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DOI
10.1016/j.enpol.2019.02.071

Publication date
2019

Document Version
Final published version

Published in
Energy Policy

Citation (APA)
van Velzen, A., Annema, J. A., van de Kaa, G., & van Wee, B. (2019). Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles. *Energy Policy*, *129*, 1034-1046. https://doi.org/10.1016/j.enpol.2019.02.071

Energy Policy 129 (2019) 1034–1046

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles

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ARTICLE INFO

Keywords:
Electric vehicles
Total cost of ownership
Technology selection

ABSTRACT

Different scholars have tried to forecast the total cost of ownership (TCO) of electric vehicles (EVs). These studies use different implicit assumptions. This research aims to develop a more comprehensive EV TCO forecasting framework based on a combination of literature review and interviews. The main finding is a framework of 34 factors that influence the future TCO of EVs. By using scenarios, we noticed that the ‘profit margin’ factor seems to be underestimated in current TCO literature. Assuming that in the years to come EV producers want to recoup their investments, we showed that even in a future with much learning and scale effects this does not imply that the TCO of a specific EV will become much lower compared to the TCO of a comparable internal combustion engine vehicle (ICEV). For policymakers this implies that if they want to stimulate the use of EVs they might also need to put policies (e.g. tax policies) in place to increase the TCO of ICEVs. Another policy implication of our analysis is that EV stimulating policies seem to require a long-term effort. EV manufacturers and dealers might be tempted (or even ‘forced’ by shareholders) to increase EV prices rather quickly.

1. Introduction

The transport sector is a major contributor to greenhouse gas emissions and pollution in cities. The sector accounted for 28% of overall global energy consumption and emitted 8.7 gigatonnes of CO_2 in 2012, which increased on average by 2% each year since 2000 (IEA, 2015). In the 2° scenario (IEA, 2015), the sector's emissions would need to be reduced to 5.7 gigatonnes of CO_2 in 2050 and even less to meet the target of well below 2° that was agreed upon at the Paris Climate Conference (COP21) in December 2015. Together with an expanded role for non-motorized transport and clean collective transport, the large diffusion of zero direct emission electric vehicles (including cars) can contribute to this sectoral reduction of CO_2, possibly with low or zero carbon electricity generation (in order to contain or eliminate indirect emissions). In order to achieve this goal, many countries have introduced fuel economy regulations and use fiscal policy to increase electric vehicle (EV) deployment. The cumulative global EV stock grew from almost none in 2009 to about 3,000,000 EVs by the end of 2017 (IEA, 2018). The total number of electric cars on the road expanded by over 50% from 2016 according to this source which indicates that EV sales worldwide are accelerating.

However, the achievement of the global goals and subsidy programmes with respect to EVs cannot be taken for granted. According to the IEA (2015) it will be hard to meet the 20 million global stock target by 2020 which is part of its 2° scenarios (IEA, 2015). There are multiple barriers that prevent EVs from penetrating through to the mass market. One of the most important barriers is the relatively high cost of acquiring an EV compared to conventional cars. According to Soulopoulos (2017), medium battery electric cars were roughly $15,000 more expensive in 2016 compared to the ICE medium and he expects that they will be more expensive than the equivalent internal combustion engine vehicles for the next 7–9 years, depending on the segment. Based on surveys from the National Research Council, respondents ranked the costs as the principal barrier to buying an EV (National Research Council, 2013). Even when the high purchase costs are spread over the lifetime of the car, the EV is still not very attractive (Nemry and Brons, 2010; Windisch, 2014). Although experts consistently argue that cost reductions will take place over the course of time, there is no consensus about the extent of this cost reduction (Cluzel and Lane, 2013; Steinhilber et al., 2013; Catenacci et al., 2013). Historically, the average EV lithium-ion battery price dropped from 800 $/kWh in 2011 to roughly 300 $/kWh in 2016 (Soulopoulos, 2017). To what extent this price fall will continue and what this means for the future TCO of EVs is uncertain. Forecasting will always be accompanied by uncertainties. However, large divergences in expectations are generating very different strategies by carmakers and tend to divide stock exchange

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https://doi.org/10.1016/j.enpol.2019.02.071
Received 8 September 2017; Received in revised form 27 February 2019; Accepted 28 February 2019

Table 1
Different cost studies of EVs.

Author (year)	Assumptions	Methodology[a]	Cum. Stock in target year	Base year/ target year	Results for BEV	BEV/ PHEV/ EREV[b]	Remarks	Peer-reviewed?
Thiel et al. (2010)	Vehicle specs based on a specific car/ technology forecasts based on a single source	Top down, 5–10% learning curve	24.6 mil BEV/115.1 mil PHEV	2010/ 2030	Purchase costs for BEV will be €3200 higher in 2030 and PHEV will be €3100 higher in the medium scenario compared to ICE.	✓/✓/X	Calculations are limited to purchase price, not TCO	Yes
Weiss et al. (2012)	Assumes a learning curve of 17% for electrification	Top down, uses ex post experience curve of HEV to apply on BEV ex ante	145 mil BEV	2010/ 2035	Purchase costs for BEV is 100 $€_{2010}\,kW^{-1}$ in 2035 compared to 103 $€_{2010}\,kW^{-1}$ for ICE, breakeven in 2026.	✓/✓/X	Calculations are limited to purchase price, not TCO	Yes
Lee and Lovellette (2011)	Assumes gasoline prices increase and battery costs decline	Bottom up, but only key parameters included (retail price, maintenance, fuel, discount rate)	N/A	2011/ 2025	TCO for BEV is $3478 and cheaper than ICE in 2025. PHEV is $449 more expensive in 2025 in real terms compared to ICE.	✓/✓/X	Very limited cost model	No
Crist (2012)	Assumes vehicle specs based on specific cars	First calculates TCO for 2012, then identifies many scenarios with (unsupported) arguments	N/A	2012/NA	General conclusion: BEV remains more costly than ICE.	✓/X/X	Focus is mainly on TCO in base year, less on forecasting	No
Palencia et al. (2014)	Assumes general mid-size sedan specs and national parameters from Colombia	Bottom up, but each component cost is based on a single source	N/A	2010/ 2050	TCO for BEV is $3000 a year and ICE is about $4000 a year in real 2010 USD terms in 2050.	✓/X/X	Neglects disposal costs	Yes
Contestabile et al. (2011)	Assumes a 5% learning rate for the powertrain. Multiple vehicle specs, scenarios and market segments	Bottom up, but each component cost is based on a single source	N/A	2011/ 2030	TCO for a 50 km range BEV is lower than ICE, a 100 km BEV is slightly cheaper and a 200 km range BEV is way more expensive than ICE in 2030.	✓/✓/X		Yes
Wu et al. (2015)	Assumes different market segment and use cases. Technological parameters based on multiple sources, but many are not academic. Vehicle specs based on one source	Bottom up, based on other sources	N/A	2014/ 2025	TCO for BEV/PHEV will remain higher than ICE until 2025 (ct €/km), except for long driving distance small cars. However, the TCOs of all types will converge over time.	✓/✓/X	Uses interviews for validation	Yes

[a] The methodology used is explained in Section 3.

[b] BEV = Battery Electric Vehicle/PHEV = Plug-in Hybrid Electric Vehicle/EREV = Extended Range Electric Vehicle.

investors. In the next section we have compared seven EV cost studies and found contradicting results (refer to Table 1). We think the limited and implicit TCO estimation frameworks applied in these studies can explain these contradictions. We suspect that more factors play a role in future EV costs that cannot be delineated clearly from the results of the seven studies because these factors are 'hidden', such as the socio-technological factors. If studies take these 'hidden' factors implicitly into account, the future cost estimates will differ, yet it is unknown why they differ. Therefore, this research aims to develop a more comprehensive framework in order to make it possible for researchers to explicitly estimate future EV cost developments.

