Christof Ziegler, BSc

The Total Cost of Ownership Method as Evaluation Tool for Electrified Powertrains

Master's Thesis
To achieve the university degree of
Diplom-Ingenieur
Master's degree programme: Production Science and Management

submitted to

Graz University of Technology

Supervisor
DI Thomas Böhm
Institute of Industrial Management and Innovation Research
Univ.-Prof. Dipl.-Ing. Dr.techn. Christian Ramsauer
Graz, October and 2016

Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master‘s thesis.

07.10.2016 ....

Date

....

Signature

“Geld ist eine Form der Energiespeicherung“

John Culkin

Kurzfassung

Durch immer straffere CO_2 und Emissionsvorschriften sehen sich Fahrzeughersteller damit konfrontiert, den Verbrauch ihrer Flotten zu senken und deren Abgaswerte unter den vorgeschriebenen Limits zu halten. Generell besteht bei konventionell betriebenen Kraftfahrzeugen das Problem, dass bei unvollständiger Verbrennung hochgiftige Kohlenmonoxide, Stickoxide und Kohlenwasserstoffe in die Umwelt emittiert werden. Technologische Entwicklungen für alternative Antriebslösungen sind seit den vergangenen Jahren im Vormarsch. Lösungsansätze wie ein hybrider oder rein elektrischer Antrieb sind dabei die Vorreiter für den zukünftigen Antriebstrang. Dennoch, der Weg aus der Erdölabhängigkeit ist vor allem eines, kostenintensiv. Verschiedene elektrifizierende Maßnahmen verursachen nach der Finanzierung in Forschung und Entwicklung auch einen Mehrkostenaufwand im Einbau in die bestehenden Antriebsarchitekturen. Diese Kosten müssen aber demnach auch dem Endverbraucher gegenüber gerechtfertigt werden. Das nötige Argument dafür können nur niedrigere Kosten über die gesamte Haltedauer und Lebenszeit des Fahrzeugs liefern.

Die Aufgabenstellung dieser Diplomarbeit lautet eine Methodik zu entwickeln, die Kosten verschiedener Antriebstechnologien über die Dauer ihrer Lebenszeit miteinander vergleicht. Als Basis dient dabei der Total Cost of Ownership (TCO) Ansatz. Im Weiteren soll die erarbeitete Methodik in eine bereits existierende Excel Umgebung eingepflegt und auf die Erfordernisse von PKWs angepasst werden. Abschließend wird in einem Variantenvergleich und einer Abwägung von möglichen variierenden Einflussgrößen, wie beispielsweise Treibstoffpreisentwicklung oder staatlichen Förderungsmaßnahmen, eine belegbare Aussage getroffen, welche Antriebsalternative die kostengünstigste darstellt. Potentielle Kostentreiber in der Haltedauer eines PKWs stellen neben dem Kostenanfall für zusätzliche Elektrifizierungsmaßnahmen Größen wie Treibstoffverbrauch, Service und Wartungskosten sowie monatliche Steueraufwendungen dar.

Abstract

Due to the reason to comply with increasingly stringent CO_2 emissions, automotive original equipment manufacturers (OEMs) are forced to decrease the fuel consumption of their fleets in a long time perspective to stay below the allowed limits. Generally, conventional vehicles emit hazardous carbon monoxides, nitrogen oxides and hydrocarbons into the environment by incomplete burning of fossil fuels. Recent technological developments of alternative powertrains are progressing. Different approaches like hybrid or pure electric drive trains are widest known examples of electrified powertrains. However, cutting the dependency on fossil fuels is primarily very cost intensive. Various electrified measures cause, after financing research and development, cost efforts when they are implemented in addition to existing conventional powertrain architectures. Further, these costs need to be justified to end customers. The necessary reason can only be provided by lower cumulated costs over the whole holding period and life time of the vehicle.

The scope of this master thesis will therefore be to develop a methodology, which compares costs of different powertrain architectures over their lifetime. The Total Cost of Ownership (TCO) calculation will serve as the basic approach. Additionally, the created methodology will be implemented into an existing Excel environment and be tailored to the requirements of passenger vehicles. Finally, the calculation will provide a purchase recommendation by comparing costs of different electrified powertrains to a conventional one. Changing context factors, like raising fuel prices and governmental funding, can be simulated to provide a realistic as possible calculation. Potential cost drivers during the holding period of a vehicle are, besides costs for the electrified measures, cost elements like fuel consumption, service and maintenance as well as monthly tax expenses.

Table of Content

1 Introduction

The presented diploma thesis has been created in correlation with the AVL List GmbH to create a Total Cost of Ownership model for electrified powertrain architectures with help of an Excel tool. In the following the framework of the thesis will be presented.

1.1 AVL List GmbH

AVL List GmbH is the world's largest independent company for development of powertrain systems and the related simulation and testing technology (hybrid, combustion engine, transmission, electric drive, batteries and software) for passenger cars, trucks and large engines.[1]

The scope of business refers to three main areas[2]:

- Development of Powertrain Systems
  AVL develops and improves various powertrain systems and is a proficient partner to the engine and automotive industry. AVL also develops the simulation methods for the development work.

- Engine Instrumentation and Test Systems
  This area includes all instruments and systems required for the testing division.

- Advanced Simulation Technologies
  The development simulation software covers all phases of the development phase and focuses on design and optimization of powertrain systems.

With 45 affiliates worldwide and an export quota of 96%, AVL employs 8050 people globally and creates 1,27 billion euro in turnover.[3]

[1] Cf. AVL List GmbH, 2016
[2] Cf. AVL List GmbH, 2016
[3] Cf. AVL List GmbH, 2016

1.2 Initial Situation and Goals

The ambitious CO_2 goals and the demand for ever increasing fuel efficiency for passenger cars forces automotive original equipment manufacturers (OEMs) to further invest in new technologies to stay ahead on the market. Therefore, various electrified powertrain concepts have been introduced recently to meet even more stringent limits in the future. The most commonly known electrified powertrain architectures are hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), extended range electric vehicles (EREVs), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). Each of them have their advantages and disadvantages and fulfill, under certain circumstances, the required regulations.

Still, developing, producing and selling different powertrain architectures on the market is also always a matter of costs and prices. From OEMs' point of view, spreading all the costs to their products and hoping that the end customer pays for it wouldn't be successful without justifying the higher purchase price with lower operation costs. That's where AVL List GmbH comes into play to provide the knowledge and the necessary capabilities to decrease the potential cost drivers in a passenger vehicle's powertrain architecture through higher fuel efficiency with lower costs. That provides the argument for OEMs to sell electrified powertrains for a competitive price on the market and to clearly vindicate how a higher purchase price can result in lower overall costs over an extending holding period.

The main task is to develop a Total Cost of Ownership (TCO) approach for electrified powertrain architectures. This approach conforms to the existing TCO calculation approach by AVL for the heavy machinery industry. First, cost influencing factors for the powertrain in a passenger vehicle are identified. Then these factors are used to restructure and rebuilt the existing Excel TCO tool environment.

Finally, the thesis evaluates and points out the changing indicators, both influenceable (like ownership period or annual mileage) and non-influenceable (like price development of oil, incentives of the governments, battery cell prices). Resulting from that, it can be argued what drives the cost development the most and under which circumstances electrified powertrain architectures can satisfy the economic and environmental point of view.

1.3 Systematic Procedure

The introduction and the theoretical part of the thesis rely on two main pillars - an economic one and a technical one. The economic part introduces the idea of Total Costs of Ownership and its life-cycle costs perspective. Further, the structure of the calculation is shown to illustrate, which potential costs could be related to which life cycle phase.

The second pillar presents the technical background of this thesis. To calculate and to evaluate costs of different electrified powertrain architectures, the technology needs to be understood. Therefore, different operation methods of hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) are introduced. In addition, advantages and disadvantages of the different approaches, both technically and economically, are discussed.

Finally, in the outcome of the technical part – potential cost drivers in electrified powertrains shown in chapter 3 - will be transferred to the TCO concept and spread to the different life cycle phases. This new TCO scheme will then be integrated into the already existing AVL tool environment to follow internal calculation and structure standards.

This advanced TCO tool has the ability to compare different powertrain architectures with different economic and technical parameters. After deciding over the degree of complexity of the calculation and after setting the input masks to the demands of users, the tool delivers a purchase recommendation to support a buyer’s decision by the means of a Delta-Cost-Illustration. The detailed approach is shown in Figure 1.

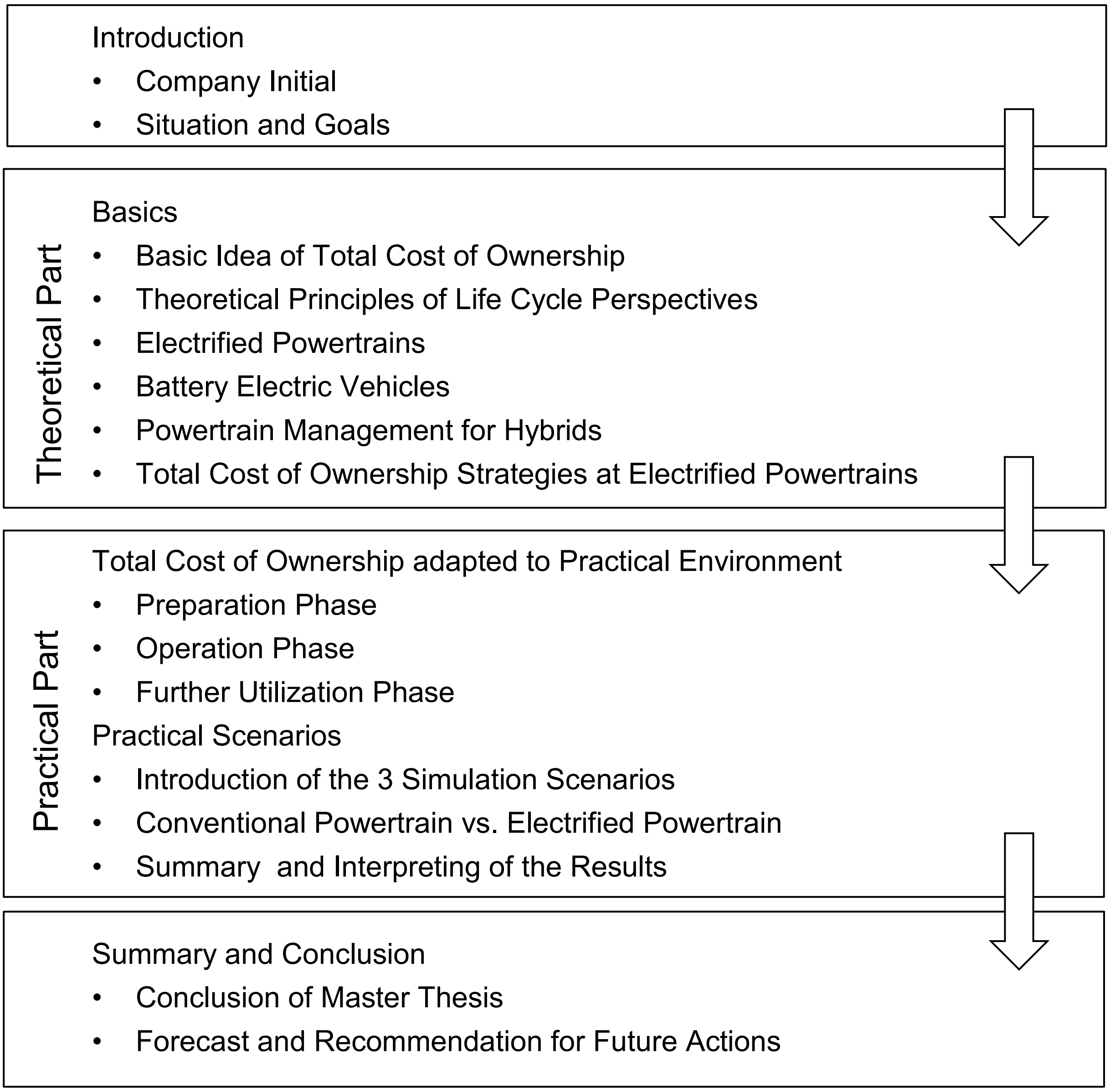


Figure 1: Systematic procedure

2 Theoretical Basis of the Thesis

The introduction and usage of a life cycle approach is comparable to natural systems of biology with an inevitable end[4]. Every system matures over time and is further influenced by changing environmental influences as well as new state variables. Life cycle concepts aim to put a whole life cycle into perspective with relation to time and the characteristic life phases itself. Basically three different concepts can be distinguished: Life-phase concepts (flow-oriented), life-cycle concepts (state-oriented) and integrated life-cycle concepts (phase and cycle oriented). Figure 2 illustrates a linear product life phase concept (flow-oriented).[5]

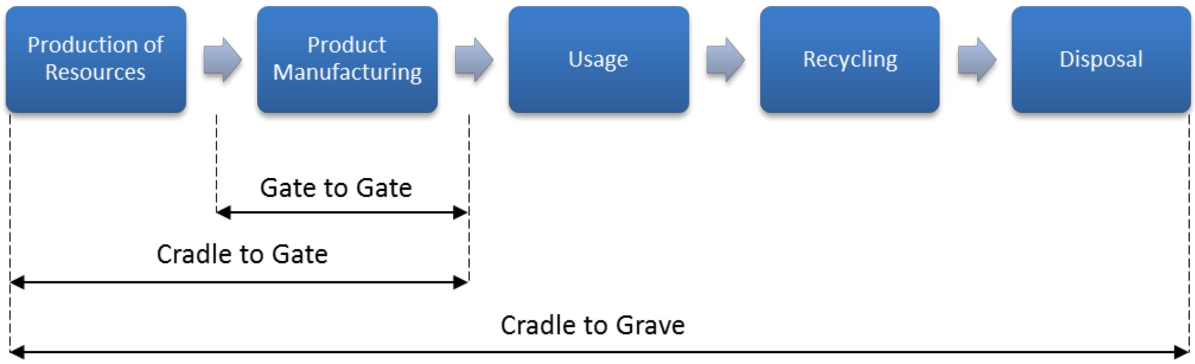


Figure 2: Linear product life phase concept[6]

A typical illustration of a product life cycle sets sales volume in relation to time (life cycle), starting with the introduction to the market. Most of the time this approach is product oriented and can often be read as relation from a certain product to the market.[7]

As shown in Figure 3, the product life cycle phases are: introduction, growth, maturity, saturation and decline. The introduction phase is often delayed due to not finalized supply channels and technical ramp up problems. The first increase in sales is in the growth phase. Early adopters are interested in the new product and boost the diffusion. A further developed market and the potential to higher product volumes lead to more suppliers and copycats. The maturity and saturation phase finally include the late majority. Sales are still increasing but the demand is already decreasing and will eventually end in the declining phase. The sales curve stays constant or even drops to zero.[8]

[4] Cf. Stratmann, 2001
[5] Cf. Herrmann, 2010, p. 63
[6] Cf. Kölscheid, 1999; Herrmann, 2010, p. 65; translated by the author
[7] Cf. Herrmann, 2010, p. 70
[8] Cf. Herrmann, 2010, p. 71

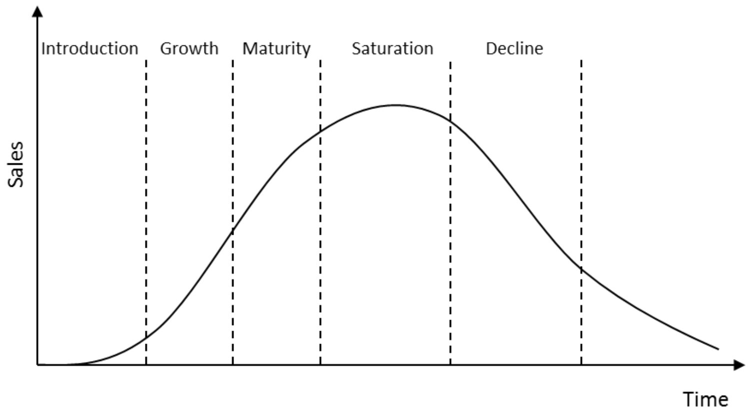


Figure 3: Product life cycle concept[9]

Also potential factors like technologies can be described with life cycle concepts. Ford and Ryan distinguish six phases, in the order of: technology development, development to application maturity, first usage of technology, growth of technology usage, technology maturity and declining of technology.[10] The state variable is now the velocity of spreading of the technology. The ideal course is an S-curve and can be used to determine performance and saturation limits for certain technologies.[11] However, the advanced technology-technique life cycle concept from Höft probably fits the approaches of this thesis the best, shown in Figure 4. Since the ongoing researches are mostly technology based, like development of battery cells, increased range of electric vehicles and fuel consumption (detailed information in chapter 3), the advanced technology-technique life cycle can compare the different powertrain architectures and its possible usage in future in one graphic. An assumption could be that all three technology types represent the different powertrain architectures: conventional internal combustion engine (ICE), hybrid electric vehicles (xEV) and pure electric vehicles (EV).

[9] Cf. Hofstätter, 1977; translated by the author
[10] Cf. Ford & Ryan, 1981
[11] Cf. Höft, 1992

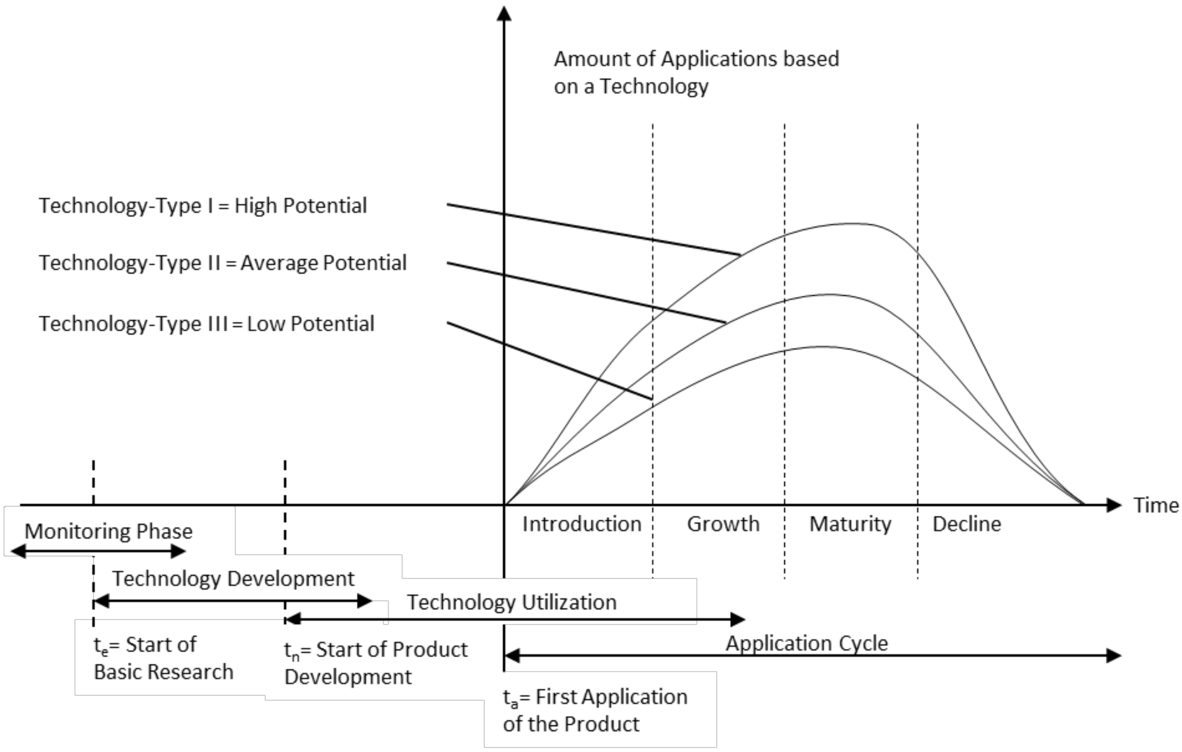


Figure 4: Advanced technology-technique life cycle concept[12]

A sustainable development through a full life cycle management not only requires to quantify the consequences of decisions, but also to track them throughout the whole life cycle. For this reason, three analysis of product life paths can be taken into consideration: a social, an economic and an ecologic analysis.[13] This thesis only concentrates on the economic path way.

2.1 Basic Idea of Life Cycle Costs and Total Cost of Ownership

The consideration of costs along a product's life is very important, in particular if the costs of operation and further utilization exceed the purchase costs[14]. That is not just valid for purchase departments in companies but also for an end consumer's perspective. Although the meaning of these costs becomes more recognized, purchase decisions mostly still rely on the purchase price and costs in the usage and recycling phases often stay neglected. [15] For example, operation and utilization costs for heavy machinery equipment can be five to ten times of the costs of purchasing, installation and commissioning.[16] It is shown in the later chapters that this cost ratio is not as high for normal vehicle powertrains as for heavy machinery equipment, but still worth considering, when oil prices increase or holding periods extend for instance.

[12] Cf. Höft, 1992, p. 82; translated by the author
[13] Cf. Herrmann, 2010, p. 131
[14] Cf. Brown, 1979, p. 109
[15] Cf. Herrmann & Spengler, 2006
[16] Cf. Geißdörfer, 2009, p. 1

Taking note of all the cumulated costs of goods over their lifetime in operation, different methods are introduced to evaluate. One of these is the TCO, the Total Cost of Ownership analysis. From a company's perspective, it is the goal to take all the costs related to the purchase, the operation, maintenance as well as recycling, into account – in particular when selecting a new supplier.[17]

Coming to a longtime perspective, an ever-increasing price level for resource, energy, personnel, service and maintenance costs combined with the stress of competition, a total cost view is becoming even more beneficial for companies.[18] Decisions based on life cycle costs are more reliable and can help to justify the higher purchase price even better. So if a potential buyer would already know all the upcoming costs related to the purchase price, a comparison from an economic point of view would become rather easy.[19]

[17] Cf. Ellram & Siferd, 1993b, p. 163
[18] Cf. Geißdörfer, 2009, p. 2
[19] Cf. Geißdörfer, 2009, p. 3

2.2 Theoretical Principles of Life Cycle Perspectives - TCO

The Total Cost of Ownership evaluates all costs of a product throughout its whole life cycle, which includes the purchase, service and maintenance as well as recycling and decommissioning.[20] In the following section the roots of the origin definition and its development to both the terms life cycle cost (LCC) and total cost of ownership (TCO) are declared. Further both notions and their differences are explained. In the further course of the thesis a uniform term is used. Figure 5 illustrates the accumulation of different powertrains and their life cycle cost development. The mentioned powertrains are: a Battery Electric Vehicle (BEV), a Plug-In Hybrid Electric Vehicle (PHEV), a Hybrid Electric Vehicle (HEV) and a vehicle with only an Internal Combustion Engine (ICE) with no electrification. Still to mention, this graphic does not show real results, but is based on assumptions. The aim of this thesis is to create such curves on real values with help of an Excel tool.

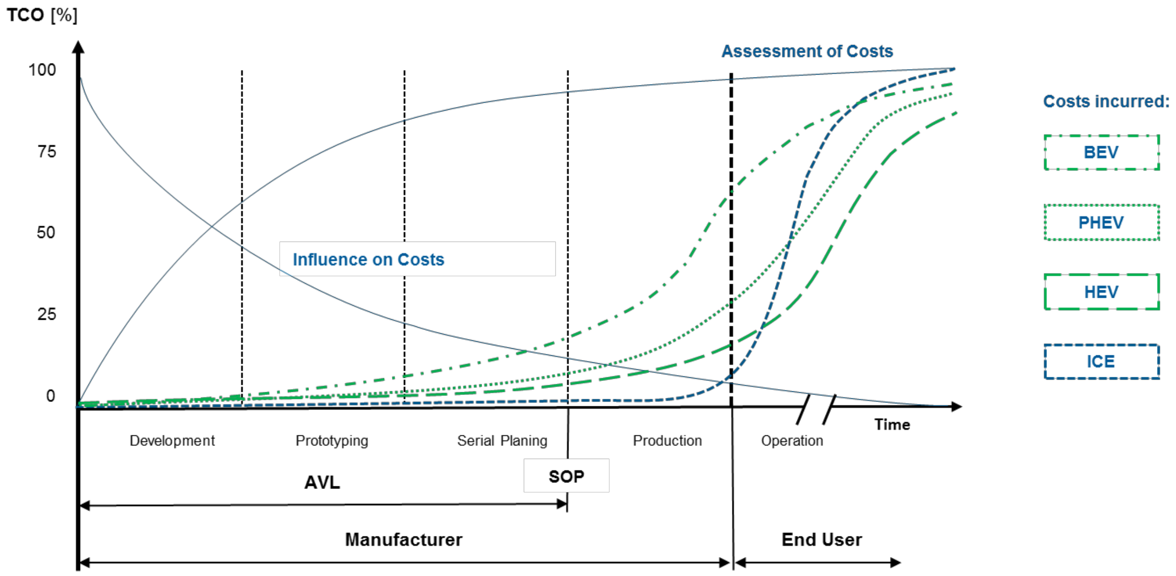


Figure 5: Cost distribution over the life cycle[21]

[20] Cf. Geißdörfer, 2009, p. 2

[21] Cf. Ehrlenspiel, Kiewert, & Lindemann, 2014, p. 13; adapted by the author

2.2.1 Current State of Research

The following chapter goes more into detail to the very first studies of publications regarding the TCO principle and its development through the last century. Therefore, an overview with the different approaches on how, where and with which focus TCO has already been a researched topic, is given in Table 1.

The idea of a total cost calculation approach is not new. The first scientific publications to TCO and LCC have already emerged in the 1970s. A more intensive research has not started until the beginning of the nineties. The most famous author was Ellram, who has played a central role on the topic TCO and has published several articles and studies since then.[22] The following summary gives an overview of the most important publications and authors.

In 1992, Carr and Ittner listed examples of how companies evaluate their suppliers based on the TCO idea.[23] However, these examples are more related to the cost-ratio method than to the TCO concept, because they base on index numbers and not on total costs.[24] Relying on Ellram and Siferd, the TCO is a combination of the costs of activities, which are related to the purchase object itself. These key purchasing activities are: Management, Delivery, Service, Communications, Price and Quality.[25] However, this kind of classification only considers direct costs.[26] Ellram developed a more general model, which is divided in Pretransaction, Transaction and Posttransaction Costs.[27] In their published work “Key Concept” in 1998, Ellram and Siferd took on that point of view of TCO in cost management.

The first Europeans who adressed the topic TCO were Degreave and Roodhooft. They started working on TCO in 1999 and developed a mathematical model, which based on current data of accounting systems (activity based costs), and calculated the TCO as a monetary value.[28] After proving their draft in various case studies, they evolved the model to a three-dimensional matrix, which should be valid for both a universal approach and a cross-product basis.[29] Further frequently expressed sources in literature in recent years are the dutchmen Wouters[30] and Hurkens[31]. In Table 1, different TCO approaches are listed.

[22] Cf. Krämer, 2007
[23] Cf. Carr & Ittner, Christopher, D., 1992, pp. 42–51
[24] Cf. Ellram, 1993c, pp. 4–23
[25] Cf. Ellram & Siferd, 1993b, pp. 163–184
[26] Cf. Ferrin & Plank, 2002, pp. 18–29
[27] Cf. Ellram, 1993c, pp. 3–12
[28] Cf. Geißdörfer & Gleich, 2009, pp. 693–715
[29] Cf. Krämer, 2007, 15ff
[30] Cf. Wouters, Anderson, & Wynstra, 2005, pp. 167–191
[31] Cf. Hurkens, van der Valk, & Wynstra, 2006, pp. 27–37

Table 1: Literature overview on different approaches of total cost perspectives[32]

Author and Year	Used definition	Understanding and cost elements
Jackson Jr. & Ostrom, 1980	Life Cycle Costing	Initial cost, plus operation, maintenance, service, overhaul and disposal cost
Shields & Young, 1991	Life Cycle Costs	Costs that the producer will incur including design, manufacturing, marketing, logistics and service.
	Whole Life Costs	Life Cycle Costs plus costs that consumers incur, such as the costs of installation, operation, maintenance, revitalization and disposal.
Cavinato, 1991b	Supply Chain Total Cost Analysis / Value Hierarchy Model	Comparing costs of the buying company and costs of the selling company to determine which company can perform which activity or function at the lowest cost. Direct and indirect costs, most effective process, lowest cost of capital, depreciation, quality costs and factors, operations and logistics cost.
Carr & Ittner, Christopher, D., 1992	Total Cost of Ownership	Costs of purchasing, holding, poor quality and delivery failure.
Smytha & Clemens, 1993	Total Cost Supplier Selection Model	Risk factors, business desirable factors, measurable cost factors (external and internal costs).
Ellram, 1993c	Total Cost of Ownership	Pre-transaction, Transaction and Post-transaction Cost
Ellram & Siferd, 1998	Total Cost of Ownership	Management, Quality, Price, Communications, Service, Delivery
Boussabaine & Kirkham, 2004	Whole Life Cycle Costing (WLCC)	Result of economic and non-economic performance indicators
Farr, 2011	Total Ownership Costs (TOC)	They are the sum total of the direct, indirect, recurring, nonrecurring, and other related costs incurred, or estimated to be incurred, in design, research and development (R&D), investment, operations, maintenance, retirement, and other support of a product over its life cycle.

