When we differentiate with respect to l_m, we need to consider that, as we increase l_m, we are increasing the number of GVs, and thereby GV emissions, while reducing the number of EVs, and thereby EV emissions. Therefore, we represent the derivative

$$\frac{\partial \Delta X_V}{\partial l_m^o} = (d_l - d_s) \cdot (f \cdot x_g^{cl} - e \cdot x_e^{cl})$$

Assuming that $x_g^{cl} > x_e^{cl}$, the change in emissions depends on the fuel efficiency of GVs and the energy efficiency of EVs. As long as $e > f$, emissions will decrease as l_m^o increases, which is the outcome we expect as the share of EVs increases.

5.3. *Optimal policy*

In the optimal case, we need to correct all externalities. There are 5 externalities that need correction: the climate externality, the other external costs associated to car use, the learning by doing externality for EV producers and the R&D pure knowledge externality for EV batteries and GV fuel efficiency and the network externality of the charging stations.

This requires at least 5 instruments: a tax per unit of carbon emitted, a tax to correct for the other externalities, a subsidy to pay for the external pure R&D externalities, a subsidy to correct for the learning by doing externalities and finally a subsidy for the network externalities in the EV recharging network.

We can solve for the optimal amount of government funded R&D σ and the optimal EV tax (or subsidy) ν to correct the knowledge spillovers, when we set the first order conditions for profit maximization equal between the market correcting and market optimal scenarios. In this way, we have for electric vehicles:

$$\sigma = \underline{1} - \rho$$

$$\nu_1 = (1-\rho)\delta n_2 G_K(K_2, q_2^E) K_H(H_2, Q_2)$$

We have similar results for the optimal level of R&D and learning subsidies. In the first-best solution, the government subsidizes R&D to compensate the share of knowledge that is not retained by the firm. The production subsidy in the first period is equal to the lost benefits of first period learning that affect second period production.

To correct for the other externalities we need distance taxes that cover the other externalities (noise, non-carbon emissions, congestion, and accidents) as well as a carbon tax. In this way, $t_d^G = y_{ot}^G$, for GVs and $t_d^E = y_{ot}^E$ for EVs.

Building the model, it is clear that electric vehicle production depends on production costs, the cost of R&D, and the share of retained knowledge. Gasoline vehicle production depends on GV vehicle production and sales tax, as well as on the possibilities to bring down the fuel efficiency costs via knowledge build up that is for GVs limited to the R&D route only. Consumer demand depends on the vehicle purchase price, annual ownership tax, vehicle emissions, usage fees, and ease of use.

5.4. Selected policies for simulation

We examine a variety of potential policies, though there are several constraints included in the simulations.

In all simulations we keep the gasoline tax unchanged. This tax acts as a high carbon tax. We also stick to a government subsidy for R&D expenditures of 10%. This type of subsidy is commonly used in the EU and is not specific to climate policies. Finally we use differentiated distance taxes that cover the advantage of EVs compared to GVs.

We will concentrate the policy analysis on 4 policies:

Tax on GV purchase or Subsidy for EVs: this policy is used widely to promote the use of a cleaner vehicle technology. As total car ownership is given, a tax on GV purchase has the same effect as a subsidy for EVs.

Tradable Portfolio mandate: One can oblige the car retail sector to sell a minimum market share of EVs. The best way to operationalize this measure is to use portfolio credits where the GV producers have to buy credits from the EV manufacturers.

Maximum tradable carbon emissions rate or minimum tradable fuel efficiency rate: An upper limit on the carbon emissions rate puts pressure on GV producers to reduce the emissions intensity of their vehicles. As EVs have zero emissions by definition, GV producers can pay EV producers to achieve the required emission rate

Subsidized charging stations: Subsidizing charging stations increases the frequency and dispersion of en-route charging opportunities, effectively extending the driving range for EVs. By expanding the driving area range, a larger cross-section of consumers is interested in driving EVs.

The common objective of all the policies is to achieve a given reduction in the average emission rate, where the carbon emission rate for EV is taken to be 0. This decrease in the average emission rate is decided exogenously at the EU level. Finally recall that in this model, the mileage and car ownership are fixed, so that also rebound effects of more efficient cars are omitted.

6. Calibration of the Numerical model

6.1. *Focus of the model*

In the EU, the emissions in the transport sector stand for a quarter of all CO_2 emissions. Cars account for 60% of total transport CO_2 emissions.

We calibrate the model to Germany. We are interested in European policy assessment, but as Europe only sets the broad policy options, it is better to look into one concrete country with its actual policies rather than to examine an average of policy measures over EU countries. But as we analyze the effect of the broad European policy options, we assume that the car manufacturers respond to the simulated policies at the European market scale when they decide on production and R&D investments, so the policy options we discuss are by assumption common to all member countries. We consider only two types of cars: gasoline cars and battery electric cars. We leave out the diesel cars as also the latest generations of diesel cars (EURO 6) do, in general, not comply with the emissions standards for conventional pollution (NOx) and may be banned in more and more areas (ICCT, 2018). We also leave out the plug in electric vehicles (PHEV). Hybrid technology may be interesting but up to now it is difficult to monitor whether they are effectively used in electricity engine mode and not in fossil engine mode.

We build a two -period model, where the first period of 5 years can be understood as covering the target year 2021 and a second period of 10 years where the target year is 2030. The present EU policy target for 2021 is a fuel efficiency of minimum 95 g CO_2 or 4.1 L/100km (tank to wheel and NEDC test procedure) and for 2030 the target is a reduction of another 37,5 % to reach 59 g CO_2 (or 2.56 l/100km). The EC allows trading of fuel efficiency credits, the so-called "pooling" and "trading"[1] schemes.

