

Modelling the Total Cost of Ownership of Electric Vehicles in the Netherlands

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Abstract

This paper describes a model that predicts the total cost of ownership (TCO) of electric vehicles (EVs) in the Netherlands up to 2035 that was developed at the request of the Dutch Ministry of Economic Affairs. **METHOD** The model uses learning curves to implement cost developments regarding battery, drivetrain, charging infrastructure, energy and residual value of different drivetrains. It uses cars with three types of luxury levels and drivetrains. **RESULTS** EVs are found to quickly get a lower TCO which has the potential to drive a quick and disruptive transition to clean cars. **LIMITATIONS** The model does not consider the supply of EVs or batteries. Charging infrastructure could become a bottleneck. Users differ in how resistant to change they are and many will not adopt EVs, not even when they have a lower total cost of ownership.

1 Introduction

Scientists are “95% certain that humans are the main cause of global warming [which] will lead to high to very high risk of severe, widespread and irreversible impacts globally” [1]. They advice “stabilizing temperature increase to below 2°C relative to pre-industrial levels” but note “this will require an urgent and fundamental departure from business as usual” [1]. Politicians in 194 countries signed the “Paris Agreement” that pledges to keep global warming below the 2°C mark [2].

Burning organic matter has brought us incredible amounts of energy [3] and wealth [4] but in order to reduce CO₂ emissions we must make the transition to renewable energy [5]. Our most abundant energy source (renewable or otherwise) is solar radiation [6], [7]. The potential for wind energy is two to three orders of magnitude smaller but still magnitudes more than we need [8]. Thus ideally our transportation would also be powered by wind and solar which means that we should use electric cars.

Why not conventional cars? Conventional cars work on fossil fuel (that emits CO₂) or biofuel. With biofuels, part of the CO₂ emissions is compensated by the CO₂ captured during production so from that perspective it is better than fossil fuel for the atmosphere but might be an even bigger threat to our ecosystem as a whole. Depleting aquifers [9] are causing food crises [10] and agricultural output is decreasing through overuse of topsoil [11]–[14]. Biofuels compete with food [15]–[17] and nature [18]–[21] for globally scarce fertile topsoil and fresh water [22] (e.g. palm oil [23]). Literature that assesses land use change based on observed reality instead of hypothesized ideal situations concludes that commercially viable biofuels are worse for the planet than fossil fuels [24]–[26]. The UN rapporteur on food has even called it a crime against humanity [27].

Thus electric vehicles are imperative if we want to achieve the Paris agreement without destroying our ecosystem in the process. Fortunately, solar energy, wind energy and electric vehicles are all poised to become cheaper than conventional options. The underlying reason is their reduced use of raw materials. E.g. wind uses between 2 grams (airborne wind energy [28]) and 10 grams of material per kWh [29] [30] while a coal fired power plant burns about 300 grams per kWh [31], [32]. Since 1980, the price of wind power has fallen by a factor of ten [33]. Electric vehicles can combine wind power with a battery of 100-400 kg to replace over 15 tonnes of crude oil [34], [35]. The cost of batteries has fallen by a factor of ten since 2000 [36]. The cost of solar has fallen by a factor of one hundred since 1980 [37].

But *when* will electric cars have a lower total cost of ownership (TCO)? This is important information for voters, activists and journalists who are interested in moving the status quo in a more sustainable direction. It is important for car makers who can e.g. decide to only develop electric engines from 2019 (Volvo[38]). And it's important for policy makers to understand that strongly promoting them now is a viable option (e.g. Norway[39]) or when to ban them in the future (e.g. France[40] and Britain[41]). The Dutch government heavily promoted plugin-hybrids and full electric vehicles for business users in the past[42], [43] and parliament has urged for a ban on conventional cars in 2025[44]. In 2016, it commissioned a report (in Dutch[45]) that would predict sales and the need for charging infrastructure in the Netherlands. The authors of this paper provided the underlying model and document the total cost of ownership calculations in this paper.