[32] Cf. Krämer, 2007, p. 21; adapted by the author

2.2.2 When does a standard TCO Model make sense?

There are already existing models for life cycle costing, both in science and in practice. The degree of standardization ranges from project based individual calculations to standardized models for a whole branch (e.g. SEMI E35 in semiconductor industry). The standardization follows three dimensions:[33]

- Standardization between supplier and customer
- Standardization within a company
- Standardization within an industry

The standardization declares the observed phases of the product life cycle, the calculation logic and its algorithm and the considered cost categories. Within the machinery and equipment industry the LCC models are showing some significant differences in goal setting, application area and structure. For that reason the calculation results end up in different values. Standardized models are missing in most branches; even the sub structures are not comparable to each other, respectively the structures for calculation models of LCC and the considered cost categories and cost drivers. As long as those models serve just the interest within a company, different perspectives are not critical. In the case, that those calculations are made for purchase negotiations or warranty agreements, the calculation basis is much more sensible and needs to be standardized from early on.[34]

Standardization makes sense as long as all the criteria for purchases remain constant to a certain degree throughout the process. However, individual models are taken when circumstances are changing in a very dynamic manner, e.g. ever changing market conditions and unique cost factors can’t be evaluated according to their occurrence. A standardized model would be inflexible and not reliable enough. The main advantages of an individual LCC are: the possibility to adapt to changing market conditions, the integration of situational cost factors and the higher accuracy of the results.[35]

The different models were investigated by the means of how they fulfill the requirements for standardization, listed in Table 2. The criterions are listed in the columns and the different models in the rows. (x) marks a considered criterion, (n) a not considered criterion and (p) or (x) are partially considered criterions, whereas (x/p) depends on the application. Further, the models are evaluated whether they are used

[33] Cf. Bode, Bünting, & Geißdörfer, 2011, pp. 10–19
[34] Cf. Bode et al., 2011, pp. 10–19
[35] Cf. Bode et al., 2011, pp. 10–19

for unique, expensive equipment (A) or for repeated purchases of low cost goods (T). In addition Geißdörfer et al. also distinguished between a flexible guidance to create a model (G) or an established model (M), and standardized (S) and individual models (I). The Gartner Group shows the best overall performance. The reason for that (fulfills 10/12 criteria) is similar to the performance of the *Semi-E35-Model.* Both this models are in practice since 1987 and 1995 respectively, and have been improved ever since. They also have an important practical meaning, they are commonly used in their branch and have often been analyzed in case studies. Worth mentioning is the model of Ellram (Ellram L. M., Total Cost of Ownership: An analysis approach for purchasing, 1993), who has already been mentioned several times and reaches 7 of 12 criteria.[36]

[36] Cf. Geißdörfer, 2009, p. 115; Geißdörfer & Gleich, 2009, pp. 707–708

Table 2: Overview TCO/LCC Models[37]

	General					**Criteria**												
Model	**Branch**	Model Type	Guidance or Model	Considered Subject	Standard vs. Individual	Qualitative Factors	Observation Period and NPV	Overall Equipment Efficiency	Given Cost Categories	Transaction Costs	Effect on Sales	Accuracy, Risk of Values	Dependency between Variables	Applicable in Purchase	Applicable in Development	Applicable in Sales	Process Cost Calc. As Basis	**Number of Fulfilled Criteria**
SEMI E35 2007	Semi	COO	M	A	S	n	x	x	x	x/p	n	x	n	x	x	x	n	**8**
Hurkens; Wynstra (2006)	General	TCO	M\G	T	I	x	x	n	n	x/p	x	n	n	x	x	x	x	**8**
VDMA (34160) (2006)	VDMA	LCC	M	A	S	n	n	x	x	n	n	n	n	x	x	x	n	**5**
NAFEM (2006)	Food	LCC	M	A	S	n	x	n	x	n	n	n	n	x	x	x	n	**5**
Degreave et al. (1997-2005)	General	TCO	M	T\A	S	x	n	p	x	x	n	n	x	x	x	n	x	**6**
Razum (Rockwell) (2003)	E-Engine	TCO	M	T\A	S	n	n	n	n	x	n	n	n	x	x	x	n	**4**
Bierma (2000)	Chemistry	TCO	M	A	S	x	n	x	x	n	n	n	n	x	x	n	n	**5**
Ellram et al. (1993-1998)	General	TCO	M	T\A	S	x	n	n	x	x	n	n	n	x	x	x	x	**7**
Carr; Ittner (1992)	General	TCO	M	T	S	x	n	p	x	x/p	x	n	n	x	x	n	n	**6**
Monczka; Trecha (1988)	Electric	TCO	M\G	T	I	x	n	n	n	x/p	n	n	n	x	n	x	n	**4**
Kaufman (1969)	Food	LCC	M	A	I	x	x	p	x	n	n	n	n	x	x	n	n	**5**
Krokowski (1998)	General	TCO	M	T	I	x	n	n	n	x/p	n	n	n	x	n	n	n	**3**
Gartner Group (2003)	IT	TCO	M	A	S	x	x	n	x	x	x	x	n	x	x	x	x	**10**
VDI 2884 (2005)	Prod. Means	LCC	M	A	S	x	x	x	x	n	n	n	n	x	x	x	n	**7**
VDV Mitteilung 2315 (2003)	Traffic	LCC	M	A	S	n	x	x	x	n	n	n	n	x	x	x	n	**6**
DIN EN 60300-3-3 (2005)	General	LCC	M\G	T\A	S	x	x	x	x	x/p	n	x	n	x	x	x	n	**9**
UNIFE LCC (1997)	Railway	LCC	M	A	S	n	x	x	x	n	n	x	n	x	x	x	n	**7**
	Number of Models					**11**	**9**	**7**	**12**	**10**	**2**	**4**	**1**	**17**	**15**	**12**	**4**	

[37] Cf. Geißdörfer, 2009, p. 115; adapted by the author

2.2.3 The TCO and LCC Calculation

The life cycle cost calculation has its roots in the US in the 1960s, where it has already been used for profitability assessments in the machinery and equipment, military and aerospace industries. Since 1980, life cycle cost perspectives gained a foothold in the German-speaking area.[38] Chosen approaches are shown in Table 3.

Table 3: Supply and demand oriented approaches[39]

		Observation Perspective			
		Supplier-oriented Approach		Demand-oriented Approach	
Operand	Cost-based Approach	Back, 1988	Life-cycle base product controlling	Blanchard, 1978	Design and Manage to Life Cycle Costs
		Shields & Young, 1991	Product Life Cycle Cost Management	Wübbenhorst, 1984	Concept of Life Cycle Costs
		Fröhlich & Reichmann, 1994	Life-Cycle oriented Planning and Controlling		
		Siegwart & Senti, 1995	Product Life Cycle Management		
		Zehbold, 1996	Life-Cycle Cost Calculation		
		Kemminer, 1999	Life-Cycle oriented Costs and Sales Management		
		Osten-Sacken, 1999	Life-Cycle oriented Income Statement for Machine Tools		
	Payment-based Approach	Rückle & Klein, 1994	Product-Life-Cycle-Cost-Management		
		Riezler, 1996	Life-Cycle Calculation		

However, the amount of existing life cycle cost concepts in theory and practice makes it clear that developing one unique model, which fits all requirements, can hardly be possible. The concept needs to be adapted to different characteristics of the object of observation. Further on, the different approaches can be divided into general and specific models[40] or into theoretical and implementation focused models[41]. The large variety of LCC concepts can be divided into supply and demand oriented approaches, whereas the demand oriented approach often relies on the costs created according to the ownership itself – The Total Cost of Ownership. Even if life cycle phases haven't been separated from each other[42], the first reference works on TCO and LCC were

[38] Cf. Wübbenhorst, 1984
[39] Adoped from Kemminer, 1999; translated by the author
[40] Cf. Zehbold, 1996
[41] Cf. Pfohl, 2002
[42] Cf. Kemminer, 1999

established by Blanchard[43] and Wübbenhorst[44]. The representatives of new supplier oriented concepts[45] base their research on lead and follow up phases from Back-Hock. That puts the supplier's perspective into focus and integrates revenue into the calculation. Additionally, the concept of product life cycle cost management from Rückle/Klein also takes operation related costs into account.[46]

Transaction Model Ellram

The TCO-model developed by Ellram (1993) is structured into cost occurrence and has set the standard in TCO literature[47]. She divided the costs into three categories (see Figure 6). Pre-transaction costs are created before the point of purchase. These costs consist of costs, which are cumulated from the first thought of making an investment and the point of ordering the product. Potential costs could be the determination of requirements or collecting the data of suppliers in internal systems. Companies tend to forget how costly it is to add a new supplier to a system or prequalify the supplier. The transaction costs are comprised of efforts from the order till the receiving of the product. That also includes the purchase price. This is the cost category which is actually recognized the most from companies because a big amount of money is spent in a little amount of time, together with the purchase itself. After putting the investment into operation, post-transaction costs are created. These costs can occur immediately (energy costs for the machine) or not until the first repair. The later these costs occur the less the costs are recognized by the company. Altogether this category gets the least amount of attention from responsible people, although most of the efforts are caused by it.[48]

[43] Cf. Blanchard, 1978
[44] Cf. Wübbenhorst, 1984
[45] Cf. Back, 1988; Zehbold, 1996; Riezler, 1996
[46] Cf. Rückle & Klein, 1994
[47] Cf. Wynstra & Hurkens, 2005, p. 465
[48] Cf. Ellram, 1993c, p. 7

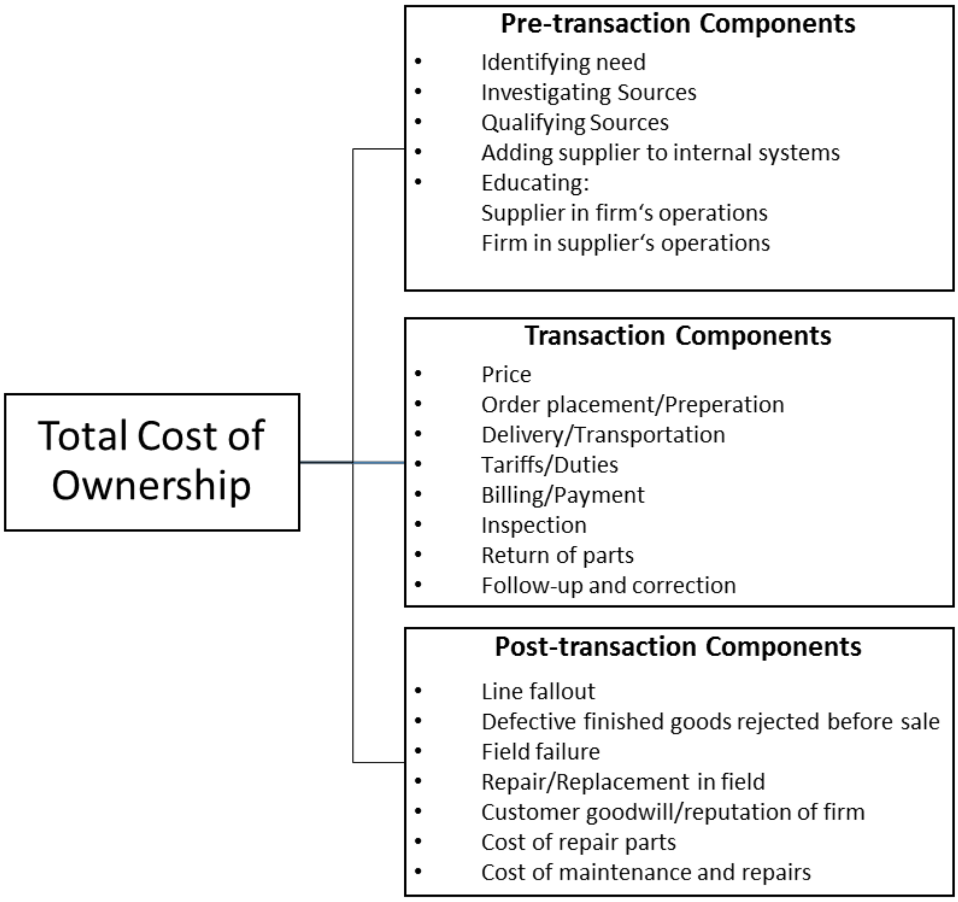


Figure 6: TCO Elements by Ellram[49]

Life Cycle Cost Model VDMA 34160:2006

The fact that there are nearly no standardized models for LCC approaches has initiated the VDMA to create a generic model to forecast life cycle costs. The main motivation was to establish a standard, which can be used and accepted by the whole branch. Otherwise every company would try to build up its own model, and the whole market would be confronted with several models and its different approaches behind it.[50]

As the globalization and accessibility of new opened markets increases, companies are more motivated to restructure and outsource their purchase to foreign countries to reduce costs. The trend is definitely going towards accessing countries from the former eastern bloc to India, China and surrounding countries. To meet the requirements of a universal accessibility, the model has been established as a generic one. For this reason the level of detail is highly adjustable and can display various combinations of cost categories. That offers the opportunity to completely neglect irrelevant cost elements and add new ones. To compare different products, only the relevant cost

[49] Ellram, 1993c, p. 7
[50] Cf. Bode et al., 2011, p. 16

elements and the grade of detail needs to be specified, this hierarchy is also shown in Figure 7:[51]

- Model 1: For this level, just the total costs for the three life cycle phases: creation, operation and recycling are determined as lump sums.
- Model 2: According to the VDMA 34160:2006 standard, the individual costs are selected on the second breakdown level.
- Model 3: This model and its life cycle cost projection is based on detailed calculation. All the structures of the product and the conditions need to be known and set.

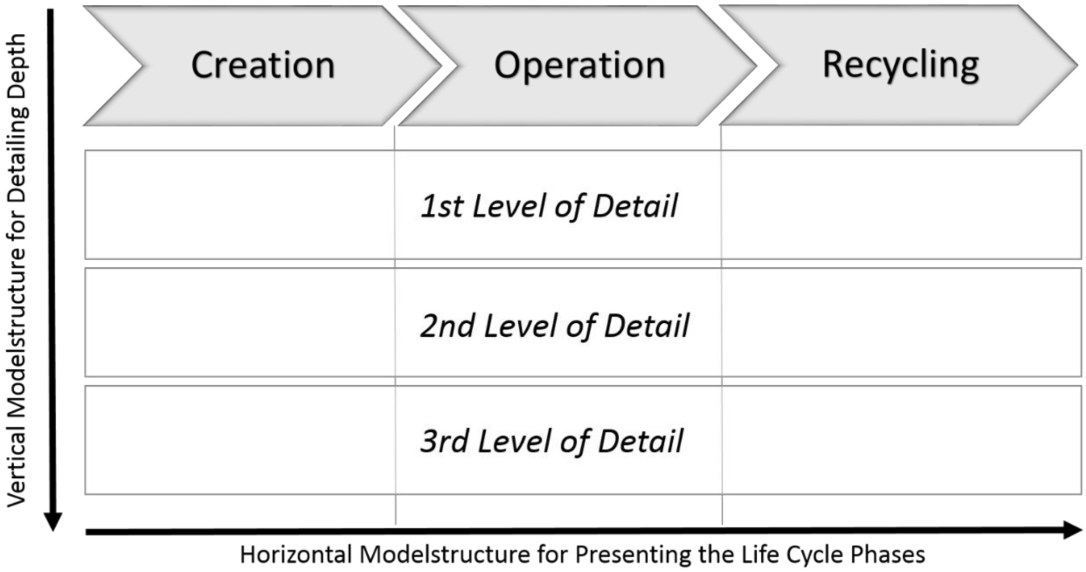


Figure 7: Model for Level of Details[52]

These possibilities combined can provide a prognoses model of LCC for customers and suppliers. In the quotation phase for example, the customer specifies the boundary conditions and defines the positions in the model, which need to be filled in.[53]

[51] Cf. Bode et al., 2011, p. 17
[52] Cf. Bode et al., 2011, p. 18; translated by the author
[53] Cf. Bünting, 2009, pp. 46–47

M-TCO Daimler

At the beginning of the twenty-first century, the Daimler AG, manufacturer of passenger and commercial vehicle[54], was also searching for new ways to optimize maintenance procedures of machinery equipment. The idea was also to base purchase decisions not on the price, but on the levels of quality and the lowest maintenance costs during the holding period. Therefore, Daimler AG and Infoman AG developed the M-TCO ("Maintenance-Total-Cost-of-Ownership") model. This TCO approach is divided into three phases: the tendering phases, the commissioning phase and the operation phase, which are also illustrated in the flow diagram in Figure 8:[55]

Phase 1:
The first phase explains the tender of a new machine. In addition to the usual documents, a TCO contract appendix is required. The supplier needs to fill in values for potential cost drivers related to chosen assembly groups and to report the TCO values MTBF, MTTR and MCRP[56]. By closing of the contract, the supplier agrees contractually to these values.

Phase 2:
This phase monitors the implementation and the ramp up of the machine by means of the agreed contract. It clarifies whether the new machine complies with the ordered machine. In case of deviations, the TCO-appendix gets updated.

Phase 3:
Phase 3 monitors the limits of the agreed TCO values. The duration of the monitoring is usually the contract period. To additionally provide the freedom of production scheduling, the user is free to revise the production volume upward. For this reason, usually the contract also contains a total production volume. That allows an earlier expiring of the contract to compensate a faster machine wear. However, if the supplier can't provide the right values anymore or if the machine breaks down earlier, the customer can shift the maintenance costs partially to the supplier.

[54] Cf. Daimler AG, 2016
[55] Cf. Albrecht & Wetzel, 2009, pp. 84–85
[56] MTBF= Mean time between failures, MTTR= Mean time to repair, MCRP= Mean costs of replacement parts

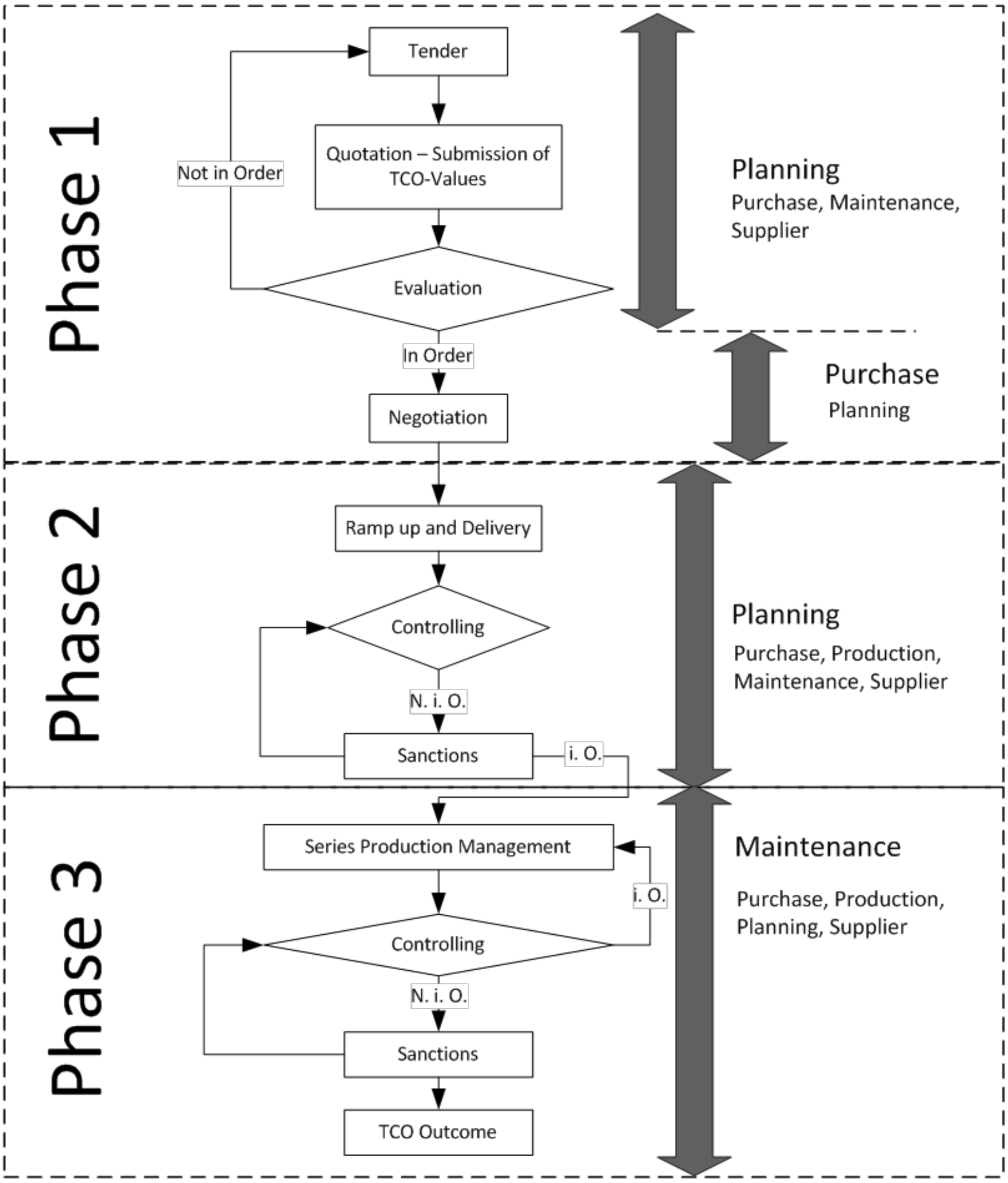


Figure 8: M-TCO process scheme[57]

[57] Cf. Schweiger, 2009, p. 84; translated by the author

Especially recently, TCO perspectives are used more often in industry and become more often binding contractually agreements. As prescribed in Phase 3 of M-TCO, Daimler AG agrees by contract the maximum TCO with its machinery equipment supplier. At non-compliance of agreed amount of TCO, even contractual penalties could become due.[58] A more practical approach on another TCO model, which focus on the evaluation of vehicles, can be seen in Table 4. The cost accumulation is shown from the producer's and the customer's perspective and illustrates the costs throughout the whole life cycle.

Table 4: TCO calculation for vehicles[59]

	Producer
	Alternative Powertrain Components (Battery, E-Engine, Charging Equipment, Hybrid Module etc.)
+	Conventional Engine Parts
+	Assembly Costs
	Manufacturing Costs
+	SG&A
+	Development Costs
	Overhead Costs
+	Profit
	Net List Price →

	Customer
	Net List Price
+	VAT (19%)
	Gross List Price
-	Incentives
	Gross Selling Price
+	Capital Costs
+	Taxes
+	Insurance
	Fix Costs
+	Fuel Costs (Type, Consumption, Mileage)
+	Infrastructure Costs
-	Ancillary Services
	Total Fuel Costs
+	Tire Costs
+	Inspection & Repair
	Maintenance and Repair
+	Parking / Road Charge / Care
	Other Costs
	TCO

58 Cf. Lorenzen, Rudzio, & Blümel, 2006, pp. 489–494
59 Cf. Kreyenberg, 2016, p. 69; translated by the author

TCO and LCC

After having introduced several practical and scientific approaches in the previous chapters, one realizes that the expressions TCO and LCC have been used almost synonymously so far. That is also due to the reason that both names are also not clarified explicitly in literature.[60] Further, both these calculations are tools from the strategic cost management[61]. The following citations out of literature will declare why this thesis continues with only one expression and justify the further usage of only the name TCO:

- Strategy oriented instruments for cost management are closely related to TCO and also include life cycle costing approaches.[62]
- Both, LCC and TCO, are equal for the evaluation of investment goods.[63]
- LCC and TCO are both evaluating the phases of acquisition, usage and recycling of a system.[64]
- According to the observed product, LCC and TCO use the interaction between user and manufacturer to optimize total costs and to minimize them for a certain product.[65]

Finally it's shown that both phrases are used most of the time equally and if not, one acts as subset from the other (LCC as subset from TCO[66]). Also in the internally understanding of AVL the term TCO is by far more used and already well known, which sets the standard for equal understanding throughout different departments and the usage of the TCO tool itself.

[60] Cf. Geißdörfer, 2009, p. 13
[61] Cf. Zsidisin, Ellram, & Ogden, 2003, pp. 129–154
[62] Cf. Ellram & Siferd, 1998, p. 57
[63] Cf.Kaufman, 1969, pp. 16–31; Razum, 2003; Heilala, Helin, & Montonen, 2006
[64] Cf. Geißdörfer, 2009, p. 80
[65] Cf.Asiedu & Gu, 1989, pp. 883–908; Cavinato, 1991a
[66] Cf. Ellram, 1993c, pp. 3–12

2.2.4 Requirements for the Implementation of a TCO-Concept

Various researches in industry related magazines suggest that it is just a matter of time until nearly all manufactures in machinery and equipment industry will use the TCO approach for their purchase and marketing departments[67]. However, the implementation often fails due to the missing regulation standards coming along with supplier contracts and the "put into practice" obstacles during the introduction phase of a TCO concept.[68] A summary of core questions, which need to be answered to lead to a sustainable and successful partnership between provider and user are the following: [69]

- What are the cost drivers?
- Which management and controlling tool is in place?
- How can suppliers be integrated into the process?
- How is the history of a machine documented?
- Does a service contract exist?
- How can the qualification and skill levels of operators, programmers and maintenance personnel be ensured?

Geißdörfer's empirical investigations, including both German and American companies, has figured out, that the scarcity of resource is the major reason (28%) to not implement a TCO approach within a company. The other main reasons are "no requirement by the customer", "no standard model available" and "too much effort in costs and time".[70]

Especially for small and medium enterprises (SMEs), missing data for failure rates, downtimes, costs for wear parts and maintenance intervals are obstacles for implementation.[71] Further, SMEs often lack of the required resources and fail to tailor existing standard models to their own requirements. However, the biggest issue is mostly the identification of relevant cost drivers.[72] For this reason, SMEs need to be aware of establishing a working personnel management, when implementing new strategies to prevent waste of effort and resources, which could result in huge damage to the company.

[67] Cf. Welle & Neugebauer, 2007, pp. 58–60
[68] Cf. Schweiger, 2011, p. 32
[69] Cf. Schweiger, 2008, pp. 15–34
[70] Cf. Geißdörfer & Gleich, 2009
[71] Cf. Ellram, 1993, pp. 49–60
[72] Cf. Wildemann, 2010, p. 102

2.3 Electrified Powertrains

The meaning of TCO, how it can be a helpful tool for companies and how certain already know applications work in detail is declared. Now it is about to build a technical knowledge base, to which the TCO tool can referred to. As already mentioned, this thesis takes the idea of a TCO approach and tries to evaluate different electrified powertrain architectures in comparison to each other. Therefore, the problems, the ideas and the advantages and disadvantages of modern powertrain architectures, as well as the potential cost drivers of powertrains, need to be understood.

Meanwhile the world is home to nearly 7 billion people and roughly 1 billion cars. The majority of the population lives in cities and the number of citizens is rapidly increasing. More and more cities are overtaking the 10 million citizens mark. The polarization of mobility leads to intolerable growth of traffic density, as well as local concentrated values of exhaust products from internal combustion engines, carbon dioxide, pollutants, particles and of course acoustic emissions. Therefore, the electro mobility with a compact, noiseless vehicle with no local emissions would lead to an ideal scenario – and further to the direct integration of the powertrain into the wheels.[73]

Results from a study for the Austrian passenger vehicle market indicate a robust trend to electrified powertrain architectures. Increasing oil prices and taxes on fossil fuels could enhance the competitiveness of hybrids and pure electric vehicles. Costs for conventional vehicles will remain the same or even increase, which results in lower €/km prices for electrified powertrains. Lastly, full electric vehicles, like Battery Electric Vehicles (BEVs), will rise to the most economic option.[74]

The only general problems in this scenario are the availability of enough electric energy on board and the source of that energy. Both, the electrified powertrain with stored electric energy (batteries and super caps) and with hydrogen converted energy (fuel cells), have been strongly researched all over the world. Nethertheless, the significant difference in energy density of batteries/fuel cells compared to the energy density of fossil fuels in a combustion engine and the system complexity and reliability limits the driving range and leads to intolerable costs.[75]

[73] Cf. Stan, 2012, p. 1
[74] Cf. Kloess, Rechberger, Haas, & Ajanovic, 2008, p. 370
[75] Cf. Stan, 2012, p. 1

The current phase of development of electrical vehicles is mainly driven by strict limitations of carbon dioxide emissions in the atmosphere together with the greenhouse effect. Therefore the development and research focuse on electrical engines, energy storage on board with batteries and the energy conversion with fuel cells. The most important advantages of the electric engines are listed and summed up to the following. The torque characteristic is nearly ideal and the maximum torque can already be reached from the start. Further the acceleration is even better than from internal combustion engines with a much higher performance:[76]

- Depending on the degree of the powertrain's electrification, the complexity of the transmission varies. Considering a BEV, an electric engine compensates an automatic transmission, which is commonly used for the same function in piston engines.
- Wheel drives with integrated electric engines on front and rear axles allow an optional on-off behavior with different criteria: two-wheel or four-wheel drive (front- or rear axle), switch-on depending on load requirements, electronic controllable stabilization of vehicle dynamics, similar to an ESP system in a more efficient form. Wheel drives also give more freedom and space in designing function modules in chassis.
- The requirements on electric engines as a drive train are those of thermal engines: high volume and mass based performance, high degree of efficiency, low technical effort and low production costs.

