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Electric Vehicles, Tax incentives and Emissions: Evidence from Norway

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Abstract

This paper empirically estimates the effects of electric vehicles (EVs) on passenger car emissions to inform the design of policies that encourage EV purchases in Norway. We use exceptionally rich data on the universe of cars and households from Norway, which has a very high share of EVs, thanks to generous tax incentives and other policies. Our estimates suggest that household-level emission savings from the purchase of additional EVs are limited, resulting in high implicit abatement costs of Norway's tax incentives relative to emission savings. However, the estimated emission savings are much larger if EVs replace the dirtiest cars. Norway's experience may also help inform similar policies in other countries as they ramp up their own national climate mitigation strategies.

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I. Introduction

Public policies to promote usage of electric vehicles (EVs) feature prominently national recovery programs from the Covid crisis (IEA, 2021), and electric vehicles are often seen as an important element of climate change mitigation strategies (Hausfather, 2019). From a policy perspective, understanding the cost effectiveness of such policies and the environmental benefits of EVs is therefore critical. The objective of this paper is to econometrically estimate emission savings from EV usage at the household level and use the results to compute, back-of-the-envelope style, the cost effectiveness of some of the tax incentives in Norway, a country with a very high share of EVs.

There is a large literature that quantifies the direct and indirect greenhouse gas emissions of the production and operation of EVs and internal combustion engine vehicles (ICEVs). Many studies find that EVs have a 'green lead' which increases the cleaner the energy mix that is used to produce and operate EVs and the longer the assumed lifespan of EVs is (see Christensen, 2017 and Hausfather, 2019, for examples; by contrast, Archsmith, 2016, finds that EVs could increase emissions in some regions of the U.S. depending on the electricity mix and other assumptions). However, under this approach, the exact emission savings of EVs depend on which specific EVs and ICEVs are compared.[2]

In this paper, we focus on the reduction of exhaust emissions from conventional cars as a result of acquisition of EVs at the household level.[3] In particular, during the transition period towards the full electrification of the passenger car fleet when both EVs and ICEVs are operating alongside one another, substitution crucially matters: The reduction of emissions as a result of the purchase of one additional EV are driven by which ICEVs are substituted and to what extent. For instance, emission savings could differ between households that replace a sparsely used but fuel-efficient ICEV by an EV to those households that add an EV to their stocks of heavily used and dirty ICEVs.

We therefore argue that household-level savings of passenger car emissions from the operation of EVs are an empirical matter and complex to predict conceptually as they are likely to depend on a complex interplay of household preferences, habits and other factors. Of course, savings of individual households do not necessarily map one-to-one to economy-wide savings. However, understanding the heterogeneity in household-level savings helps designing EV-promoting policies that maximize emission savings. For instance, policies could precisely incentivize the scrapping of ICEVs that are replaced by EVs to prevent them from being sold at home or abroad so that our estimated emission savings materialize.

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[2] This is explicit in online tools that quantify greenhouse gas emissions over the lifecycle of cars. See for instance https://www.connecting-project.lu/tools/climobil/

[3] For the purpose of this paper and to estimate the CO_2 emission impact of EVs, we ignore other types of exhaust emissions (mainly NO_x and PM), emissions during the production of EVs, which are substantial and sometimes found to be higher than those of ICEVs (Dillman et al. 2020, Hao et al. 2017), and relatively high non-exhaust particle emissions during operation, including from wearing down of tires over time (Timmers and Achten, 2016). We also ignore the possibility that higher electricity use in Norway reduces Norwegian electricity exports to other European countries and could indirectly result in higher electricity generation and CO_2 emissions abroad, and we do not analyze whether higher electricity demand through increased EV usage will reduce the share of electricity from renewable sources.

We use unique data on the universe of Norwegian cars and households provided by Statistics Norway. The data contain exceptionally rich information on the households themselves and the cars they own, over the 2010-2019 period (with some gaps for the last year). Focusing on Norway as a case study for the effectiveness of tax incentives for EVs has also other advantages beyond data availability. First, electricity in Norway comes almost entirely from renewable sources which makes the environmental impact of EVs easier to analyze. In other countries, the share of non-renewable electricity sources is typically much higher, which prima facie could partially offset the beneficial impact of adopting EVs.

Second, the share of EVs is much higher in Norway than in other countries. Around half of the cars sold annually in Norway are EVs, thanks to generous tax and other incentives. EVs are exempt from VAT, and EVs are not subject to the one-off motor vehicle registration taxes (EVs are exempt from the weight-based component and not taxed under the green component). In combination, both incentives can amount to more than 40 percent of the pre-tax price depending on assumptions.[4] Apart from not having to pay fuel excises and taxes, owners of EVs also benefit from other advantages, including lower annual vehicle license fees, reductions of (or even exemptions from) certain tolls and parking fees and the possibility to use special road lanes, although there are plans to roll back the latter (and indeed the government is taking a second look at the tax incentives); see Bjerkan et al. (2016) and Figenbaum et al. (2015) for a detailed summary of incentives in Norway. Fridstrøm (2021) calculate the price of carbon implicit in the fiscal incentives bearing on vehicles, fuel or road use. Norway has also one of the largest number of public charging stations per capita (Hall and Lutsey, 2020).

We first motivate our analysis by presenting a few stylized facts. We argue that despite the high market share of EVs in Norway, the full greening of the car fleet would still take several decades at current trends, underlining that the transition period could be lengthy which would increase the relevance of our analysis. We also show that the majority of households that own EVs own one or several conventional cars. In addition, the annual mileage of EVs is lower than that of ICEVs controlling for a range of unobserved household characteristics, suggesting that the degree to which EVs replace ICEV usage is potentially interesting. Finally, we show that emissions from passenger cars are highly skewed: a small share of cars and richer households generate disproportionally large emissions.