The model was developed because we did not find a model that took all the aspects we deemed relevant into account and that we will summarize here. Including learning curves is essential[46] and they should not only drive the cost of batteries and drivetrains but also resale value since we determined that this has a large impact on the TCO of first buyers: new cars that are kept for a limited time are much more expensive. Car class is important because the TCO development for luxury vehicles like the Tesla Model S are very different from those of average vehicles like the Nissan Leaf. The EV has the advantage of strongly reduced energy use but the impact on the TCO depends on the price and availability of chargers so we needed to include that in our model. We have incorporated an estimated change over time of these factors in our model. We think it illustrates why the EV is becoming both environmentally and economically attractive.

This paper describes how the model was constructed and then presents the findings.

2 Methodology

The model is build from a sequence of steps (so this version does not include endogenous feedback loops yet) that are described in this chapter.

2.1 Battery cost learning curves

Battery costs are important because they used to constitute up to 50% of the cost of an EV [47]. They are also developing rapidly from more than \$1000/kWh in 2010 to \$200-\$300 in 2016 and probably less then \$100 in 2030 [36], [48].

We calibrated estimated battery prices using three approaches simultaneously: market prices as mentioned by companies; expert predictions of future prices and; our own bottom-up model based on raw materials and production cost. We did this for different chemistries (although NCM was found to be dominant for at least ten years). We did not (yet) include a feedback loop but simply constructed a best case, worst case and best guess scenario of battery price over time. We noticed that in the popular literature (scientific articles do provide up to date battery prices) cell price, pack price, wholesale price and retail price are often used interchangeably.

We always talk about pack prices and the graphs show our estimates of battery price developments from 2016 to 2035 for both wholesale users like carmakers and for consumers.

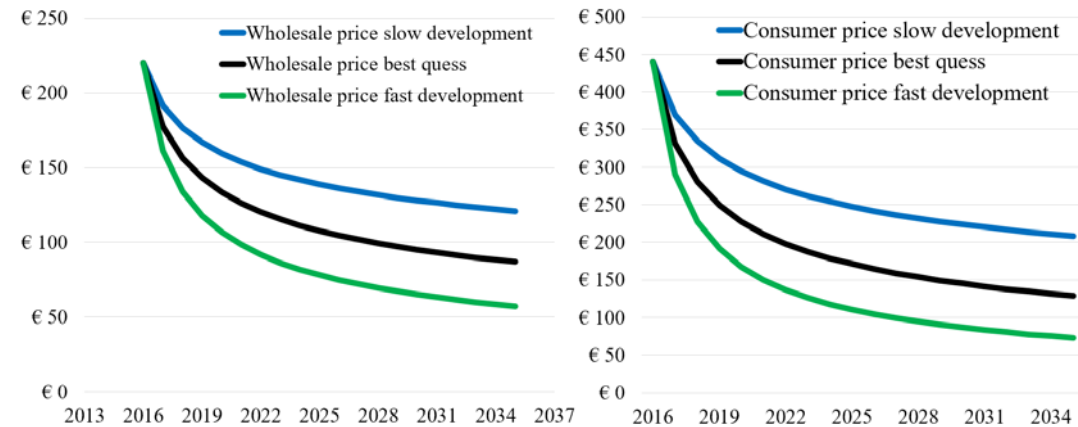


Figure 1 Battery prices (original research by Auke Hoekstra and Vedant Linesh Sundrani).

A quick sanity check learns that our wholesale battery price predictions mesh closely with the recent predictions of Bloomberg New Energy Finance[48]. Our best guess customer battery price for 2017 is EUR 331/kWh and the recently introduced Tesla Model 3 asks USD 9000 for a 23 kWh battery pack extension which corresponds to EUR 340/kWh (2.5% difference).

Unless otherwise noted, scenarios described in this paper use the consumer best guess learning curve.