The scientific contribution of this paper is that there has not yet been a more comprehensive TCO estimation framework for EVs than this one. Societally, this framework might help to better explain future TCO estimates for EVs. In our view, differences in these future cost estimates are not worrying per se, but the causes of these differences must be clear for policymakers to make sound decisions.

In Section 2 we first give an overview of current literature covering EV TCO studies. Second, we discuss scientific literature about total cost of ownership and technology selection theories in general. Here, we argue that the literature about technology selection may provide supplementary guidance to cost research, as socio-technological factors are important for the technology selection, which in turn affect costs. In Section 3 the methodology of this study is explained. Next, in the subsequent Section 4 we present the main outcomes of this research, which consist of a more comprehensive TCO framework to determine EV costs. Section 5 outlines the potential implications of the results, as more factors can be incorporated when future EV costs are estimated. Finally, in Section 6 we discuss and conclude on these implications.

2. Literature study

2.1. Seven TCO studies of EVs

A brief overview of seven studies (Table 1) is listed below including the assumptions, base year, target year and the relevant TCO results. The forecasted TCO of EVs shows that the results are contradictory. In addition, there is not much information about the expected cumulative EV stock, which may greatly influence the TCO results through scale and learning effects. The method used in each study is also explained in the table. These methods will be discussed in this section.

2.2. Cost literature stream

As Table 1 also shows, for cost estimations of products such as EVs, the notion of total cost of ownership is often used. Total cost of ownership (TCO) is a purchasing philosophy for getting a better understanding of the true costs of buying a particular product or service (Ellram and Siferd, 1998). A TCO analysis covers all costs occurring over the lifetime of the object. For a vehicle, this includes one-time costs like the purchase costs, but also recurring expenses like fuel and maintenance costs (Redelbach and Friendrich, 2012). Since TCO takes all the costs over the life cycle into account, it can be used as an evaluation tool to compare the costs of different products (Hurkens et al., 2006). This is especially important for the comparison of conventional and electric vehicles, since the latter have relatively high purchase prices, but might face lower operating expenses (Wu et al., 2015). A limitation of using TCO is the need to identify assumptions for the driving characteristics of the owner (Redelbach and Friendrich, 2012). For example, the annual mileage will affect the TCO results, but may be unique for each individual. Multiple scenarios to account for these assumptions can be used. The total cost of ownership from a customer's perspective looks like the scheme presented in Fig. 1. These factors relate directly to the TCO.

In mathematical terms, the TCO can be determined by using the following equation:

$$TCO = OTC + \sum_{n=1}^{N} RC \times \frac{1}{(1+i)^n} \tag{1}$$

In this equation (1) *TCO* represents the total cost of owning the car for the holding period, the *OTC* represents the One Time Costs and the *RC* represents the Recurring Costs. These costs are discounted for future expenses with *i* being the discount factor and *n* the holding year starting with 1. In literature relatively recent stochastic or probabilistic TCO models can also be found (e.g. Wu et al., 2015; Danielis et al., 2018). In these probabilistic TCO estimation models authors include stochastic and non-stochastic variables, vehicle usage and contextual assumptions.

However, these approaches to TCO estimation (both non-probabilistic and probabilistic approaches) do not provide any means to estimate future costs. The cost literature stream outlines two methods for doing this: the top-down experience curves or bottom-up engineering assessment. As can be seen from Table 1, in four of the seven papers estimating future EV TCOs the bottom-up engineering method was used.

The experience curve shows that performing a repetitive task results in a fixed production cost reduction each time the cumulative output doubles (Cunningham, 1980). These curves are used as a tool to predict future cost reductions by analysing the historic cost reductions of a certain piece of technology (Hax and Majluf, 1982). Based on historical data, the past cost reduction can be visualised in a graph that describes the costs as a function of the cumulative output. In order to predict future cost reduction, researchers extrapolate this curve for up to 50 years in the future (Neij, 2008; Nemet, 2006; Day and Montgomery, 1983). The usual form, as explained by Ferioli et al. (2009) is as follows:

$$C(x_t) \;=\; C(x_0)\,\frac{x_t}{x_0}^{-b} \tag{2}$$

In this equation x_t represents cumulated production, $C(x_t)$ is the cost of a product at x_t, $C(x_0)$ and x_0 are the cost and cumulated production, respectively, at an arbitrary starting point. Finally, *b* represents a positive learning parameter (Ferioli et al., 2009).

The cost reductions, as expressed by the experience curve, can be attributed to three main components. First, the term 'learning by doing' is used for all increased efficiency of labour-related improvements as capacity increases. It encompasses improved work methods, specialization and more experienced personnel. Second, technological improvement includes process improvement in terms of standardization of work processes or automation as output increases. Finally, economies of scale are based on the notion that an increase in throughput does not require an equivalent increase in capital investment and overhead functions (Candelise et al., 2013; Nemet, 2006; Day and Montgomery, 1983).

While the top-down method uses historical information about the industry or technology and extrapolates those into the future, the bottom-up method can also be used when no data is available (Candelise et al., 2013). The bottom-up method is based on a set of inputs on a very detailed component level to come up with estimation of future costs. In this paper we call this method 'engineering assessment', although different names are used interchangeably and no common name is recognized in current literature.

Engineering assessment usually starts with an extensive review of literature about a specific piece of technology. Many details are provided in terms of the manufacturing process, materials used and the individual components of the product. This way it is possible to determine the direct and indirect costs attributed to the process. Cluzel and Douglas (2012) use this approach to predict battery costs. They start at the lowest level with material costs. Next, they estimate the costs to produce the battery pack. Finally, they use fixed assumptions for overhead costs, yields, financing and production volume (Cluzel and Douglas, 2012). In order to estimate potential future cost reductions, new trends in product design, production processes and use of materials are identified. As well as gathering technology-specific data, expert

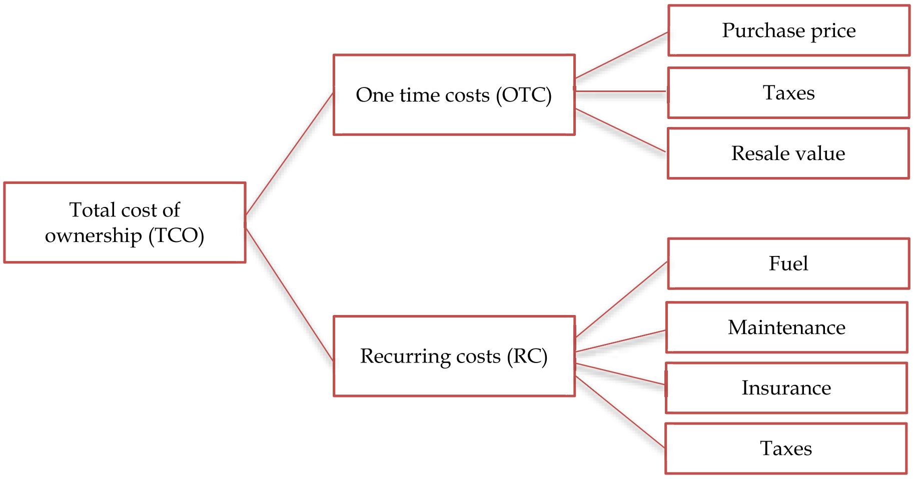

Fig. 1. Total Cost of Ownership framework as used in many studies (Redelbach and Friendrich, 2012; Wu et al., 2015; Windisch, 2014).

judgments are also used for cost estimations and reductions (Candelise et al., 2013; Neij, 2008).