We then present our econometric results from household-level regressions, where household emissions from passenger cars are the left-hand side variable, which is our main contribution. In contrast to the existing literature, we empirically estimate emission savings of EVs at the household level, reflecting how household preferences and behavior shape EV usage and substitution of ICEVs. We show that purchasing an EV is associated with a significant decrease in passenger car emissions at the household level, controlling for a range of observed variables and unobserved effects, although the magnitude seems limed on average.

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[4] The VAT exemption for electric cars has been in place for almost two decades, but the one-off motor vehicle registration taxes have been changed recently to further strengthen the preferential treatment of electric cars.

As a result, the cost of the fiscal incentives relative to emissions saved is relatively large. The emission savings can be much higher depending on whether and which type of conventional cars newly purchased EVs replace.

We build upon previous literature that examines fiscal incentives for EVs. There is broad consensus that Norway's subsidies have been an important factor in driving the increase in the sale of EVs (Aasness et al., 2015; Figenbaum, 2017; Holtsmark and Skonhoft, 2014), although there is some disagreement about whether subsidies for the purchase or the operation are more important (Bjerkan et. Al, 2016, Mersky et. al, 2016). Holtsmark and Skonhoft (2014) present a specific example of a case where subsidies for EVs in Norway deliver low emission savings at relatively high costs. Ciccone (2018) finds that a past vehicle registration tax reform in Norway led to a decline in the average CO_2 intensity of new vehicles.

Our paper also extends the international literature. Using survey data from the U.S., Sheldon and Dua (2019) suggest that cost-effectiveness of federal incentives for EVs in the U.S. can be improved significantly through better targeting. Helveston et. al (2015) model consumers' preferences in both the U.S. and China and argue that EV subsidies played a limited role in EVs adoption in both countries. There is also a large literature on gasoline taxes (e.g. Reanos and Sommerfield 2018; Nikodinoska and Schröder, 2016; Bureau 2011; Fullerton and West, 2010; Bento et al. 2009; West 2004; Safirovaet al., 2004; West and Williams III 2004; Poterba, 1991). These papers typically rely on consumer expenditure surveys or experimental data) and broadly finds evidence of declining gasoline consumption and to a lesser extent an increased demand for better fuel economy cars.

Our findings of the regressive nature of Norway's tax incentives are also in line with existing evidence. Subsidizing new vehicles favor richer households who are more able to purchase new cars. Grösche and Schröder (2014) assess the redistributive effects of a key elements of the German climate policy and make the broader argument that environmental subsidies for the purchase of durable goods typically increase inequality. Overall, this literature stresses that regressivity can be alleviated by returning the additional tax revenue to households while accounting for both income levels and actual gas consumption (Bento et. al 2009).

The paper is organized as follows. We present the data in the next section. In Section 3, we discuss stylized facts to motivate our econometric analysis in Section 4. Section 5 concludes.

II. Data

We compile a unique dataset, combining car registry data and information from tax records. Norway's registry of passenger cars contains rich information of the engine, fuel type, brand, model type, year of registration and kilometers driven per year. The latter information is the combination of actual meter readings during car inspections every four years and estimates made by Statistics Norway for the intermittent years. Using individual identifiers of the car owners, we then combine these data to tax record data of all individuals in Norway, containing the post-tax income, net wealth, age, gender, place of residence and a unique household identifier. Given that cars can be used by several household members, we aggregate the individual tax records and cars to the household level for a large part of our analysis.

Our data cover the 2010-2019 period and the universe of cars and individuals residing in Norway. Those cars owned by households (88 percent of cars are owned by households, whereas the remaining cars are owned by businesses) can be linked to individual tax record data covering the 2010-2018 period. After cleaning (we notably omit any cars not owned by households and other than internal combustion engine vehicles (ICEVs), battery powered plug-in vehicles (EVs) and hybrid electric vehicles (HEVs), and any households that own cars without emission information which would distort the compilation of household-level emissions), we obtain 16.4 million household-year-level observations for our econometric analysis. We provide variable definitions and descriptive statistics in the Appendix.

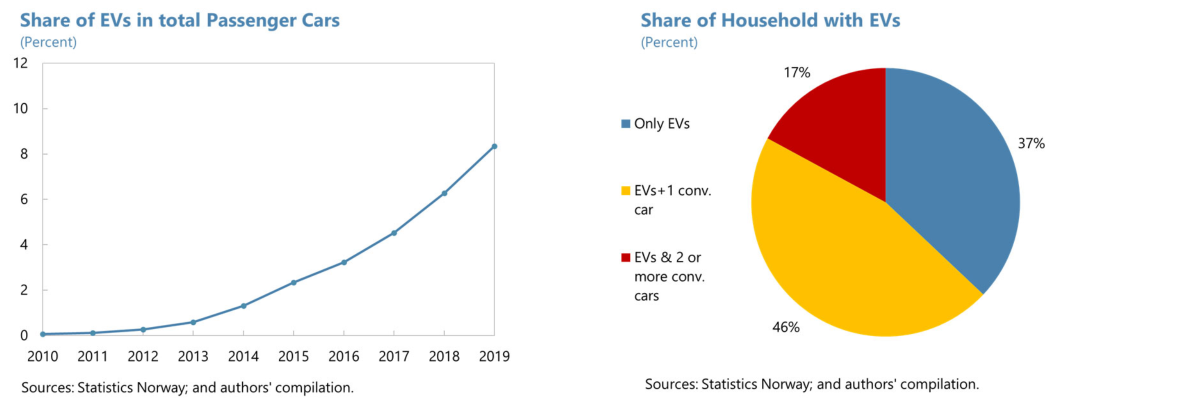
We also use information on the pre-tax price of new cars provided for each year starting in 2012 by the Norwegian tax administration for tax assessment purposes. We merge this information to our car registration data using brand and model names, and engine characteristics for new cars registered since 2012. When there are several prices for one type of car in the car registration data, we compute their average.