2.2 Drivetrain cost

2.2.1 Observed cost

For motor prices we noticed a few interesting dynamics. Our model uses three car classes: A-class, C-class and E-class. When we estimated motor prices for these three different classes using sticker prices in the Netherlands from some representative models in every class we noticed that the cost per kW is significantly higher when the cost of the entire car increases (by moving to a higher class). Also the cost per kW increases within the class. E.g. moving from a 100kW to a 135 kW motor on BMW 3 series car sold in the Netherlands costs EUR 94/kW while moving from 135 to 185 costs EUR 130/kW, 185 to 240 EUR 200/kW and 240 to 317 costs EUR 706/kW. Finally we noticed that electric cars for which such an estimate can be made (we where only able to use the Tesla Model S in the E-class when we wrote this paper) had a much lower price per kW and moving to higher power made much less of a difference.

This dynamic has a large impact on the E-class segment where power is highly prized in both meanings of the word. An electric car can not only offer more instant torque (from zero RPM) but also more overall power for the same price which is especially advantageous for more expensive cars with more powerful motors that are more expensive per kWh.

We have not incorporated the rising price/kW within different classes into our model because the consumer preferences needed to implement this dynamic where not available to us. This is clearly something that could be valuable in future research and it would be something that we would recommend carmakers to include in their analysis.

We have however incorporated the averages per class that have a large impact on the overall TCO. The values found were EUR 66/kW for A-class cars, EUR 131/kW for C-class cars and EUR 258/kW for E-class cars. We hypothesize these differences are due to the fact that more expensive cars have less economies of scale but yet yield higher profit margins. Electric vehicle types that offer different motor configurations are few. We had only Tesla Model S and X to work with and here the observed price per kW was EUR 55/kW which we took as the average for the E-class.

2.2.2 Calculated cost

The underlying component cost for the manufacturer are found in the literature with the observation that assembly et cetera accounts for a factor 1.7 in cheaper cars and a factor 2 in more expensive cars [47], [49].

Based on information in [47] we deconstructed the different drivetrains. The EV drivetrain as follows:

$$\text{Cost of Powertrain (EV AC)} = \text{Required power} * (\text{CAC} + \text{CPE}) + \text{CConv} + \text{Ccharger}$$

$$\text{Cost of Powertrain (EV DC)} = \text{Required power} * (\text{CDC} + \text{CPE}) + \text{CConv} + \text{Ccharger}$$

Where

- Cconv is the cost of DC-DC step down converter (€)
- Ccharger is the cost of the On-board Charger (€)
- CAC is the cost of the AC Motor (€/kW)
- CDC is the cost of the DC Motor (€/kW)
- CPE is the cost of the power electronics (€/kW)

For the ICE the cost of the drivetrain is as follows:

$$\text{Cost of Powertrain (gasoline ICE)} = \text{Required power} * \text{CGICE} + \text{CSGG} + \text{CGE} \quad (4)$$

$$\text{Cost of Powertrain (diesel ICE)} = \text{Required power} * \text{CDICE} + \text{CSGD} + \text{CDE} \quad (5)$$

Where:

- CGICE is the cost of gasoline drivetrain (base) (€/kW)
- CDICE is the cost of diesel drivetrain (base) (€/kW)
- CSGG is the cost of gasoline stop & go system (€)
- CSGD is the cost of diesel stop & go system (€)
- CGE is the cost of gasoline exhaust treatment (€)
- CDE is the cost of diesel exhaust treatment (€)

For the PHEV, the following formula is used:

$$\text{Cost of Powertrain (PHEV)} = \text{Required power} * (\text{CGICE} + \text{CAC} + \text{CPE}) + \text{CSGG} + \text{CGE} + \text{CConv} + \text{Ccharger}$$

Electric Vehicle Drivetrain	2010	2035	Gasoline and Diesel drivetrain	Gasoline	Diesel
DC motor / kW peak	8	4.5	Motor incl. transmission / kW peak	35	50
AC motor / kW peak	5	2.7	Stop & go system + exhaust treatment	500	1000
Power electronics / kW peak	15	1.6			
DC-DC converter	300	300			
On-board charger	600	600			

Table 1, Drive train cost components in the model for different drivetrains and years in EUR.