2.3. Technology selection and dominant designs

At first sight the cost studies might provide enough of a basis to develop a TCO for EVs, as was done in many previous studies. However, we think that literature about dominant designs and technology selection provides supplementary guidance to research which additional factors may be important for explaining future EV costs. Scholars that focus on dominant designs argue that technology evolves through periods of incremental change until at some point in time a major breakthrough is introduced in the industry. These so-called technological discontinuities increase the uncertainty in the industry and usually change it considerably (Tushman and Anderson, 1986). Different technological paths can be developed resulting in designs that compete with each other until a 'dominant design' emerges (Abernathy and Utterback, 1987; Utterback and Abernathy, 1975). Scholars have developed a three stage life-cycle model of technology according to which, in a new industry, at the end of the first 'fluid' phase, a standard emerges that remains stable over time (Abernathy and Utterback, 1987, p. 45; Utterback, 1994). Literature about technology selection focuses on factors that influence the selection of dominant designs or standards. Following so-called experience curves, if the adoption rate increases, the unit costs of products will decline. It is our expectation that in the case of Electric Vehicles it will be more complicated, as the conventional TCO building blocks (Fig. 1) appear to suggest, and that there are more factors playing an important role. Therefore, in this research we attempt to develop a more extensive TCO framework using these two streams of literature, instead of just one.

One of the factors is technological superiority, but superiority on its own does not necessarily mean the technology is adopted by the mass market (van de Kaa et al., 2014c,d; David, 1985). Another important factor is network effects, which refers to the phenomenon whereby the user's individual benefits increase as more consumers (installed base) use the same technology (Katz and Shapiro, 1985). When the base of users increases, the technology becomes more attractive and adjacent complementary technologies are developed as well. Therefore, the installed base itself becomes a factor for technology success (Shapiro and Varian, 1998). The effect of the installed base and complementary goods reinforce one other, since the installed base increases the development of complementary goods, and the availability of these goods attracts a bigger installed base (Gallagher and Park, 2002). This may sometimes result in a 'winner takes all' market (Schilling, 2002; Suarez, 2004; van den Ende et al., 2012). According to Schilling (1998), many markets force one technology to become dominant, resulting in technological lock-in, which means there is no room for other technologies in that market (Schilling, 1998). However, this is not always the case. In other markets two types of technology may exist side by side, but other would-be technology is locked out of the market (Schilling, 2002; van den Ende et al., 2012). Once a piece of technology has achieved dominance, manufacturers, distributors and consumers can benefit from the increased compatibility that the standard allows through economies of scale (van de Kaa et al., 2014c,d).

But there are more factors influencing technology selection and dominance. According to studies by Van de Kaa et al. (2011); Van de Kaa et al. (2014a); Van de Kaa et al. (2014b); van de Kaa and de Vries (2015) many different factors explain the emergence of single dominant designs. These factors have been studied by these authors in various case studies of standard battles. In total, 29 factors were identified in these studies, which were split into five general categories. The first category concerns the characteristics of the supporter of the technology. This includes factors like financial strength, brand reputation and learning orientation. The second category is about the characteristics of the technology itself. This involves technological superiority, but also compatibility and complementary products. Third, the strategy used to win a battle influences the outcome as well. Pricing strategy, timing of entry and marketing communication will increase the market share. The fourth factor relates to other stakeholders: the number of units of the technology actually in use (installed base), a player exercising a lot of influence – also called a 'big fish' – and regulations. Finally, market characteristics impact the outcome as well. Examples of market characteristics are: the bandwagon effect, which implies that when some users chose a certain type of technology, others will follow; network externalities, which implies that the utility for a user increases when more users choose the technology, and the numbers of options available.

3. Methodology

The goal of this study is to compose a more comprehensive future TCO estimation framework for EVs with factors and its relations. A combination of an analysis of existing literature and interviews has been conducted to achieve this.

3.1. Literature analysis

Two streams of literature were reviewed: cost studies and technology selection studies. In addition, many building blocks (both factors and relations) can also be derived from other literature that focuses on EV development in general. This concerns studies that explicitly discuss factors that influence the TCO.

Table 2
List of companies interviewed for this research.

Segment	Companies
Automotive branch	Renault, H-D Systems, GridCars
Charging infrastructure	Fastned, The New Motion
Knowledge organisations	ICCT, CE Delft, PBL, ANWB
Energy companies	Nuon
Insurance companies	Achmea, Meeus
Universities	TU Delft, TU Eindhoven, Hogeschool Rotterdam, Hogeschool van Amsterdam
Government Departments	City of Amsterdam

For the selection of studies, the following criteria were used:

- The study was not published before 2010, since at that point in time the EV industry started to expand (IEA, 2015);
- The study attempts to provide a clear explanation why a factor is relevant;
- The study is preferably scientific (published in a peer-reviewed Journal), but at least recognized by the industry. Recognized by the industry means that it is published by an organization with a reputation in the field of energy or transport (e.g.: the International Energy Agency; the International Council of Clean Transportation).

When a factor, or relation between factors that influences the TCO, is found in a study, it is extracted and explained (see section 4). Based on the original study, a factor is identified as directly or indirectly influencing the TCO and connected to any other factors, if applicable, also based on that particular source of literature.

3.2. Interviews

Seventeen interviews (Tables 2 and 3) were used to validate the data from the literature analysis and to verify whether all information was taken into account. Semi-structured interviews were performed. Since there was a clear set of questions to be answered based on the literature review, semi-structured interviews provided more in-depth knowledge about how the experts would cope with uncertainties and assumptions identified in the desk research. Experts from different disciplines with diverse positions in various organisations were interviewed to reflect the diversity of the population (Sekaran and Bougie, 2009). Questions were tailored to match the expertise of the interviewee, e.g. the focus for battery manufacturers is on battery technology and less focused on the maintenance of other car components. To be clear, the interviews were used to validate the initial framework which was based on the literature study, which explains why interviewees did not bring up new factors that had not previously been identified in research literature.

A list of which topics were discussed with whom can be found in the table below (Table 3).

4. Results

Table 4 below shows the factors found that might directly influence the future TCO of EVs and their empirical evidence by literature stream and/or by interviewee(s). Our literature analysis and interview results especially show that as well as these direct factors, many more factors play a role in accurately determining the TCO. In this paper these factors are referred to as ‘indirect factors’ because they do not affect the TCO directly. However, they do determine scale and learning effects and innovation, which in turn affect the production costs of an EV. The production costs directly influence the TCO. These indirect factors – such as customer understanding and symbolic and affective factors, to name but a few, are subject to the typical ‘chicken and egg problem’ and could be the requisites to ‘kick-start’ the reinforcing cycle of economies of scale and innovation to bring down the TCO. Innovation and/or scale and learning effects are incorporated into other TCO studies as well, but it is often unclear how the predicted production numbers are estimated.

4.1. How do these factors relate to the TCO and to each other?

Having combined the results from Table 4 with additional insight from the literature and interviews about the possible relationship between factors, we propose a conceptual framework of 34 factors that either directly or indirectly influence the future TCO of EVs (Fig. 2). The relationships between these factors are based on the literature and interviews, often using their implicit assumptions.[1] The red boxes in Fig. 2 directly influence the TCO, while black boxes indirectly influence the total cost of ownership.