6.2. *Calibration challenges*

Dealing with new technologies is inherently difficult for several reasons. First there is the uncertainty on the costs of future technologies. Second, the present prices may already be set strategically in the sense of selling more in order to benefit from the learning by doing mechanism. Third, the car market is a monopolistic competition market. We neglect the monopolistic feature of the market by assuming perfect competition as this allows us to analyze more carefully other mechanisms like technological progress.

We proceed in the following way. We start by recalling the empirical basis of car consumers and producers in the EU. Next we calibrate the model to the Norwegian policy experience that achieved a 30% market share for new cars in 2017 using a 100% purchase tax on GVs. This is

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[1] EC 2017

the only case where EV achieved a large market share up to now. In a final step we look into the estimates of the cost development of new technologies. We conclude with a set of parameter estimates that will be used in the policy analysis.

6.3. Empirical basis for the EU car market

A crucial assumption for the choice between fossil fuel and electric cars is the trade-off between purchase costs and fuel costs. For an accurate characterization of the trade-off, we rely on Grigolon et al. (2018) who estimated a supply and demand model for the EU car market exploiting the differences across EU countries in fuel costs and purchase costs for gasoline and diesel cars and including the monopolistic competition features of the car market. They found that consumers are not systematically myopic in their car purchase decisions. Their central estimate is a discount rate of 5.7% for a vehicle lifetime of 10 years[1]. This is the estimate we will use in the model.

A second empirical insight we will use is the explanation given by Reynaerts (2017) for the gap between the current fuel efficiency of cars and the fuel efficiency standard imposed by the European Commission. As car manufacturers were not fined for the fuel efficiency gap, they offer vehicles with a fuel efficiency that minimizes the sum of total user costs and purchase costs. The gap of 20 to 40% in the fuel efficiency achievements becomes then a rational response of the car manufacturers. This implies that, for the consumer, the possible fuel expenditure savings of 1 liter of gasoline per 100km, or 225 Euro per year (15000 km/year, price of fuel 1.5 Euro/liter), are smaller than the manufacturing cost of making a car that is 1 liter per 100km more efficient. This implies that the cost of increasing the fuel efficiency by 1 liter per 100 km has to be larger than the discounted value of fuel savings for 10 years at 5.7% interest rate so larger than 1679 Euro extra per vehicle.

In this model the mileage for each type of trip is kept constant. This raises a problem when through fuel efficiency improvements for GVs and the switch of GV to EV, the variable costs decrease as the rebound effect can become important. As we focus on the choice between two car technologies, we decided to only take into account the effect of the changes in the variable costs on the selection of the two car technologies. The disadvantage of EVs for long trips is taken into account by the subjective costs of refueling of EVs. However, we also need to take into account the low variable cost advantage of EVs for short trips. The fuel cost advantage of EVs is taken into account in the comparison of the total user costs of the two technologies but not the consumer surplus of additional short trips that is generated by the lower variable cost. According to the Norwegian experience, there is evidence for an additional mileage for the short trips when car owners shift from GV to EV. We therefore include for the EVs an extra consumer

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[1] See Table 3, model I in Grigolon et al (2017). If one uses a longer lifetime, one needs to adjust the discount rate downwards.

surplus under the form of a lower user cost for the difference in variable costs between GVs and EVs. But we also include an additional external cost for short trips as these are mostly in urban areas.

6.4. Fuel efficiency costs and technical progress

We can compare two approaches, one is the technical cost curve using engineering estimates and the other is the revealed preference approach using market data.

The EC (2017) produced technical cost estimates for an improvement of fuel efficiency with 15% in 2025 and with 30% in 2030. Their results (expressed as additional manufacturing costs) are summarized in TABLE 1.

	2025 (-15% compared to..)	2030 (-30% compared to…)
In absolute values (€)	400-500	1000-1200
In % increase of vehicle cost	1.5 to 3%	4.5 to 6.5%

TABLE 1 Engineering estimates of additional vehicle costs to achieve fuel efficiency targets (Source: EC (2017))

Assuming rational consumers and the non-compliance we found for the EU-fuel efficiency standards, the additional cost is larger than 360 Euro per year to improve the fuel efficiency of the car from 5.6 l/100km to 4.1 l /100 km or 2686 Euro [1] per car otherwise the manufacturers would have complied with the standard. We add 50% to this cost of fuel efficiency improvements and use then 540 Euro as the additional yearly cost to comply with the emission standard for 2021 (from 5.6 to 4.1 l/100 km)and 2804 Euro additional yearly cost to achieve the standard for 2030 (from 5.6 to 2.56 l/100km). Both cost estimates assume there is no specific R&D effort to bring these costs further down.

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[1] The consumer saves 225 € per year if fuel costs 1.5 €/l and he drives 15000 km/year. So improving the fuel efficiency from 5.6 to 4 will cost 1.6 (225) or 360 € on a yearly basis and using a discount rate of 5.7% for 10 years produces a car cost increase of 2686 €.

	Present realization	2021-standard	2030-standard
Emission standard	5.6 l/100 km	4,1 l/100 km (95g CO_2/vkm)	2.56 l/100 km (59,4 g CO_2/vkm)
Additional manufacturing cost		540 Euro/year/vehicle 4029 Euro/vehicle	2804 Euro/year/vehicle 20 921 Euro/vehicle

TABLE 2 Revealed preference estimates of costs of more fuel efficient GV before specific technical progress.