2.2.3 Combining the observed and calculated model

Unfortunately there are large differences between the calculated model and observed reality. Based on [47] we expected to find a factor of 1.7 for A class cars and 2.0 for C-class and E-class cars. In reality we found 1.9 for A-class, 3.7 for C-class and 7.4 for E-class. For the E-class Tesla we found “only” a factor of 2.75.

After private consultation with experts we assume that the extreme price differential at higher prices is mainly marketing and could be subject to change if the competition with EV becomes more serious. We arbitrarily brought it down to a factor of 3. The C-class we arbitrarily brought down to 2.5 and the A-class we left at 1.9.

We decided to keep the observed factor for the E-class EV because design and assembly is much easier due to less moving parts and due to the fact that electric wires are a simpler way of connecting parts than gasoline and exhaust lines. For C-class cars we took a conservative factor 2.25 and for A-class cars 1.8.

2.3 Constructing virtual cars to model

Virtual cars were constructed based on aforementioned research and on reverse engineering the most authoritative website with customer information in the Netherlands (ANWB). Table 1 shows the characteristics of the cars that were modelled. Note that the EVs have higher motor power and that the EV range is much larger than what is currently normal. It is however congruent with what we see in the market in terms of new and predicted developments. The onboard energy used is the average amount of kWh used from the battery to drive a km. E.g. the Tesla Model 3 that we class as a C-class car (although it is actually closer to the D-class) achieves 0.15 kWh/km on the EPA cycle.

Car type	Price excl. drivetrain	Motor kW	On board energy use kWh/km	Tires per km	Maintenance per km	EV range km
A-class gasoline	10847	60	0.5	€ 0.008	€ 0.036	
A-class PHEV	10847	60	0.3	€ 0.008	€ 0.025	25
A-class FEV	10847	90	0.14	€ 0.008	€ 0.011	300
C-class gasoline	15830	90	0.7	€ 0.010	€ 0.047	
C-class PHEV	15830	90	0.45	€ 0.010	€ 0.032	40
C-class FEV	15830	135	0.15	€ 0.010	€ 0.014	400
E-class gasoline	18831	180	1.1	€ 0.017	€ 0.075	
E-class PHEV	18831	180	0.6	€ 0.017	€ 0.053	60
E-class FEV	18831	270	0.19	€ 0.020	€ 0.021	500

Table 1 Chosen characteristics of modelled cars

It is important to note that these cars are not cars actually on the market but cars that *could* be on the market with characteristics that were based on cars that are predicted to come onto the market in coming years and on our own surveys and focus group research. Figure 3 visualizes the result of these characteristics and the steps described in the model so far in terms of predicted sticker prices in Netherlands.

2.4 EV versus ICE residual value learning curve

Residual value is important for the new car buyers that drive EV adoption in the years to come since a car loses a relatively large part of its value in the first few years which means that the first owner pays a large part of the expensive battery while he only enjoys the lower energy cost and maintenance cost for a limited period.

We determined the residual value of conventional cars by reverse engineering the site of the ANWB[50]. The residual value was approximated as:

$$\text{Conventional residual value} = (\text{years owned} + 1)^{-0.4 * \text{years owned}} + \text{km driven} * 10^{-06}$$

Discussions with experts (e.g. dealers and leasing companies) taught us they used much lower resale values for EVs, due to people being unfamiliar with and untrusting of the new technology. They assumed the cars were sold to new buyers who looked at tax incentives and were not interested in resale value because they leased the car anyway (which is true for about 90% of (PH)EVs in the Netherlands).

The strange contradiction is that second hand EVs are much better value for money than a conventional car from a total cost of ownership perspective. The reason is simply that the advantage in terms of energy costs and maintenance cost of a second hand EV is comparable to a new one while the depreciation on the battery is much lower. So in practice EVs had a much lower resale value while from a TCO perspective they should have a much higher resale value.

In our model we have assumed that the 2015 resale value was 70% of a comparable conventional vehicle but that in 2026 the resale value would be comparable and in 2025 the resale value would be 9% higher. This in effect gives a conservative form to our hypothesis that resale value will rise once consumers learn the new technology can be trusted and has a much lower TCO.