Government EV policies (bottom right box) are currently the most important drivers for EV deployment (IEA, 2018). According to our conceptual framework these policies influence customers' willingness to purchase EVs which, in turn, influences the number of EVs sold globally. Via the impact of scale and learning effects on price decreases more EVs will be sold globally, which further decreases production costs and, thus, potentially TCOs. Vehicle manufacturing takes place in a highly international market. Therefore, it is important to note that the reinforcing circle just mentioned will only take place if many ‘large’ countries or regions deploy EV policies. Hence, the usage of the term ‘sold globally’ in our framework. According to IEA (2018, p. 10) the deployment of EV policies in large countries or regions seems to take off: ‘*the strongest current policy signals emanate from electric car mandates*

Table 3
Background per interviewee and the topics discussed during the interview.

Interview	Background	Vehicle technology	Battery	Maintenance	Charging	Demand	Depreciation
1	Science			✓			✓
2	Science			✓		✓	✓
3	Science		✓		✓	✓	✓
4	Automotive	✓	✓	✓	✓	✓	✓
5	Charging				✓	✓	✓
6	Government				✓	✓	
7	Research/consulting		✓	✓	✓	✓	✓
8	Non-profit	✓	✓			✓	
9	Energy			✓		✓	
10	Research/consulting		✓	✓	✓	✓	✓
11	Research/consulting	✓	✓	✓		✓	✓
12	Science				✓	✓	
13	Non-profit			✓		✓	✓
14	Automotive	✓	✓	✓	✓		✓
15	Insurance						
16	Insurance						
17	Charging				✓		

Table 4
List of factors as identified in different literature streams and by interviewees.

Factor	Backed by cost literature	Backed by technology selection literature	Backed by other literature	Backed by Interviewees
DIRECT FACTORS				
Production costs	(Weiss et al., 2012; Lee and Lovellette, 2011; Crist, 2012; Palencia et al., 2014; Contestabile et al., 2011; Wu et al., 2015)	(Schilling, 2002; Suarez, 2004; van den Ende et al., 2012; van de Kaa et al., 2014c,d; van de Kaa et al., 2011; Schilling, 1998)	(FHA, 2009; Green et al., 2014; Wiederer and Philip, 2010; Sierzchula et al., 2014; CE Delft, 2011; Hill et al., 2015; Redelbach and Friendrich, 2012; ARF & McKinsey, 2014; Thiel et al., 2010; Windisch, 2014)	1–13
Profit margin	(Lee and Lovellette, 2011; Wu et al., 2015)	(van de Kaa et al., 2011; Suarez, 2004; van den Ende et al., 2012)	McKinsey (2016)	7,10,11
Resale value	Wu et al. (2015)	–	(Windisch, 2014; Redelbach and Friendrich, 2012)	1-5,7,10,11,13,14
Tax/fiscal policy	(Crist, 2012; Palencia et al., 2014; Wu et al., 2015)	–	Tietge et al. (2016)	1–13
Charging costs	(Lee and Lovellette, 2011; Crist, 2012; Palencia et al., 2014; Contestabile et al., 2011; Wu et al., 2015)	–	Nemry & Brons (2010)	3-7,10,12,13
Maintenance	(Lee and Lovellette, 2011; Crist, 2012; Palencia et al., 2014; Wu et al., 2015)	–	(Cleary et al., 2010; van Vliet et al., 2010; Windisch, 2014; CE Delft, 2011)	1,2,4,7,10,11,13,14
Insurance	(Crist, 2012; Wu et al., 2015)	–		14,15
Discount rate	(Weiss et al., 2012; Lee and Lovellette, 2011; Crist, 2012; Palencia et al., 2014; Contestabile et al., 2011; Wu et al., 2015)	–	(Tsang et al., 2012; Windisch, 2014; van Vliet et al., 2010)	1,5,6,10,11
INDIRECT FACTORS				
Range	–	*See EV performance*	(Perujo et al., 2012; Cluzel and Lane, 2013; National Research Council, 2013; Steinhilber et al., 2013; Axsen et al., 2010; Elkind et al., 2012; Brown, 2013; ARF & McKinsey, 2014; Nemry and Brons, 2010; Catenacci et al., 2013)	1–13
Charging infrastructure	–	(Schilling, 2002; Suarez, 2004; van den Ende et al., 2012; van de Kaa et al., 2014c,d; van de Kaa et al., 2011; Schilling, 1998)	(Windisch, 2014; National Research Council, 2013; Elkind et al., 2012; Sierzchula et al., 2014; Tsang et al., 2012; Boulanger et al., 2011; Nemry and Brons, 2010; Steinhilber et al., 2013; Green et al., 2014)	1–13
EV performance	–	(van de Kaa et al., 2011; Suarez, 2004; van den Ende et al., 2012; van de Kaa et al., 2014c,d; Schilling, 2002)[a]	–	1-3,6,7
ICEV performance	–	*See EV performance*		2,4,6,7,10,11
Variety of EV models	–	–	(Cluzel and Lane, 2013; Windisch, 2014)	2-4,6-10
Emission regulations	–	(van de Kaa et al., 2011; Suarez, 2004)		1,7,10
Customer understanding	–	–	(Elkind et al., 2012; Boulanger et al., 2011; Muller-Seitz et al., 2009; Cluzel and Lane, 2013; Axsen et al., 2010; Tsang et al., 2012; Brown, 2013; Windisch, 2014)	2,3,7
Symbolic and affective motives	–	van de Kaa et al. (2011)	Steg (2005)	2,3,7,10,12
Range anxiety	–	–	(Hacker et al., 2009; Boulanger et al., 2011; Azadfar et al., 2015; Tsang et al., 2012; Windisch, 2014; Cluzel and Lane, 2013; Nemry and Brons, 2010; Green et al., 2014)	1,3,7
Income elasticity	–	–	Geilenkirchen et al. (2010)	1,7,10
Bandwagon effect	–	van de Kaa et al. (2011)	Langezaal (2015)	3,5,10
Government policies	–	*See emission regulations*	(Windisch, 2014; ARF & McKinsey, 2014)	5,6,10,11,12
Institutional barriers	–	van de Kaa et al. (2013)	(Tsang et al., 2012; Stone, 2016)	1-3,7,10
Change in mobility landscape	–	–	McKinsey (2016)	1-3,7,9,10
R&D investments	–	–	(Orbach and Fruchter, 2011; Hacker et al., 2009)	2-4,6–8,10
Market factors	–	van de Kaa et al. (2011)		1
Vehicle specifications	–	–	(EPA, 2013; Kay et al., 2013; EPA, 2013; TNO, 2011; Hill et al., 2013; Hacker et al., 2009; Fui Tie and Wei Tan, 2013)	1-5,7,8,11
Battery technology	–	–	(Axsen et al., 2010; Elkind et al., 2012; ARF & McKinsey, 2014; Tsang et al., 2012; Boulanger et al., 2011; Brown, 2013; Cluzel and Lane, 2013; Cluzel and Douglas, 2012; Dinger et al., 2010; Hill et al., 2015)	1–13

(*continued on next page*)

Table 4 (*continued*)

Factor	Backed by cost literature	Backed by technology selection literature	Backed by other literature	Backed by Interviewees
Commodity prices	–	–	(Boulanger et al., 2011; Goldman Sachs, 2015; Catenacci et al., 2013; Hacker et al., 2009)	–

[a] The technology selection scholars do not explicitly discuss EV performance, but technological superiority in general.

in China and California, as well as the European Union's recent proposal on carbon dioxide (CO_2) emissions standards for 2030'.