All kinds of electric engines are working with the principle of electrically generated magnetic fields. A magnetic field can be static (direct current) or rotating (alternating current). Dependent on achievable performance and rotational speed on the one side and the efficiency on the other side, both types of magnetic fields have been implemented in practice in different variants. The following table shows examples from recent developments.[77]

[76] Cf. Stan, 2012, pp. 267–268
[77] Cf. Stan, 2012, p. 268

Table 5: Electric Engines for Automobile Drive Train[78]

Vehicle	Performance [kW]	Torque [Nm]
Direct Current engines (n≤7000 U/min)		
Jinan Baoya Vehicle BY5000EV-1A	7	100
Alternating Current - Asynchronous (n≤14000 U/min)		
Jinan Baoya Vehicle BY6500EV-1	6,50	120
Alternating Current - Synchronous		
Renault Kangoo Z.E.	44	226
Peugeot iOn	47	180
Mercedes Benz Vito E-Cell	60	280
Beijing Automotive BE701 EV	110	300
Shelby Aero EV	750	1088

Due to necessities, accessible energy sources, impacts on the environment, technical complexity, certain use cases of a vehicle, limitations and of course acceptance, it is still an ongoing development and research on different configurations of powertrains. To meet all these requirements, especially the following criteria are more critical for a future powertrain: [79]

- Mass-performance ratio, respectively performance-volume ratio
- Torque and acceleration characteristics
- Specific energy/fuel consumption, specific emissions of chemical substances, acoustic intensity and acoustic frequency
- Availability and storage capability of energy sources
- Technical complexity, costs, safety
- Infrastructure and service possibilities

[78] Cf. Stan, 2012, p. 269
[79] Cf. Stan, 2012, p. 29

2.3.1 Definition and Classification of Hybrid Concepts

According to the base structure, the combination of combustion engine, E-engine, generator and battery and transmission, hybrid drive trains can be divided into:[80]

Types of Powertrain:

- Serial hybrid drive
- Parallel hybrid drive
- Power-split hybrid drive

Types of Hybridization:

- Micro-hybrid
- Mild-hybrid
- Full-hybrid
- Plug-In-hybrid

An overview on functionality and usability of the various types of hybrid is given by Figure 9. Micro-, mild- and full-hybrids are also described as autarkic hybrid drives, since there is no possibility to recharge the electrical energy storage through an external power supply. [81]

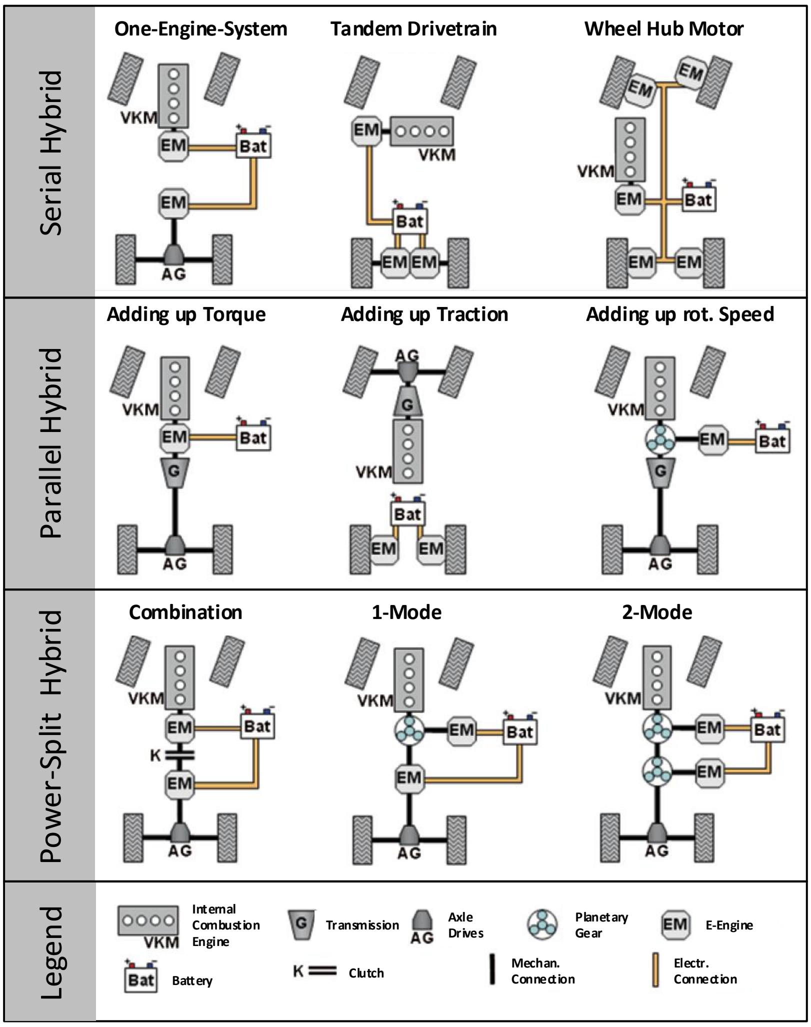


Figure 9: Different structures of hybrid drive trains[82]

[80] Cf. Hofmann, 2014, 23f
[81] Cf. Hofmann, 2014, 23f
[82] Cf. Hofmann, 2014, p. 24; translated by the author

2.3.2 Serial Hybrid Drive Train

The serial hybrid consists of an internal combustion engine, which is linked to a generator and an electric engine to drive the wheels. There is no mechanic connection between internal combustion engine and the drive axle. The connection is purely electric. It is done by two inverters (or 1 inverter and 1 rectifier) and an electric intermediate. The components of the drive train are set electrically in series. The energy created by the loading group, combustion engine and generator is transferred directly to the electric drive engine as well as used to recharge the battery. The loading group can also be used at still standing to load the battery.[83]

The serial hybrid combines three equally dimensioned machines: combustion engine, generator and drive engine. For a required maximum speed of the vehicle, the electric drive engine needs to be dimensioned the size, that it can provide performance continuously. Due to the limited storage capacity, the energy cannot be taken permanently out of the battery. The required performance has to be created by the loading group directly. So these machines need to be the same size at least (due to losses maybe even bigger).[84]

Pros and Cons of Serial Hybrid Drive Trains

The advantage of serial hybrid is basically the possibility to regulate the *loading group* independently from the wheel drive. This allows different construction layouts. For example, the electric engine can drive a differential, each engine can drive a half-shaft or the car is driven by wheel hub motors, which could also realize a four-wheel drive.[85] Therefore this drive technology has the biggest potential for emissions reduction, relied on the following possibilities:[86]

- Delayed start of the loading group, combustion engine and especially exhaust gas treatment can be prepared for the launch; engine and catalyst pre-heating is possible
- Emission optimized launch strategy
- Operation of the combustion in best-case condition (consumption- and/or emissions-oriented)
- Stationary operation and avoidance of dynamic emission peaks
- Shut-down strategy

[83] Cf. Hofmann, 2014, p. 23
[84] Cf. Hofmann, 2014, p. 25f
[85] Cf. Fischer, Kücükay, Jürgens, & Pollak, 2016, p. 313
[86] Cf. Hofmann, 2014, p. 27

- Strategies for intermitting operation (e.g. dependent on catalyst cooling)
- More possibilities on positioning of the loading group – new vehicle concepts

However, these advantages can't be used until all the electric machines are configured accordingly, which is hardly achievable for passenger cars due to ever changing conditions. Most of the time the classical serial drive trains are used for rail and ship drivetrains, but less suitable for passenger cars.[87] The disadvantage of the serial hybrid is the repeated energy conversion, which could add up to 11 individual losses in the worst case. That's why until now, fuel consumption values in comparison to conventional direct drive trains haven't been reached. Especially when a lot of energy needs to be stored in the battery, bad consumption values are expected. Big progress was made with Li-ion batteries because these types of batteries have significantly lower charging and discharging losses.[88] Additionally, costs from two high power electric drive trains and increased vehicle weight due to more complex powertrain architecture, need to be taken into consideration.[89]

2.3.3 Parallel Hybrid Drive Train

The second large group of hybrid drive trains is the parallel hybrid drive train, where the mechanical force is brought straight through, from the combustion engine to the wheels. In contrast to the serial drive train, the parallel drive train only contains one electric engine (working as engine or as generator)[90]. The electrical part of the drive train is therefore built in parallel and can be switched on and off on demand. Both the combustion engine and the electrical engine can ideally be disconnected – therefore the vehicle can be driven electrical, conventional or mixed. It is possible to combine the performance from the combustion engine and the electric engine. These concepts include, beside the two engines and energy storages, additional transmissions, freewheel and clutches. The superimposition of power can be done by adding up rotational speed of the engine (planetary gear), torque (direct connection with spur gearings or chain) or traction (electric engine and combustion engine operate in different driving axles).[91]

[87] Cf. Tschöke, 2012, pp. 413–419
[88] Cf. Hofmann, 2014, p. 27
[89] Cf. Fischer et al., 2016, p. 315
[90] Cf. Tschöke, 2012, pp. 413–419
[91] Cf. Hofmann, 2014, p. 28

Pros and Cons of Parallel Hybrid Drive Trains

The big advantage of this configuration is the necessity of only one electric engine, which can be used as engine or generator. Further the conversion losses are decreased because of the direct connection of the combustion engine to the wheels - especially valid at high speed. Therefore the parallel drive train has the biggest potential for reaching lower fuel consumption.[92]

2.3.4 Power Split Hybrid Drive Train

At power split hybrid drives, respectively mixed hybrid drives, the transferable power is split into a mechanical and an electrical path. Power-split hybrids tend to decrease the amount of mechanical components while still reaching the same performance in comparison with automatic transmission. A special case is a combined hybrid, which allows a serial and a parallel operation due to two electric engines and a clutch.[93] This operation principle not only combines the advantages of both, the serial and the parallel hybrid drives, but also their disadvantages. Therefore, this results in a higher technical complexity of design and development and leads to major challenges for the required control strategy.[94]

Electrical power-split hybrids or electrically continuous variable transmissions (E-CVT) are a coupling of transmission elements and an electrical variator. This variator is set together from at least two electrical machines (one motoric, one generatoric) and the needed power electronics. With help of the conversion from mechanical to electrical energy, precise adjustments of both rotating speed and torque of the variator shaft are possible. The essential element of this transmission system is the power split from the combustion engine to an electric and a mechanic path with help of a planetary gear set.[95] Figure 10 shows the schematic structure of a power split transmission with two electric engines, which are used as a variator in combination with a wheel set. Therefore the wheel set could be arranged with planetary gear sets, simple gear transmissions and clutches. The selection of a suitable wheel set as well as the right ratio for the gear transmission is of great significance for the power output of the electric machines.[96]

[92] Cf. Hofmann, 2014, p. 30
[93] Cf. Hofmann, 2014, p. 31
[94] Cf. Williamson, 2013, p. 10
[95] Cf. Reif, 2010, p. 20
[96] Cf. Hofmann, 2014, p. 31

Pros and Cons of Power Split Hybrid Drive Trains

The biggest advantage of the power split hybrid drive is the continuously variable transmission ratio. Resulting from that is the adjustable operating point of the combustion engine. Additionally, the powertrain can be realized without a conventional transmission, which leads to fewer mechanical components. For the reason that a major part of the power is led to the electrical path, e-engines with higher performances are required. The related energy conversions influence the overall efficiency negatively.[97]

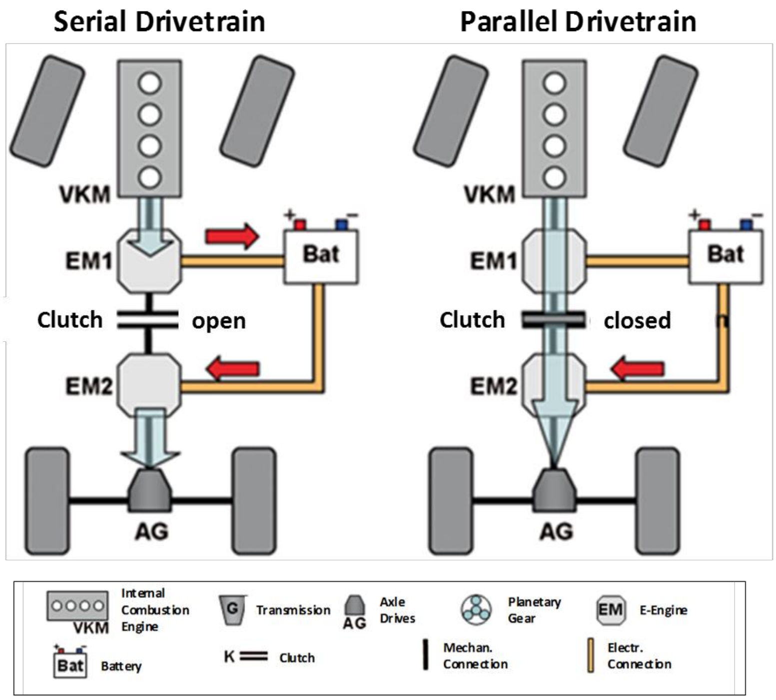


Figure 10: A Combined Hybrid in serial and parallel operation[98]

[97] Cf. Reif, 2010, p. 22
[98] Cf. Hofmann, 2014, p. 32; translated by the author

2.4 Battery Electric Vehicle

Battery Electric Vehicles (BEVs), which have been in serial production so far, get their power supply by stored energy from batteries. The most important parameters – Performance [kW] and Torque [Nm] – are competitive to those of modern internal combustion engines with one additional advantage: the maximum torque is already available from zero speed. Just the acceleration is affected by the battery mass.[99] Figure 11 shows battery electric vehicle in form of a BMW i3.

Figure 11: BMW i3[100]

Basically, the battery has a significant volume, requires a lot of space and is built into the vehicle's floor. That is problematic in a compact vehicle. For large vehicles it is not that of a big issue, due to the availability of more space. However, if the vehicle gets bigger, performance needs to go up as well, which requires a bigger battery.[101]

There are two general solutions: a compact battery in the rear axle area or between the two axles. Another possibility is to separate the battery to modules and distribute them within the whole vehicle (see Figure 12).

[99] Cf. Stan, 2012, p. 303ff
[100] BMW AG, 2016
[101] Cf. Stan, 2012, p. 304

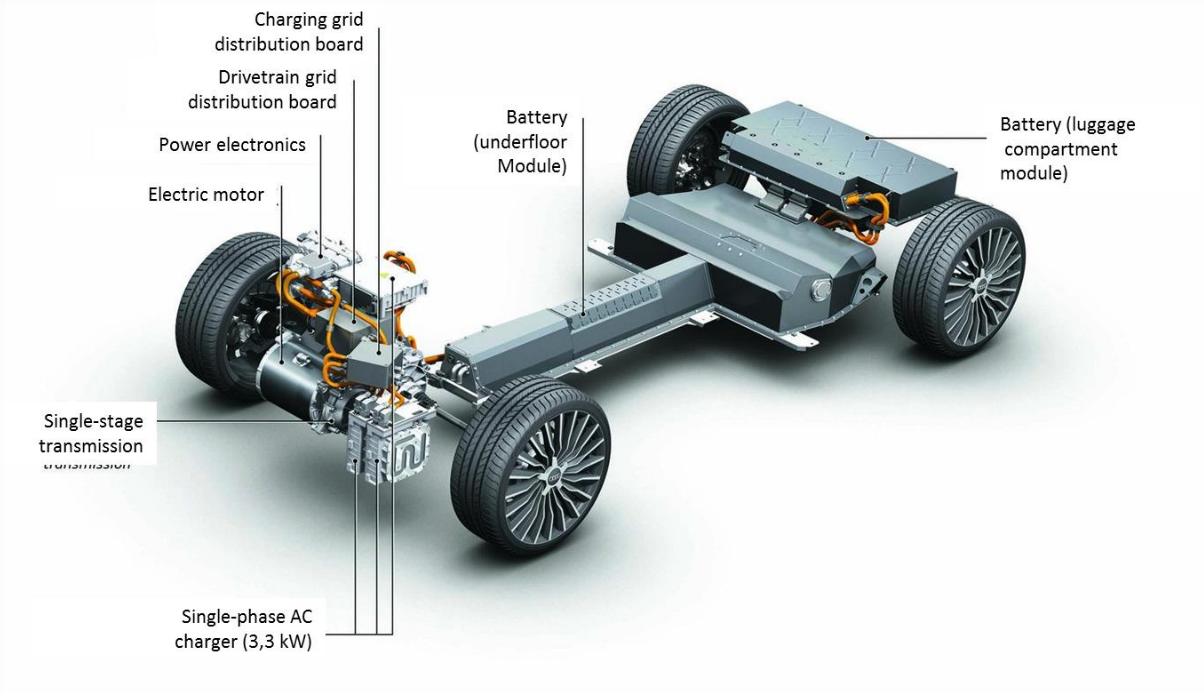


Figure 12: Battery electric vehicle - Audi e-tron - battery modules [102]

Bringing together all the important vehicle parameters, the following 4 categories can be divided:[103]

- Mass of vehicle including batteries
- Powertrain characteristics: type of engine, performance, torque
- Energy storage: type of battery, energy content
- Driving performance: range, maximum speed

Due to the high energy consumption, it is fact that the limited energy storage capability requires a decreased vehicle mass, driving speed and range. Despite the lack of storage capability, compact battery-electric vehicles are still a considerable option for city centers, as radical restrictions to even zero emissions are expected in the future. The local zero emission standard and the opportunity to keep the electric energy consumption low, are both arguments for a light and compact battery-electric vehicle used in cities. Nethertheless, such vehicles aim for a certain potential buyer profile and will not be produced for the low cost segment. On the other hand, such characteristics are providing new possibilities for car rent, car sharing and car leasing options.[104]

[102] Cf. AUDI AG, 2011; translated by the author
[103] Cf. Stan, 2012, p. 307
[104] Cf. Stan, 2012, p. 311

2.4.1 Batteries

Energy storages are commonly used to store energy for the reason of usage on a later point in time. Basically energy storage systems can be divided by different types of stored energy.[105] Different types of energy used in vehicles, currently or in the near future, are shown in Figure 13.

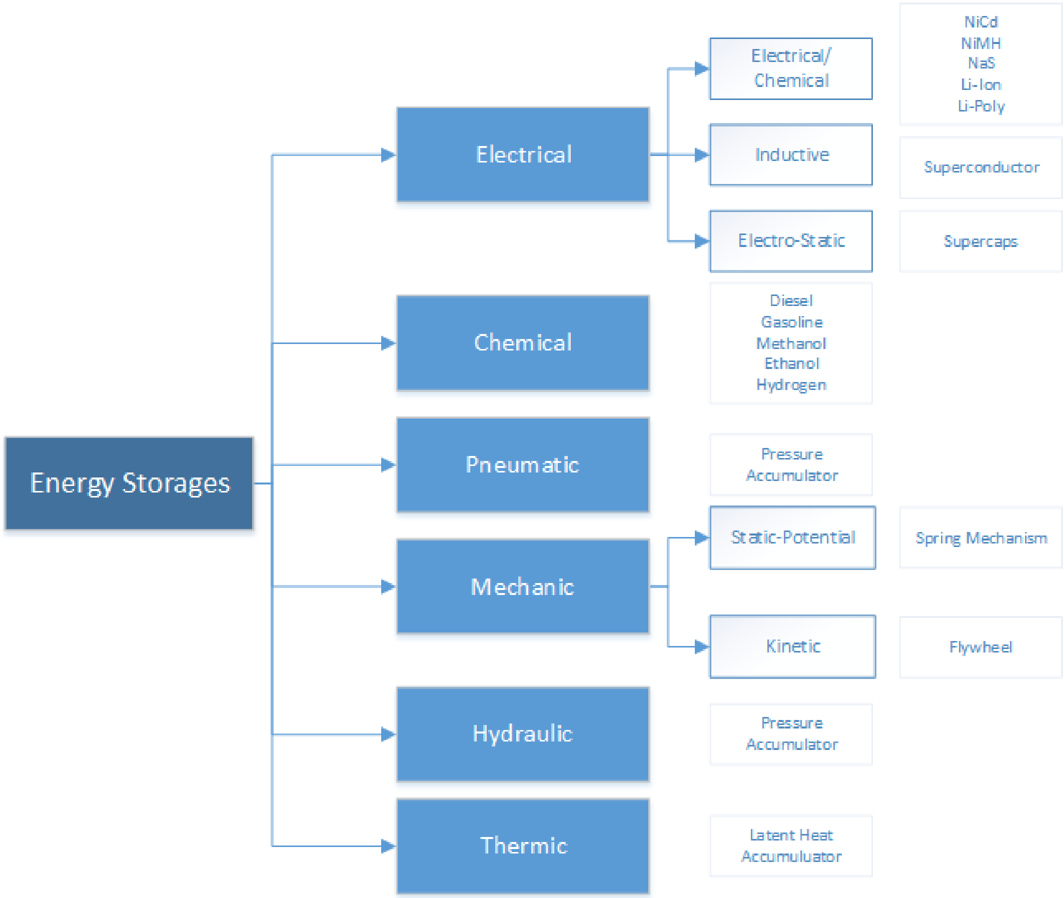


Figure 13: Energy storage systems[106]

A combination of conventional chemical energy storages, like diesel or gasoline, with a rechargeable storage, electric or mechanic, can bring advantages due to fast energy availability from conventional fuel and an ever recharging energy storage system while driving. For hybrid vehicles, both the electrochemical – especially batteries, and capacitive systems (super capacitor), have been the most important ones recently. Compared to the theoretical and practical energy density and the mass/volume ratio, the battery is still a critical part in terms of energy density, specific energy and costs. For the reason of huge research investments, various joint-ventures between car manufacturers and suppliers have already been established. Further options on energy

[105] Cf. Hofmann, 2014, p. 209
[106] Cf. Hofmann, 2014, p. 210; translated by the author

storage, which can be combined with conventional powertrain systems to hybrid vehicles are listed below:[107]

- Batteries, secondary elements (reversible process, loadable batteries)
- High-temperature secondary elements (reversible, loadable, e.g. 300-400°C)
- Redox-flow cell
- Super-capacitor
- Flywheel-generator
- Hydro-pneumatic storage

According to different purposes, the requirements on storage systems regarding energy storage capacity and performance vary greatly. Table 6 gives an overview on different vehicle applications and requirements.

Table 6: Purposes and requirements on battery systems[108]

Purpose	**Electric Range**	**Energy-/Power Requirements**
Electric Vehicles	>150km	> 20kWh/> 40 kW
Hybrid Buses	Limited Range	> 10kWh/> 80 kW
Full-Hybrid-Car	Short Electric Range	1 to 3 kWh/25 to 50 kW
Mild-Hybrid-Car	No Electric Range	0,5 to 1 kWh/< 20 kW

The choice of the appropriate energy storage system related to the table of different applications above, is led by the system depending characteristics:[109]

- **Specific energy (gravimetric) [Wh/kg]:** describes the weight related energy storage capability of the battery system. It is an important requirement for long and continuous charging and discharging procedures. In automotive area it is an indicator for the electric range.
- **Energy density (volumetric) [Wh/l]:** describes the requirement on how much room is needed to install the battery in the vehicle.
- **Specific performance (gravimetric) [W/kg]:** If the required maximum charging and discharging times become shorter (<1min), the importance of the specific performance increases. This is especially relevant for start/stop systems, as well as for typical acceleration and recuperation processes.

[107] Cf. Hofmann, 2014, p. 212
[108] Cf. Hofmann, 2014, p. 213
[109] Cf. Hofmann, 2014, pp. 213–215

- **Performance density [W/l]:** Especially hybrid vehicles with packaging issues and difficult installation cases due to limited room in the vehicle body, require high performance density.
- **Energy output [Wh]:** At hybrid vehicle applications, the energy output together with the duty cycle define the life cycle requirements for the cell. At conventional vehicles, there are no great demands on the 12 V starting battery according to the energy output. However, if the battery is working permanently, because of acceleration and braking procedures, like in hybrid vehicles, the specific energy output becomes an important criteria for the choice of the appropriate energy storage system.
- **Cycle life time:** The cycle life time is related closely to the maximum energy output. It is defined by how many duty cycles can be driven within set environmental limits till the criteria for an end of usage are reached.

The best case is an equal or even longer lifetime of the energy storage system than the lifetime of a complete vehicle. Nowadays, vehicles are designed to last at least 10 years. An ever changing environment and new priorities lead to new requirements for the energy system. For example by developing high energy batteries, the main focus is on increasing the energy density to reach longer driving ranges, which incidentally results in lower performance density. On the other way round higher performance density and lower energy density – a high performance battery – is required for a better acceleration behavior.[110] Figure 14 illustrates the variety of options for energy storages.