III. STYLIZED FACTS

In this section, we present a few stylized facts to motivate our analysis. First**,** the full greening of Norway’s car fleet will take many years at the current pace. The share of battery electric vehicles in total sales of new cars has reached over 50% in 2020 and is significantly higher than in comparator countries including Sweden, Germany or the U.S. At current trends, the transition to full electrification of Norway’s car fleet would take several decades. However, the transition could be substantially faster, given that the share of EVs in the sale of new cars has been growing quickly and given Norway’s goal that all new vehicles sold are tailpipe emission-free by 2025.

Second, the majority of households that own electric cars also own conventional cars. Out of all households that owned EVs in 2018, just over one-third (37 percent) owned only EVs, whereas 46 and 17 percent of households had also one or more conventional cars in addition to EV(s), respectively. This suggests that the degree of substitution between EVs and ICEVs could be an important factor for the environmental impact of EVs.

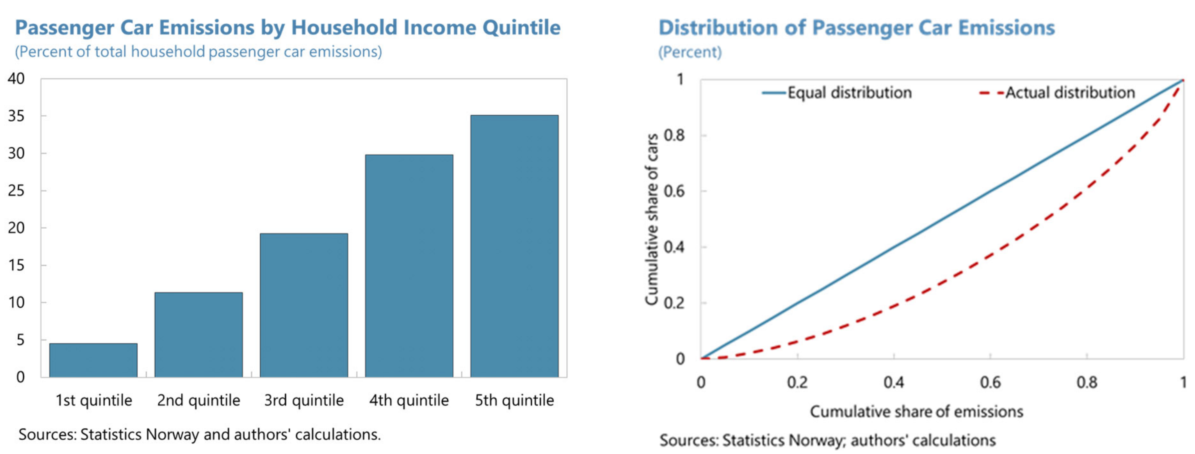
Figure 1: Electric Vehicle Ownership



Third, EVs are used less than conventional cars. We find that on average, the annual driving distance of EVs is 18 percent lower than that of the median car when controlling for a range of unobserved and potentially confounding household characteristics. There is some indication that the difference is narrowing, possibly due to improvements of the range of EVs (see Appendix).

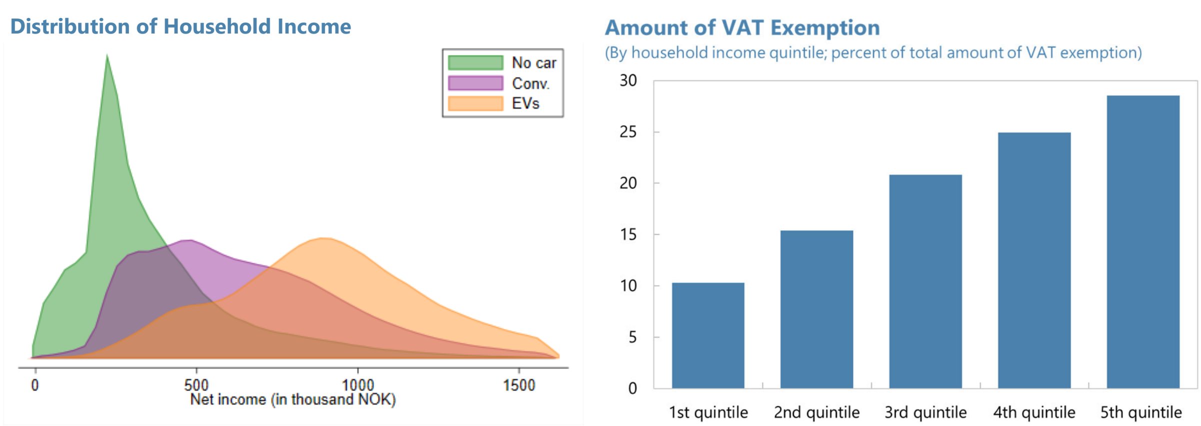
Fourth, CO_2 emissions from conventional cars are unevenly distributed across households and cars. The combined CO_2 emissions from passenger cars used by households in the highest income quintile are more than seven times higher than those of households in the lowest income decile. In addition, 5 percent of passenger cars account for 15 percent of all emissions from all passenger cars, which reflects a combination of poor fuel efficiency and the level of the annual mileage driven.