4.2. New direct factors influencing TCO

There are many new *indirect* factors included in this framework compared to previous TCO studies (see Table 1). However, the three new *direct* factors identified seem to be of special importance in this case. These three new direct factors are a) the profit margin, b) the associated pricing strategy and c) original equipment manufacturer (OEM) competition. Other cost studies use the production costs as a proxy for acquisition price and ignore the fact that the profit margin can affect the TCO as well. Based on the interviews (with automotive consultants, among others) we conclude that, at the time of writing this paper (early 2018), the production costs are indeed a proxy for the acquisition price, but this assumption may not hold in the future. In other words, the reinforcing circle just mentioned might explain that the production costs of EVs will go down in the future, but this does not mean that the TCOs of EVs will continue to go down as well, as will be explained in the next paragraph.

According to interviews and literature, the Retail Price Equivalent[2] (RPE) of ICEVs is about 1.6 (Kolwich, 2013), which means that 60% of the direct manufacturing costs are indirect costs and profits. In multiple interviews it is argued that EVs are sold at or below production costs. This is a common strategy in the automotive industry, as initial investments are high. Once market share has increased by offering a low price, standardization efficiencies kick in and this lowers the production costs. EVs are not subject to a competitive market and hence little to no standardization efficiencies are present at the moment. Therefore we estimate the RPE of battery electric vehicles (BEVs) to be about around 1.0 in 2015, which means no mark-up is covered by the BEVs' retail price. However, producers will need to increase the RPE at some point in the future in order to recoup investments. This directly influences the TCO of BEVs in a negative way, explaining why the reinforcing circle might not decrease the ongoing TCO of BEVs in the future. Of course, our RPE of 1.0 for 2015 is a very rough and aggregate estimation because in reality the BEV market is highly differentiated. An RPE of 1.0 especially signifies the notion that, currently, most BEVs are sold below cost price, as mentioned in the interviews.

4.3. What are important factors influencing the TCO?

Both the literature and interviewees pointed out factors influencing the future TCO of EVs that are relatively 'important'. Each interviewee was asked to select his/her top 3 important factors for TCO development. Their aggregated selection is rather clear. According to the interviewees, production costs, range, charging issues, government policies and battery technology development are important factors affecting EV TCO development (Table 5, second column). The literature analysis (Table 5, third column) also points at production costs, range and charging issues as being important factors. These factors are interrelated (as shown in our framework, Fig. 4). For example, battery technology developments result in lower battery prices (as has occurred

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[1] Take 'Variety of EV models', for example. There is no study that explicitly says: "*Variety of EV models directly influences the customer's willingness to purchase EVs*". However, one study concluded: "*Customers that show a specific preference for a vehicle type* (..), *are more likely to find satisfaction with one of the numerous ICEVs on the market*" *(*Cluzel and Lane, 2013, p. 67*, p. 67)*. In such cases – using our own analytical thinking – in our framework we assume that 'Variety of EV models' affects the customer's willingness to purchase EVs.

[2] The Retail Price Equivalent (RPE) is a multiplier (> 1.0) which stands for all indirect costs and the mark-up. This includes corporate overheads, dealer costs, transportation, marketing, etc. (Kolwich, 2013; Whinihan et al., 2012). Kolwich (2013) calculated the RPE for nine different car manufacturers using European retail prices. The weighted average of the results is a value of 1.6.

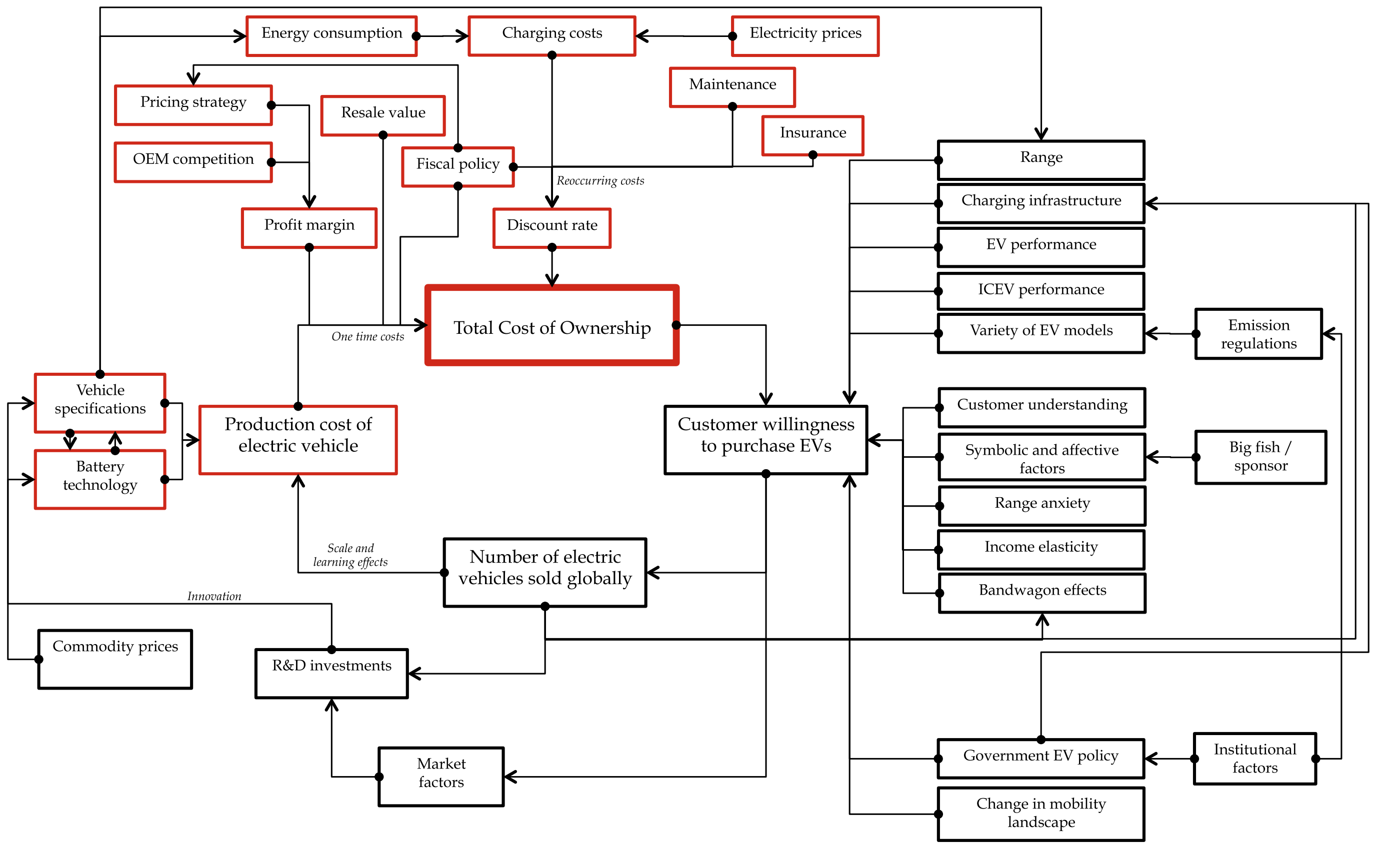

Fig. 2. A conceptual framework of factors influencing directly or indirecly the future TCO of EVs.

Table 5
Relatively important factors (included in both interview Top 3 and literature, or mentioned relatively often in one of them).