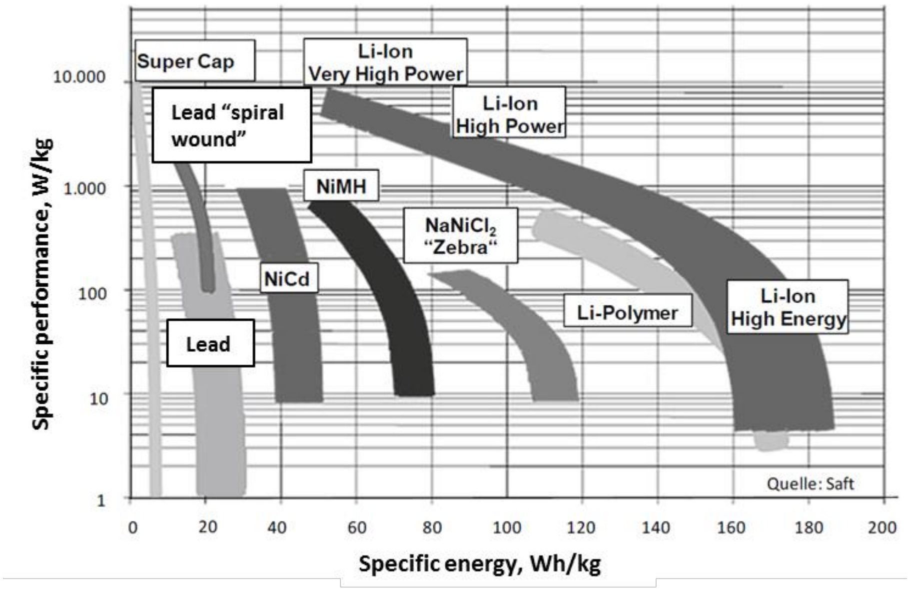


Figure 14: Specific performance and specific energy[111]

[110] Cf. Wallentowitz & Freialdenhoven, 2011, p. 86
[111] Cf. Wallentowitz & Freialdenhoven, 2011, p. 86; translated by the author

2.4.2 Designs of Batteries

In the area of battery cells for automotive industry, three different designs of batteries are used: a cylindrical cell, a prismatic cell and pouch cells. All of these three designs are in the focus of an ongoing research, with no recognizable tendencies to a certain type. There are hardly any differences in the chemical definition or the function, whereas the construction influences the cooling behavior and the package of the battery modules, shown in Figure 15.[112]

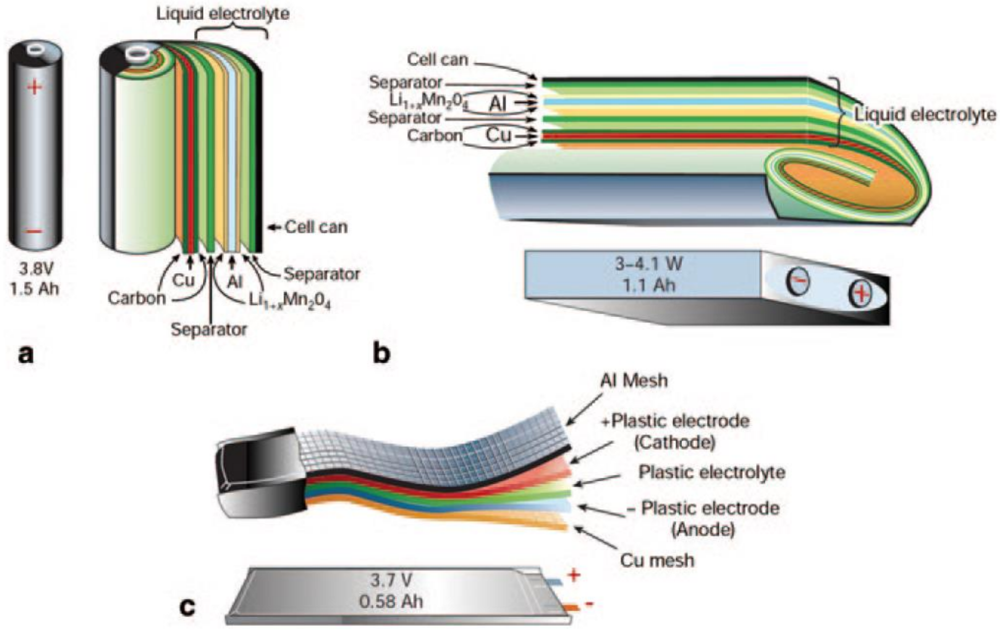


Figure 15: Schematic structure of different battery cells[113]

Cylindrical Cells (a): The cylindrical cell is already well known and commonly used. The set-up consists of four layers (separator, anode, separator and cathode) which are layered on each other and then wrapped around a mandrel until thickness reaches the required capacity. The production of this cell type is already in solid command for years and the production costs are low. A very big advantage is the mechanical strength. The cell can withstand inner pressures up to 40 bar. For that case, the cell also has an overpressure valve. The circular cell has two considerably disadvantages. Its design is hindering an optimal space utilization, which leads to cavity between the cells. Therefore, also the energy content per volume decreases. Such a design also comes with poor cooling behavior. The pretty low surface-volume ratio affects the heat dissipation from the inner cell to the surface, which leads to higher temperature gradients in the inner cell. [114]

[112] Cf. Wallentowitz & Freialdenhoven, 2011, p. 86
[113] Hofmann, 2014, p. 222
[114] Cf. Hofmann, 2014, pp. 222–223

Pouch Cells (c): The production of pouch cells is similar to the cylindrical cells. Most of the time they are also wrapped cells. The difference is that the cells are not wrapped around a mandrel but wrapped flat to end up with the desired flat prismatic dimensions. The cell stacks are shrink-wrapped in laminated foil and passed on to the outside with sheet metal contacts. The cells are stacked tightly and built into the module housing with slight tension. Figure 16 shows the tight stacking and the cooling system beneath the pouch cells. Slim metal sheets are stack between the cells to conduct the created heat to a fluid cooling plate. The disadvantages of the pouch cell are the missing stiffness of the housing and the related suspension points.[115]

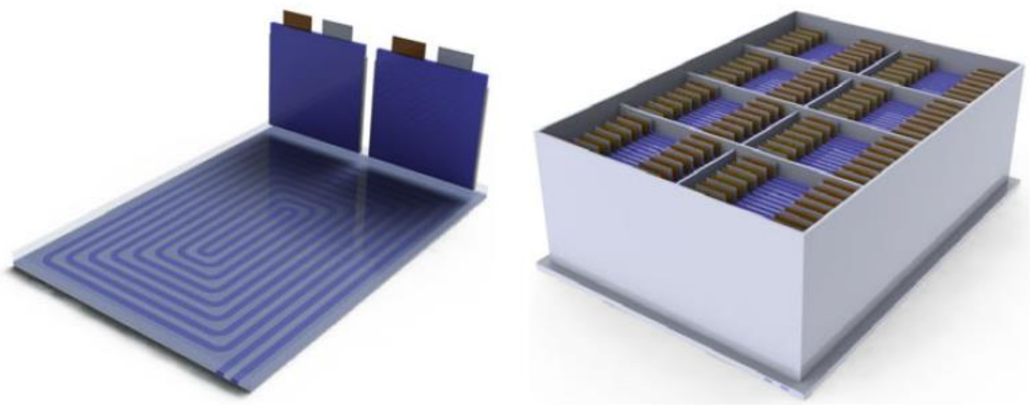


Figure 16: Pouch Cells cooling system[116]

Prismatic Cells (b): Prismatic cells are a mix of cylindrical cells and pouch-bag cells. Similar to the pouch-bags, the electrical connections are both mounted on the same side, which requires only one production step without turning the whole battery pack. In comparison to the pouch-bag, the prismatic cell has a lower surface-volume ratio. That’s the reason for worse cooling behavior, which leads to more complex housing constructions as the battery needs more space for thermal expansion.[117] However, the prismatic cell as well as the pouch bag, still own the better cooling behavior characteristics for the usage in vehicles in comparison to cylindrical cells.[118]

[115] Cf. Tschöke, 2015, p. 88
[116] Cf. Tschöke, 2015, p. 88
[117] Cf. Tschöke, 2015, p. 88
[118] Cf. Hofmann, 2014, p. 224

2.5 Powertrain Management for Hybrids

The following chapter introduces the idea of powertrain management for hybrids and the strategies, which are used to reach certain standards and the operation conditions those vehicles can apply to practice.

The powertrain management coordinates all the functions of the powertrain components, which are depending on the drivers intends and their operation conditions. This management is based on different strategies, which not only fulfills the driver's intends, but also reaches for the goals of lower fuel consumption and emissions or set ups for the convenience of the driver. That also includes for example life cycle requirements for the battery. The powertrain strategy primarily organizes the electrical energy production and the electrical energy consumption, whereas the main focus is the interaction between the internal combustion engine and the electric engine. Due to the possible presence of two energy storages and two energy converters, it is possible to optimize the driving behavior of the combustion engine in regards to fuel consumption or even to completely decouple the combustion engine – without neglecting the drivers intends. On that basis one could pursue different objectives, which are originated either from the driver or the operation strategy:[119]

- Reduction of energy consumption and emissions
- Increase of dynamic and driving pleasure
- Increase of comfort
- Improvement of driving dynamics

Boundary conditions for electrified powertrains are: the limit of battery status (SOC = state of charge), energy output of the battery and allowed temperatures of electric engine and battery. The operation strategy also includes comfort requirements (vehicles air condition). Besides the mechanical power output, the thermic and electric environment is managed as well. That comprises the high and low-voltage power supply, electric consumers like the air-condition compressor and different pumps and fans. Further tasks are the whole data and information exchange among different systems, the control units, the driver and the diagnosis functions.[120]

[119] Cf. Hofmann, 2014, p. 287
[120] Cf. Hofmann, 2014, p. 287

That's the reason why efficiency is on the one hand a matter of emissions reduction or fuel consumption and on the other hand related to overall management and coordination within a vehicle. Figure 17 illustrates the influencing management sub-systems.

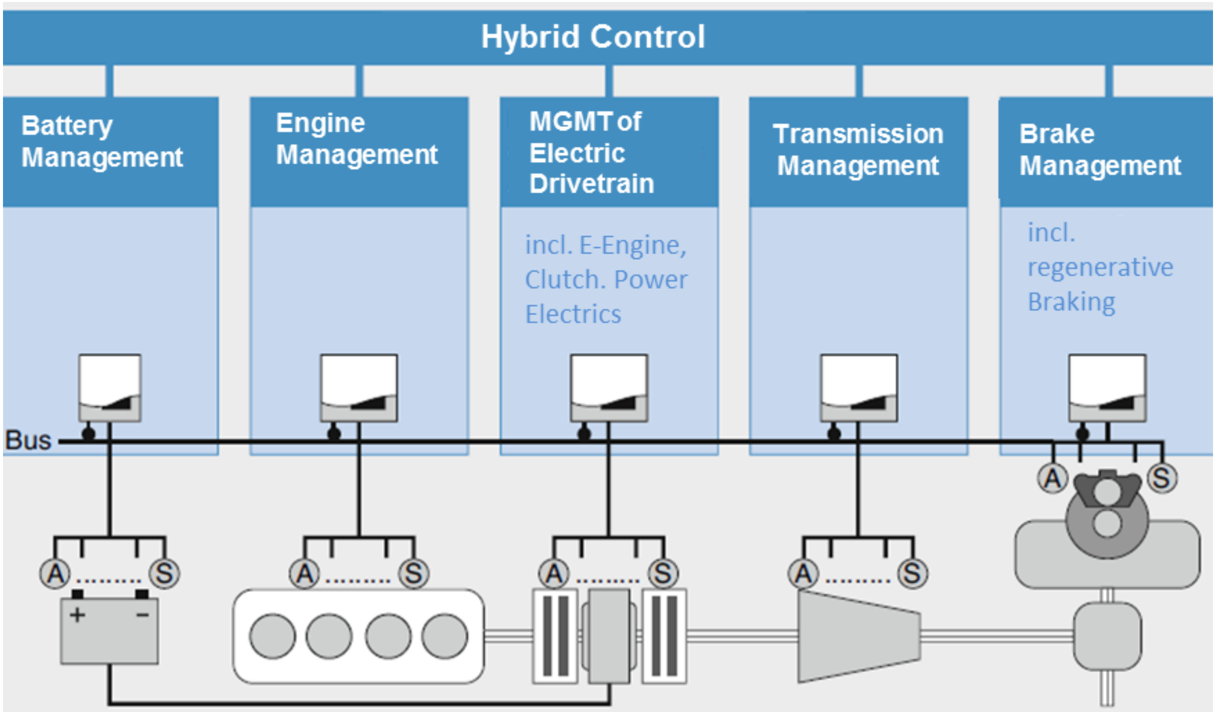


Figure 17: Hybrid management, example from a parallel hybrid[121]

Operation Status of Hybrid Vehicles

The presence of two energy storages and two energy converters allows different set up approaches in operation with the individual powertrain components to fulfill driver's intentions. The following operation states are basically possible at parallel and power split hybrid concepts:[122]

At standstill:

- *Engine off: start/stop:* vehicle in standstill, all powertrain power units are switched off
- *Raising of the load point in standstill:* At vehicle standstill, the combustion engine drives the electric engine for the reason of electricity generation.

[121] Cf. Reif, 2010, p. 23; translated by the author
[122] Cf. Hofmann, 2014, p. 289

While driving:

- *Recuperation (regenerative braking):* The braking action is done by the generational operation of the electric machine to produce electricity.
- *Raising of the load point while driving:* The mechanical energy produced by the combustion engine is used to power the car as well as to produce electricity with the electric engine.
- *Electric driving with special case sailing:* The driving of the car is completely done by the e-engine. The combustion engine is standing still. At *sailing* there is also no torque created by the e-engine. Therefore the vehicle is moving without driving power.
- *Boosting:* The electric engine is supporting the combustion engine to drive the car.
- *Exclusive combustion engine drive:* The drive is done exclusively with the internal combustion engine.

Beside these operation states, the change between these states is also worth considering. For example, there are different possibilities to start a combustion engine (pinion starter, belt driven starter/generator or electric machine) and different approaches to the start itself (slow-start, pull-start). The individual operation states are subject to defined conditions. These conditions are set from the operation strategy in dependence from the input values:[123]

- *Driver intentions*: accelerator position brake, pedal position, driving direction
- *System internal data*: current rotating speed and torque, battery status, temperature
- *Lessons learned data*: history, road profiles, data from traffic info systems and car2x communications[124]

[123] Cf. Hofmann, 2014, p. 290
[124] Car2X combines all kinds of data exchange between the vehicle and various data providers e.g. other vehicles, traffic tracking systems, infrastructure etc.

Table 7 relates the different operating states to the powertrain types, which are explained in chapter 2.3.1.

Table 7: Operation strategy matrix[125]

		Full Hybrid		
	Mild Hybrid	**Parallel Hybrid**	**Serial Hybrid**	**Power-Split Hybrid**
Start-Stop	✓	✓	✓	✓
Recuperation	✓	✓	✓	✓
Boosting	✓	✓	✓	✓
Pure Electric Driving	✗	✓	✓	✓
Mechanical Connect. Engine-Wheels	✓	✓	✗	✓
Plug-In	✗	✓	✓	✓

[125] Cf. Tschöke, 2015, p. 8

2.6 TCO Strategies at Electrified Powertrains

A total cost of ownership calculation cumulates all created costs through a whole life cycle of a certain product. As the intention has always been making purchase decisions based on the purchase price, it's already a matter of fact, that in most cases the real value is not added at the beginning, but in the later life time. Service and maintenance, recycling, disassembling or just pure supply costs to keep the product working, come into consideration.[126] People tend to take a long time to compare the purchase prices of various vehicles, but forget to think about costs that come afterwards. These are for example fuel costs, spare part costs, service and maintenance costs, recycling of the car, potential reselling price, incentives given from the government to purchase a certain type of vehicle or fuel consumption behavior and where the car will be used – is it just to go to work for 20km a day or is it needed to travel long distances daily. To combine the idea of TCO with the electrification of vehicles, it's necessary to understand which type of vehicles with an electrification approach are already available and what are the advantages and disadvantages, what are the cost drivers of electrified vehicles and which cost drivers will influence the TCO calculation the most.

[126] Cf. Ellram, 2002, p. 661

Markets

Table 8 compares the five most important markets to electric mobility as well as the Austrian market. In addition, the state subsidies and incentives are listed.

Table 8: Comparison of incentives in different countries[127]

	Austria[128]
Purchase Incentives:	Varying between federal states (Burgenland, Carinthia, Salzburg, Lower Austria); from 750 € to 4000 €; additional payments for usage of "Ökostrom" and photovoltaic systems; no subsidies in Styria currently.
Tax Incentives:	No engine related insurance tax for battery electric vehicles; deduction for input tax for commercial vehicles with purchase price up to 48.000 €.
Charging Infrastructure:	Partially free wall boxes with purchase of vehicle; partially free public loading.
Model Regions:	7 model regions

	Germany
Purchase Incentives:	from 02.07.2016 1,2 billion € total subsidy, 3000€ - 4000€ per vehicle
Initiatives:	Nationaler Entwicklungsplan E-Mobilität (2009); NPE (2010), NPE (2011): Regierungsprogramm E-Mobilität;
R&D Subsidies:	State subsidy KoPa II 2009-2011: 500 Mio. €; 1 billion € until in 2013; Cluster "Elektromobilität Süd-West" and "MAI-Carbon" with 40 million € each for 5 years
Tax Incentives:	Tax exemption for 10 years for BEVs; Taxation privileges for company cars - BEV/REEV/PHEV
Model Regions:	255 million € for 17 model regions in 2011, from 2012 4 hotspots - Baden-Württemberg, Berlin/Brandenburg, Niedersachsen and Bayern/Sachsen

	France
Purchase Incentives:	5000 € per vehicle with emissions lower than 50g Co2/km
R&D Subsidies:	1,5 billion € subsidies for 4,75 billion € total investments until 2020 for development of alternative powertrain architectures
Charging Infrastructure:	The objective is the establishment of 10% public and 90% private/workplace related charging spots
Production:	State supported building of a battery factory
Procurement:	100.000 vehicles should be purchased by companies and the state sector until 2015

[127] Cf. NPE, 2012, p. 59; adapted and translated by the author
[128] Cf. Klima- und Energiefond, 2016

	Japan
Initiatives:	Energy Conservation Law 2015: Eco Car & Next Generation Vehicle (NGV) subsidies to reduce CO2 emissions
Purchase incentives:	Within the scope of NGV e.g. 10.000€ for Nissan Leaf; within scope of Eco Car ca. 1.000€
R&D:	Roadmap to increase performance of Li-Ion batteries up to 150%; development of post Li-Ion technology
Tax Incentives:	Tax exemption of VAT for 3 years
Charging Infrastructure:	Depending on charging speed, subsidies up to max. 50% of purchase price
Model Regions:	Development of 11 model regions with a total of 34.000 BEVs/PHEVs

	USA
Purchase Incentives:	Tax incentives of ca. 7.500 US$, tax benefits of 50% of purchase price for company vehicle fleets
R&D:	226 million US$ for thematic fields powertrain, charging infrastructure, power electronics, batteries and battery design; 650 million US$ for lightweight materials, compound materials, battery research, powertrain and charging technology
Model Region:	1 billion US$ subsidies for 10-15 model regions; establishment, infrastructure to reach a critical mass of vehicles

	China
Purchase Incentives:	Depending on powertrain concept and size of battery; from 6000€-7200€ per vehicle.
Tax Incentives:	Tax exemption for 42 BEV and 7 FCEV models
Charging Infrastructure:	Installation of 2500 charging spots, 100 charging stations and 20 battery exchange stations, depending on region - subsidies up to max. 30% for charging stations
Model Regions:	Step by step establishment of model regions, until end of 2015 100.000 vehicles per region.
Production:	Installation of annual production capacity of 2 million electric engines, 200.000 batteries and 2 million super caps.

In comparison to how states are investing money and trying to influence potential intends to purchase an electric vehicle, the absolute market volume is shown in Figure 18. Further the amount of stationary loading stations are listed. On a more widely bases, Norway, Denmark and the Netherlands are also shown. Germany is also up to follow the obvious market leader USA. From the beginning of 2014 to the end of 2015, Germany's automotive industry has launched almost 30 models of electric vehicles with series maturity. That's of course the result of intensive research and development investments and big initiatives supported by the state. With such a big amount of investments, both from the state and the economy, Germany already offers the widest model range compared to other countries and is growing continuously. With that manner, Germany will not only fill up the gap to the USA, but also will boost the selling of electric vehicles even more.[129]

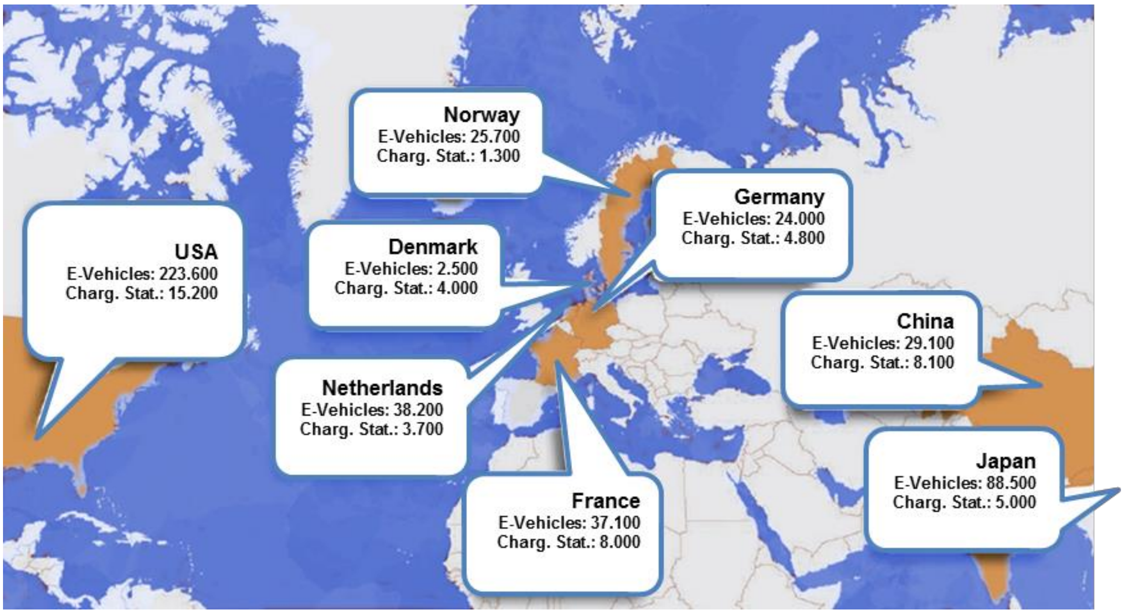


Figure 18: Absolute numbers of electric vehicles and loading stations[130]

At an European perspective, it gets even more interesting if the European countries are ranked by market share of electric vehicles and not absolute numbers. Norway is with a market share of 22.9% at the first quarter of 2015 not just leader in Europe but also in the whole world. That percentage accounts for the sum of Plug-In Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs), shown in Figure 19. The reasons for this is, again, fiscal incentives from the Norwegian Government. Second biggest player are the Netherlands with 3.1% of PHEVs and 0.9% of BEVs sales in 2014. The Netherlands introduced a specific taxation scheme, which provides high rebates for vehicles emitting less than 50g/km CO_2.[131]

[129] Cf. NPE, 2014, pp. 9–10
[130] Cf. NPE, 2014, p. 8
[131] Cf. Mock, 2015, p. 7

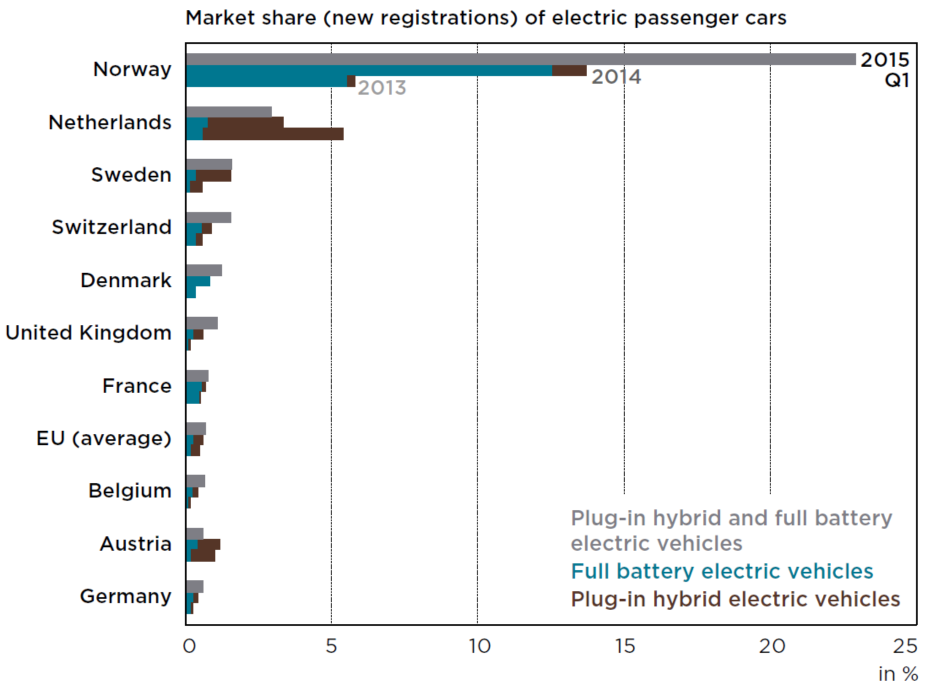


Figure 19: Market share (new registrations) of electric passenger cars[132]

[132] Cf. Mock, 2015, p. 7

3 TCO adapted to Practical Environment

The following Excel-based TCO calculation is based on the already named phase model from Bode. The chapter follows the calculation steps and input process from the Excel tool.

In the following chapters, each phase (preparation phase, operation phase and further utilization phase) is described separately. If necessary, the author provides the theoretical knowledge, which will be needed to use the input masks appropriately and according to the end user's expectations.

To finalize the chapter of the practical implementation, the results and the graphic preparation of the output parameters are explained. Especially the cost-effectiveness and analysis of the related time of occurrence is from great significance and is the most important graphic in terms of great expressiveness. That is taken into account with help of the dynamic investment calculation.

Finally the practice part closes with clarification on how and why the complexity and the grade of detail of the calculation can be manipulated. Some guidelines are offered in which the calculation is valuable in detail, but still not too complex to exceed the limits of reasonable efforts from the end users perspective.

3.1 Phases of Lifecycle

To ramp up a valid model and tool for calculation of total costs for electrified drive trains, all the necessary cost drivers and cost categories need to be identified and differentiated from those which do not make sense regarding time and effort or due to negligibility. Then these categories and drivers are assigned to the according phases in the life cycle. These 3 phases are: Preparation Phase, Operation Phase and Further Utilization Phase.[133] All these actions eventually result in an overall calculation structure, shown in Figure 20.

Equation 1: Total Cost of Ownership Calculation

$$Total\ Costs\ of\ Ownership\ (TCO) = \\ Costs\ Preperation\ Phase + Costs\ Operation\ Phase + Costs\ Further\ Utilization\ Phase$$

[133] Cf. Bode et al., 2011

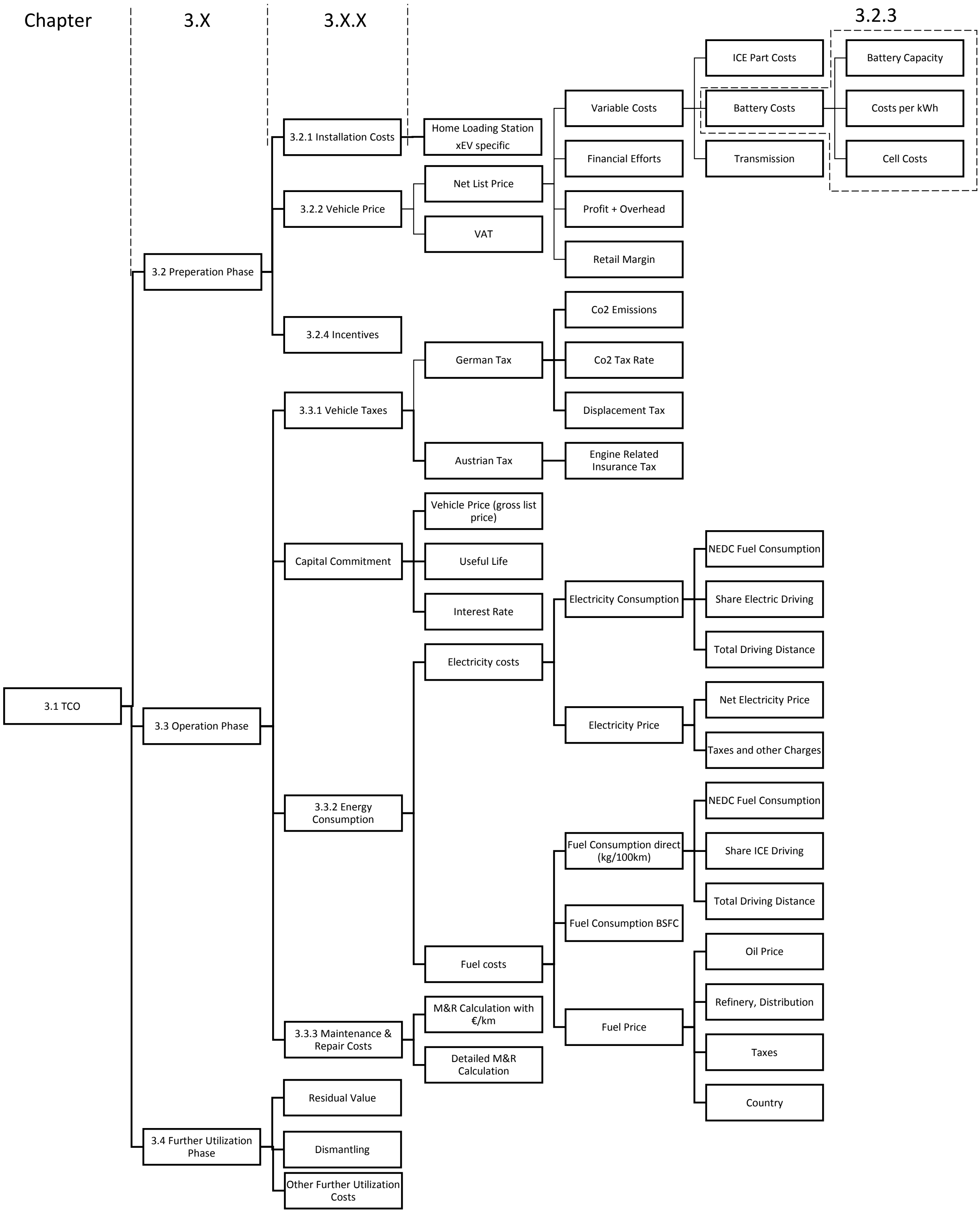


Figure 20: TCO calculation structure in the Excel tool[134]

[134] Cf. Neumann, Eckstein, & Olschewski, 2013, p. 1647; adapted by the author

3.2 Preparation Phase

The preparation phase includes all costs from the idea of purchasing or producing a product to the point where the operation or the usage begins. In the case of this thesis, the purchase of a product, a variable powertrain architecture, is simulated. In theory, that includes all costs invested to contact and get into relation with a supplier, the quotation phase, contract negations, the purchase itself and all the actions, which need to be taken to set the product ready for operation. The costs related to market and supplier analysis, the evaluation of suppliers, the physical connection to a supplier and the change of existing suppliers are summed up to transaction costs. Still to mention, that transaction costs are just investigated by one third of companies.[135] Therefore, these costs are neglected as well as the costs for the evaluation of investments spent for supplier search and the determination of costs attached to quotation and contract phase. They are rather hard to assume or to measure.

3.2.1 Installation Costs

Installation costs are lump sums from on-time payments. In this case, the only installation which needs to be taken into account is the installation of a loading station for powertrain architectures with partial electric drive train or fully electric drive train.