2.5 EV versus ICE energy cost and maintenance cost developments

Although clean electricity is often taxed higher than gasoline and especially diesel (e.g. in the Netherlands [51]) the electric vehicle is cheaper because the engine is on average 3-4 times more efficient. We will use the energy use as described in Table 1 but assume 15% losses while charging the battery.

Predicting the price of diesel and gasoline is like playing the lottery but the International Energy Agency (IEA) predicts that the oil price will rise again with a factor 2-4 between now and 2040 [52]. Thus we assume a moderate 2% rise per year and (following dieselgate) 3% per year for diesel. For charging we base ourselves on studies we conducted for the NKL (Dutch knowledge platform for charging infrastructure) [53]. Table 2 presents our assumptions.

Energy source	Perc. Energy	2015	2020	2025	2030	2035
Diesel	100%	€0.12	€0.13	€0.15	€0.16	€0.19
Gasoline	100%	€0.17	€0.18	€0.20	€0.22	€0.24
Flex value		€0.00	€0.02	€0.03	€0.03	€0.04
Home charging	35%	€0.22	€0.21	€0.20	€0.19	€0.18
Work charging	25%	€0.18	€0.17	€0.16	€0.14	€0.13
Street charging	25%	€0.35	€0.32	€0.29	€0.26	€0.24
Fast charging	15%	€0.35	€0.30	€0.24	€0.20	€0.16

Table 2 Our assumptions regarding energy sources and their price per kWh

From Table 2 it's clear that not everybody will pay the same for electricity. E.g. some may be able to charge exclusively at work and get their energy cheap. Furthermore the price per kwh per charging source is just an approximation of the average. E.g. someone who charges a lot at a fast charger is already able to charge for EUR 0.19/kWh. In the next iteration of our model we will be able to address this heterogeneity by using an agent-based model.

By multiplying energy use per km, price per kWh and km driven we get energy cost. E.g. someone driving 2000 km a month in a C-class vehicle in 2020 will pay either EUR 288/month for gasoline or EUR 73 for electricity. That's a very relevant savings.

Maintenance is problematic in the sense that there is little history on the maintenance for EVs and that batteries pose a separate problem. Regarding batteries we know that some Tesla Model S vehicles have now driven 500.000 km with less than 15% range degradation[54] and Tesla has claims it's simulated 800.000 km with less than 20% degradation in the lab. Battery experts at the Eindhoven University of Technology tell us that improvement in production techniques and battery management can decrease the degradation of current chemistries still much more. This basically means a battery already lasts two to three times longer than a conventional car and has the potential to last longer. We will ignore this issue in our model.

Regarding other maintenance our conversations with experts of both dealers and the ANWB have resulted in a consensus in the Netherlands that maintenance is about 1/3 of a conventional vehicle (plug-in hybrids 70%). The motor is basically maintenance free and the brakes need less maintenance due to regenerative braking. The resulting assumptions can be found in Table 1.

2.6 Discount rate

People don't value advantages in the future as much as they value advantages today. This is also the thinking behind interest rates. For this model we assume a discount rate of 5%. If a higher interest rate is

chosen the advantages of the EV become smaller but the impact is limited. E.g. if we increase the interest rate to 10% in the first scenario in Figure 4 the break-even point moves less than 1 year to the future.

3 Results

3.1 Drivetrain costs

Figure 2 shows that even a 50% more powerful EV is considerably cheaper than a conventional drivetrain. This dynamic will make it very hard for the combustion to compete in the “supercar” segment and it explains why the Tesla Model S is not only the fastest production car in terms of acceleration from 0-100 km/h but also much cheaper than gasoline cars with similar performance on this metric.

We chose to give EVs a 50% higher power because it is what we see occurring in the market and because it is a relatively cheap functionality to offer for EVs. Thus carmakers apparently think it will boost sales. However, it is good to keep in mind that EVs would be even cheaper if they had the same power.