Figure 2: Distribution of Passenger Car Emissions



Finally, poorer households are less likely to own electric vehicles, in line with findings of Fevang et al. (2020). The median income of households that own EVs was above 900,000 NOK, around 50 percent higher than that of households that own conventional cars only. The distribution of household income of these groups is shown in Figure 3 (left chart). As this could be efficient from an environmental perspective (as richer households account for more emissions, and greater EV ownership among these households has therefore a greater potential for lowering emissions), this nevertheless raises equity concerns as any tax incentives also provide primarily benefits to the rich. In this regard, there is a trade-off between climate and equity objectives. High income households are by far the largest emitters, which implies that emission reductions from the purchase of EVs are largest among this group. On the other hand, the concentration of the benefits of the VAT exemption in the upper quintiles of households is regressive. This dichotomy deserves attention but should be taken in a broader context of social policies in Norway, which have resulted in one of the most equal societies in the world, relatively speaking. This could also be partially offset by high taxes on conventional cars which are likely to be borne by higher income households to a significant extent.

Figure 3: Electric Vehicles and Household Income



Source: Statistics Norway and authors' calculation

Source: Statistics Norway; and authors' compilation.

IV. Econometric Results

A. Baseline

We econometrically estimate the fall in emissions associated with EVs in Norway at the household level. We focus on emissions from household-owned passenger cars which depend on household preferences and behavior; intuitively, the change in emissions depends on the degree of substitution of conventional cars by EVs which is driven by household behavior and preference; for instance, this could widely differ between a household that only owns EVs to one that also owns conventional cars. In the latter case, the effects on emissions depend on the usage of each car.

In particular, we estimate the effects of EV ownership on emissions at the household level using the following specification:

$$Emission_{hmt} = \beta_0 + \beta_1 NumberEV_{hmt} + X_{hmt}\theta + \gamma_h + \gamma_{mt} + \varepsilon_{hmt} \quad (1)$$

$Emission_{hmt}$ denote total CO_2 emission of household h located in municipality *m* in year *t,* calculated as the product of annual mileage and CO_2 emissions per km, summed over all cars owned by household h. $NumberEV_{hmt}$ denote the number of EVs owned by household h located in municipality *m* in year *t*. We also include several socio-demographic control variables at the household level including household income and net wealth. To address any potential omitted variable bias, we also control for unobserved effects at the household and at the municipality-year level (where the municipality refers to the place of residence of the household). Our sample includes all households that own electric vehicles or conventional cars.[5]

In Table 1, we present the results. Specification 1 is our baseline. With respect to the control variables, the results suggest that household emissions decrease in the age of the head of the household, defined as the member with the highest annual income, and are lower if the head of the household is female. By contrast, larger households with more adults and more children unsurprisingly produce higher emissions annually, potentially because they own more cars (we explore this aspect in greater detail in the next section). Richer households also show larger annual emissions from passenger cars, while an increase in larger net wealth is associated with lower emissions, potentially because net wealth and age are correlated.

Our baseline specification (specification 1) further shows that EV ownership is correlated with significantly lower emissions at the household level. Table 1 shows that purchasing an additional EV lowers household-level emissions by 1.17 tCO_2 annually (specification 1, Table 1). The results are statistically and economically significant: Household-level emission savings of one additional EV amount to around half of the level of emissions from passenger cars of the average car-owning household (2.3 tCO_2 annually).

This coefficient estimate can be used for a back-of-the-envelope calculation to infer the cost effectiveness of the VAT tax incentives as follows:

$$effectiveness = subsidies \,/\, (emissions\_saved \times lifetime) \quad (2)$$

where *emissions_saved* denote the regression-based estimates of annual emission savings from buying one additional EV (i.e., the coefficient on the number of EVs which is expressed in $kgCO_2$), *lifetime* denotes the assumed lifespan of the average EV (which we assume to be 15 years, though foreseeable technological progress may make older EVs obsolete sooner),

[5] We omit from the analysis those cars that are plug-in hybrid cars and some other car types (i.e., cars that are not EVs, internal combustion engine cars and non-plug-in hybrid cars) as the emissions of some of these cars are difficult to calculate. These cars represent only a small fraction of all vehicles owned in Norway as of 2019.

and *subsidies* denotes the cost of the VAT exemption (around USD 12,500) of the averaged priced EV.[6]

This type of back-of-the-envelope calculation is for illustrative purposes and comes with several caveats. We ignore the one-off registration taxes because they have a strong green component and other incentives which depend on usage of EVs, so that implicitly, we attribute the emission savings to the VAT exemptions; the estimated cost per tCO_2 saved is hence a lower bound. We also ignore the possibility that in the absence of the VAT exemption, households may opt for a cheaper conventional car, costs due distortions from car taxation in Norway, and any other indirect costs or benefits. In this paper, we do not estimate the causal effects of tax incentives on decision to buy an EV, an issue which we discuss briefly below.

The baseline estimate in Table 1, specification 1, suggests that the lifetime emission savings from the purchase of one additional EV are $15 \times 1.17tCo2 = 17.55tCo2$ under these assumptions. This implies a cost (from the VAT exemption for EVs) per tCO_2 of around USD 710. It is important to mention that this cost refers to the VAT exemption of household-owned cars only, reflects the average of the 2010-2018 period, and makes no assumptions about the substitution of conventional cars.