To the state-of-the-art knowledge, in 2020 half a million electric vehicles will be on road in Germany. But for that reason, which is such an ambitious goal, the framework conditions need to change as well. That means public loading stations in the scale of close to 100.000 new loading stations, mainly DC-load points, need to be created. The next two years will be highly important to the whole ramp up phase of the market and the development of the electric vehicle market itself. One of these critical factors to success will be the public loading infrastructure. The German “Nationale Plattform Elektromobilität” (NPE) suggests not to over develop this infrastructure too early and to stick to a vehicle to loading point ratio of 10 to 1.[136]

Due to different types of loading and different locations, the infrastructure costs for loading points can vary. For this reason the usage of an own loading infrastructure for the consumer with garages are commonly cheaper than the public loading infrastructure[137]. Therefore, the loading infrastructure has an important impact on the profitability of electric vehicles in the different use cases. To underline the possibility of

[135] Cf. Geißdörfer, 2009, p. 312
[136] Cf. NPE, 2014, p. 44
[137] Cf. Plötz, Gnann, Kühn, & Wietschel, 2013, p. 13

home loading systems, respectively *wallboxes*[138] the following picture shows the distribution of parking spots in Germany over night.

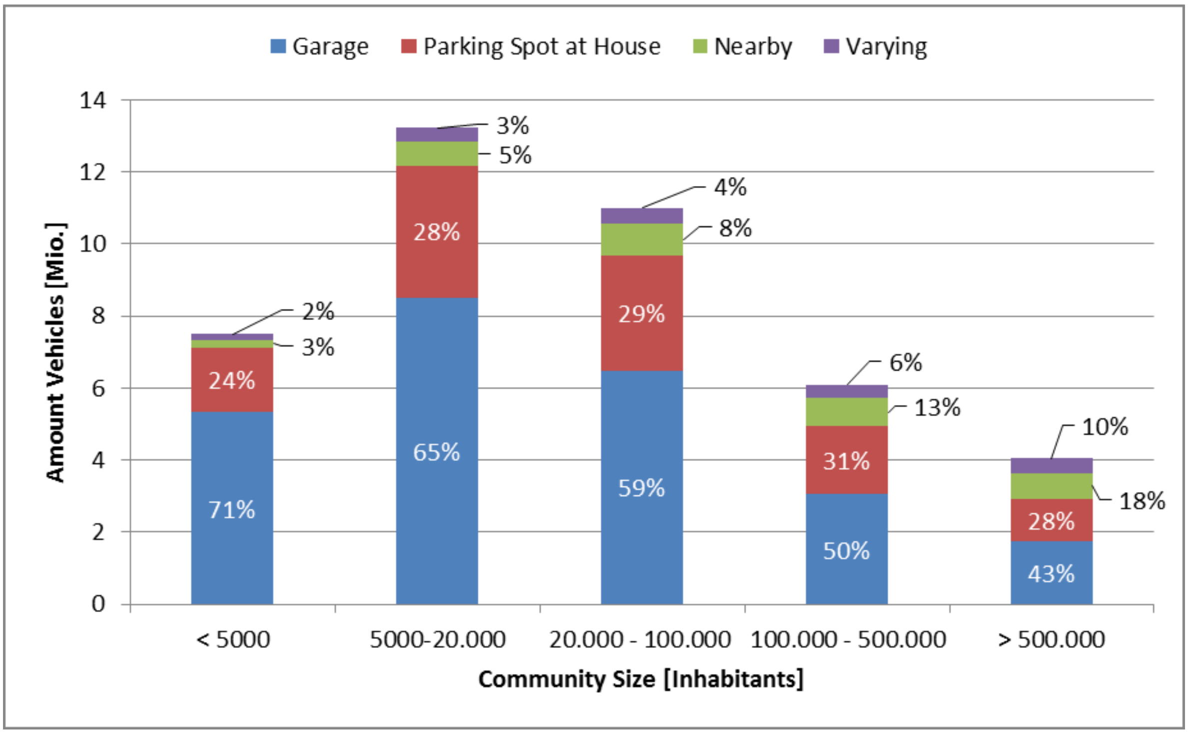


Figure 21: Distribution of parking spaces of German vehicles over night[139]

That means, that on average 60% of German car owners have a garage and the installation of wallboxes could be done fairly cheap. However, people with no fixed parking spot also need an ever accessible loading point or charging pole. This applies above all for users with high annual mileage due to an economic interest in electric vehicles.[140] This is also shown in Figure 22, where an increase of commercial wallboxes and public charging facilities of nearly 400.000 till 2020 is illustrated.

[138] A charging device attached to a wall, mostly in private garages.
[139] Cf. Plötz et al., 2013, p. 126; adapted by the author
[140] Cf. Plötz et al., 2013, p. 126

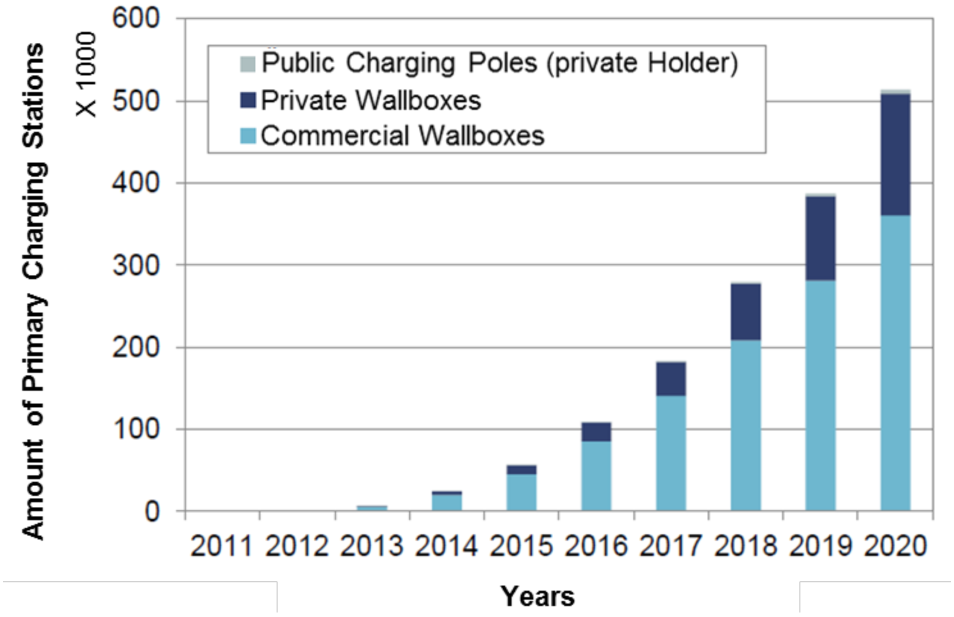


Figure 22: Market forecast for loading infrastructure[141]

The TCO tool implements these costs as a one-time payment, which is named as home loading station costs, and can be set to the users demand. The following graphics illustrate the tool environment (see Table 9 and Table 10). The values are based on the data of online seller Petring Energietechnik GmbH[142].

Table 9: Installation costs - dropdown menu[143]

P4	Homeloading Station	€	1.099	0	1.699	0	0
P4.1	Loading Option		Wallbox	Wallbox	Loading column	Loading column	Loading column
	Loading Power		wallb-e pro 7,4kW	wallb-e pro 3,7kW	wallb-e Ladesäule22kW	wallb-e Ladesäule22kW	wallb-e Ladesäule22kW
P4.2	Costs	€	1.099	999	1.699	1.699	1.699
P4.3	Other Costs	€					

Table 10: Installation equipment costs[144]

Main Application	Abbreviation used in tool	Options	Costs	Graphic	Description
Wallbox	WB				
		wallb-e pro 3,7kW	999,00		3,7kW Ladeleistung - 16A, 1Phasig, 230V Steckdose Typ 2 EIN/ AUS Taster Montageplatte inkl. Kabelhalter IP-Schutzklasse: Gehäuse - IP54, Ladestecker - IP54 Gehäuse: Vollmetalgehäuse inkl. Wechselcover (Standard: weiß)
		wallb-e pro 4,6kW	1049,00		
		wallb-e pro 7,4kW	1099,00		
		wallb-e pro 11kW	1149,00		
		wallb-e pro 22kW	1199,00		
Loading column	LC				
		wallb-e Ladesäule 3,7kW	1499,00		3,7kW Ladeleistung - 16A, 1Phasig, 230V Steckdose Typ 2 EIN/ AUS Taster IP-Schutzklasse: Gehäuse - IP54, Ladestecker - IP54 Gehäuse: Vollmetalgehäuse inkl. Wechselcover (Standard: weiß) Ausstattung Ladesäule...
		wallb-e Ladesäule 4,6kW	1549,00		
		wallb-e Ladesäule 7,4kW	1599,00		
		wallb-e Ladesäule11kW	1649,00		
		wallb-e Ladesäule22kW	1699,00		

The costs are added directly to the installation costs in the first year (Preparation Phase).

[141] Cf. Plötz et al., 2013, p. 127; translated by the author
[142] Cf. Petring Energietechnik GmbH, 2016
[143] Own illustration
[144] Own illustration

3.2.2 Vehicle Price

The vehicle price is one of the greatest cost drivers in the TCO calculation. The longer the holding period is and the higher the annual mileage is, the less significance the amount of the vehicle price has. Most of the time only the net list price[145] is needed for calculation. For the case that the user would like to calculate with a more detailed price structure, the Excel tool allows to calculate through different levels of detail. These levels (BOM costs, Production costs, Total costs, Sales price ex works, Sales price pre-tax, Sales price after tax) are shown in Figure 23.

COSTS INCURRED IN PREPARATION PHASE

Code	Forecasted lifecycle costs	Dimen-sion	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
P1	**Procurement costs** Basis for the investment calculation	€	19.352	18.195	23.141	31.205	37.446
1.)	Please select your level of detail regarding the cost and price structure of your product. (based on how detailed your informations are)		Accumulated cost and price structure	Accumulated cost and price structure	Accumulated cost and price structure	Accumulated cost and price structure	Accumulated cost and price structure
2.)	Please select your level of the chosen cost and price structur, which makes up your procurement costs and therefore the basis for the investment calculation.		BoM costs	Production costs	Total costs	Sales price ex works	Sales price after tax
P1.1	**Accumulated cost and price structure**						
P1.1.A	= BOM costs	€	19.352,00	17.165,00	18.042,00	22.118,00	22.118,00
	+ Assembly, painting & test costs	%	6,00%	6,00%	6,00%	6,00%	6,00%
P1.1.B	= Production costs	€	20.513,12	18.194,90	19.124,52	23.445,08	23.445,08
	+ Development costs	%	5,00%	5,00%	5,00%	5,00%	5,00%
	+ SG&A (Sales, General & Administration)	%	16,00%	16,00%	16,00%	16,00%	16,00%
P1.1.C	= Total costs	€	24.820,88	22.015,83	23.140,67	28.368,55	28.368,55
	+ Profit margin	%	10,00%	10,00%	10,00%	10,00%	10,00%
P1.1.D	= Sales price ex works	€	27.302,96	24.217,41	25.454,74	31.205,40	31.205,40
P1.1.E	+ Transportation costs	%					
	+ Dealer & import costs	%					
	= Sales price pre tax	€	27.302,96	24.217,41	25.454,74	31.205,40	31.205,40
P1.1.F	+ Taxes	%	20,00%	20,00%	20,00%	20,00%	20,00%
	= Sales price after tax	€	32.763,56	29.060,89	30.545,68	37.446,48	37.446,48

Accumulated cost and price structure (– ↑ … + ↓)

Figure 23: Options for calculating the purchase price[146]

[145] Calculating with net list prices exclude distortion effects through different tax amounts in different countries
[146] Own illustration

3.2.3 Battery Cell Costs as Main Cost Driver at Electrified Vehicles

This chapter focuses on the costs and price structure of battery cells and how the price behavior in the next years could influence the competitiveness of electrified vehicles on the market. This can also be seen in chapter 4.3, where the influence of batteries to overall life cycle costs is displayed. Figure 24 shows the influence of the battery to the total costs, which accounts for 38% in this case.

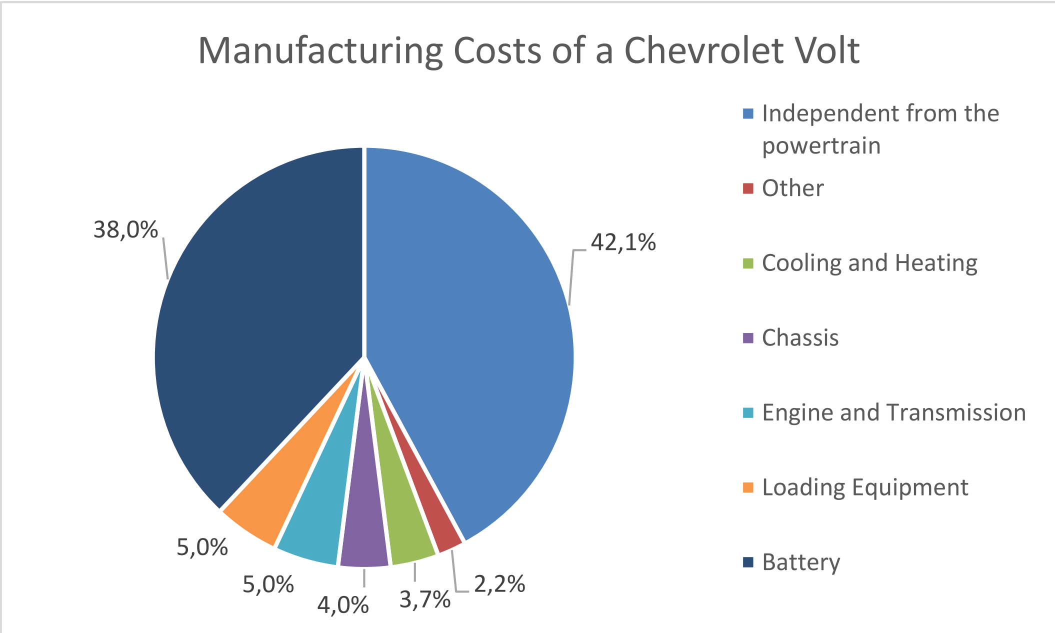


Figure 24: Manufacturing Costs of a Chevrolet Volt[147]

Lithium-Ion batteries (LiB) have been exposed as the most promising battery technology according to its application potential within the current developments. The LiB market is still driven by the high tech consumer sector, like cell phones, tablets and notebooks, and of course mobility applications – primarily plug-in hybrid vehicles. Back in 2014, the market was dominated by Asian cell manufacturers with more than 90% market share.[148] Investments announced in 2010 have been prognosticated to a significant overcapacity for 2016, mainly affecting Japan and the United States. Prices for OEMs were forecasted to 500$/kWh.[149] Back in 2012, prognoses for cell prices have been adjusted due to the entry of new cell manufacturers and a price decrease for technological advances, to be 250$/kWh for 2014/2015. As the study back in 2012 concentrated on the three approaches, current state (2012), mid-term cost structure (2015) and long term cost structure (2015-2020), the author will skip the 2012's state and concentrate on the mid-term and long term cost structure. Referring to the cost benchmark from Roland Berger, the cost structure of cells is shown in Figure 25.

[147] Cf. Randelhoff, 2010; translated by the author
[148] Cf. Pistoia, 2014, p. 554; Bernhart, 2010a
[149] Cf. Bernhart, 2010b

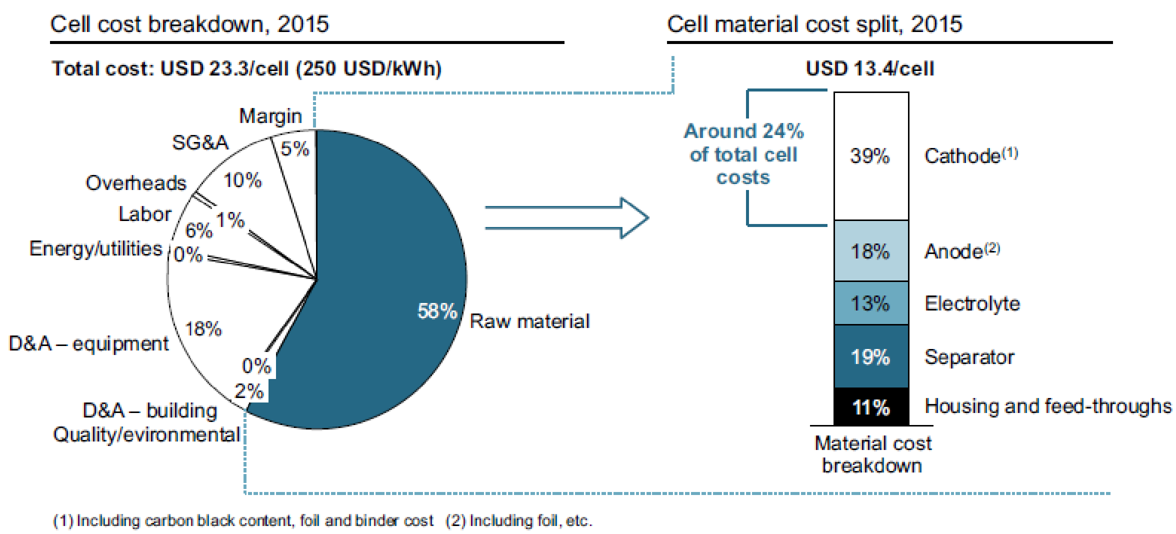


Figure 25: Cost structure prognoses for cells 2015 - Typical 96Wh PHEV cell[150]

That is cost breakdown of a typical 96Wh cell, where the cathode material (NCM[151]) is the main cost driver with almost 40% of cell material costs. The decline of cell prices will lead to more pressure on margins for cell manufacturing and cathode material suppliers, as they also need to invest more into: [152]

- Fast and more efficient production technologies and processes, especially for coating and cell assembly
- Development and research for new materials and optimization of material combinations

Due to the development and market launch of higher density NCM cathode material, which leads to higher specific cell energy, a cut in cathode material costs per cell, will lead to further price decrease till 2020, aiming for 25$/kWh. That would result in a cell price at about 180-200$/kWh in 2018 to 2020. Cell manufacturing is one of the most competitive business fields at the moment with high uncertainty how it will develop in the future. A strengthened market behavior from the competing companies will be inevitable and be driven by the following factors:[153]

- The large-format Li-Ion cell market will face overcapacity and price wars due to:
  - Price will continue falling form 250$/kWh to 180-200$/kWh till 2020
  - Already huge capacity with more efficient equipment
  - Lower demand than expected

[150] Bernhart, 2012
[151] NCM=Lithium nickel manganese cobalt oxide
[152] Cf. Pistoia, 2014, p. 561
[153] Cf. Pistoia, 2014, pp. 564–565

- Developments of new materials – mainly cathodes, anodes, electrolytes and separators – and new production technologies will drive costs down even further. However, these developments will require high financial investments to be brought to market maturity. With current margins, especially the early mover on the market cannot sustain the pressure over a longer period of time to stay a leap ahead.
- Only the large players and big joint ventures with the necessary financial background will be successful.

Excursus: The Influence of the Gigafactory to the Lithium Battery Value Chain

Back in 2013, Tesla and Panasonic announced their ongoing relation to the signed supply contract from 2011, which includes the production and delivery of approximately 2 billion 18650-series cells in the next 4 years. The 18650 cells are round cells, used by Tesla's Battery Electric Vehicles. In February 2014 Tesla announced to build an integrated battery factory, which would be the biggest factory ever built. This factory will include an annual capacity of 35 GWh and the electricity will be supplied entirely from renewable resources (solar and wind). The completion of that factory in 2017 will shake up the entire LiB cell market and will have a huge impact on the whole value chain. For example, in 2012, sold lithium-ion cells were approximately in the range of 40 GWh, of which just one eighth was used for automotive applications and mostly based on large format cells. As already mentioned, manufacturing costs for these EV cells are currently in the price range of $250/kWh.[154]

The Gigafactory could lead to a huge increase of the 18650-cells, also because Tesla is using them already. Due to their efficient cell production of cylindrical cells (explained in chapter 2.4.2), they own a more attractive cost range between $190/kWh and $200/kWh. Nethertheless, this also requires a more strategic battery management. The Gigafactory could also improve the cost benefit even more due to scale effects in overheads and investments with lowered energy costs. That could drop the price for cell production by another $30-$35/kWh and cell material by 10-12%, leading to a total cost benefit by $40-$45/kWh. This cost difference would set some real pressure on the market price, but could also lead to a slower pace of innovation of the industry – it would be just less attractive for material suppliers to improve cell chemistry. The second unknown will be the behavior of the other car OEMs, if there is one willing to adopt to 18650 round cells and become dependent on a competitor.[155]

[154] Cf. Bernhart, Schlick, Olschewski, Thoennes, & Garrelfs, 2014, p. 5
[155] Cf. Bernhart et al., 2014, p. 5

As shown in chapter 4.3, the battery itself adds up a huge impact to the total vehicle price. Exchanging such an expensive part due to lack of function or capacity losses would therefore lead to a big disadvantage in a cost perspective. The tool provides the possibility to exchange the battery in a total adjustable manner (adjustable costs and adjustable time). This simulates a battery exchange after the warranty has run out. Table 11 shows the time related cost allocation for variants 2 to variant 5. (Period under review = 8 years, Battery lifetime = 5 years). According to these boundary conditions the battery will be replaced every five years in each vehicle, but with different costs, due to different battery sizes. Variant 1 is a conventional powertrain with no battery.

Table 11: Battery exchange[156]

ECONOMICAL SPECIFICATIONS						
Country of operation		Germany	Germany	Germany	Germany	Germany
Number of units purchased	#	1	1	1	1	1
Period under review	years	8	8	8	8	8
Equity ratio for engine	%	100,00%	100,00%	100,00%	100,00%	100,00%
Equity ratio for infrastructue	%					
Write-off period for engine	years	5	5	5	5	5
Write-off period for infrastructure	years					
Interest rate on borrowed capital engine	%	5,00%	5,00%	5,00%	5,00%	5,00%
Interest rate on borrowed capital infrastructure	%					
Due date		At the end of the period	At the end of the period	At the end of the period	At the end of the period	At the end of the period
Imputed interest rate	%/year	3,00%	3,00%	3,00%	3,00%	3,00%
Rate of fuel price increase	%/year	3,10%	3,10%	3,10%	3,10%	3,10%
Rate of electricity price increase	%/year	1,20%	1,20%	1,20%	1,20%	1,20%
Battery costs	€	0	450	9000	1800	3500
Battery Lifetime	years	5	5	5	5	5
The calculation currency in this tool is Euro (€)						

[156] Own illustration

3.2.4 Incentives

The purchase of a vehicle could bring more costs in the early phase than expected. Extra features of the vehicle add up to the price, a potential home loading station like a wall box is maybe required or certain expanses need to be taken to get the vehicle road ready. However, there could also be some beneficial actions which can be taken to lower a certain tax on the vehicle or additional governmental subsidies to lower the purchase price. The following shows the incentives and possibilities related to the preparation phase to have a beneficial impact:[157]

- Purchase price reduction (private user): The investment or purchase price which has to be paid, is reduced once. In that case, 2 options are possible: One-time payment at the beginning of the lifecycle, at the start of "owning" the car – or - expected incentives in the future to assume a potential purchase of a vehicle in the coming years.
  The TCO tool only simulates the first option with immediate impact on payments.
- Lower interest rates for private drivers (private user): Private vehicle owners get a special loan with a decreased interest rate (Reduction of investment interest rate from 5% to 4% e. g.).
- Motor vehicle tax reduction (all vehicles): Currently all BEV's are exempted from motor related taxes. This political approach removes the engine displacement related tax.

Table 12 shows the purchase price reduction in the tool environment. These values for ever changing incentives need to be inserted by hand, according to the current situation and the governmental regulation of the observed country. Then the values are immediate subtracted from the purchase price. The shown values are just place holders.

Table 12: Incentives calculation[158]

Incentives Country specific							
Incentives	Dimension	Remarks	Brasil	China	Germany	India	Russia
Incentives	Euro		1.000,00	2.000,00	3.000,00	4.000,00	5.000,00

[157] Cf. Plötz et al., 2013, p. 19
[158] Own illustration

3.3 Operation Phase

The operation phase focuses on all occurring costs from the first usage until the vehicle breaks down or is sold. The main cost drivers for this phase are: vehicle taxes, energy consumption and maintenance & repair. The higher the costs in the operation phase are, the less important is the purchase price of a vehicle.

3.3.1 Vehicle Taxes

In addition to costs for energy consumption and costs for maintenance and repair, the Excel tool for this diploma thesis also considers the payment of engine related insurance tax. Although this detailed calculation option is only available for vehicles in the Austrian (considering the Austrian tax law) and German (considering the German tax law) market, it is still worth considering for other markets too. The implementation into the tool environment is shown in Table 14.

Austria:

Motor vehicles with a total weight up to 3.5 tons cause, additionally to the vehicle insurance tax, engine related insurance taxes. That is paid to insurance companies. The legal basis is the Austrian tax law from 1953 (VersStG) in its current version. The calculation basis for pure motor vehicles and hybrid electric vehicles is the power of the ICE (reduced by 24kW). All battery electric vehicles are therefore exclude from these taxes. The exact calculation scheme looks as follows[159]:

- Up to 24kW listed power: 0 € per kW
- For additional 66kW listed power: 0,62 € per kW
- For additional 20kW listed power: 0,66 € per kW
- For additional listed power: 0,75 € per kW

Example:
Motor vehicle 120 kW, annually payment of tax, new tax calculation since 01.03.2014:
Calculation basis: 120 kW - 24 kW = 96 kW
66 kW x 0,62 € = 40,92 €
20 kW x 0,66 € = 13,20 €
10 kW x 0,75 € = 7,50 €
That accounts for a total of 61,62 € per month or 739,44 € engine related insurance tax per year.

[159] Cf. BmF, 2016

Germany:

Different from Austria, Germany has introduced a CO_2 oriented approach (see Table 13). The annually tax is a combination of a displacement oriented value and a CO_2 related value. The following parameters influence the final amount:[160]

- Engine type (Otto, Diesel)
- Displacement (in cm^3)
- CO_2 Amount (g/km)

Table 13: Tax Calculation Germany[161]

Engine Type	Taxes with registration since 01.07.2009	Tax Exemption Limit
Otto	2,00€ per 100 cm³ + CO_2-award (2,00€ per g/km exceeding the tax limit)	1.07.2009-31.12.2011: 120 g/km 01.01.2012-31.12.2013: 110 g/km from 01.01.2014: 95 g/km
Diesel	9,50€ per 100 cm³ + CO_2-award (2,00€ per g/km exceeding the tax limit)	

Example:
Otto engine vehicle with $3000cm^3$ displacement and CO_2 emissions 109g/km, annually payment of tax, new tax calculation since 01.07.2009:
2€ x 30 + 2€ x (109g/km – 95g/km) = 88€ per year

Table 14: Calculation of country specific taxes[162]

COSTS INCURRED ENGINE RELATED TAX INSURANCE (JUST AT and DE)

Code	Forecasted lifecycle costs	Dimen-sion	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
T1	Tax insurance	€	286,67	509,83	137,42	0,00	0,00
	Power reference value	kW	120	92	199	99	99
	Country of Operation		Germany	Austria	Germany	India	Russia
	Fuel Type		Diesel	Gasoline	Gasoline	Diesel	Gasoline
T1.1a	Motorbezogene Versicherungssteuer (AT)	€/year	739,44	509,83	1.446,84	561,04	561,04
T1.1b	Kraftfahrzeugsteuer (DE)	€/year	286,67	78,89	137,42	254,67	72,46
	CO2 Emissions		109	109	109	93	104
	Displacment		2,72	2,54	5,47	2,72	2,72
T1.2	Compulsory liability insurance	€					
T1.3	Other Taxes	€					

160 Cf. Deutscher Bundestag, 2009
161 Cf. Deutscher Bundestag, 2009
162 Own illustration

3.3.2 Energy Consumption Calculation

The fuel consumption is built on two pillars. One is the already existing fuel consumption calculation by Sams[163]. This fuel consumption calculation is already implemented into the Excel environment and related to heavy duty engines for break specific fuel consumption in g/kWh. The other is the AVL internal based fuel consumption calculation with help from the system simulation tool AVL CRUISE. The task is to implement the idea and the parameters from the simulation study (Tank to Wheel=TTW) into the Excel environment, without removing or taking apart any functionality of the heavy duty calculation. Strictly speaking, the goal is to take an existing TCO tool, advance it and to keep both calculation capabilities; heavy duty calculations and electrified powertrain architecture calculations.