Comparing TABLES 1 and 2, the “revealed preference estimates” from the car market are an order of magnitude (4029/500) larger than the engineering estimates. According to Gillingham &Stock (2018) this is not uncommon and is partly a matter of concept.

6.5. *Costs and technological progress in batteries*

There are several estimates about future battery costs. The following figure summarizes the estimates of the Department of Energy (US DOE) for the progress in costs for a battery pack designed to deliver 320 km range. For sufficiently large battery volumes (200 000/ year), the price of batteries could decrease to 200 $/ Kwh.

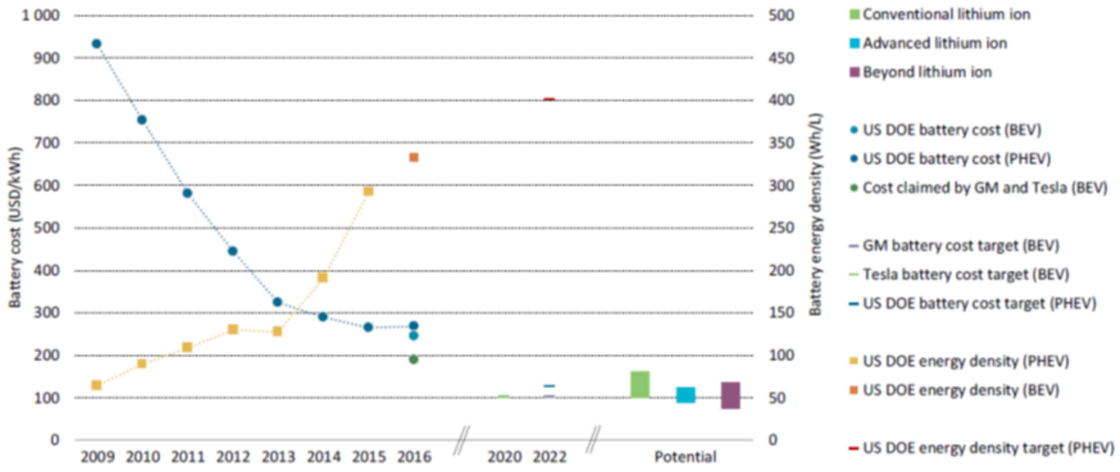

FIGURE 2 Estimates of progress in battery costs - Source: OECD/IEA (2017) Global EV Outlook 2017

Batteries in a 60 Kwh car represent nowadays up to 40% of the costs of an EV (Kochhan (2017) and IEA (2017)). For an electric car with a 30 kWh battery, the purchase cost (before taxes and subsidies) is around 36000 Euro. This is in the range of prices we find on the European market. The total EV price is decomposed into a 9000 Euro cost for the battery (300 €/Kwh) and a 27 000 € cost for the rest of the car.

For GVs we use a consumer price of 26 110 € for a car that has a fuel efficiency of 5.6 liter/100km.

6.6. A calibration test with the Norway experience

It is difficult to calibrate a model with a new type of vehicles when this new type has in most EU countries a market share of only 1 or 2%. For this reason we calibrate the model, using the Norway experience, (more precisely the greater Oslo area) that achieved a 30% penetration of EVs in the new car market in 2017. Of course this is a very rough approach but it can be justified for the very simple model we use here. Norway achieved this result using a wide set of policies (see Wangsness et al, (2018)). We focus on two of the policy parameters: a purchase tax for fossil cars of 100% and a dense refueling network for EVs. When we use our dynamic two period model we also have to specify the policy goals and instruments for the second period. Norway has announced to ban fossil fuel cars in 2025. However, it is not clear whether the car manufacturers will adapt their R&D and whether economics of scale and learning by doing will really be set in action to make this happen as Norway is a small country. Setting on hold the technical progress, the model is calibrated by an additional cost constant for EVs such that the 100% purchase tax on GVs achieves indeed the 30% penetration of EVs in the first period. In Norway the price of electricity is uniform so V2G operations play no role.

6.7. Other calibration parameters

The full list of parameter values and sources are listed in appendix. Here we discuss a few assumptions.

First we use a triangular distribution of long trips days between 20 and 100 long trip days per year. On short trip days (365 days – number of long days), cars drive 10 km and on long trip days they drive 350 km. This gives the average mileage of 14000 km per year in Germany.

The second assumption that merits attention are the peak and off-peak prices of electricity. In many European countries there are not yet peak and off-peak differentiated prices. When the European power sector will be largely renewable, there will be a need for prices that are differentiated between periods with enough wind and solar energy (off-peak) and the other periods (peak). Prices in the off-peak will be low (0.15 €/kWh) but not 0 as there are other uses of electricity in off-peak periods. In the peak period we use a value of 0.30 €/Kwh that corresponds to the price of generation power with a peaking gas plant during a few hundred hours a year. Charging and EV can also raise balancing and distribution network issues when it is not coordinated. This is the reason why we used a high price per kWh (0.60 €/Kwh) for charging en-route.

6.8. Choice of model parameters on technical progress

One of the uncertainties relates to the effects of knowledge building on the costs of the two types of cars. We use the following five assumptions:

First, EVs and GVs have many components in common and technological progress is important for all kinds of functionalities of a vehicle. This means that we are not interested in technological progress regarding safety, entertainment, suspension, self-driving cars etc.. So we concentrate only on the cost components that are directly related to the fuel efficiency for GV and to the battery costs of an EV. More precisely, for GVs we only consider the additional costs related to improving the fuel efficiency. For EVs we consider only the costs of batteries.