Factor	Included in Top 3?	Mentioned in literature?
Production costs	14 interviews	13 studies
Profit margin	–	–
Resale value	1 interview	1 study
Tax/fiscal policy	–	–
Charging costs/infrastructure	–	–
Maintenance	–	–
Insurance	–	–
Discount rate	–	–
Range	10 interviews	13 studies
Charging infrastructure	5 interviews	9 studies
EV performance	1 interview	–
ICEV performance	–	–
Variety of EV models	1 interview	2 studies
Emission regulations	–	–
Customer understanding	–	7 studies
Symbolic and affective motives	–	–
Range anxiety	–	–
Income elasticity	–	–
Bandwagon effect	–	–
Government policies	4 interviews	–
Institutional barriers	–	1 study
Change in mobility landscape	–	–
R&D investments	–	–
Market factors	–	–
Vehicle specifications	–	–
Battery technology	4 interviews	–
Commodity prices	–	–

in the past, see section 1) which may lead to batteries with more power (kWh) and thus a longer range, or in a fall in production costs (per kWh). When ranges are large enough (from a willingness to purchase point of view) further battery price decreases might be used, for example, to increase profits (resulting in a higher RPE) or they might be used to provide new features (e.g. advanced driving assistance and, in the long run, self-driving features).

5. Potential implications: the case of future TCO for a C-segment BEV

In this section the newly developed TCO framework presented in the previous chapter is applied to illustrate the potential implications of using this more comprehensive framework rather than frameworks such as the one represented in Fig. 1. The main advantage of the new framework is the possibility to incorporate new factors such as the profit margin (RPE) and to see the effects of the scale and learning effects on the TCO. We use two future scenarios in this section to illustrate the implications of using the framework.

The first scenario incorporates a very optimistic BEV adoption rate due to favourable government policies (e.g. due to the Paris Agreements many more regions, other than just California, China and the EU (see section 2), give all kinds of R&D subsidies, implement policies to build and maintain charging infrastructure, adopt favourable fiscal policies for EVs, and so forth). It can be assumed that these policies will contribute to (partly) solving the typical ‘chicken and egg problem’ as mentioned in the previous section. The policies will indeed ‘kick-start’ the reinforcing cycle of economies of scale and innovation. For example, these policies increase consumers' willingness to purchase EVs (Fig. 2) which, in turn, boosts battery technology developments, resulting in lower battery prices and longer ranges, which will stimulate EV sales even further. The reinforcing cycle of economies of scale and innovation will definitely decrease EV costs in this scenario. In this scenario we assume that the manufacturers increase their profit margin (the BEV RPE will become equal to the original RPE of 1.6). One reason might be that, gradually, the EV market will become a ‘normal’ market where car producers aim to make ‘normal’ profits. Another reason

Table 6
Operationalization of the factors used in the two scenarios for TCO calculation and explaining the differences and similarities in the operationalization.

Factor	Operationalization
1. Production costs	Based on the current retail price[a] (excl. taxes), we subtracted indirect costs (a Retail Price Equivalent (RPE) of 1.6 for ICEVs and 1.0 for BEVs). Then we estimated the possible cost reductions per scenario to end up with the future product costs. Next, the indirect costs were added back (1.0 or 1.6 RPE) to get the future retail price. There's more on RPE below. Technical cost reductions of specific components are based on desk research[b]. Cost reductions as an effect of scale and learning effects (especially in scenario 1) are based on our own experience curve[c], in which a vehicle technology premium is calculated for EVs compared to ICEVs: $(6951 {*} x_t/750{,}000)^{-0.2345}$. Future demand is based on literature reviews as well as how we have explained later in this paper[d].
2. Battery technology	Battery costs are officially part of the product costs, but we estimated costs for this technology separately because the cost may decline faster than other car components given the high R&D work. Based on high quality studies we estimated the battery cost to decline until 2030, using a pessimistic (in scenario 2) or optimistic approach (in scenario 1)[e]. This is validated by means of applying our own experience curve $(y = 377.26^{e-0.22x})$[f].
3. Profit margin	The profit margin is based on an RPE taken from existing literature[g] for conventional vehicles. For EVs it is based on multiple interviews with EV experts and consultants (1.6 for ICEVs and 1.0 for BEVs). In the first scenario the RPE is gradually increased from 1.0 to 1.6.
4. Resale value	Other studies and question whether resale value is significantly different than what it is for ICEVs (Windisch, 2014). This is validated in our study by using a large database of second hand vehicles including their depreciation rate. Using a statistical regression analysis it was concluded that EVs are not subject to a significantly different depreciation rate ($P = 0.6612$/coefficient $= -0.5779$) and therefore this is not taken into account in further calculations.
5. Charging costs & infrastructure	Future charging costs & infrastructure may significantly change over time but the extent of the change is uncertain. We took into account an optimistic approach (declining electricity price, low charging infrastructure costs and high utilization rate) in scenario 1 and the opposite in scenario 2. The cost figures are based on a desk research[h].
6. Maintenance	Maintenance is based on existing literature[i], which results in a 50% cost reduction compared to ICEV, but no further decline over time.
7. Insurance	For insurance, data from Dutch insurance companies is used. No additional change over time is included.[j]
8. Discount rate	In this study, the discount rate is used as fixed input data for the results, using a 10% discount rate.
9. Range	When battery cell costs decline (see factor 2), a producer can decide to either decrease the battery pack price or increase the range of the car. If we would use two different range patterns over time in scenario 1 and 2, it would be impossible to compare the costs. Therefore, we used one single range pattern over time for both scenarios. It is assumed to range increases rapidly to until 250 km, then gradually increases until it stabilizes at 300 km.
10. Variety of EV models (through demand)	Demand figures are based on desk research. Studies in which we could retrieve the original study or actual data were used to project a pessimistic (scenario 2) and optimistic (scenario 1) demand curve for both BEVs and EVs as a whole[k]. For the BEVs, the pessimistic scenario expects a 3% market share of BEVs in terms of annual new sales, while optimistic scenario expects a market share of 25%. For EVs in general (including BEV, PHEV and EREV) the market share for the three scenarios is expected to increase from 3% at present to a 16%, 21% or 42% market share.
11. Customer understanding (through demand)	
12. Government (fiscal) policies.	The government's fiscal influences can either be included or excluded and are used as fixed input data just like the discount rate. In this case all financial government influences are included, such as VAT, energy taxes, fuel taxes and taxes imposed when buying a car.

[a] Current retail prices are based on BOVAG information (Bovag, 2015).

[b] The technical cost reduction is based on a TNO study (TNO, 2011).

[c] Vehicle technology premium is defined as components that are both included in an ICEV and EV, but are more expensive for EVs due to the absence of scale and learning effects. This premium is calculated at €7000 per car (for a C-segment BEV), but will decrease over time following an experience curve.

[d] The production costs experience curve is calculated using a learning rate of 15% and the future demand expectations for BEVs according to high quality studies (BNEF, 2016; Book et al., 2009; Guo and Zhou, 2016; Lutsey, 2015; Nemry and Brons, 2010).

[e] Out of the 19 studies to battery costs, six are selected as high quality because of comprehensiveness, scientific foundation and date of publication (Cluzel and Douglas, 2012; EPA, 2013; Hill et al., 2015; Gerssen-Gondelach and Faaij, 2012; Kromer and Heywood, 2007; Wolfram and Lutsey, 2016).

[f] The battery cost experience curve is calculated using a learning rate of 22% taken from previous studies (Matteson and Williams, 2015; Weiss et al., 2012) and future demand expectations for EVs according to high quality studies (BNEF, 2016; Book et al., 2009; Guo and Zhou, 2016; Lutsey, 2015; Nemry and Brons, 2010).

[g] The 1.6 RPE for conventional vehicles is estimated by Kolwich (2013) and this rate was confirmed in the interview with the automotive expert.

[h] Charging costs are based on 10 studies (ECN, 2015; Movares, 2016; May and Mattila, 2009; National Research Council, 2013; EPA, 2013; Hill et al., 2013; Weeda, 2013; Madina, 2015; Nissan, 2016; Tesla Motors, 2016).