Our estimates can be compared to several imperfect benchmarks. They exceed simulated marginal abatement costs in Norway, but the latter are at best imperfect benchmarks for our paper. Fæhn et al. (2020) use a multi-sector CGE model to simulate marginal carbon abatement cost to reduce non-ETS GHG emissions by 27.4 per cent in 2030 relative to the reference scenario. They find that marginal abatement cost amount to up to around USD 420 depending on assumptions.

Our estimates can also be compared to previous estimates of incentives for EVs. The implicit cost of all tax benefits for the purchase and operation of EVs including the VAT exemption have been estimated at around USD 1,400 per tCO_2 saved by Norway's Ministry of Finance in the 2021 budget, which is broadly consistent with our estimates (which focus only on the VAT exemption). Holtsmark and Skonhoft (2014) suggest that the cost could be much higher using one specific example and including all subsidies and other benefits, such as an exemption from parking fees.

Gillingham and Stock (2018) present a survey of estimated abatement costs of different interventions mostly in the U.S., i.e., estimates of the cost to reduce one ton of CO_2. Our estimates are in the upper range of those estimates and are notably much larger than those of

[6] We use the average price of newly purchased EVs in 2019 by households which is around NOK 525,000; the implicit cost of the VAT exemption is then around NOK 131,000 or USD 12,500.

a cash-for-clunker program, changes in land use, or increases in energy efficiency for example.[7]

In specifications 2 and 3, we test the robustness. In specification 2, we include all households, irrespective of whether or not they own cars (although we continue to exclude a small number of households that own PHEVs and other types of cars). In specification 3, we exclude all specifications where the annual mileage has been estimated by Statistics Norway. The coefficient on the number of EVs that a household owns remain robust. In specification 3, the magnitude of coefficient savings slightly increases, suggesting that the estimates of annual mileage would at best downward - rather than upward - bias the estimates magnitude of emission savings.

In the remaining specifications, we explore whether depending on circumstances and characteristics of the household, the emission savings can be much smaller or larger than the average effects. In specification 4, we show that the first EV that a household owns has the largest effects on emissions, whereas the emission savings from any additional EVs are smaller. In specification 5, we show that the household-level emission savings from EVs have increased after 2015, possibly because of increased usage of EVs as a result of technological improvements. Specification 6 shows that the emission savings from purchasing are larger in households that only own EVs, which is not surprising, given that they have fully rather than partially replaced conventional cars.

[7] The authors present a detailed table of various interventions obtained from the literature, available here: https://www.aeaweb.org/content/file?id=8325.

Table 1. Baseline Results

VARIABLES	(1) Emissions	(2) emissions	(3) emissions	(4) emissions	(5) emissions	(6) emissions
no_ev	-1,171.96***	-1,187.54***	-1,206.76***			
	(3.78)	(3.42)	(4.58)			
ev_1st				-1,187.88***		
				(4.03)		
ev_2nd				-1,082.85***		
				(15.41)		
ev_3rd_more				-287.63***		
				(88.16)		
pre2016#no_ev					-996.74***	
					(6.29)	
post2015#no_ev					-1,209.00***	
					(3.89)	
only_ev#no_ev						-2,176.03***
						(5.17)
icev&ev#no_ev						-630.94***
						(4.33)
head_age	-15.82***	-9.23***	-15.37***	-15.82***	-15.82***	-15.72***
	(0.22)	(0.19)	(0.30)	(0.22)	(0.22)	(0.22)
head_female	-84.00***	-60.84***	-80.59***	-83.96***	-83.73***	-84.12***
	(2.38)	(1.69)	(3.15)	(2.38)	(2.38)	(2.36)
no_adult	535.78***	353.68***	534.00***	535.77***	535.93***	525.87***
	(2.01)	(5.59)	(2.46)	(2.01)	(2.01)	(1.99)
no_child	122.50***	91.93***	127.69***	122.62***	122.38***	123.08***
	(1.65)	(1.19)	(2.17)	(1.65)	(1.65)	(1.64)
netinc	0.01*	0.01*	0.00	0.01*	0.01*	0.01*
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
netwealth	-0.09	-0.07	0.08	-0.09	-0.08	-0.10
	(0.12)	(0.12)	(0.17)	(0.12)	(0.12)	(0.12)
Constant	2,549.95***	1,473.57***	2,529.72***	2,550.16***	2,548.65***	2,563.51***
	(12.94)	(16.59)	(17.38)	(12.94)	(12.94)	(12.89)
Observations	9,358,297	16,420,910	5,605,934	9,358,297	9,358,297	9,358,297
R-squared	0.65	0.79	0.66	0.65	0.65	0.65
Mun.-Year FE	YES	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Spec. (2) includes households that do not own any cars.
Spec. (3) excludes observations where the annual mileage has been estimated.