The second assumption relates to the initial stock of knowledge for both types of cars and the modelling of the learning by doing component of the knowledge building. The problem is that for EVs, one starts with a small initial production (1 or 2% of car market) and one can argue that there are learning and possible scale effects in the production and the marketing of EVs. For GVs, there is a long history of mass scale production and they have already a dominant market share. So it is difficult to argue that there are important learning by doing effects for GVs even if it is specific for the fuel efficiency related component. For this reason we only kept the learning by doing component for the knowledge building in the battery costs of EVs.

The third assumption relates to the production of knowledge by pure R&D. Is there a reason to have another cost function for R&D for EVs than for GVs? Of course there is more experience with GVs but labs and universities have studied electric cars for many years and there are trained scientists for both technologies. So we assumed the same cost function for R&D for both technologies.

The fourth assumption relates to the initial stock of knowledge for both technologies. Our formulation is based on the ratio of new knowledge versus existing knowledge (K_2/K_1). We set the initial knowledge base for both technologies equal to 1.

In the next TABLE, we illustrate the effects of the two types of learning on the battery costs of EVs and on the fuel efficiency costs of GVs.

The coefficient used for the technical progress is η =0.15 where the decrease in costs is given by

$$K_2 = \left(\frac{H_2}{1}\right)^{\eta^h} \left(\frac{Q_2}{1}\right)^{\eta^Q}$$

Costs in 2nd period – current costs have index 1	Gasoline vehicle (cost of fuel eff improvement)	Electric car (battery cost)
production x 2 for EV and doubling R&D expenditure G-vehicle $\eta^{h}=0.15$ (R&D) E- vehicle $\eta^{h}=0.15$ (R&D)and $\eta^{Q}=0.15$ (LBD)	0.901	0.81
Production EV x 4 and R&D expenditure x 4 G-vehicle $\eta=0.15$ (R&D) E- vehicle $\eta^{h}=0.15$ (R&D)and $\eta^{Q}=0.15$ (LBD)	0.81	0.66

LBD= learning by doing

TABLE 3: Effect on costs of Technological Progress coefficients in base case

For GVs, we only have knowledge building by R&D as the GV market is a more mature market.

A final parameter that needs to be calibrated is the cost of pure R&D. We know that there is a large R&D investment in the European automobile sector. In 2016 the top 2500 companies in the sector "Automobiles and parts" invested some 55 billion EU in R&D (Brueghel), part of which was for the power trains. If we can assume that half of the total R&D investment is related to power trains, and using a total EU car production of 17 million vehicles (ACEA(2019)), this would mean an investment for R&D per car of the order of 3235 Euro. Translated into annual equivalent investments per car (annuity factor of 7,466) , this is 433,3 Euro/car.

7. Policy simulations

Our central research question is what is the cost of reducing carbon emissions in the car sector and how is this cost related to the choice of policy instruments. We emphasize the role of the choice of policies on the induced technical progress.

As mileages and car ownership are fixed, reducing CO_2 emissions implies moving to a combination of more fuel efficient gasoline cars and electric cars. More particularly, we take as given the EU objective to reduce average CO_2 emissions of new cars to 95 g/vehkm (or 4.1 liter gasoline/vehkm) over a period of 5 years and a reduction to 59 g/vehkm (or 2,56 liter of gasoline /vehkm) after 15 years.

Figure 3 gives the intuition of the results to be expected from the policy simulations. Figure 3 measures from left to right the share of EVs and the social marginal cost in the second period of achieving a given penetration of EVs. This cost is upward sloping because, for given technology and battery size, an EV has a handicap for substituting longer trips. When there is no technological progress for EVs and GVs do not improve their fuel efficiency, we need to reach point A where the share of EVs equals 54%. This share is needed to reach the required average efficiency in period 2. Now introduce the option for GVs to improve their fuel efficiency. The marginal cost of increasing the share of GV beyond 46% (100%-56%) consists in increasing the fuel efficiency and is measured from right to left starting at the axis 54%. This gives a new optimum given by point B. Introduce now technological progress for EVs and GVs that is produced by learning by doing and R&D in the first period. In FIGURE 3 this means that the two marginal cost curves decrease and one ends up in point C.