The TTW study describes several different fuel-powertrain configurations for conventional (“ICE-only”) as well as electrified (“xEV”) powertrain variants. These variants are considered for 2010 (with technologies from 2010-2012) and for 2020+, as a realistic forecast for future technical developments of passenger cars. This study is based on the expectations by experts from EUCAR[164] and AVL. All the fuel-powertrain configurations were investigated for fuel consumption, greenhouse gas (GHG) emission and electric energy consumption based on the New European Driving Cycle (NEDC). The reference vehicle will be from the C-Segment. All the conventional or xEV variants will be derived from this reference. The xEV variants include definitions of powertrain topologies and system architectures, educated estimations of hybrid functionalities and operational strategies, and powertrain components including optimized layout and detail mass balance. All the data and results in the following are calculated and simulated for the different powertrain variants in AVL CRUISE. However, none of these variants represent a real existing vehicle or a real brand. Figure 26 shows all different powertrain-fuel combinations. Combinations marked in blue are modeled in powertrain simulation in detail, whereas gray marked combinations are derived from them, based on their fuel properties.[165]

[163] Cf. Sams, 2015
[164] European Council for Automotive R&D
[165] Cf. Edwards et al., 2013, pp. 8–9

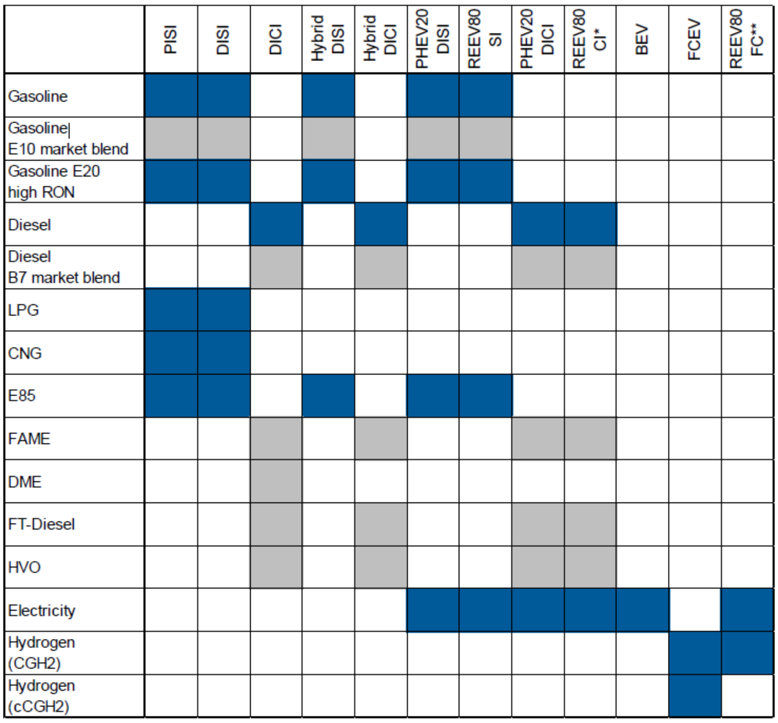


Figure 26: Matrix of fuel-powertrain combinations[166]

The different abbreviations in Figure 26 are explained in Table 15.

Table 15: Legend for Figure 26

Abbreviation	Definition	Abbreviation	Definition
CNG…	Compressed Natural Gas	PISI…	Port-Injection Spark Ignition
E85…	Ethanol	DISI…	Direct-Injection Spark Ignition
FAME…	Fatty Acid Methyl Esther	DICI…	Direct-Injection Compression
DME…	Dimethyl Ether	PHEV20…	Plug-In Hybrid; 20km electric driving range
FT-Diesel…	Fischer-Tropsch Synthese Diesel	REEV80…	Range Extended Electric Vehicle; 80km electric driving range
HVO…	Hydrotreated Vegetable Oil	BEV…	Battery Electric Vehicle
LPG…	Liquefied Petroleum Gas	FCEV…	Fuel Cell Electric Vehicle

[166] Cf. Edwards et al., 2013, p. 15

Due to the fact that within the scope of the practical part of this thesis not all combinations can be shown, Table 16 displays the reduced matrix with the most common applications.

Table 16: Powertrain configuration table for TCO tool

	DISI	DICI	Hybrid DISI	Hybrid DICI	PHEV20 DISI	PHEV20 DICI	BEV
Gasoline E10 Market Blend	✓		✓		✓		
Gasoline E20 high RON	✓		✓		✓		
Diesel B7 Market Blend		✓		✓		✓	
DME		✓					
FT-Diesel		✓		✓		✓	
Electricity					✓	✓	✓

DISI… Internal combustion engine with Direct-Injection Spark Ignition
DICI… Internal combustion engine with Direct-Injection Compression Ignition
PHEV20… Plug-In Hybrid Electric Vehicle with 20 miles pure electric driving
BEV… Battery Electric Vehicle

Next, the operational strategies, which can be fulfilled by the study's xEVs are defined. Since all the necessary theoretical knowledge has been provided in chapter 2.5, Figure 14 only shows which powertrain can provide which functionality. A quick review of the different operational strategies is done afterwards.

Table 17: Implemented operational strategies for xEVs[167]

xEV Operational Strategies	HEV	PHEV	BEV
Start & Stop	✓	✓	
Regenerative Braking	✓	✓	✓
ICE Off Mode	✓	✓	
ICE Load Point Moving	✓	✓	
ICE Only Mode	✓	✓	
Battery Assistance	✓	✓	

The different operational strategies are influenced by the driver and a consequence of his behavior and the vehicle status:

- ***Start & Stop*** is activated, if the vehicle is at standstill and the ICE temperature is above a certain limit.
- ***Regenerative Braking*** is activated in case of a negative torque request by the driver. In case of HEV and PHEV variants, the ICE is disengaged by opening its

[167] Cf. Edwards et al., 2013, p. 17; adapted by the author

separation clutch or switched off in case of warm condition. Traditional brakes are still enabled during heavy braking. Both the points $dec_{veh,1}$ and $dec_{veh,2}$ defines the braking ratio between pure regenerative braking (torque split=1) and pure traditional braking, shown in Figure 27. For the NEDC, no restrictions in regenerative braking are observed due to lack of braking actions.[168]

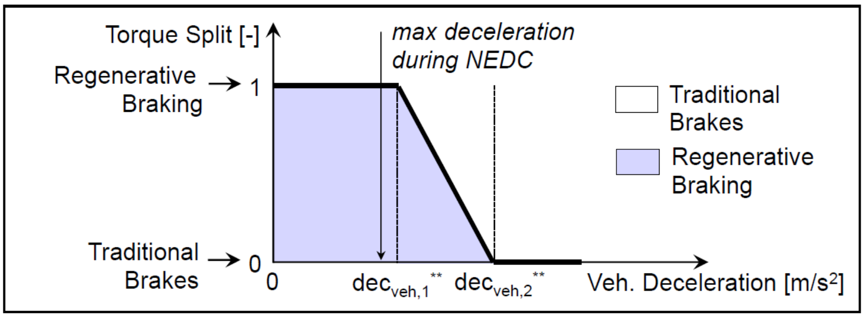


Figure 27: Regenerative Braking[169]

- ***ICE Off Mode*** is activated when the vehicle is driving purely with the energy from the battery.
- ***ICE Load Point Moving*** is activated when the electric engine artificially rises the load point to let the internal combustion operate in a more economic state.
- ***ICE Only*** is activated when the vehicle is getting the power only from the internal combustion engine.
- ***Battery Assistance*** is activated in case of a full load request by the driver. Assuming that enough battery energy is available. This mode is linearly enabled, shown in Figure 28. The battery energy gets available as soon as the point $APP_{bst,on}$ (Acceleration Pedal Position) is reached. This point is calibrated and usually close to 100%, which means a nearly full load request. Although this function is not active during the NEDC, it is necessary to assess the power of a vehicle at full load request.[170]

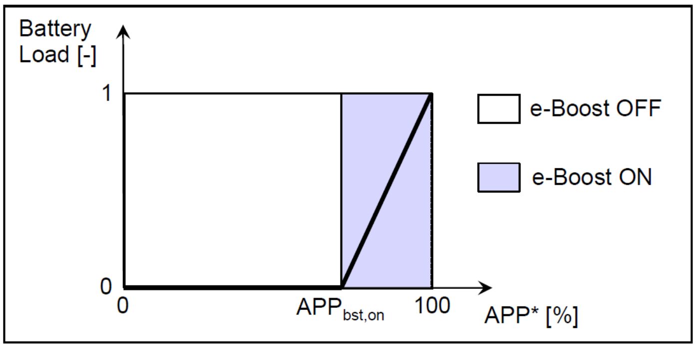


Figure 28: Battery Assistance[171]

[168] Cf. Edwards et al., 2013, p. 16
[169] Edwards et al., 2013, p. 16
[170] Cf. Edwards et al., 2013, p. 17
[171] Edwards et al., 2013, p. 17

AVL CRUISE as Simulation Environment

AVL Cruise is a system simulation tool for vehicle and powertrain systems. It supports everyday tasks for analyzing vehicle systems and drivetrains in all vehicle and powertrain development phases. The tool environment covers various powertrain architectures, from pure conventional to highly-advanced hybrid drive trains and pure electric vehicles. The modeling library provides mechanical powertrain components, hybrid electric components like battery and e-machine, vehicle, driver, test track and freely designable simulation cases like certain test cycles and performance tasks. Therefore it's the best fit to provide proven results for the simulation of powertrain configurations.[172]

To compare different vehicles and their fuel consumption, a comparable base needs to be defined in terms of setup, driving behavior and speed characteristics. The results are fuel consumption and CO_2 emissions. For that reason certain driving procedures and cycles have been invented. For this simulation, the New European Driving Cycle (NEDC) has been the testing procedure. Figure 29 illustrates the sequence of the NEDC.

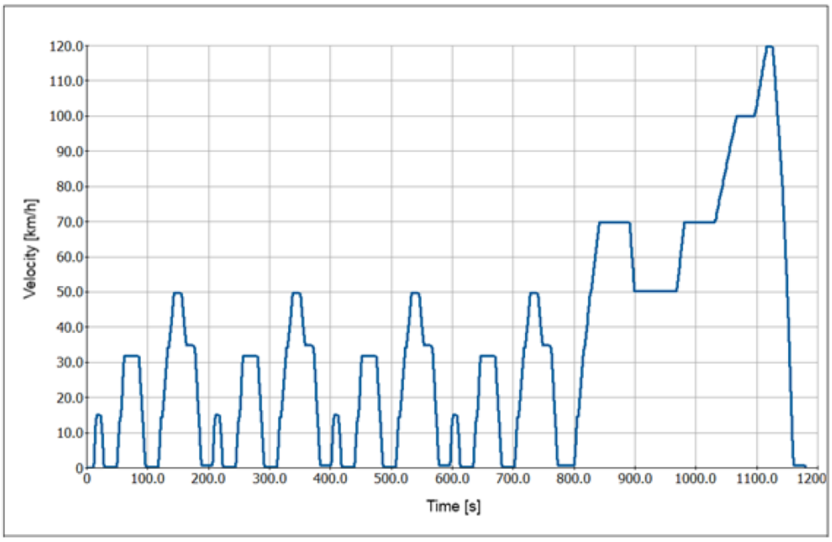


Figure 29: Velocity profile of the New European Driving Cycle (NEDC)[173]

The NEDC is a defined driving cycle by the European legislation – ECE R 83. For a driving cycle several characteristics have an impact on the outcome: starting temperature, gear shifting points, vehicle pre-conditioning, loading and start of exhaust gas measurements. Usually these cycles are driven on test benches to make results

[172] Cf. Edwards et al., 2013, p. 20
[173] Edwards et al., 2013, p. 20

reproducible and comparable. However, in case of the usage of a PHEV, new regulations need to be found and set due to the loading of the battery and the battery usage characteristics. For this reason the European legislation considers the evaluation of the fuel consumption (FC_{cert}) of a PHEV with intermittent ICE use. Both the charge depleting (CD) and the charge sustaining (CS) modes get weighted.[174] The NEDC for PHEVs is shown in Figure 30.

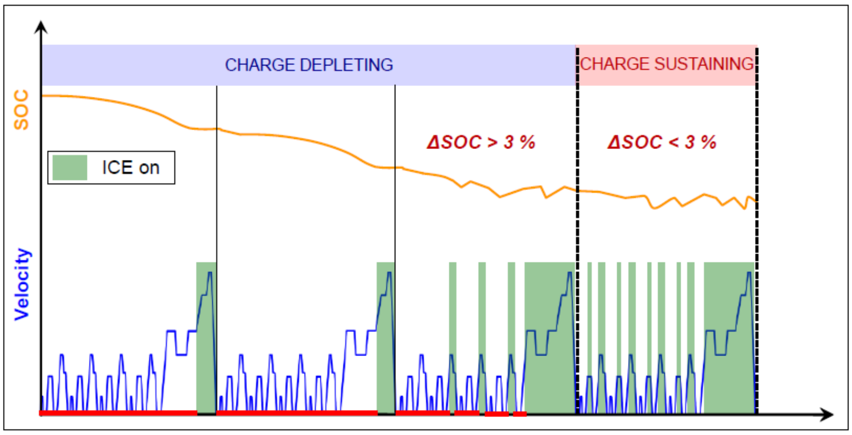


Figure 30: PHEV fuel consumption based on UN ECE R 101[175]

The fuel consumption is calculated is shown in Equation 2.

Equation 2: Fuel Consumption Calculation for PHEVs

$$FC_{Cert.} = \frac{D_{ovc} * FC_{ovc} + 25 * FC_{CS}}{D_{ovc} + 25}$$

FC_{OVC}: Fuel consumption during Charge Depleting
FC_{CS}: Fuel consumption during Charge Sustaining
D_{OVC}: Total electric range during Charge Depleting (red)

[174] Cf. Edwards et al., 2013, p. 20
[175] Edwards et al., 2013, p. 21

The different simulation results are related to the reference vehicle, a C-segment vehicle, and follow the specifications listed in Table 18.

Table 18: Characteristics of a generic C-segment vehicle[176]

Generic C-segment reference vehicle DISI ICE (2010)		
Curb weight	kg	1235
Inertia test weight	kg	1360
Length	mm	4326,5
Width	mm	1789,4
Height	mm	1484,8
Cross-sectional area	m2	2,2
Air drag coefficient	-	0,30
Rolling resistance coefficient	-	0,007
Wheel base	mm	2638,9
Height of gravity center	mm	600
Distance of gravity center from front axle	mm	1200
Dynamic rolling radius	mm	309

The calculation is done with values from 2010, since future developments are simulated through different scenarios in the later chapters. Table 19 presents the results for the different variants in 2010. Only the shown fuels are used for the calculation.

[176] Cf. Edwards et al., 2013, p. 11; adapted by the author

Table 19: Simulation results for electrified variants 2010[177]

2010 Variants	Curb Weight	Fuel Tank Capacity	Fuel Consumption			El. Energy Consumption w/o charging losses	El. Energy Consumption with charging losses
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km
DISI, ICE Only, 2010							
Gasoline	1310	55	203,8	6,33	4,72	#	#
LPG	1380	80	207,8	8,22	4,52	#	#
CNG	1450	150	211,8	#	4,7	#	#
E85	1310	55	198,6	8,67	6,81	#	#
DICI, ICE Only, 2010							
Diesel	1370	55	162,5	4,53	3,77	#	#
FAME	1370	55	162,5	4,91	4,37	#	#
HVO	1370	55	162,5	4,73	3,69	#	#
Hybrid DISI, 2010							
Gasoline	1417	55	141,7	4,44	3,28	#	#
LPG	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#
E85	1417	55	138,1	6,03	4,74	#	#
Hybrid DICI, 2010							
Diesel	1477	55	128	3,6	2,97	#	#
FAME	1477	55	128	3,87	3,44	#	#
HVO	1477	55	128	3,73	2,91	#	#
PHEV DISI, 2010							
Gasoline	1479	55	101,2	3,17	2,34	3,12	4,07
LPG	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#
E85	1479	55	98,6	4,3	3,38	3,12	4,07
PHEV DICI, 2010							
Diesel	1539	55	91,6	2,57	2,12	3,17	4,14
FAME	1539	55	91,6	2,77	2,46	3,17	4,14
HVO	1539	55	91,6	2,67	2,08	3,17	4,14
BEV 2010 Single Stage Transmission, 2010							
Electricity	1365	#	#	#	#	11,38	14,49

Yet to mention that the start and stop approach has not been included into these values, but still the values reflect the 2010 EU C-segment average.

The following result tables will represent the xEV variants for electric energy consumption with both considering battery charging losses and not considering them. Due to the UNECE R101 the charging losses have to be included for all Plug-in vehicles.

[177] Edwards et al., 2013, p. 31; adapted by the author

The Fuel Consumption Calculation integrated in the TCO tool

It has been shown where the inserts for the TCO tool come from and which strategies and fuel types influence the fuel consumption. Now the values will be implemented into the tool. But first of all, the tool surface gets introduced with the ongoing calculations behind it.

Table 20: TCO tool fuel consumption calculation (direct)[178]

Engine variant		Data taken from the LCC configuration sheet		Unit	Data taken from the LCC configuration sheet			Total annual fuel consumption	Total annual urea consumption	Annual fuel costs	Annual Urea costs	Total fluid costs over engine lifetime
								kg/yr bzw. kWh/yr	kg/yr	€	€	€
VARIANT 1	ICE	Power	92	kW	Displacement	1,40	l	747,88	0	1.234,01	0	9.872,06
		Energy	Gasoline	#	Operating hours	4000,00	h/yr					
		Consumption Direct Input	yes	#	Rated speed	1800,00	rpm					
		Consumption Direct	5,30	kg/100km	BMEP at rated	24,20	bar					
		Mileage	14111	km	Fuel	Gasoline	kg					
Conventional ICE	Battery	Power	0,00	kWh	Hybrid Rate Fuel	100%	%	0,00		0,00		0,00
		Energy	Electricity	#	Hybrid Rate Elec.	0%	%					
		Consumption Direct Input	yes	#								
		Consumption Direct	0,00	kWh/100km								
		Mileage	0	km								
											Summe	9.872,06
VARIANT 3	ICE	Leistung	235,00	kW	Displacement	5,47	l	0,00	0	0,00	0	0,00
		Energy	Diesel	#	Operating hours	4000,00	h/yr					
		Verbrauch Direkteingabe	yes	#	Rated speed	1800,00	rpm					
		Verbrauch Direkt=	0,00	kg/100km	BMEP at rated	24,20	bar					
		Laufleistung	0	km	Fuel	Diesel	kg					
BEV e-Range 400km	Battery	Leistung	60,00	kWh	Hybrid Rate Fuel	0%	%	2.116,65		529,16		4.233,30
		Energy	Electricity	#	Hybrid Rate Elec.	100%	%					
		Verbrauch Direkteingabe	yes	#								
		Verbrauch Direkt=	15,00	kWh/100km								
		Laufleistung	14111	km								
											Summe	4.233,30

Table 20 illustrates the fuel consumption calculation from the tool. The TCO tool will have the ability to calculate the fuel consumption in two different ways. The first option will provide the possibility to directly input the fuel consumption in kg/100km.

Equation 3: Annual fuel consumption calculation

$$AFC = FC_{direct} * \frac{(KM_{year} * Hybrid\ Rate\ Fuel)}{100}$$

AFC…	Annual fuel consumption [kg/year]
FC_{direct}…	Fuel consumption direct [kg/100km]
KM_{year}…	Driven km per year [km]
Hybrid Rate Fuel…	Describes the ratio between pure electric driving and pure ICE use (100% means just ICE use) [%]

[178] Own illustration

The TCO tool can display pure ICEs, BEVs and hybrids of both – PHEVs and HEVs. To simulate these conditions the tool provides two ratio regulators (Hybrid Rate Fuel, Hybrid Rate Electric). That means by inserting a Hybrid Rate Fuel of 70%, the tool would assume, that 70% of the mileage is driven purely on ICE and 30% purely with electricity. This is also shown in comparison from Variant 1 to Variant 2, as Variant 1 is a conventional Diesel (only fuel costs) and Variant 2 is a BEV (only costs for electricity).

The second approach calculates the consumption through the BSFC (Brake Specific Fuel Consumption) measured in different load points.

Table 21: TCO tool fuel consumption calculation (BSFC)[179]

Average load factor	Operating points	Time in %	BSFC	BTE	LHV	NOx EO	NOx TP	Alpha	Specific Urea consumption	Power	BMEP	Time absolut	Annual fuel consumption in operating points	Annual Urea consumption in operating points
%	%	%	g/kWh	%	MJ/kg	g/kWh	g/kWh		g/kWh	kW	bar	h/yr	kg/yr	kg/yr
≤ 75 %	100,00%	38,00%	188,80	0		10,00	0,50	1,0000	19,10	99	24,20	1520	28.364	2.869
	75,00%	38,00%	190,40	0					0,00	74	18,15	1520	21.453	-
	50,00%	14,00%	194,30	0					0,00	49	12,10	560	5.377	-
	25,00%	5,00%	215,10	0					0,00	25	6,05	200	1.063	-
	10,00%	5,00%	271,40	0					0,00	10	2,42	200	536	-

The urea and fuel consumption calculation is a carryover. It is focused on the consumption calculation for heavy duty machinery, which is also shown by providing average load factor parameters. In fact that could provide another calculation approach with load point calculation for the TCO tool.[180]

[179] Own illustration
[180] Cf. Sams, 2015

3.3.3 Maintenance & Repair

The higher purchase price and the lower running costs, like fuel usage and payments for electricity of electrified drivetrains require a life cycle perspective with total coast approach when comparing them to conventional ICEs. In addition to that, a big advantage of electrified drivetrains lies in the far less maintenance intensive drivetrain components, due to less complex parts (ICE vs. Electric machine). Nevertheless, previous studies on life cycle perspectives on different drivetrains have neglected on maintenance and repair costs[181]. Therefore this thesis also puts maintenance and repair costs (M&R) into perspective.

The M&R approach will follow the studies of Propfe et. al. . M&R costs are estimated on a component level and differentiated by powertrain type and vehicle size, depending on mileage and mean times between failures (MTBF). [182] A Failure declares a condition where a certain unit is not working appropriately anymore, according to its required functions. The failure rate λ expresses the probability, when a component will fail in a given time frame. Therefore it's a measure of reliability and is given in 1/h.[183] The reciprocal of the failure rate λ indicates how much time to failure goes by. For maintainable equipment the abbreviation MTBF is used – mean time between failures – and indicates the time between 2 failures. MTTF – mean time to failure – indicates the time to the final failure, the equipment is therefore not maintainable anymore.[184]

The already mentioned model for different powertrains will evaluate the M&R costs in €/km and will differentiate between scheduled and unscheduled maintenance. The basement for vehicle size will be medium (C-segment). Based on the MTTF/MTBF approach 31 drivetrain components – ranging from spark plugs to Li-Ion batteries - have been investigated in terms of component costs and required labor input (labor base is Germany) for replacing the components. The vehicles are defined by the type of powertrain, vehicle size, battery size, shares of Charge Depleting vs. Charge Sustaining (as shown in Figure 30) driving including regenerative braking and the output power and energy provided by ICE and E-motor.

[181] Cf. Graham, 2001; Delucchi & Lipman, 2001; Delucchi & Lipman, 2006; van Vliet, Kruithof, Turkenburg, & Faaij, 2010; Ruth, Timbario, & Laffen, 2011
[182] Cf. Propfe, Redelbach, Santini, & Friedrich, 2012
[183] Cf. Kiel, 2007, p. 256
[184] Cf. Kiel, 2007, p. 256

Hence the costs for M&R $C_{M\&R}$ can be expressed as function of the MTBF, the replacement costs of spare parts C_i, the time it takes to replace the spare parts T_i and the corresponding labor costs C_{labor}. The calculation for all types of powertrain j and vehicle sizes k can be summarized to Equation 4.

Equation 4: Maintenance and repair costs[185]

$$C_{M\&R,j,k} = \sum_{i=1}^{n=31} MTBF_{i,j,k} * \left(C_{i,j,k} + T_{i,j,k} + C_{labor}\right) \forall j,k$$

Costs and MTBFs for spare parts are taken from the ADAC database[186]. For hybrid drivetrains these values have been adjusted according to their CS and CD share and their regenerative to conventional braking ratio, as shown in Figure 27. For all the new parts, such as Li-Ion batteries, power electronics or electric motors, individual costs and MTBFs have been incorporated. For the Li-Ion batteries e.g., MTBF have been calculated with a lifetime model, which was developed for this reason. MTBF is result driven by the following parameters: driving range, SOC (state of charge) limits of the battery and the number of cells connected in parallel or in series. The real driving profiles of the Mobility in Germany database were used.[187]

The results for the maintenance and repair costs are shown in Figure 31 based on the following assumption. All the calculations focus on the middle segment and try to compare costs of electrified powertrains to conventional ones. The figure also shows that electrified powertrain architectures are estimated to have lower maintenance and repair costs than conventional architectures due to less amount of mechanical parts and therefore less wear.[188] These assumptions were considered as most suitable for the TCO tool implementation and will serve the tool's demand the best.

[185] Propfe et al., 2012, p. 3
[186] Cf. Allgemeiner Deutscher Automobil-Club, 2010-2011
[187] Cf. Institut für angewandte Sozialwissenschaft GmbH, 2010
[188] Cf. Propfe et al., 2012, pp. 4–5

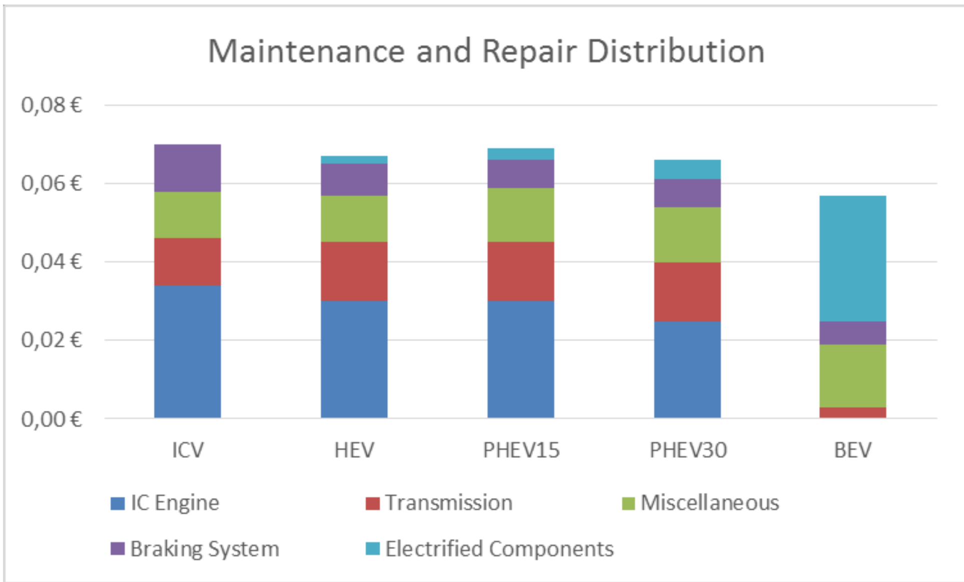


Figure 31: Distribution of Maintenance and Repair Costs[189]

ICV… Vehicle with an Internal Combustion Engine
HEV... Hybrid Electric Vehicle
PHEV15… Plug-In Hybrid Electric Vehicle with 15 miles electric driving range
PHEV30… Plug-In Hybrid Electric Vehicle with 30 miles electric driving range
BEV… Battery Electric Vehicle

Table 22 shows the implementation of the described context into the Excel environment.