B. Emission Savings and Replacement of ICEVs

In this subsection, we further explore the emission savings of EVs depending on whether they replace ICEVs and make the underlying assumptions explicit. For simplicity, we only include households that own EVs and/or ICEVs and show that the type of ICEVs strongly matters. Given the following identity and to avoid collinearity in the regression, we cannot simultaneously control for the number of total cars that a household owns ($NoCars$), the number of ICEVs (*NoICEV*) and the number of EVs in our regressions:

$$NoCars_{hmt} = NoICEV_{hmt} + NoEV_{hmt} \tag{3}$$

We therefore can only include two of these variables at a time; the omitted variable is then effectively the assumed 'compensating' element.[8]

In Table 2, specification 1, we start by including the number of ICEVs that a household owns, implying that the coefficient on $NoEVs$ measures the increase in EVs when no conventional cars are replaced (as the number of ICEVs is held constant). The coefficient estimate suggests that the emission savings of purchasing one additional EV drop significantly, presumably because usage of ICEVs continues, albeit at a (slightly) reduced rate. In Table 2, specification 2, we instead control for the number of total cars. This implies that the coefficient of interest measures the increase in EVs offset by a decrease in the number of ICEVs as the household's total number of cars is held constant. The estimated emission savings from purchasing one additional EV increase to 1.9 tCO_2 annually. Note that the coefficient on the number of total cars reflects the emission impact of increasing the number of ICEVs (as predicted by Equation 3) and as evidenced by the fact that the coefficient estimate on the number of ICEVs in specification 1 is identical).

In the remaining specifications, we further explore the emission savings depending on which type of ICEV is replaced. In specification 3, we distinguish ICEVs by their total annual emissions (which are driven by both their CO_2 intensity and annual distance driven) and introduce five new variables: $NoICEV\_em1Q$ … $NoICEV\_em5Q$ correspond to the number of cars whose emissions are in the 1st, 2nd, 3rd, 4th and 5th quintile for each year of our data, respectively. Instead of including $NoEV$ we include $NoCars$. The negative of the coefficients on the $NoICEV\_em1Q$ … $NoICEV\_em4Q$ variables therefore measures the changes in emissions associated with an increase in EVs offset by replacing ICEVs in the respective emission category (as we hold constant the number of total cars). The coefficient on $NoICEV\_em5q$ implies that when an additional EV replaces ICEVs with the emissions in the 5th quintile, household emissions from passenger cars drop by 3.8 tCO_2 annually, more than three times as much as in our baseline specification which makes no assumptions about whether cars are replaced.

In specification 4, we include deciles instead which are defined analogously. The coefficient on $NoICEV\_em10d$ implies that when an additional EV replaces ICEVs with the emissions

[8] This is similar to the literature estimating the long-run growth effects of fiscal policy, where the government budget constraint can imply collinearity between various fiscal aggregates; see Kneller et al. (1999) for a detailed discussion.

in the 10th decile, household emissions from passenger cars drop by 4.6 tCO_2 annually, around four times as much as in our baseline specification.

In specification 5, instead of distinguishing ICEVs by their total annual emissions, we categorize them by their CO_2 intensity (measured as CO_2 emissions per km). The negative of the coefficient on $NoICEV\_eff5Q$ analogously measures the annual savings in household-level emissions when households purchase an additional EV to replace an ICEV that is among the 20% of the least fuel efficient cars in a given year. Again, the coefficient is larger than in the baseline, but not as large as in specifications 3 and 4.

Specification 6 is identical to specification 5 except that we include $NoEV$, but to avoid collinearity, we omit $NoICEV\_eff3Q$, which refers to cars whose emission intensity is around the median. We focus on the negative of the coefficient on the least efficient ICEVs ($NoICEV\_eff5Q$) which measures the effects of increasing the number of around median efficiency ICEVs (i.e., ICEVs in the 3rd quintile) to replace the least fuel efficient ICEVs (i.e., ICEVs in the 5th quintile). The annual emission savings would amount to 0.6 tCO_2 annually, around half of the average effects of EVs.

Table 2. Emission savings and replacement of ICEVs

VARIABLES	(1) emissions	(2) emissions	(3) emissions	(4) emissions	(5) emissions	(6) emissions
no_ev	-86.83***	-1,993.12***				-2,004.44***
no_icev	1,906.29***					
no_car		1,906.29***	-8.94***	4.76***	-123.65***	1,878.48***
no_icev_em1q			747.00***			
no_icev_em2q			1,451.76***			
no_icev_em3q			1,991.58***			
no_icev_em4q			2,577.35***			
no_icev_em5q			3,831.44***			
no_icev_em1d				456.05***		
no_icev_em2d				953.28***		
no_icev_em3d				1,296.36***		
no_icev_em4d				1,588.46***		
no_icev_em5d				1,854.62***		
no_icev_em6d				2,114.10***		
no_icev_em7d				2,401.43***		
no_icev_em8d				2,742.30***		
no_icev_em9d				3,234.81***		
no_icev_em10d				4,649.06***		
no_icev_eff1q					1,542.51***	-459.99***
no_icev_eff2q					1,794.11***	-208.45***
no_icev_eff3q					2,002.87***	
no_icev_eff4q					2,215.41***	212.91***
no_icev_eff5q					2,592.00***	589.61***
Constant	404.87***	404.87***	70.10***	30.53***	385.35***	385.59***
Observations	9,262,573	9,262,573	9,262,573	9,262,573	9,262,573	9,262,573
R-squared	0.74	0.74	0.89	0.91	0.75	0.75
Controls	YES	YES	YES	YES	YES	YES
Mun.-Year FE	YES	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

C. Emission Savings and Household Income

In this subsection, we explore whether the emission savings differ by household income which could be the case because car ownership and car usage preferences differ depending on household income. To start off, in specification 1, Table 3, we first show that emissions of households in the richest quintile are 0.4 tCO_2 higher than those in the lowest quintile (which is the omitted category and where the *netinc2q…netinc4q* variables are dummies that denote whether a given household is in the respective income quintile).

In specification 2, we interact $NoEVs$ with the household income quintile dummies. Interestingly, the emission savings of EVs in households of different income groups are almost identical. There could be two opposing factors at play: on the one hand, higher income households produce more emissions (so that EVs could help save more emissions if they replace conventional cars). On the other hand, higher income households can afford several cars, so that substitution is more limited compared to lower income households.