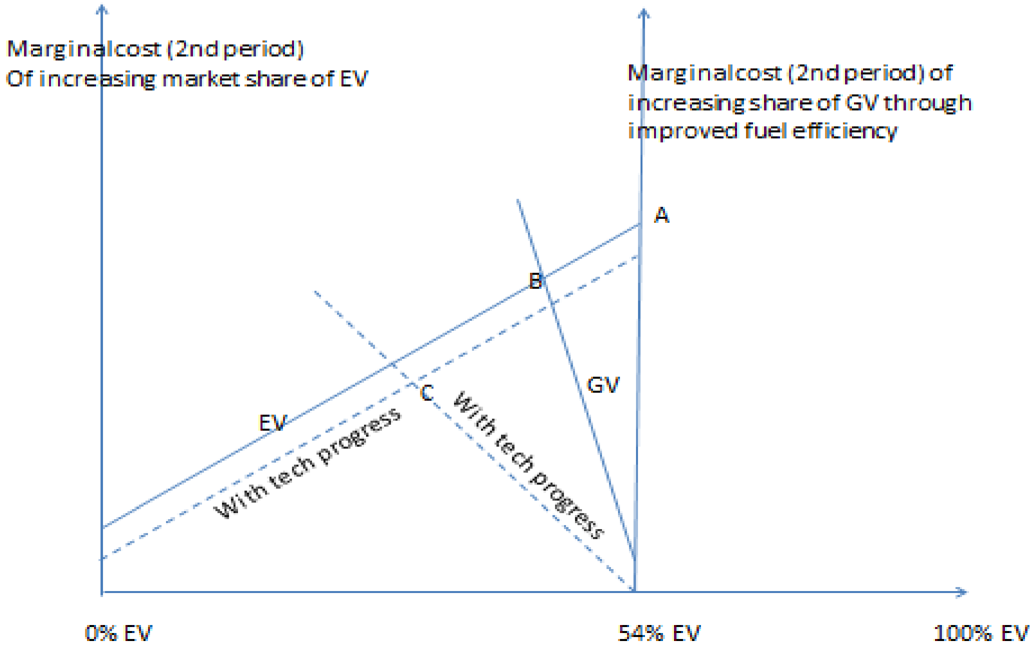

FIGURE 3 Marginal cost of different market shares of EV and GV to achieve the average emission target

7.1. The role of policy instruments in the induced technological progress

TABLE 4 compares two popular policy instruments and illustrates the role of induced technological progress. The common policy goal is to reduce emissions of cars from current 130 g/vehkm to 59 gram CO_2/vehkm after 15 years (end of period 2) with an intermediate target of 95 g CO_2/vehkm after 5 years (end of Period 1). We will use as equivalent unit the improvement of the fuel efficiency from the current 0,056 liter of gasoline per vehicle km to 0.041 liter per vehkm (after 5 years) and 0.0256 liter per vehkm. Overall results in terms of average costs are represented in FIGURE 4.

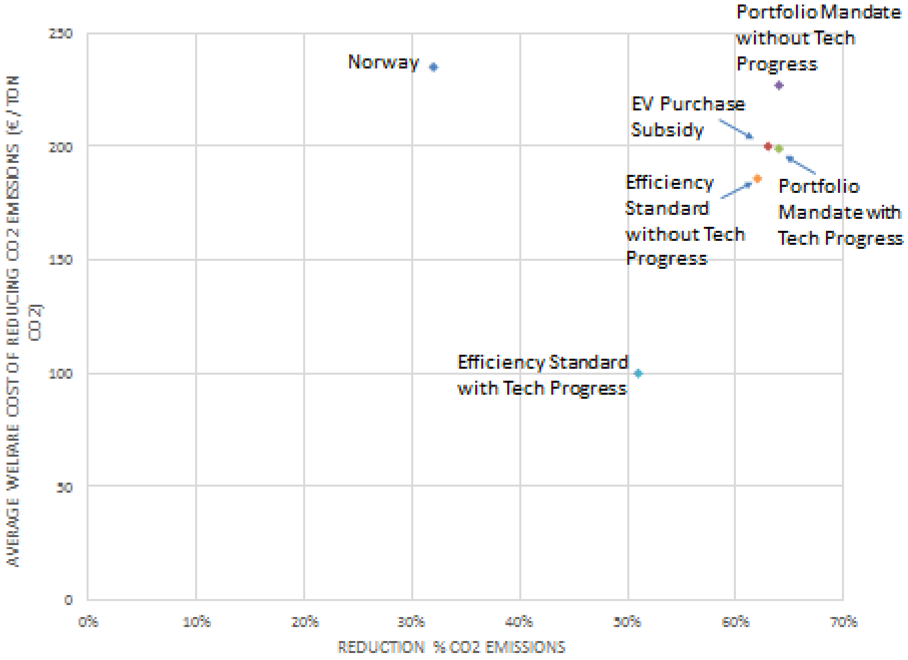

FIGURE 4 Average welfare cost of achieving the target average CO_2 emission rate in the second period (2030) for new cars, using different instruments and with/without technical progress.

The easiest instrument to understand is the portfolio mandate where the targets have to be met by increasing the market share of EVs that have 0 emissions. We assume here that the GVs keep their current fuel efficiency level of 0,056 liter/ vehkm[1]. This implies that the EVs have to reach a market share of 27% at end of period 1 as (1-0.27) 0.056 = 0.041 and a market share of 54% at the end of period 2. The GV producers have no incentive to improve the fuel efficiency as the policy instrument requires them to contribute to the EV market share by buying portfolio credits from the EV producers. If all car producers produce both GVs and EVs, the portfolio mandate could also be achieved with a cross-subsidy for the production of EVs. In the absence of induced technological progress (Column 1) we see that in the first period, the GV producers have to pay 886 €[2] for every EV, so per GV is this 886 times 27%/73% or 328 € on an annual basis. In the second period, the share of EVs needs to be higher, as EVs have a higher user cost for longer trips, they need a lower purchase price and this requires a higher portfolio credit for the EVs (1764 €). Together with the lower market share of GVs, this results in an increase of the purchase cost of GVs on an annuity basis of 1764 times 54/46 or 2070 € per gasoline car. The purchase cost of EVs is but one of the elements in the user cost equilibrium (cfr; section 5.1)

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[1] We assume that GV producers do not decrease the fuel efficiency of their cars. In our model simulations we keep the gasoline tax unchanged so that they have no incentive to change the initial fuel efficiency level.