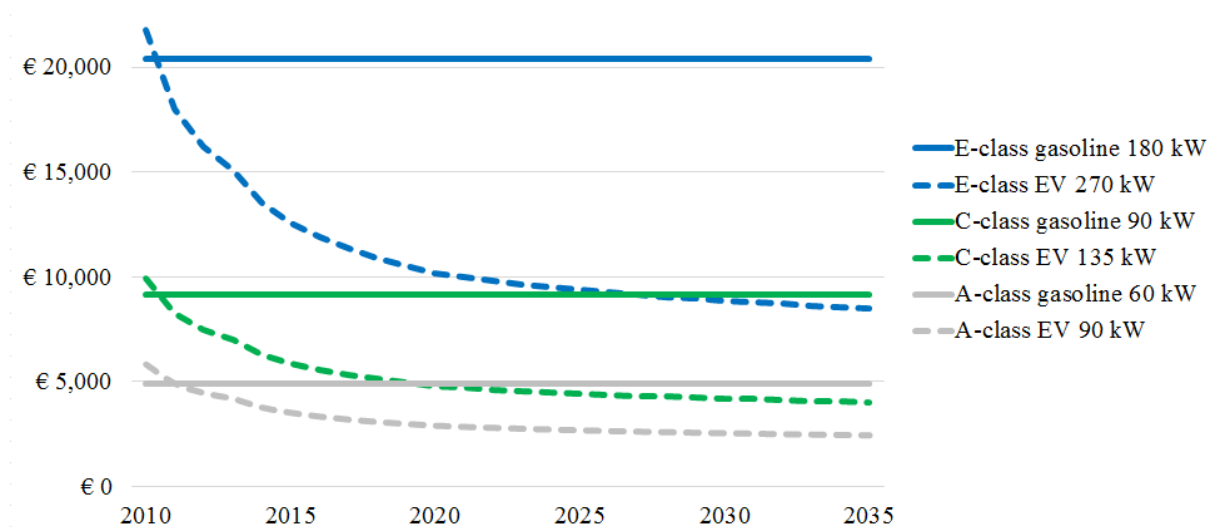


Figure 2 Drivetrain costs (original research by Auke Hoekstra and Anand Vijayashankar).

3.2 Sticker price developments

Figure 3 shows the sticker prices in the Netherlands as generated by the model. We see the result of two opposing trends. On the one hand the EV has an advantage because the drivetrain is cheaper (even though we chose to make it 50% more powerful) and this is especially apparent in the E-class where the amount of power is high. On the other hand the battery makes the car more expensive.

Note that we chose rather generous ranges and that they are real (EPA) ranges and not the inflated European (NECD) ranges. For the E-class we chose a range of 500 km, for the C-class 400 km and for the A-class 300 km.

As Figure 3 shows this makes the E-class cheaper in 2018, the C-class in 2027 and the A-class doesn't get a lower sticker price at all. This makes us more pessimistic than e.g. Bloomberg that predicts EVs will have a lower sticker price by 2025 [48] but this is largely due to the fact that we have given the EVs more generous motors and ranges and look at different car classes.

However, the total cost of ownership achieves a break even point long before the sticker price does and this is what we will concentrate on in the next steps.