Table 22: Preventive maintenance calculation[190]

PREVENTIVE MAINTENANCE PROCEDURES									
			Please select your type of preventive maintenance procedure	Preventive maintenance/ IMO task (Maintenance or inspection task)	Part or assembly	Used parts / article number	Number of assemblies / parts per assembly	Totals for the viewed assemblies/parts for all machines	Interval
			[Classification]	[Description]	[Name]		[Quantity]	[Quantity]	[km]
VARIANT 1	Conventional Diesel								
km per year	15.000		Inspection	Check thickness of oil residue layer.	Centrifugal oil filter		2	2	10.000
M&R €/km	0,068		Maintenance	Fit new fuel injectors	fuel injector		3	3	6.000
M&R calculation acc. Dexheimer(2003)	yes	No →	Overhaul					0	
			General overhaul	Downtime for all the following tasks entered only once			1	1	24.000
				Fit new piston rings			5	5	24.000
	Yes ↓			Fit new conrod bearings			10	10	24.000
				Fit new crankshaft bearings			5	5	24.000
Total M&R Costs	1.013			Fit new cylinder liners			8	8	24.000
				Fit new fuel delivery pump			5	5	24.000
								0	

By setting the dropdown parameters to “yes”, the tool calculates the maintenance and repair costs on the basis of the calculations of Dexheimer and Propfe. The only requirement is to insert the correct M&R €/km value from Figure 31 and according to the powertrain type. For a more detailed calculation, the dropdown can also be set to “no”, which requires a more detailed input procedure by the user. All kind of different

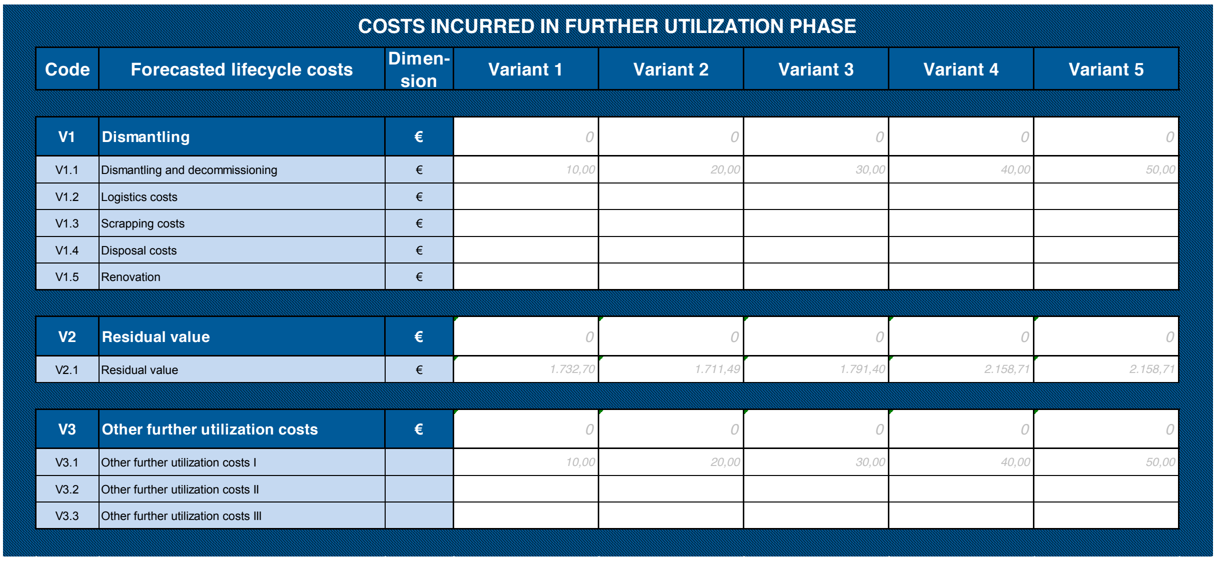
[189] Cf. Propfe et al., 2012, p. 4; adapted by the author
[190] Own illustration

service and M&R procedures can be simulated (e.g. oil exchange every 15000km, small service every 20000km, big service every 50000km etc.). Also the service intervals (in km) as well as the costs, amount of service personnel, duration of maintenance, costs of personnel per hour etc. are required to be inserted.[191]

[191] Cf. Sams, 2015

3.4 Further Utilization Phase

The further utilization phase concentrates on life cycle related actions, which happen after the end of usage. This could be recycling, dismantling or reselling. The tool offers three different approaches to relate costs to this phase; resale value calculation, dismantling and other utilization costs. But only a detailed resale value calculation for electrified powertrains makes sense. To calculate costs for dismantling and further utilization costs lump sums can be used (shown in Figure 32).


COSTS INCURRED IN FURTHER UTILIZATION PHASE

Code	Forecasted lifecycle costs	Dimen-sion	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
V1	Dismantling	€	0	0	0	0	0
V1.1	Dismantling and decommissioning	€	10,00	20,00	30,00	40,00	50,00
V1.2	Logistics costs	€					
V1.3	Scrapping costs	€					
V1.4	Disposal costs	€					
V1.5	Renovation	€					
V2	Residual value	€	0	0	0	0	0
V2.1	Residual value	€	1.732,70	1.711,49	1.791,40	2.158,71	2.158,71
V3	Other further utilization costs	€	0	0	0	0	0
V3.1	Other further utilization costs I		10,00	20,00	30,00	40,00	50,00
V3.2	Other further utilization costs II						
V3.3	Other further utilization costs III						

Figure 32: Further utilization phase cost parameters[192]

Resale Value

Assessing a vehicle's total cost of ownership costs not only means taking maintenance and repair costs into account but also considering resale values. For example in Germany the resale value accounts for 36% of the initial purchase price.[193] That's especially true for industrial purpose because of the short holding periods[194]. The following calculation approach for resale values of vehicles has been created by a study of the "*Statistisches Bundesamt*". Yet to mention, that the original calculation approach was introduced in 2003[195]. However, the depreciation is calculated with multiple influencing factors – age, mileage and initial purchase price are the most important ones.

[192] Own illustration
[193] Cf. Propfe et al., 2012, p. 5
[194] Cf. NPE, 2011
[195] Cf. Dexheimer, 2003; Linz, Dexheimer, & Kathe

The calculation of the resale value for the TCO excel model is shown in Equation 5.

Equation 5: Residual value equation[196]

$$RV_{fs} = e^{\alpha} * e^{12*\beta_1*\alpha} * e^{\frac{\beta_2}{12}*AMA_f} * \left(NLP_{r,s,t} + \kappa_{r,s,t} + p_{Batt_{s,t}}\right)^{\beta_3} * (1+VAT)_f$$

RV_{fs}: Resale Value of type s and driving profile f
α: Age of vehicle
AMA_f: Annual mileage of driving profile f
$NLP_{r,s,t}$: Net list price of a vehicle with size r, type s, without battery in year t
$\kappa_{r,s,t}$: Capacity of battery of vehicle with size r, type s in year t
$P_{Batt\ s,t}$: Battery price of a vehicle of type s in the year t
$(1+VAT)_f$: Factor for considering value added tax

The parameters are summed up in Table 23.

Table 23: Parameters for resale value calculation[197]

Variable	Parameter	Value	Standard Deviation
Age	β_1	$-1{,}437*10^{-2}$	$2{,}79*10^{-6}$
Monthly mileage	β_2	$-1{,}17*10^{-4}$	$6{,}13*10^{-7}$
ln(Initial Price)	β_3	0,91569	$4{,}42*10^{-4}$
Constant	α	0,97948	$3{,}60*10^{-3}$

196 Plötz et al., 2013, p. 46
197 Cf. Dexheimer, 2003, p. 7; adapted by the author

For a fixed initial price and different mileage the graph could look as the following.

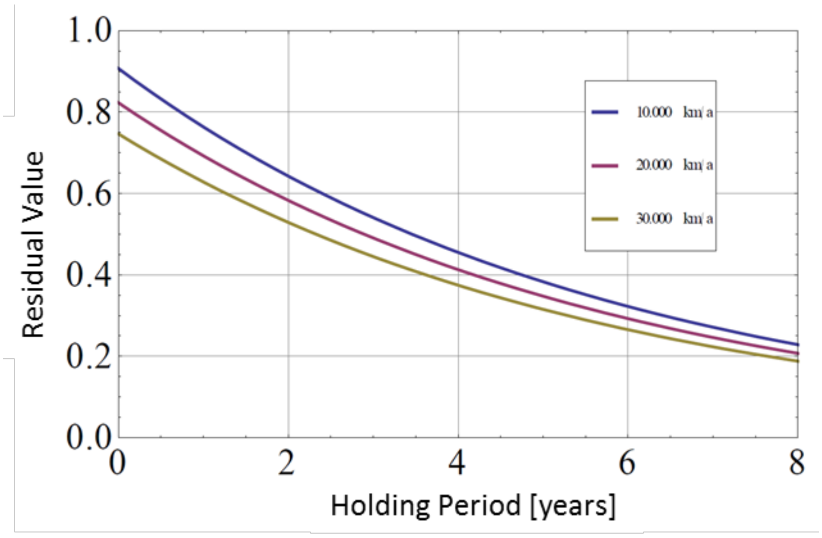


Figure 33: Resale value calculation[198]

This calculation approach has also been used by Kreyenberg (2015). The only difference is the usage of fixed parameters. Kreyenberg used the original formula from Dexheimer (2003), where also different vehicle brands, variable parameters according to vehicle type and certain coefficient estimators where used[199].

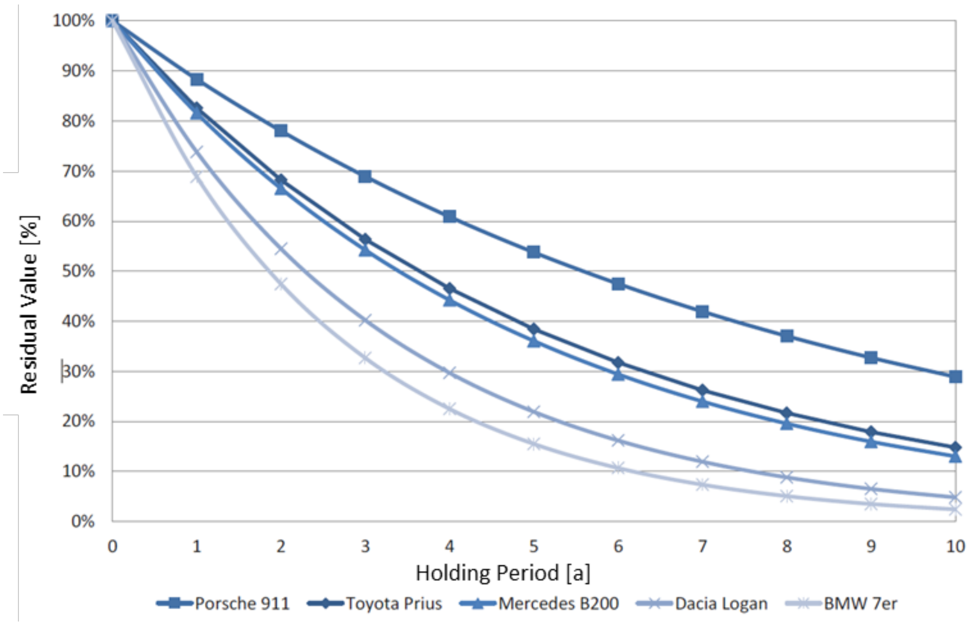


Figure 34: Regression of vehicle resale values with annual mileage of 14111 km[200]

Nevertheless the author has decided to keep using fixed parameters as shown in Table 23 due to two reasons. The first reason is, that it would exceed limits of effort to always

198 Cf. Plötz et al., 2013, p. 45; translated by the author
199 Cf. Dexheimer, 2003, p. 6; Kreyenberg, 2016, p. 57
200 Cf. Kreyenberg, 2016, p. 57; adapted by the author; 14111km is the average annual mileage of a German vehicle user according to a study of Mobilität in Deutschland (MiD)

export the different data from the ADAC data bank[201] and the second reason is, that data for alternative powertrain architectures is still rare to get or just not available. Table 24 illustrates depreciation in the value for the different powertrain architectures. The considered parameters for the calculation, initial price and annual mileage, are also shown as well as the fixed parameters already mentioned.

Table 24: Calculation of resale values[202]

Resale Values over Lifetime												
	Parameter			α= 0,97948		β1= -0,01437		β2= -0,000117		β3= 0,91569		
Variant	Influencing Data			Timeline								
				0	1	2	3	4	5	6	7	8
Variant 1	Initial Price	19.352	Resale Value €	19.352	16.304	13.721	11.548	9.719	8.180	6.884	5.794	4.876
	Annual Mileage	15.000	Resale Value %	100%	84%	71%	60%	50%	42%	36%	30%	25%
Variant 2	Initial Price	17.165	Resale Value €	17.165	16.104	13.554	11.407	9.600	8.079	6.800	5.723	4.816
	Annual Mileage	5.000	Resale Value %	100%	94%	79%	66%	56%	47%	40%	33%	28%
Variant 3	Initial Price	18.042	Resale Value €	18.042	16.856	14.186	11.939	10.048	8.457	7.117	5.990	5.041
	Annual Mileage	5.000	Resale Value %	100%	93%	79%	66%	56%	47%	39%	33%	28%
Variant 4	Initial Price	22.118	Resale Value €	22.118	20.312	17.095	14.387	12.109	10.191	8.577	7.218	6.075
	Annual Mileage	5.000	Resale Value %	100%	92%	77%	65%	55%	46%	39%	33%	27%
Variant 5	Initial Price	22.118	Resale Value €	22.118	20.312	17.095	14.387	12.109	10.191	8.577	7.218	6.075
	Annual Mileage	5.000	Resale Value %	100%	92%	77%	65%	55%	46%	39%	33%	27%

In addition, Figure 35 shows the fall of value in five years graphically.

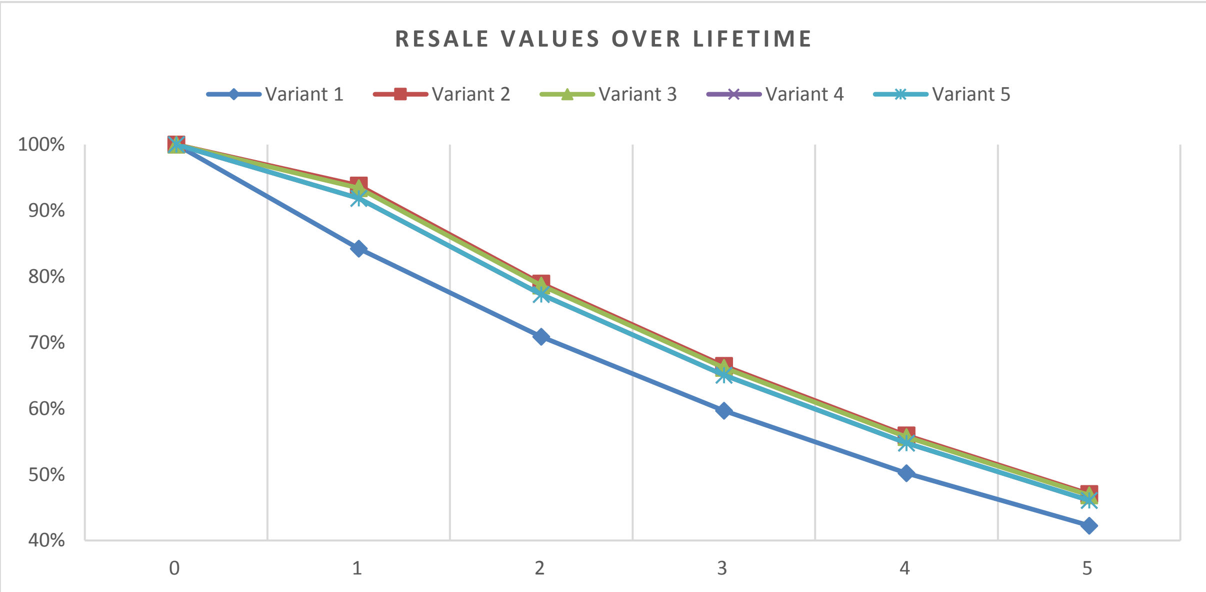


Figure 35: Illustration of resale values over lifetime[203]

[201] Cf. Allgemeiner Deutscher Automobil-Club, 2010-2011
[202] Own illustration
[203] Own illustration

3.5 TCO Input Data

The TCO configuration sheet is the first input interface the user comes in contact with, when starting the excel tool. All the different adjustable options define the boundary conditions of the grade of detail of the TCO tool. The input interface is divided into three different sub categories: technical specifications, economical specifications and specifications for the complexity of the TCO tool. All the different parameters for technical and economical specification are self-explaining or have already been explained in the recent chapters. Coming to the specifications for complexity and detail grade, this is where the real differences between a fast and straight forward calculation and a detailed and complex total cost perspective occurs. While setting one of the dropdowns to “no” still calculates costs with the given parameters, they are not taken into consideration for the TCO. However, when setting the dropdowns to “yes”, it’s the user’s responsibility to consider the influencing factors, which come along with that (considering fuel costs also means to think of the right values for mileage, diesel and gasoline prices and fuel consumption for the determined powertrain architecture) and to adjust them. The TCO input interface is shown in Figure 36.

FORECASTING THE TOTAL COST OF OWNERSHIP (TCO) - MAIN SPECIFICATION OF THE VARIANTS AND MODEL

Step	Topic	Dimension	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
1.)	**BRIEF DESCRIPTION** in written form		BEV	Conventional Gas	BEV	PHEV Diesel	PHEV Gas
2.)	**TECHNICAL SPECIFICATIONS**						
	Powertrain Architecture		Conventional	Conventional	BEV	PHEV20	PHEV20
	Energy 1		Diesel	Gasoline	Gasoline	Diesel	Gasoline
	Energy 2 (only for HEV, PHEV and BEV)		Electricity	Electricity	Electricity	Electricity	Electricity
	Rated power	kW	120	92	199	99	99
	Driven km per year (for direct input calculation)	km	15000	5000	5000	5000	5000
	Operation hours per year (for BSFC calculation)	h	4000	4000	5	4000	4000
	Hybrid Rate Fuel	%	0%	100%	0%	96%	96%
	Hybrid Rate Electricity	%	100%	0%	100%	4%	4%
	Additional information for better overview and understanding:						
3.)	**ECONOMICAL SPECIFICATIONS**						
	Country of operation		Germany	Austria	Germany	India	Russia
	Number of units purchased	#	1	1	1	1	1
	Period under review	years	14	14	14	14	14
	Equity ratio for engine	%	100,00%	100,00%	100,00%	100,00%	100,00%
	Equity ratio for infrastructue	%					
	Write-off period for engine	years	5	5	5	5	5
	Write-off period for infrastructure	years					
	Interest rate on borrowed capital engine	%	5,00%	5,00%	5,00%	5,00%	5,00%
	Interest rate on borrowed capital infrastructure	%					
	Due date		At the end of the period	At the end of the period	At the end of the period	At the end of the period	At the end of the period
	Imputed interest rate	%/year	3,00%	3,00%	3,00%	3,00%	3,00%
	Rate of fuel price increase	%/year	7,00%	7,00%	7,00%	7,00%	7,00%
	Rate of electricity price increase	%/year	7,00%	7,00%	7,00%	7,00%	7,00%
	Battery costs	€	3500	2000	3000	4000	5000
	Battery Lifetime	years	4	2	5	2	2
	The calculation currency in this tool is Euro (€)						

4.)	**SPECIFICATION OF THE TCO MODEL**	Possibility of activating different lifecycle phases and costs for further calculation: yes / no					
Lifecycle phase	**Forecasted lifecycle costs**	**Abbreviation**	**Variant 1**	**Variant 2**	**Variant 3**	**Variant 4**	**Variant 5**
Preparation	Procurement costs	P1	yes	yes	yes	yes	yes
	Infrastructure Costs	P2	no	no	no	no	no
	Application, installation and start-up costs	P3	no	no	no	no	no
	Home Loading Station	P4	yes	no	yes	no	no
	Incentives	P5	yes	yes	yes	yes	yes
	Other preparation costs	P6	no	no	no	no	no
Operation	Energy costs (Fuel + Electricity)	FC	yes	yes	yes	yes	yes
	Urea costs	UC	yes	yes	yes	yes	yes
	Production and process materials	PPM	no	no	no	no	no
	Preventive Maintenance	PMP	no	no	no	no	no
	Unscheduled repairs	UR	no	no	no	no	no
	Disposal and penalty costs	DPC	no	no	no	no	no
	Personnel costs (additional)	PC	no	no	no	no	no
	Interest costs for engine	ICE	no	no	no	no	no
	Interest costs for infrastructure	ICI	no	no	no	no	no
	Vehicle Tax	VT	yes	yes	yes	yes	yes
	Battery Replacement	BR	yes	no	no	no	no
	Other operating costs	OOC	no	no	no	no	no
Further utilization	Dismantling	F1	no	no	no	no	no
	Residual value	F2	no	no	no	no	no
	Other further utilization costs	F3	no	no	no	no	no

Figure 36: TCO configuration input mask[204]

[204] Own illustration

4 Practical Scenario

In this chapter the final result of this thesis is presented. Four different electrified powertrain architectures by means of their TCO over a set holding period with help of the established TCO Excel tool are compared. These four powertrains are referred to a conventional vehicle with no electrification at all and an internal combustion engine. The result of the calculation should proof, if an electrification pays off or not. A C-segment vehicle with an initial price of 25.000€ serves as reference vehicle. The costs for different electric measures are based on the changes in the bill of material. They are added up the 25.000€. This only makes a difference for the total cost perspective, since this vehicle basement cost gets cancelled for the Delta-Cost approach.

In the first step, the results for the three scenarios with relation to the holding period are introduced. The different technologies and their cost development are compared to each other along the holding period of eight years. Additionally, total costs per life cycle phase are compared to each other to illustrate the cost difference in relation to the preparation phase, operation phase and further utilization phase.

In the second step, each cost segment of a powertrain's technology in relation to the reference vehicle is illustrated. These results will not only show the potential TCO gap at the end of the holding period of eight years, but clearly determines how these TCO gap cumulates within the different cost segments.

4.1 Initial Situation and Boundary Conditions

Altogether five different powertrain architectures are investigated. The first variant, an only ICE driven vehicle, still represents the most common solution on the market. However, also the four vehicles with different degrees of electrification are offered by various OEMs and retailers. The vehicle parameters follow the values in Edwards et al.'s study and relate to the C-segment. The different architectures are:

- A conventional vehicle with only an internal combustion engine and no electrification, in the following Conventional ICE.
- A Mild Hybrid Electric Vehicle with additional 48V electrical on-board system with a belt starter generator (BSG), in the following MHEV 48V BSG.
- A Battery Electric Vehicle with an electric driving range of 400km, in the following BEV e-Range 400km.
- A Plug-In Hybrid Electric Vehicle with an electric driving range of 50km, in the following PHEV e-Range 50km.
- A Plug-In Hybrid Electric Vehicle with an electric driving range of 100km, in the following PHEV e-Range 100km.

The chosen target market for the TCO calculation is Germany, since this market is about to lead the international development for electrified powertrains by 2020[205]. The measure and battery costs and the fuel/electricity shares for the different powertrain technologies are provided by AVL's experts. The fuel consumption values were taken out of EUCAR's study from chapter 3.3.2. Further, the CO_2 emissions are also provided by experts and, especially for the two types of PHEVs, set under 50 g of CO_2/km to grant the possibility of primary purchase funding. To also simulate a potential cost expenditure created by a battery breakdown, the battery lifetime is kept under eight years. This is mainly driven by a lack of information how battery lifetimes will develop over the next decade and should cover worst case scenarios. Table 25 shows the summary of the parameters.

[205] Cf. NPE, 2014, p. 4

Table 25: Initial fixed Parameters for the TCO calculation

	Dimension	Conv. ICE	MHEV 48V BSG	BEV e-Range 400km	PHEV e-Range 50km	PHEV e-Range 100km
Procurement Costs	**€**	0	850	12.000	4.800	7.800
Power	**kW**	90	90	90	90	90
CO2 Emission	**g CO2/km**	149,6	126,8	0	49	49
Fuel Consumption	**kg/100km**	4,72	4,01	0	1,55	1,55
Electricity Consumption	**kWh/100km**	0	0	14,49	6,14	6,14
Fuel Share	**%**	100	100	0	30	30
Electricity Share	**%**	0	0	100	70	70
Country	**#**	Germany	Germany	Germany	Germany	Germany
Incentives	**€**	0	0	4000	3000	3000
Battery Lifetime	**Years**	-	5	5	5	5
Battery Costs	**€**	-	450	9.000	1.800	3.500
Maintenance & Repair	**€-Cent/km**	7,3	7,3	5,9	6,7	6,3
Fuel Price Gasoline	**€/kg**	1,65	1,65	1,65	1,65	1,65
Electricity Price	**€/kWh**	-	-	0,25	0,25	0,25
Home Loading Station	**€**	-	-	1.699	1.699	1.699
Engine related Tax	**#**	yes	yes	no	no	no

4.2 The Three Scenarios

The future development of electrified powertrains and their demand on the market is strongly dependent on different factors. Prices for fossil fuels, electricity, batteries and the acceptance rate of potential customers are uncertain. Therefore, the Excel tool doesn't provide one prognosis for the next eight years, but creates three different scenarios for possible future developments. These three scenarios show both, the applicable power of the TCO tool and the sensitivity and reliance of the cost development on varying, non-controllable factors. The price increases follow the values from the International Energy Agency and their World Energy Outlook study (WEO) from 2012. The prices for gasoline are current prices[206].

The Pro Scenario will demonstrate the best case for electrified powertrains and will benefit lower fossil fuel consumption and therefore electrified driving. In contrast to that, the Contra scenario benefits the conventional powertrain, where the fuel price will not raise significantly over the next decade or the fuel consumption will not make a big impact on total costs. The Middle scenario illustrates a combination of both. None of the assumed parameters represent extreme conditions. The following parameters vary in the three scenarios: Price Increase Gasoline, Price Increase Electricity, Authorization of Incentives[207] and necessity of a Battery Exchange. All assumptions and parameters are summed up in Table 25 and Table 26.

Table 26: The three scenarios[208]

			Pro Scenario	Middle Scenario	Contra Scenario
Parameters	Fixed	Fuel Price Gasoline[€/l]	1,24	1,24	1,24
		Electricity price [Cent/kWh]	0,25	0,25	0,25
	Variable	Price Increase Gasoline [%/year][209]	4,1	3,1	0,2
		Price Increase Electricity [%]/year[210]	1,2	1,2	2,7
		Incentives Included	Yes	Yes	No
		Battery Exchange	No	Yes	Yes

[206] ADAC Online, 2016
[207] Schwarzer, 2016
[208] Cf. Plötz et al., 2013, p. 22; adapted by the author
[209] Cf. Plötz et al., 2013, p. 91; International Energy Agency, 2012
[210] Cf. Plötz et al., 2013, p. 91; International Energy Agency, 2012

4.2.1 The Pro Scenario

The Pro Scenario is the most optimistic calculation approach for the TCO tool. It bases on the assumption, that on the one hand electrified powertrains are the preferred vehicle architecture in the future, according to best market parameters, and adverse conventional powertrains with the relevant, worst parameters. On the other hand, the costs of a battery exchange will not be considered, since the battery life exceeds the holding period of the car or a necessary battery exchange is protected by warranty of the vehicle manufacturer. The primary cost funding will be approved for Battery Electric Vehicles (4.000€) as well as Plug-In Hybrid Electric Vehicles (3.000€).

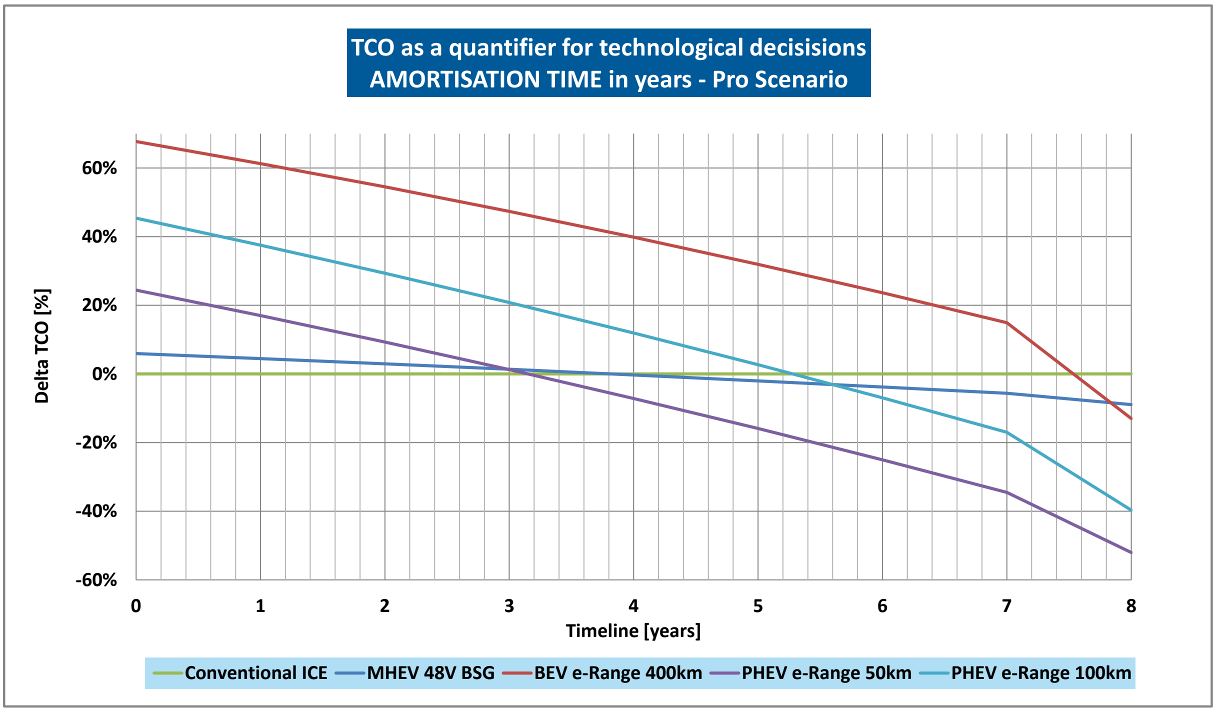


Figure 37: Pro Scenario - Delta TCO

Figure 37 illustrates the delta curve function for the Pro Scenario. As can clearly be seen, all electrified powertrains cross the reference vehicle mark. They equal the Total Cost of Ownership and even gain a total cost advantages of over 30% in the case of the both PHEVs. For that reason, these are the best purchase options for a holding period of eight years. Yet to mention, that even the BEV e-Range 400km can justify its cost disadvantage at the beginning with over 60% in the end.