In specifications 3 and 4, we make specific assumptions about whether ICEVs are replaced, in analogy to Table 2. In specification 3, we estimate the effects of purchasing additional EVs by household quintiles, holding constant the number of ICEVs that a particular household owns. The annual emission savings fall across all household quintiles, but now the savings slightly increase with household income. In specification 4, we assume that ICEVs are replaced by controlling for the total number of cars. The emission savings of purchasing EVs (again and unsurprisingly) increase across all income groups as expected. Again, the savings slightly increase with household income in line with specification 3.

Table 3. Emission savings and household income

VARIABLES	(1) emissions	(2) emissions	(3) emissions	(4) emissions
no_icev			1,788.37***	
			(1.72)	
no_car				1,888.52***
				(1.78)
netinc2q	47.70***	45.45***	34.87***	34.51***
	(2.28)	(2.28)	(2.01)	(2.00)
netinc3q	171.08***	168.19***	74.07***	68.42***
	(2.94)	(2.93)	(2.53)	(2.51)
netinc4q	311.66***	317.70***	107.33***	96.78***
	(3.44)	(3.43)	(2.92)	(2.90)
netinc5q	430.75***	464.99***	132.53***	116.45***
	(4.05)	(4.03)	(3.42)	(3.39)
netinc1q#no_ev		-1,200.34***	-74.95***	-1,845.49***
		(14.92)	(11.83)	(11.70)
netinc2q#no_ev		-1,234.38***	-129.67***	-1,896.30***
		(10.25)	(7.73)	(7.64)
netinc3q#no_ev		-1,140.46***	-185.94***	-1,969.65***
		(8.19)	(6.34)	(6.29)
netinc4q#no_ev		-1,109.10***	-181.21***	-1,971.62***
		(5.92)	(4.58)	(4.56)
netinc5q#no_ev		-1,227.43***	-216.69***	-2,001.69***
		(5.11)	(3.90)	(3.85)
head_age	-13.62***	-13.55***	-4.61***	-3.89***
	(0.22)	(0.22)	(0.18)	(0.17)
head_female	-60.95***	-57.41***	-39.60***	-39.27***
	(2.38)	(2.36)	(1.96)	(1.95)
no_adult	431.19***	443.92***	80.47***	60.27***
	(1.94)	(1.93)	(1.56)	(1.55)
no_child	73.52***	82.26***	67.26***	66.51***
	(1.68)	(1.66)	(1.36)	(1.35)
netwealth	-0.02	-0.00	-0.02**	-0.02**
	(0.01)	(0.01)	(0.01)	(0.01)
Constant	2,409.31***	2,418.95***	503.46***	353.15***
	(12.88)	(12.82)	(10.42)	(10.36)
Observations	9,358,297	9,358,297	9,358,297	9,358,297
R-squared	0.64	0.65	0.74	0.74
Mun.-Year FE	YES	YES	YES	YES
Household FE	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

V. CONCLUSIONS

In this paper, we have estimated the emission savings at the household level that result from purchasing EVs. We show that they dramatically differ depending on circumstances: if it is assumed that households replace some of the most polluting ICEVs, the savings are largest, whereas if they replace fuel efficient cars or merely increase the overall stock of cars owned by a particular household, they are much smaller. While we show that the VAT exemption is regressive given the higher pick up by higher-income house, the emission savings of EVs are broadly similar across households of different incomes. Of course, the emission savings of EVs could grow in the future, for instance if their maximum range further increases so that they are used more. In addition, aggregate emission savings can only be inferred from such estimates if any replaced cars are scrapped, rather than sold domestically or abroad for continued use. We also ignore any externalities that may arise from the use of EVs and non-exhaust emissions.

Using these estimates, we have then inferred the cost effectiveness of the VAT exemptions for new EVs, using a simple back-of-the-envelope calculation that is based on the average price of newly purchased EVs. We show that the implicit cost of these tax incentives is high relative to average emission savings at the household level.

Our results have interesting policy implications. Some of the most polluting cars are of low value: Among the cars with annual emissions in the top quintile in 2018, 10 percent are older than 15 years and/or have odometer readings of almost 200,000 km, or more. Further analyses could examine whether recalibrating the tax incentives to encourage the replacement of low-value-high-pollution cars by EVs in a revenue-neutral way is feasible. This could potentially be achieved through a combination of targeted subsidies to scrap dirty cars when they are replaced by EVs, and tax or regulatory measures. Revenue neutrality could be satisfied by increasing the tax burden on high-end EVs (e.g., by capping the amount of the VAT exemption and/or levying annual road tax on some of the most luxurious EVs). Further research based on data used in this paper could determine more exact parameters of such a recalibration.

Obviously, our results come with caveats. The estimated emission savings ignore any domestic and international externalities of EV usage in Norway and emissions during the production. The cost effectiveness of VAT exemption is a simple back-of-the-envelope calculation that converts the estimated average emission savings at the household level into parameters that are relevant from a policy perspective. Future research could combine our analysis with the explicit econometric modelling of the decision to buy cars (as done by Johansen, 2021). This would help estimating the cost effectiveness of tax incentives in a more careful way, taking into account to what extent they incentivize the purchase of EVs.