[2] This is an annual equivalent; this means that the EV's receive a credit of 6610 € per car produced.

as also the fuel costs, the V2G benefits and the endogenous refueling network density play a role. Column 1 further reports the fuel efficiency for GVs in period 1 and period 2, as well as the battery cost reduction (0 as there is, by assumption, no technological progress). The table further reports the total cost index as well as the % reduction in CO_2 emissions and the average cost of emission reduction per ton of CO_2 that is high (226€). To put this cost in perspective, it can be compared with the current gasoline tax (0,68 €/liter) that comes down to 293 €/ ton of CO_2 . The 293 €/ ton means that for a gasoline car producer, making his car more fuel efficient so that it reduces emissions by 1 ton, would increase the manufacturing cost by 293 € . Replacing part of the GVs by EVs would save emissions at a lower cost: 165 € per ton because EVs have very low emissions. This average cost of emission reduction is computed in welfare terms taking into account the differences in other external costs between the two types of vehicles. An EV has an advantage over GVs in terms of air pollution and noise for short trips (mainly in urban areas) as well as the benefits of V2G.

Although the average emission per car is the policy target and is the same for all scenarios, there will be differences in CO_2 emissions. A higher share of EVs decreases the total emissions more than proportionally because the EVs are used for more and more long trips.

	N0 techn progress Portfolio mandate	WITH techn progress Portfolio mandate	NO techn progress Fuel efficiency mandate	WITH techn progress Fuel efficiency mandate
Mkt share EV P1	27%	27%	1%	9%
Mkt share EV P2	54%	54%	50%	11%
Price EV P1 (€)	4826 -886	4832-888	4826-106	4826-90
Price EV P2 (€)	4826 -1764	3658-1130	4826-72	3658-174
Price GV P1 (€)	3500+886(27/73)	3500+888(27/73)	4025+106(1/99)	3829+90(9/91)
Price GV P2 (€)	3500+1764(54/46)	3500+1130(54/46)	3621+72(50/50)	4201+174(11/89)
Fuel Eff P1 (liter/km)	0,056	0,056	0,04088	0,0449
Fuel Eff P2 (liter/km)	0,056	0,056	0,04088	0,0288
Battery cost reduction %	0%	97%	97%	97%
Total cost index	100 (=211)	97	102	82
Unit Cost CO_2 saved (€/ton)	226	199	186	100
CO_2 emission reduction P1,P2	27%, 64%	27%, 64%	26%, 62%	23%,51%

TABLE 4 Effects of technological progress on portfolio mandate and on fuel efficiency mandate

We can now introduce the effects of technological progress. In the case of the portfolio standard, the technological progress is limited to the EVs because the fuel efficiency of the GVs does not matter for meeting the portfolio standard. The producers of EVs benefit from the two mechanisms to reduce the costs of EV batteries. First they realize that producing a larger quantity (and selling below the marginal cost in the first period (cfr.1st eq in (13)) decreases their production cost in the second period, part of this cost reduction spills over to the rest of the industry but their remains a clear incentive to produce more and achieve a stronger learning by doing effect. When the market share of EVs increases in the first period to 27%, there is a significant learning by doing effect. The second mechanism that is activated by the EV producers is the pure knowledge build up about battery production that requires firms to invest in R&D. EV producers invest some 10% of their income in the first period in pure R&D. This allows to reduce the cost of batteries by 97%. This does not increase the share of EVs because the EV-share is determined by the portfolio obligation that is still binding. But the technological progress reduces the costs of meeting the target and the costs per ton of CO_2 saved is reduced to 199 €/ ton of CO_2.

We can now analyze the fuel efficiency mandate that forces car producers to achieve a lower average emission rate in the first period and an even lower emission rate in the second period. The incentives for the GV producers are now different. They have to meet the average emission rate. They can do this by making their cars more efficient but also by buying fuel efficiency credits from EV producers. They will balance the two options so as to minimize their overall production costs. When technological progress is excluded, this forces the GV producers to make more efficient GVs (0.0488 liter/vehkm) but this is expensive and increases the production cost of GVs (annual equivalent) to 4025 €. They need to complement this effort with fuel efficiency credits they buy from EV producers. In the second period, reaching the fuel efficiency target becomes very expensive for the GV producers and they have to rely on purchasing fuel efficiency permits from the EV producers. In the end this solution produces slightly less CO_2 emission reduction: there are less EVs but the GVs are more fuel efficient. CO_2 emissions are also reduced at slightly lower cost than in the case of the portfolio standard, all this in the absence of technological progress.

Introduce now technological progress: we have learning by doing and pure knowledge build up for EVs and for GVs but we only take into account the pure knowledge build up. With the fuel efficiency mandate, the GV producers have a strong incentive to reduce the cost of fuel efficiency improvement via R&D expenditures as the cost of reaching the target in the second period is very high. The investments in R&D allow them to improve the fuel efficiency from 0.056 liter/vkm (starting value) to 0.0288 liter/vkm after 15 years. For the last bit (to reach the target 0.0254), they rely on fuel efficiency credits of EVs. The share of EVs in the second period is lowest in this scenario.

The most important advantage of this scenario is the lower cost of reducing CO_2 emissions. Total emission reductions are somewhat lower than in the other scenarios (51% in the second period rather than 64%) but the overall cost of the scenario is much lower and so is the cost per ton of CO_2 saved that becomes 100 €/ton CO_2. The main reason is that the option to improve the fuel efficiency of GV has become interesting for GV producers so that they will invest in bringing down the cost of fuel efficiency improvements.

Figure 4 summarizes our results in terms of average costs of CO_2 emission reduction. This figure adds the EV Purchase subsidy case that has the same average cost as a portfolio mandate because, in our model, the car ownership is fixed and there is no penalty for the use of public funds. The "Norway" scenario that achieves the 30% penetration with a purchase tax on fossil cars performs worse as an action by one isolated country is unlikely to stimulate technological progress.