[i] Maintenance costs are based on (private) CE Delft data sheets that were used as input for "The Brandstofvisie" (CE Delft, 2011).

[j] The Dutch website independer.nl is used to compare the Dutch insurance fees. The average fee of the best three insurances were used.

[k] Future demand expectations for EVs are based on the following sources: BNEF (2016), Book et al., 2009, Guo and Zhou (2016), Lutsey (2015), Nemry and Brons (2010).

might be that in this scenario multi-divisional legacy manufacturers with a BEV division are put under pressure by other divisions and by shareholders to increase their profits rather quickly; perhaps even 'too early', as a further fall in the EVs' purchase prices, due to economies of scale, might result in a higher market share and, thereby, in the longer term, even higher profits.

The second scenario is the opposite, and shows the future TCO when there is only modest government support for BEVs and, hence, not a very strong kick-start. The EV market will stay relatively small, so it can be assumed that producers will continue to accept no profit margin.

A numerical example based on the two scenarios follows. For the calculations in the example, a C-segment BEV was used and compared to a reference ICEV. All calculations are based on Dutch (fiscal) policies in both scenarios, where applicable. The following factors were used for the TCO estimation (Table 6). The input data and accompanying references for each factor are discussed in Table 7 or in the footnotes.

In order to operationalize the factors of Table 6 and estimate future development over the next 10 years, we used input data as shown in Table 7. The 'remarks' column explains the development over time.

A user profile has been developed for an average Dutch person. It is based on 15,000 km per year, 6 years of ownership, 80%/20% home/public charging, charging once a day and a 10% discount rate.

5.1. Results scenario 1

In the first scenario it is assumed that there is an optimistic kick-start for BEVs and the RPE will increase as well. In this scenario government policies favour the adoption of EV, for example through

Table 7
Input data for TCO (before actual calculations, not discounted).

Category	Unit	EV Value$_{2015}$		EV Value$_{2030}$		Remarks
Scenario		1	2	1	2	
Vehicle costs						Decrease of vehicle technology through applying the experience curve in two scenarios. Decrease of powertrain based on existing literature, no scenarios.
- Vehicle technology	€	€11,844	€13,429	€10,863	€11,997	
- Powertrain	€	€2,768	€2,768	€2,320	€2.320	
Battery costs	€/kWh	€233	€401	€150	€258	Price per kWh. Decrease based on literature study for two scenarios. Verified by other cost studies and experience curve.
Resale value (compared to ICEV)	€	€0	€0	€0	€0	No significant difference between BEV and ICEV assumed (refer to Table 6 for a detailed explanation).
Energy consumption	Km/kWh	5.60	5.60	5.92	5.92	Decrease based on literature studies.
Charging costs						Excludes all taxes. Electricity price and public charging based on three scenarios. Home charging based on literature studies.
- Electricity	€/kWh	€0.035	€0.085	€0.024	€0.096	
- Home charging	€	€1,189	€1,189	€1,053	€1,053	
- Public charging var.	€/kWh	€0.08	€0.13	€0.022	€0.052	
- Public charging fixed	€/year	€48.81	€48.81	€48.81	€48.81	
Maintenance	€/km	€0.015	€0.015	€0.015	€0.015	Fixed based on literature studies and interviews.
Insurance	€/year	€717	€717	€717	€717	Fixed based on literature studies and interviews.
Range	km	154	154	292	292	I is assumed to range increases rapidly to until 250 km, then gradually increases until it stabilizes at 300 km.
Profit margin	€	€2,310	€0	€6,895	€0	The profit margin increases linearly in scenario 1 and is kept zero in scenario 2.
Taxes						The one-time tax is based on the retail price. Annual taxes are related to VAT and electricity taxes.
- One-time tax	€	€5,985	€7,186	€6,033	€5,978	
- Annual tax	€/year	€662	€808	€621	€756	
Expected demand (annual new sales)	Million cars	BEV: 9 EV: 7.2	BEV: 0.9 EV: 1.8	BEV: 25.6 EV: 43.5	BEV: 3.0 EV: 17.0	Demand is based on at least six high quality studies that predicted BEV and EV demand (both conservative and progressive).

subsidies. Production costs, including battery costs, decline very fast over time due to technological innovation. Because of government support, the BEV becomes popular with the mass market. This kick-starts the scale and learning effects, which in turn results in a lower price. However, since the TCO of the BEV decreases rapidly, the producers will gradually increase the RPE to recoup initial investments and hence the BEV becomes profitable for the producers.

The resulting lifetime TCO is presented in the figure above (Fig. 3). Because the most optimistic scenario was used regarding technological development and government policies, the BEV TCO is relatively close to the ICEV reference from 2020 and beyond. Taking only scale and learning effects into account would normally result in a decrease in TCO every consecutive year, but because of the assumed increase in RPE the EV TCO remains more or less stable, and just slightly below ICEV TCO. The blue dotted line represents the BEV TCO as if there were no RPE increase.

5.2. Results scenario 2

In the second scenario there is no BEV kick-start at all. We take the most pessimistic scenario with regards to government policies and technological innovation. Battery and production costs remain fairly high and there is low demand for BEVs. This results in a lower BEV adoption rate and low scale and learning effects. Consequently, producers will not increase the RPE because that would only increase the TCO even more.

The results are presented in the figure above (Fig. 4). In this scenario there is a huge TCO gap between the BEV and ICEV reference because of the lack of strong government support and innovation. As there is no kick-start, the TCO remains quite stable in the early years. A decrease is only notable after the range stabilizes from 2030 and beyond. The TCO break-even point between BEV and the ICEV reference is in 2030. Only after that point might the RPE kick-in.

Our more comprehensive framework shows that the ‘profit margin’ factor may have a big impact on the future TCO. For us, the importance of this factor was unexpected because ‘profit margin’ is ignored in other

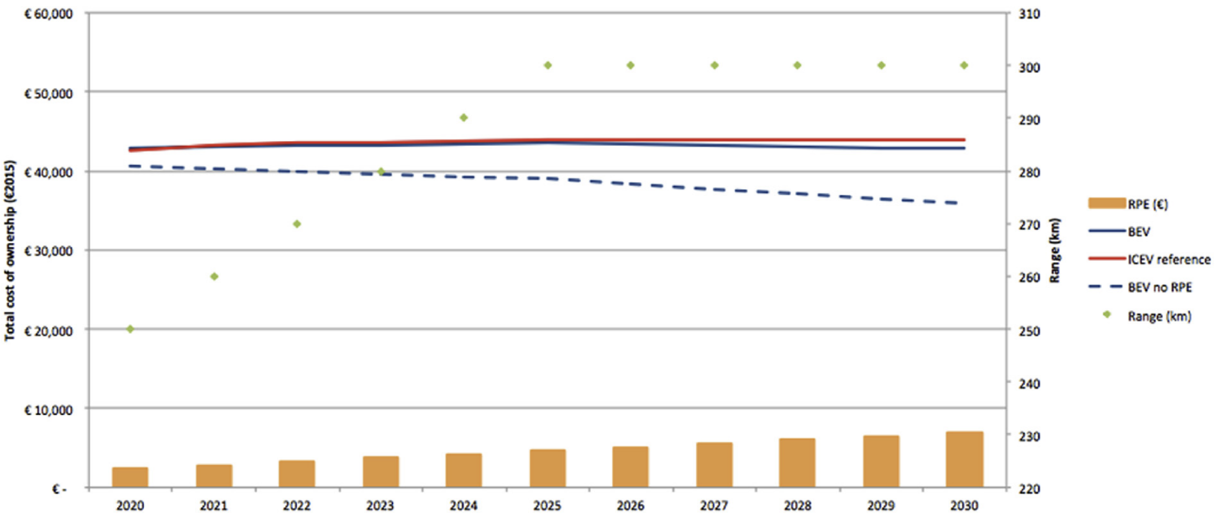

Fig. 3. Lifetime TCO results for an optimistic BEV cost reduction, including an increase in the RPE. Expressed in real €2015.