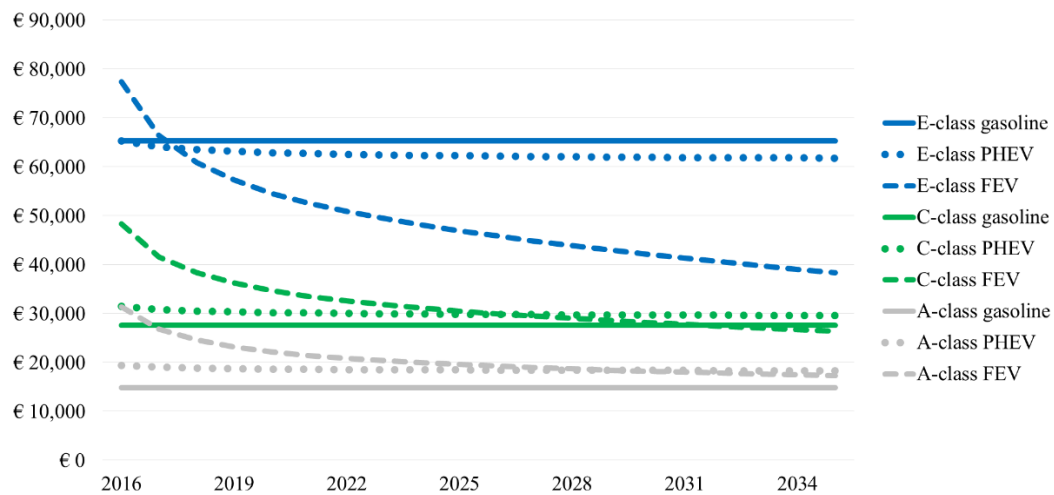


Figure 3 Predicted sticker price on the Dutch market of various car types

3.3 Total cost of ownership developments

For TCO we follow the steps described in methodology up to energy and maintenance. This is a relatively complete picture but without incentives and specifically for the Dutch situation with regard to energy prices and taxes. To show the impact of km driven we show the situation both for 13000 km/year (the Dutch average) and 25000 km/year (the Dutch average for new car buyers that currently buy most EVs). In the first case we assume an ownership period of 4 years and in the second case of 5 years.

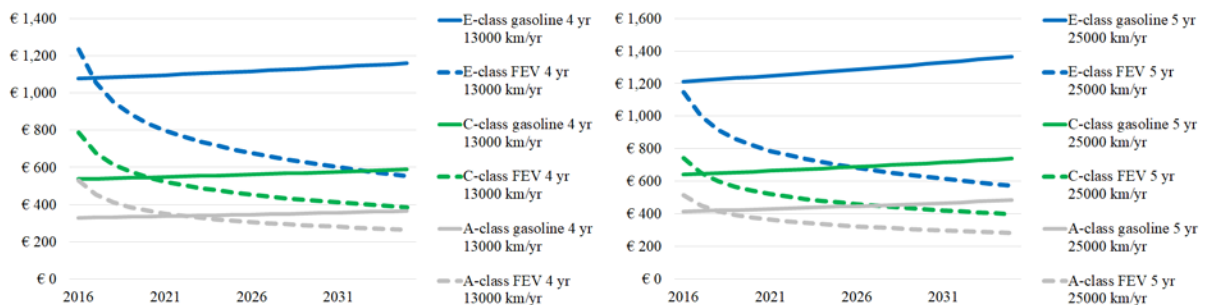


Figure 4 TCO of different types of vehicles in two scenarios

Comparing the two scenarios we can see that in all cases EVs get a lower TCO than gasoline vehicles but the advantage is much higher for owners driving more and keeping the car longer because this way they have more km in which the battery investment pays itself back.

We can also illustrate why we assume the EV will gradually get a resale value just as good or better as a conventional car. Figure 5 shows the advantage of the EV becomes significantly larger for a second hand car.

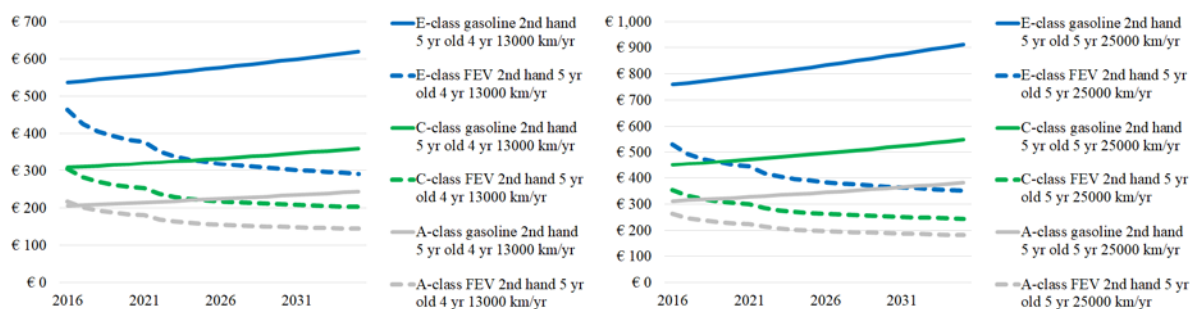


Figure 5 TCO of different types of 2nd hand vehicles in two scenarios

This finding could go a long way to ameliorating the fears that electric vehicles will be underappreciated on the second hand market.