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APPENDIX I: LIST OF VARIABLES

Appendix Table 1: Variable labels and definitions

Label	**Description**
head_age	Age of the head household
head_female	Dummy for the female head household
no_adult	Number of adults per household
no_child	Number of children per household
netinc	Net income of household in 100,000 NOK
netwealth	Net wealth of household in 100,000 NOK
netinc1q, …, netinc5q	Dummy variable if household income is in the 1st, …, 5th quintile for each year
no_ev	Number of electric vehicles (EVs) owned by the household
no_icev	Number of conv. cars (ICEVs) owned by the household
no_car	Number of cars owned by the household
ev_1st	Dummy variable for the first EV owned by the household
ev_2nd	Dummy variable for the second EV owned by the household
ev_3rd_more	Dummy variable for the third and subsequent EVs owned by the household
pre2016	Dummy variable for years before 2016
post2015	Dummy variable for years after 2015
only_ev	Dummy variable if the household owned only EVs
icev&ev	Dummy variable if the household has EV and ICEV
emissions	Total CO_2 emissions per household in kg
no_icev_em1q, …, no_icev_em5q	No. of ICEVs whose emissions are in the 1^{st}, …, 5^{th} quintile for each year
no_icev_em1d, …, no_icev_em10d	No. of ICEVs whose emissions are in the 1^{st}, …, 10^{th} decile for each year
no_icev_eff1q, …, no_icev_eff5q	No. of ICEVs whose CO_2 intensity are in the 1^{st}, …, 5^{th} quintile for each year

APPENDIX II: DESCRIPTIVE STATISTICS

Appendix Table 1: Descriptive Statistics (sample of baseline specification)

VARIABLES	mean	sd	p5	p10	p50	p90	p95
no_ev	0.0425	0.212	0	0	0	0	0
no_icev	1.232	0.549	1	1	1	2	2
no_car	1.297	0.550	1	1	1	2	2
co2_emi_hh	2,702	1,910	527.0	854.7	2,306	5,003	6,170
head_age	52.13	15.84	28	31	51	74	79
head_female	0.340	0.474	0	0	0	1	1
no_adult	1.822	0.680	1	1	2	3	3
no_child	0.598	0.953	0	0	0	2	3
netinc	6.691	10.23	2.300	2.800	5.960	10.88	12.99
netwealth	29.78	169.9	-6	-1.600	18.30	62	87.20

Appendix Table 2: Descriptive Statistics of Total CO2 Emissions per household

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Emissions	mean	p5	p10	p25	p50	p75	p90	p95
All	2,736	633.0	923.0	1,520	2,326	3,454	5,019	6,188
2010	3,047	774.3	1,128	1,859	2,687	3,728	5,315	6,485
2011	2,945	736.1	1,077	1,753	2,554	3,640	5,228	6,380
2012	2,911	714.9	1,049	1,711	2,512	3,627	5,220	6,361
2013	2,831	679.6	1,002	1,642	2,424	3,553	5,123	6,263
2014	2,750	655.8	962.4	1,557	2,335	3,464	5,019	6,170
2015	2,687	622.7	915.7	1,480	2,266	3,407	4,962	6,117
2016	2,634	600.6	868.9	1,418	2,194	3,339	4,908	6,095
2017	2,589	574.5	834	1,374	2,144	3,287	4,865	6,061
2018	2,518	549.3	798.3	1,325	2,081	3,198	4,756	5,942

Appendix Table 3: Descriptive Statistics of Total CO_2 Emissions per car

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Emissions	mean	p5	p10	p25	p50	p75	p90	p95
All	2,129	512.9	771.2	1,290	1,969	2,725	3,573	4,233
2010	2,577	665.6	995.4	1,677	2,457	3,244	4,086	4,765
2011	2,441	623.2	938.5	1,571	2,295	3,072	3,929	4,630
2012	2,374	611.1	917.6	1,527	2,233	2,990	3,834	4,528
2013	2,270	579.5	870.4	1,454	2,131	2,861	3,691	4,373
2014	2,180	558.3	836.7	1,375	2,028	2,751	3,575	4,257
2015	2,104	521.2	786.7	1,297	1,940	2,685	3,510	4,178
2016	2,043	500.4	747.4	1,230	1,876	2,605	3,450	4,112
2017	1,994	479.3	715.9	1,188	1,828	2,555	3,395	4,051
2018	1,939	459.1	687.6	1,150	1,776	2,492	3,317	3,959
2019	1,849	414.3	642.0	1,101	1,709	2,383	3,167	3,781

APPENDIX III: ANNUAL MILEAGE OF DIFFERENT TYPES OF CARS

To compare the intensity of use of EVs and conventional cars, we estimate the following OLS specifications at the car level, using the annual driving distance as the dependent variable:

$$distance\_km_{cth} = \beta_0 + \beta_1 EV + \gamma_{ht} + \gamma_{mt} + \varepsilon_{ht}$$

where *distance_km* is the annual driving distance (in thousand kilometers) of car c in year t owned by household h, and where EV is a dummy variable. We control for any unobserved effects at the household-year and the municipality-year level.

Appendix Table 5 presents the results. Specification 1 suggests that EVs are used significantly less than conventional cars (the difference is 2,200 km per year which is significant relative to the median annual driving distance of around 12,000 km). Specification 2 suggests that in 2018, that difference became smaller but still exists.

Appendix Table 5: Annual driving distance of EVs

	(1)	(2)
VARIABLES	kmyear	kmyear
ev	-2.20***	-2.86***
	(0.01)	(0.02)
ev_2018		2.17***
		(0.03)
Constant	12.21***	12.20***
	(0.00)	(0.00)
Observations	12,634,975	12,634,975
R-squared	0.43	0.43
Household-Year FE	YES	YES
Mun.-Year FE	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1