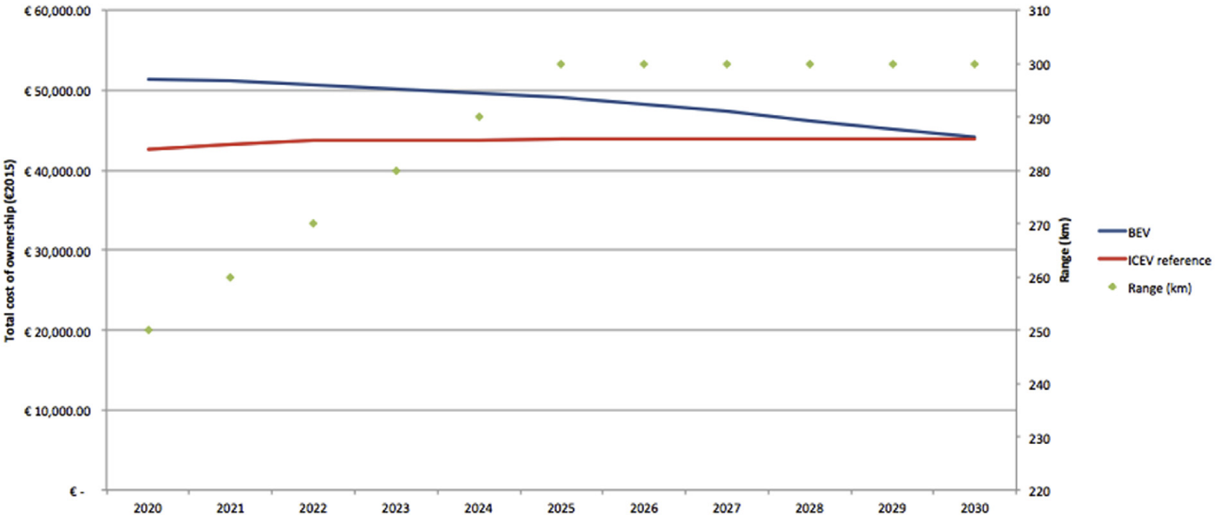

Fig. 4. Lifetime TCO results for a pessimistic BEV cost reduction, with RPE stable at 1.0. Expressed in real €2015. The average range for 2020 is estimated to be 250 km based on the current (2019) ranges to be found on the market of about 200–300 km.

studies. Additionally, the 'profit margin' factor was not mentioned as a critical barrier in the literature and also not in the interviewees' top 3 of important factors (see Table 5). However, at some point in the future, EV producers will want to recoup their investments. Even in a future scenario with a lot of learning and scale effects, a future decline in EV production costs does not necessarily lead to a decline in the BEV retail price, as many might expect.

These two scenarios are illustrative. They show just a few of the many possibilities that may occur in the future with the TCO of EVs. The more comprehensive framework (Fig. 2) can be used to construct plausible future stories. Other numeric assumptions about the future can be made; for example, another slope of the range and its maximum of 300 km can be assumed, or by removing an RPE of €0, as assumed in scenario 2. Also, developments in electricity prices (e.g. for wind and solar power) can be assumed differently in future scenarios, in order to estimate the future TCO of EVs.

In any case, previous studies have already shown that production costs, range, and charging infrastructures (refer to Table 4) are important factors influencing the TCO. Based on our analysis, using a more comprehensive TCO framework, it has become clear, in any case, that the OEM's profit margin should be added to this list, as the RPE will eventually increase and, hence, influence the TCO.

6. Conclusion and discussion

This research integrated cost literature with technology selection literature to shed new light on the total cost of ownership of electric vehicles. To conclude, the cost development of EV for the next few decades is more complex than simply adding up the costs of individual components or applying an experience curve. Many reinforcing cycles, feedback loops and qualitative factors play a role as well, which may tip the balance, creating a more mature market for EVs in the next 10 years.

The main finding is a list of 34 factors that may directly or indirectly influence the total cost of ownership of EVs, that has been composed by combining the literature streams of cost theory and technology selection. By using this existing literature and undertaking interviews we could also draw relationships between these factors and rank their importance for TCO development. When comparing our newly developed framework to existing TCO frameworks for EVs, we conclude that we were able to include many more indirect factors, such as the factors influencing the willingness to purchase. In addition, we identified the profit margin as a new direct factor, explaining future TCO for EVs that has not been incorporated in previous frameworks. By applying our framework we could show that assumptions about profit margins should be made explicitly in future BEV TCO estimates because the profit margin has a big impact on the future TCO of EVs.

It seems a safe assumption to think that at some point in the future EV producers will want to recoup their investments. Using this assumption, we showed that, even in a future scenario with high scale and learning effects, a future decline in EV production costs does not necessarily lead to an on-going decline in the BEV retail price. Car manufacturers have many strategies to use to react to falling production prices, as previously mentioned. They can increase RPE (even 'too early') or they can increase RPE combined with adding new features (e.g. self-driving features), and so forth. In any case, even if OEMs accept an EV business case without covering their indirect costs and markup for years to come, the EV will probably be sold just below the ICEV retail price and a big price differential will not emerge. Whatever assumptions researchers make on this relationship, our framework points out that these assumptions should be made explicitly, as they will have a high impact on TCO outcomes.

Governments may play a crucial role in the development of EVs, as our framework shows, especially by kick-starting the adoption rate. In section 4, it is mentioned that currently the EV kick-start seems to be taking off in large economic blocks such as China, California and the EU, through implementing many policies to stimulate the use of EVs. As our framework shows, these policies may lead to increased EV attractiveness and falling production costs. However, we argue in this paper that this does not mean that the TCO of a specific EV will become much lower compared to comparable ICEV TCO in the future, not even if almost all economic blocks in the world were to stimulate EVs. For policymakers this implies that, if they want to stimulate EVs as an important measure to meet the Paris Agreement, they might also need to put policies in place to increase the TCO of ICEVs (e.g. by abandoning petroleum support,[3] increasing fossil fuel levies or increasing ownership taxes for ICEVs) as well as policies stimulating the use of EVs. Another policy implication of our analysis is that policies stimulating the use of EVs seem to require a long-term effort. OEMs and dealers might be tempted (or even forced by shareholders) to increase the RPE of EVs rather quickly, even 'too early' from the perspective of a viable EV market share. If policymakers were to abandon stimulating

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[3] In OECD countries, total government petroleum support (e.g. subsidies, transfers of risks to governments, foregone tax revenues, etc.) was around USD 50 billion (OECD, 2018).

EV policies in such a situation (where there seems to be a respectable market share but it is actually not viable yet), the EV market share may decline, making the Paris Agreement even harder to meet.

The main theoretical contribution is that we have developed a more comprehensive EV cost development framework for future TCO studies. In addition, although only one case has been investigated in this report (the case of a C-segment BEV), the results indicate that researchers who focus on the cost development of technology could improve their framework by involving technology selection theory. In this research we have used factors from technology selection scholars.

This research is subject to some limitations. The result presented is an initial exploratory framework that is not set in stone. It should be made clear that the factors and relationships of the framework are based on initial desk research and interviews. Future research is necessary to determine the robustness of this framework.

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