A portfolio mandate forcing a bigger market share for EVs is currently discussed by several governments: Norway wants to ban fossil cars by 2025, France and the UK have announced plans to ban the sales of fossil cars by 2040 and some big cities also want to ban fossil cars by 2030 (case of Paris). According to our analysis, this is a costly policy at the aggregate level. The high cost results from neglecting the option to make gasoline cars more fuel efficient.

7.2. The importance of the battery size and the vehicle to grid option

Up to now we assumed a standard battery size of 30 kWh in all scenarios. The optimal battery size depends on the importance of the V2G benefits and on the number of long trips. A larger battery is more expensive but allows to store and sell more electricity on days with short trips and allows to lose less time for refueling during long trips (see Greaker et al, 2019). In principle, one needs to choose an optimal battery size for their annual number of long trip days, so it would be different for every individual.

We only used one size of batteries in all the simulations: 30 kWh. When we vary the size of the battery (40, 50 kWh) we find that the costs of emission reduction decreases but that the market share of EVs is not strongly affected.

In €/ ton of CO_2	30 kWh	40 kWh	50 kWh
Portfolio mandate	151	124	98
Fuel efficiency mandate	82	78	74

TABLE 5 effect of the battery size on the cost of reducing CO_2 emissions

The V2G option was embedded in all simulations and is driven by the difference between peak and off-peak electricity prices. When we use uniform electricity prices, the V2G option is no longer interesting for the EV owners and there is no transfer anymore from off-peak to peak periods. This will increase the cost of reducing CO_2 emissions mainly in the portfolio scenario because in this scenario their market share is highest. The high share of EVs in the portfolio mandate also allows to significantly increase the CO_2 emissions savings in the second period (P2). Turning the V2G option on or off has almost no effect on the market share of EVs because this share is mainly dictated by the average fuel efficiency target.

	With V2G		Without V2G	
	In €/ ton of CO_2	% emission reduction P2	In €/ ton of CO_2	% emission reduction P2
Portfolio mandate	151	78	192	64
Fuel efficiency mandate	82	51	100	51

TABLE 6 Role of V2G for the cost of emission reduction and for the emission reduction in the second period

Results are illustrated in FIGURE 5.

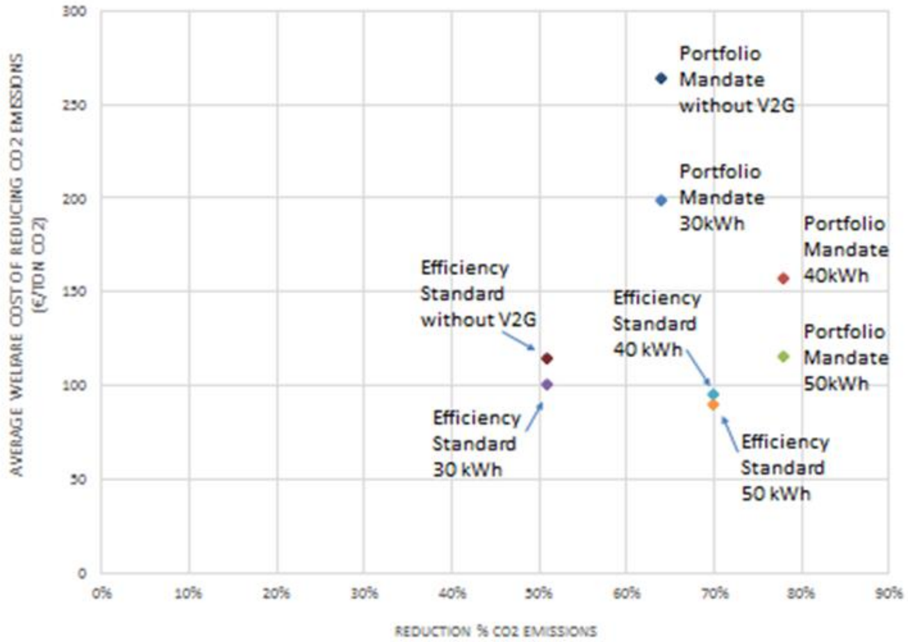

FIGURE 5 Average cost of emission reduction for different battery sizes.

7.3. Commitment issues

In our two period model, the endogenous technological progress is driven by the possibilities to decrease the costs of meeting the stricter targets in the second period. The R&D investments have to be made in the first period and firms will only make these investments when they are sure that the government commits to the strict targets. The experience with fuel efficiency targets in the EU shows that imposing strict targets is not sufficient: car manufacturers did not comply and only delivered fuel efficiency justified by the present gasoline tax. The commitment and enforcement problem also appeared for conventional emissions of diesel cars ("dieselgate"). When there is no strict monitoring and strong sanctioning, the GV producers will simply select the fuel efficiency that minimizes the full user costs of GV owners, the fuel efficiency will not improve and the EVs will almost not enter the market. Table 6 illustrates that, in the absence of technological progress, meeting the targets becomes very costly. This could happen when automobile firms do not believe the commitment of the government and do not invest in R&D.

Yao (1988) studied the emission regulation of cars in the US in the early seventies. The US government did not know the efficiency of investments in R&D, though the industry knew or had at least less uncertainty about the costs. In a multi-period model, the industry association is afraid of revealing its R&D productivity in the first period as it risks the ratchet effect. Government may in this case impose an even stricter target in the second period. So the industry may very well chose a strategy where it underinvests in R&D and shows high costs of meeting the target in the first period hoping that the government will set more lax targets. This story has been repeated later in California for the portfolio mandate imposing a minimum share of zero emission cars.