4 Conclusion

For consumers, heavy and expensive batteries are the bane of electric vehicles while cheaper drivetrains and lower energy and maintenance costs are the boons. Our multifaceted model shows that the development in battery prices is rapidly creating the conditions that could give electric vehicles a significantly lower total cost of ownership.

This means that at least one conviction of policy makers needs to be reexamined: the idea that more stringent fuel efficiency norms will determine the speed of EV adoption. Rather their lower cost of ownership might lead to a quick and disruptive transition, analogous to the quick transition from horses to conventional vehicles at the start of the 19th century.

However, lower costs do not automatically lead to fast adoption. First our model did not consider the actual availability of electric vehicles in all segments. Currently few popular models with the characteristics we describe are available in showrooms. Also the costs might be higher for the first models that carmakers manage to bring to market due to lacking economies of scale in this startup phase. Second, battery research needs to be intensified and battery manufacturing capacity needs to be ramped up. Third, charging infrastructure needs to be available, e.g. for potential owners that cannot charge the car on their own driveway. Also fast chargers need to become abundant and cheap. Fourth, most consumers will not switch voluntarily if the advantage is small or unclear. Just as with LED lights the government could speed up this process by making electric vehicles mandatory once they are cheaper.

5 Discussion and further research

During the construction of our model we encountered many areas that should be researched further.

The most important avenue of new research we identify is the electrification of heavy duty long-haul vehicles. This was long thought to be impossible but a separate model we are developing shows that the business case is even better than for electric passenger cars, both for the trucks themselves and for the charging infrastructure. It will however require an EU wide implementation of a heavy duty fast charging network and it would be highly beneficial if EU rules for axle loads would be standardized so the placement of batteries can be the same for in all countries.

Very little is known about user preferences, characteristics, and their distribution. Bringing this information into the public domain is vital for the construction of models that make accurate adoption predictions and that show which policy instruments will be most effective. We are currently working on an agent-based model to predict EV adoption that allows us to model highly heterogeneous and realistic agents but there is a severe lack of information that can be used for parameterization.

The energy system was not yet included in our model. By combining the energy system with the mobility system it becomes clear that smart charging EVs can be very beneficial as a flexible load to optimise the use of solar and wind energy while at the same time balancing the grid. In the agent-based model we are constructing a realistic energy supply and the electricity grid is included. This makes the model more

relevant and interesting because the role of EVs in the entire energy transition can be accurately modelled. E.g. this allows us to predict CO2 reduction over time and the construction of synergistic business cases.

If the transition to EVs would be well understood it should be possible to define interventions that achieve enormous acceleration at low or even negative economic cost. We give some out of box examples. EU wide adoption of not only physical plugs but also open ICT standards for (smart) charging infrastructure. The commission could bypass the slow and incumbent-heavy IEC standardization process and opt for a multi-million euro prize for the best open high power charging technology with the promise that the winner will become the EU standard. Rewarding the formation of self-driving road trains by allowing the drivers of follower trucks (a relatively easy form of self-driving) to go to sleep. New testing protocols that can be trusted and no longer confuse customers as to what the range of an electric vehicle is (EPA vs NEDC). TCO education through standardized energy labels and online tools.

We think our model shows that electric vehicles are a radical innovation. We propose to forego the current focus on small incremental improvements through tightening efficiency standards and harmful biofuels and to focus on quickly replacing the internal combustion engine by the electric drivetrain.

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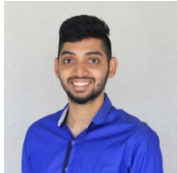


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