The problem is solved when the government can commit itself for a long period. This is difficult as a new government can easily change the law. Probably the best guarantee for commitment by the EU is a good cost benefit analysis showing that the costs of the regulation are in line with the benefits. In the current assessment of the fuel efficiency standards, there are two weak points. The first is the use of engineering estimates that are much lower than the revealed cost estimates. The second weak point are the climate objectives of the EU that may not be shared by the rest of the world and that mechanisms like the green paradox decrease the credibility of the fuel efficiency targets.

8. Conclusions and Caveats

We used a two-period model for the car manufacturing sector with gasoline car producers and electric car producers to compare the cost efficiency of different policies to decrease the CO2 emissions of cars . Both types of cars have endogenous technological progress that is triggered by environmental policies, including tradable fuel efficiency standards, portfolio standards, carbon taxes, purchase taxes and subsidies for R&D. EVs can also be used for vehicle to grid operations where off peak (renewable) electricity can be stored in the battery to reduce the load in the peak hours.

The current EU policy instrument is a tradable fuel efficiency mandate where gasoline fueled cars have to improve their fuel efficiency but can buy in efforts from EV producers as EVs are considered as 0 emission cars. We show that this instrument outperforms the portfolio mandate where the same reduction of the average emission rate is obtained via a tradable portfolio mandate. The fuel efficiency mandate is better because it contains an incentive to improve the fuel efficiency of GVs through R&D. The fuel efficiency mandate is dynamically more efficient than a portfolio mandate that targets a high share of EVs. With endogenous technological progress, the cost of saving CO_2 emissions is reduced to about 100 €/ton CO_2.

The investments in technological progress require that car producers consider the EU target as credible and a real commitment. The EU fuel efficiency target for 2021 will very likely not be met and this means that car producers may not take the current targets as a strong commitment from the side of the policy makers.

We used a simple model that is missing some important dimensions. First it focusses on the sales of new cars and takes the mileage and lifetime of cars as fixed. This may overestimate the savings of fuel and CO_2 emissions as there will be a rebound effect. On the other hand, more fuel efficient cars , electric or not, will be more expensive and this may decrease car ownership and prolong the life of cars.

The simple model was focusing on the EU and the climate problem is a world problem where the role of EU emissions is decreasing as its emissions will approach 10% of total emissions. EU efforts can have a positive and a negative spillover on the rest of the world.

The positive spillover can come from the transfer of fuel efficiency technology to the rest of the world. Car manufacturers in the rest of the world will be forced to adopt the same efficiency standards if they want to sell cars in the EU (Barla & Proost, 2012). The negative spillover of the EU fuel efficiency efforts can come from the green paradox as fuel efficiency efforts may shift rather than reduce the consumption of oil (see Aune et al . 2015).

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APPENDIX PARAMETER VALUES

Parameter	Value	Units
Distance Tax	0	€/km
Annual ownership fee	100	€
Distance Tax	0	€/km
Annual ownership fee (purchase subsidy)	-400	€
Govt subsidy for charging stations	0	€
GV market price	3500	€/veh
GV Production tax	0	€/veh
GV Vehicle Cost	3000	€/veh
GV Non-Fuel Efficiency Cost	2500	€/veh
Target Fuel Efficiency 1	0.041	liter/vkm
Target Fuel Efficiency 2	0,0287	liter/vkm
i	99,5	
j	50,4	
Production Tax (subsidy)	0	€/veh
ρ	0,5	
σ	0,1	
Rate of learning-by-doing	0,15	
Rate of learning with direct R&D investment	0,15	
EV Market Price	6073	€/veh
Battery Cost	2429	€/veh
Non-Battery Cost	3644	€/veh
Period 1	5	years
Period 2	10	years
Discount Rate	0.62	
Minimum number of long trips	20	days
Maximum number of long trips	200	days
Short Trip Distance	25	km
Long Trip Distance	350	km
Discount Rate (Vehicle Lifetime)	0,057	
Lifetime EV	10	yr
Gasoline cost	0,6	€/Liter
Gasoline tax	0,68	€/Liter
Fuel efficiency	0,056	Liter/km
Carbon intensity gasoline	0,023	tons CO_2/ L
Carbon intensity	0,000118	tons CO_2/ km
External cost of non-C air pollution (long trips)	0,0049	€/km
External cost of non-C air pollution (short trips)	0,0148	€/km
External cost of noise pollution (long trips)	0,0002	€/km
External cost of noise pollution (short trips)	0,02	€/km

EV energy efficiency	0,2	kWh/km
Carbon intensity (peak)	0,0004408	tons CO_2/kWh
Carbon intensity (off-peak)	0	tons CO_2/kWh
External cost of non-C air pollution (long trips)	0,0099	€/km
External cost of non-C air pollution (short trips)	0,0072	€/km
External cost of noise pollution (long trips)	0,0001	€/km
External cost of noise pollution (short trips)	0,0105	€/km
Battery capacity	30	kWh
Price of off-peak e-	0,15	€/kWh
Price of on-peak e-	0,3	€/kWh
Price of charging e-	0,600	€/kWh
Disutility of charging	1	€/kWh
Subsidy for home charging	0%	
Avg cost of charging station (home)	500	€
Price of network externality	0,0000003	€/kWh
Emissions Tax	25	€/ton CO_2
External cost of congestion (short)	0,28	€/km
External cost of accidents (short)	0,0543	€/km
External cost of congestion (long)	0,11	€/km
External cost of accidents (long)	0,0214	€/km
Initial Stock of EVs	75000	vehicles
Initial Stock of GVs	2500000	vehicles