Figure 38 gives a detailed view on cost distribution in the life cycle phases. In this figure the cost gap at the beginning between the conventional powertrain and the BEV and PHEV e-Range 100km is more obvious. Although the preparation costs exceed the 25.000€ by far, costs are minimized enough in the operation phase to beat the conventional ICE in the long run.

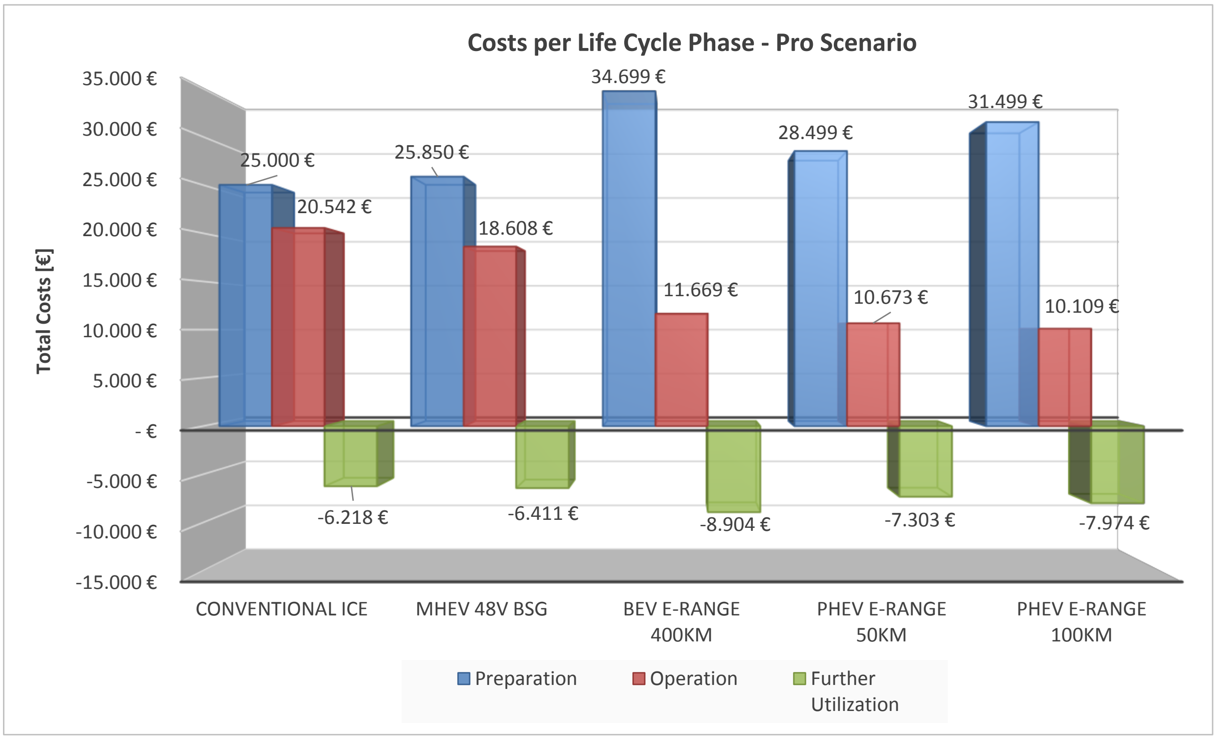


Figure 38: Life Cycle Costs - Pro Scenario

4.2.2 The Contra Scenario

The Contra Scenario assumes adverse market conditions for electrified powertrains. In contrast to the Pro Scenario, the parameters are exactly the other way round. Battery costs need to be paid every five years (complies with a battery exchange) due to wear of the battery or natural loss of capacity. The battery has no warranty. State provided funding pots are either empty or not accessible due to missing investments in the electric vehicle market or other possibilities, which prevent the primary cost funding.

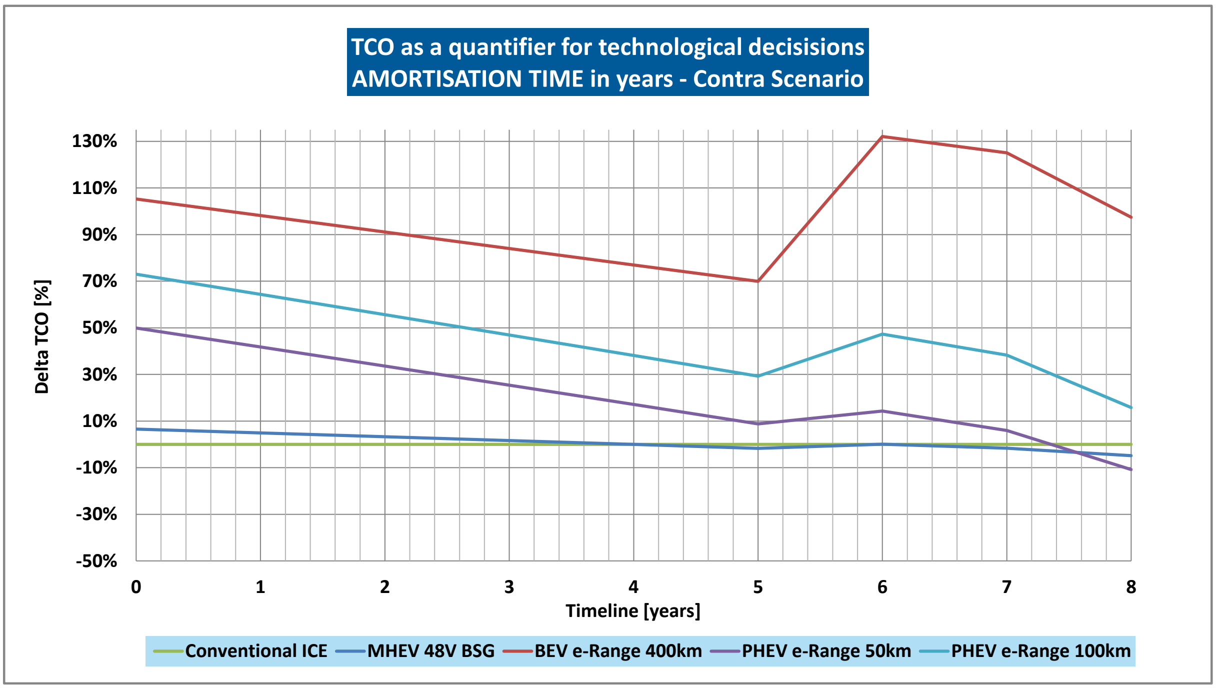


Figure 39: Contra Scenario - Delta TCO

Altogether, the Contra Scenario doesn't benefit any of the electrified powertrain architectures at all. While the MHEV 48V BSG seems to be the best option regarding its total costs, the cost curve is still almost the same as the conventional ICE curve. Even the PHEV e-Range 50km needs nearly eight years to be preferable from a total costs perspective. Under this conditions, it's hard to argue that electrified powertrains definitely justify their purchase over the years.

Figure 40 also gives a detailed view on cost distribution in the life cycle phases. Obviously, the BEV doesn't have any chance to catch up to the other powertrain options because of the high purchase price in the beginning and the stable fuel price over the years.

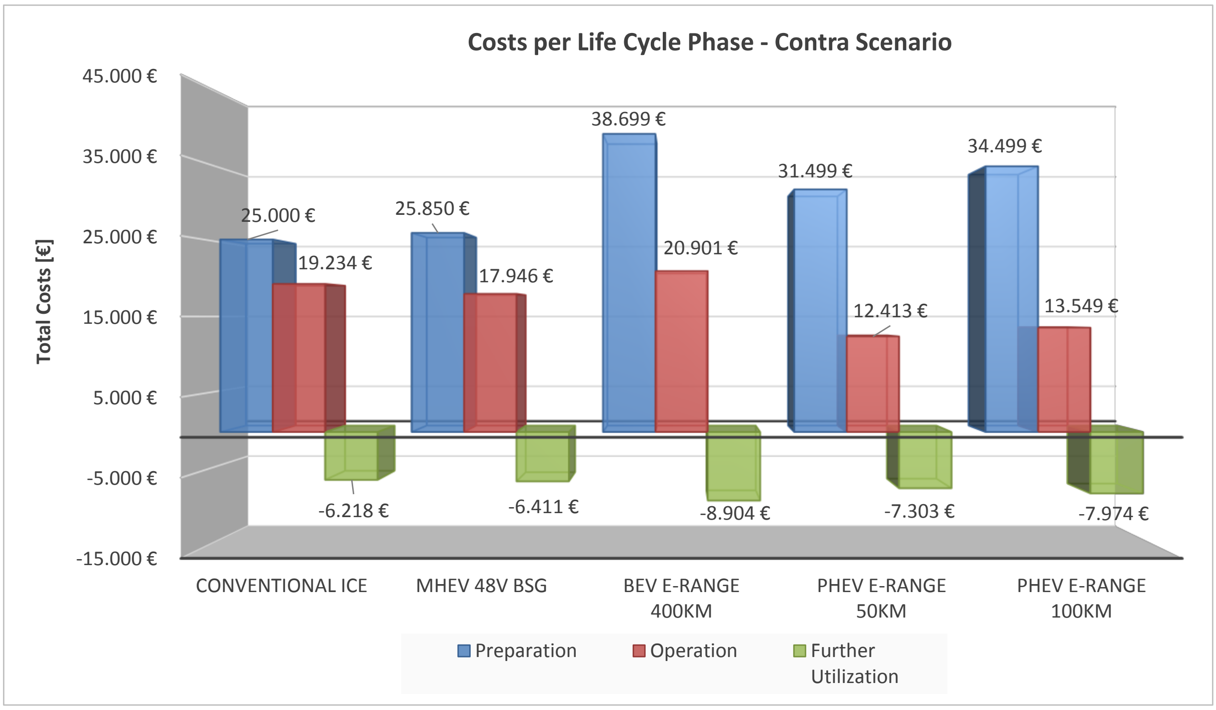


Figure 40: Cost Distribution - Contra Scenario

A cost gap of nearly 15.000€ in the preparation phase and almost stable and low fossil fuel prices over the next years don't provide a sufficient environment where the BEV e-Range 400km could amortize the cost gaps.

4.2.3 The Middle Scenario

The Middle Scenario is a combination of the Contra and the Pro Scenario. Incentives are accessible and the price increase relates to current expectations on the market[211]. For the reason that different battery holding models (leasing, 8 years warranty, battery insurance etc.) are on the market, but very few cause no costs over the holding period, the battery exchange costs are included.

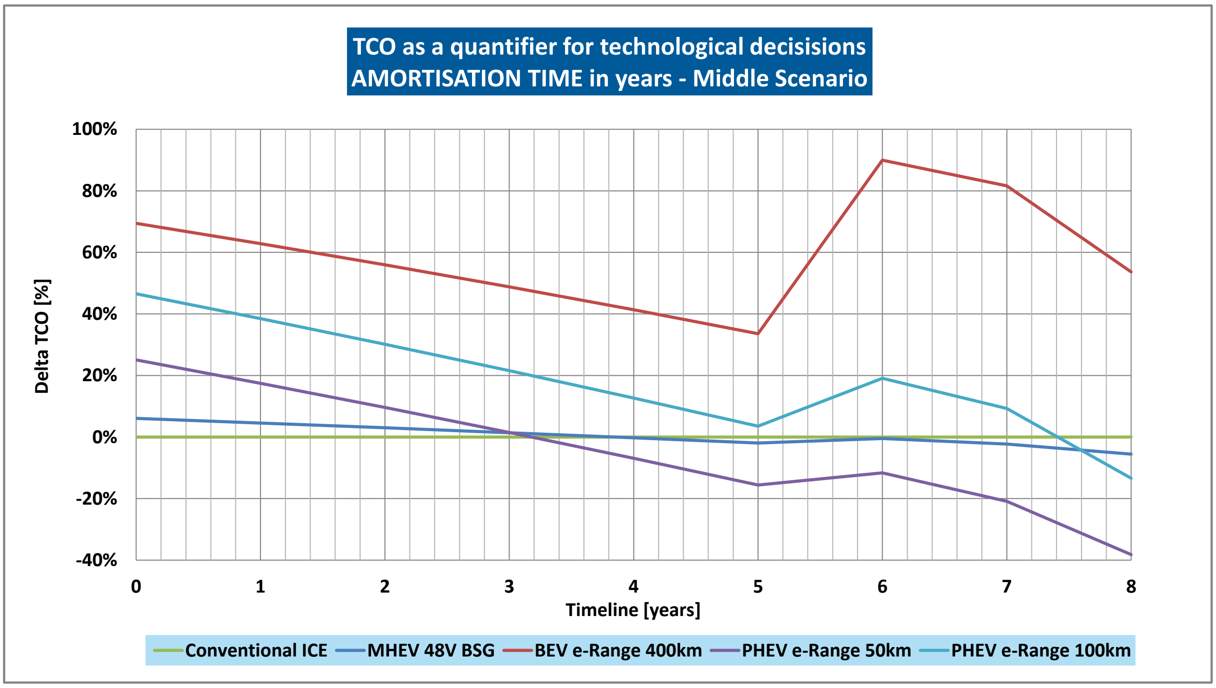


Figure 41: Middle Scenario - Delta TCO

The Middle Scenario benefits the PHEV e-Range 50km almost the same as the Pro Scenario, shown in Figure 41. This is due to the fact that on the one hand the market conditions harm the reference vehicle and on the second hand still boost the economic performance of the PHEV e-Range 50km. The total cost investments compensate after 3 years for the PHEV e-Range 50km. Like in the Contra Scenario, the BEV isn't competitive enough to become more profitable than any of the other powertrain architectures. The reason for the major cost difference is the size of the battery required for the high mileage of pure electric driving. A cost comparison in detail of the different powertrains is shown in Figure 42.

[211] Cf. International Energy Agency, 2012

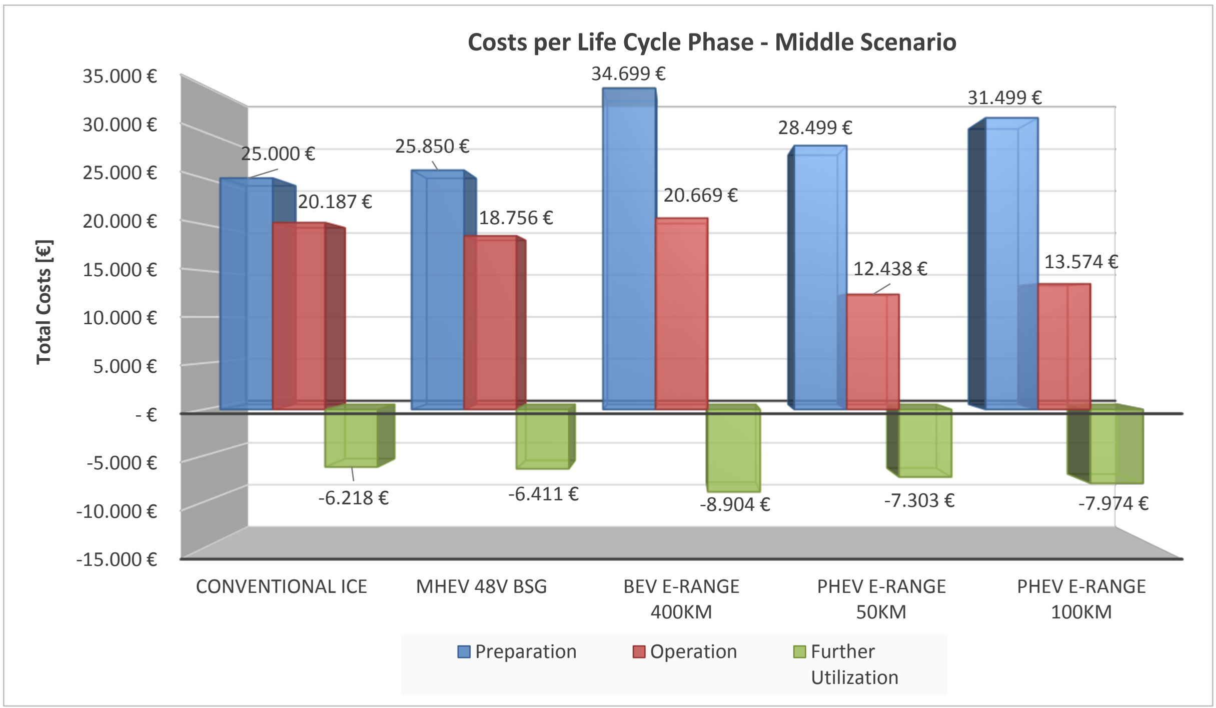


Figure 42: Cost Distribution - Middle Scenario

The BEV e-Range 400km benefits from its higher residual value in the further utilization phase, but due to its high costs in the preparation phase and almost equal costs in the operation phase compared to the conventional powertrain, it's still the least profitable powertrain in the Middle Scenario.

4.3 The Conventional Powertrain vs. the Electrified Powertrains

The last chapter shows which electrified powertrain configurations beat the conventional ICE in the observed holding period. This chapter points out the differences in the cost positions and illustrates where the electrified powertrains gain their ground against the internal combustion engine. The cost positions are set in relation to the reference vehicle. That means, that a positive value (green bar) accounts for a positive cost difference when comparing the identical cost positions. Therefore, negative values (red bar) illustrate a cost gap and an advantage for the conventional ICE. The bar rightmost shows the ultimate Delta-TCO and justifies a potential investment, when positive.

4.3.1 Conventional ICE vs. MHEV 48V

The MHEV 48V has the smallest degree of electrification and hasn't the ability of pure electric driving. Nethertheless, the fuel consumption of the MHEV beats the conventional ICE by 15% (4,72 l/100km vs. 4,01 l/100km), which results in reduced fuel costs.

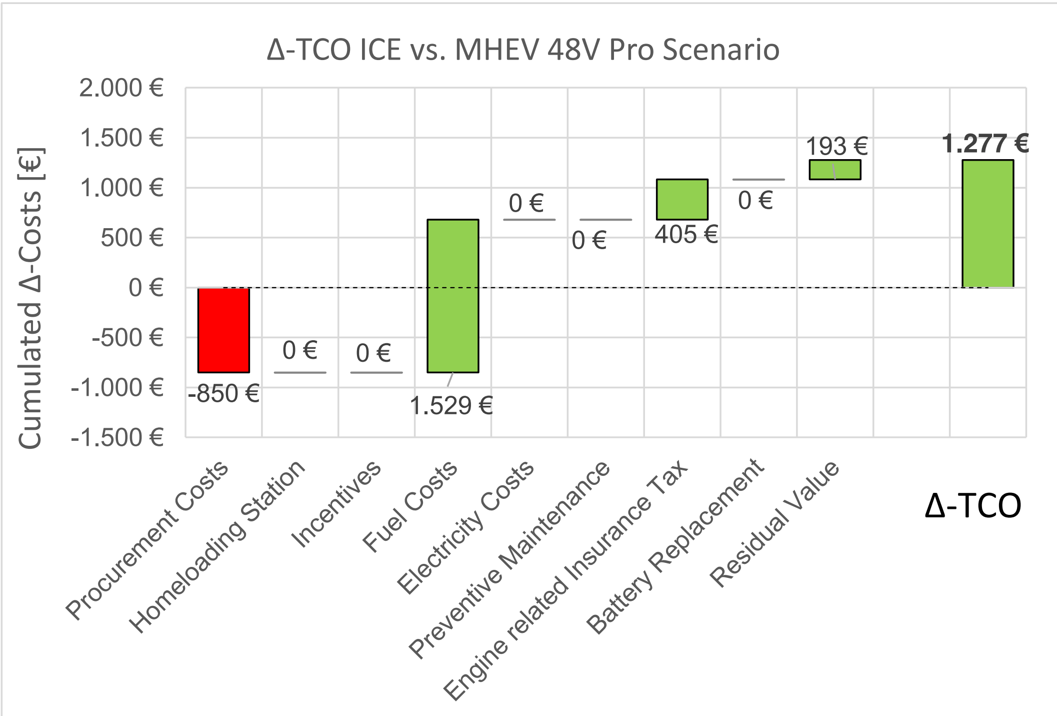


Figure 43: Delta-TCO MHEV Pro Scenario

Figure 43 illustrates the Pro Scenario. The only negative cost difference occurs in the preparation phase for the electrification measures. All the other cost positions account for a positive impact on the final Delta-TCO. Figure 44 and Figure 45 compare the Contra and the Middle Scenario. In addition, their Delta-TCO got influenced by the battery exchange at the end of the fifth year and higher prices for fossil fuels over the years. Although the cost advantages for fuel costs got smaller, the amount of money spent for the battery is not big enough to drop the Delta-TCO below zero.

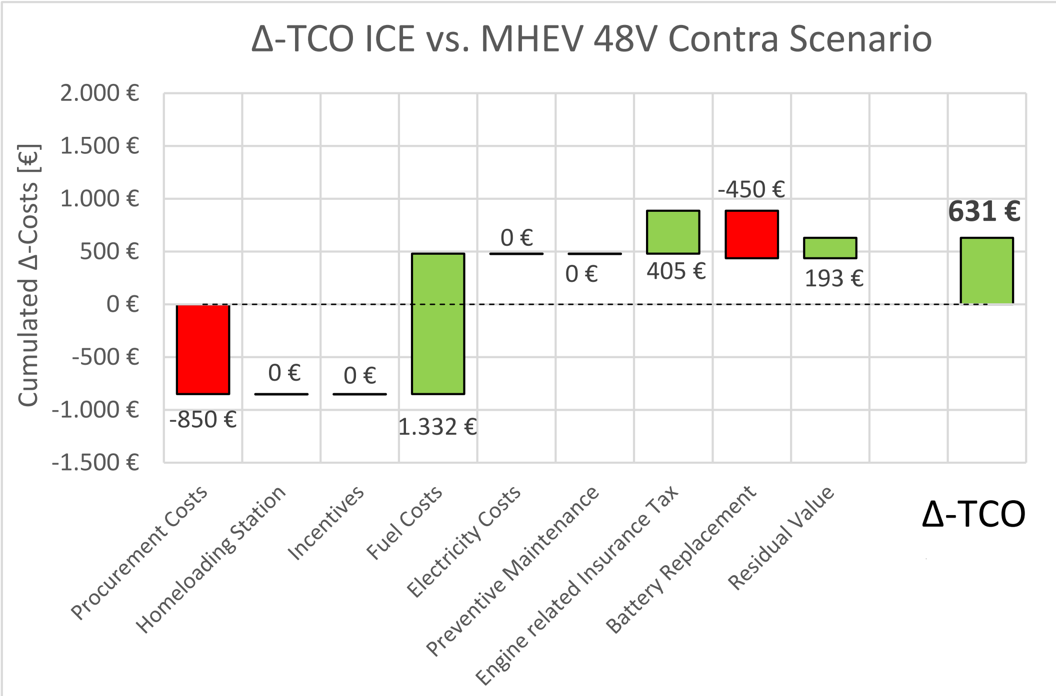


Figure 44: Delta-TCO MHEV Contra Scenario

Due to the fact that even in the Contra Scenario the MHEV can be seen as the better choice, the Middle Scenario also results in a positive outcome. The only difference occurs for fuel costs to the already mentioned varying price increase over the years.

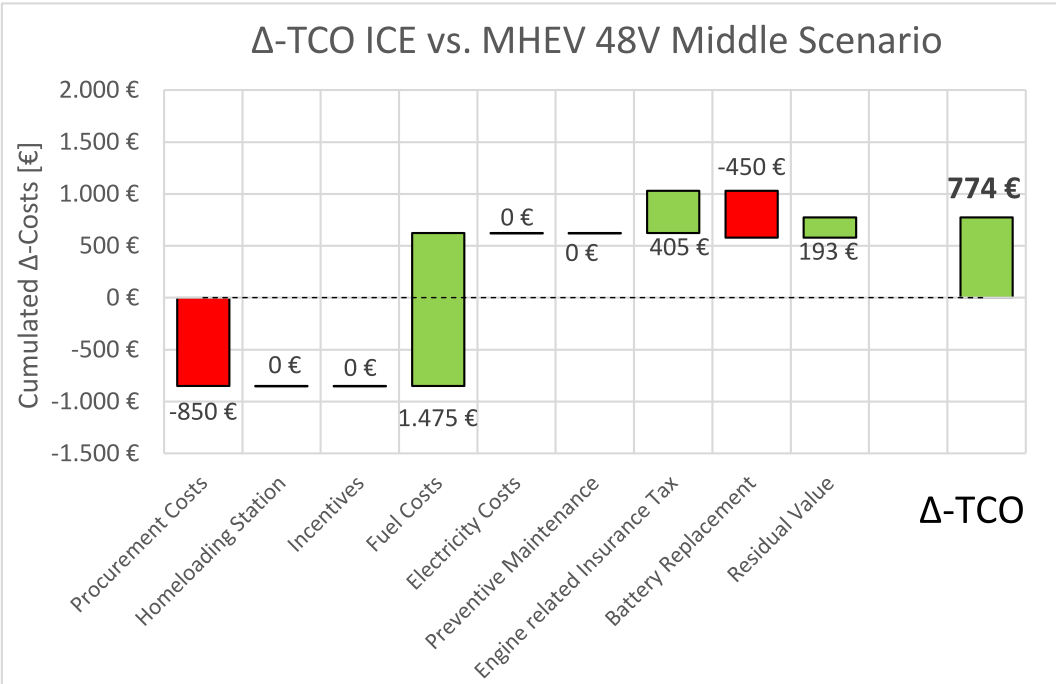


Figure 45: Delta-TCO MHEV Middle Scenario

4.3.2 Conventional ICE vs. BEV e-Range 400km

The only battery electric vehicle in the comparison is the BEV e-Range 400km. Its highest degree of electrification is strongly dependent on its high costs for electrification measures, fuel and energy price development and possible battery exchanges. However, it is also the most favored powertrain architecture for potential incentives, engine related tax exemptions and the high residual value in the end of the holding period.

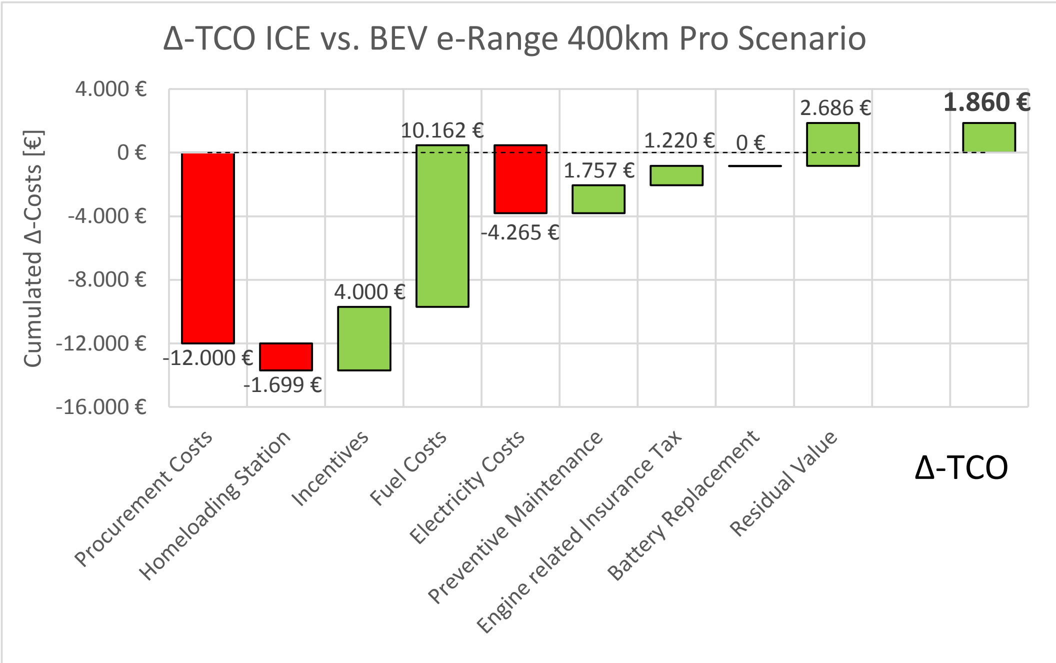


Figure 46: Delta-TCO BEV Pro Scenario

Figure 46 illustrates all expected advantages against an internal combustion engine. While cost savings due to no fossil fuel consumption and primary purchase funding, due to paid incentives, are quite obvious, the figure also shows the hidden strengths. A cost difference of 1.757€ in the preventive maintenance cost position results from less wear of the powertrain components of an electric powertrain. Furthermore, also the tax exemption pays off and results in 1.220€ cost advantage, which also can be seen in Figure 47 and Figure 48. The difference is, that although costs for measures and the homeloading station remain the same in the three scenarios, the conditions for incentives, battery exchange and costs for electricity vary.

Figure 47 represents the Contra Scenario and displays the highest negative Delta-TCO in the investigation of this thesis. That results mainly from battery exchange. As already explained in chapter 3.2.3, the battery is the most expensive part in an electrified powertrain. The bigger the battery, the more expensive the vehicle gets.

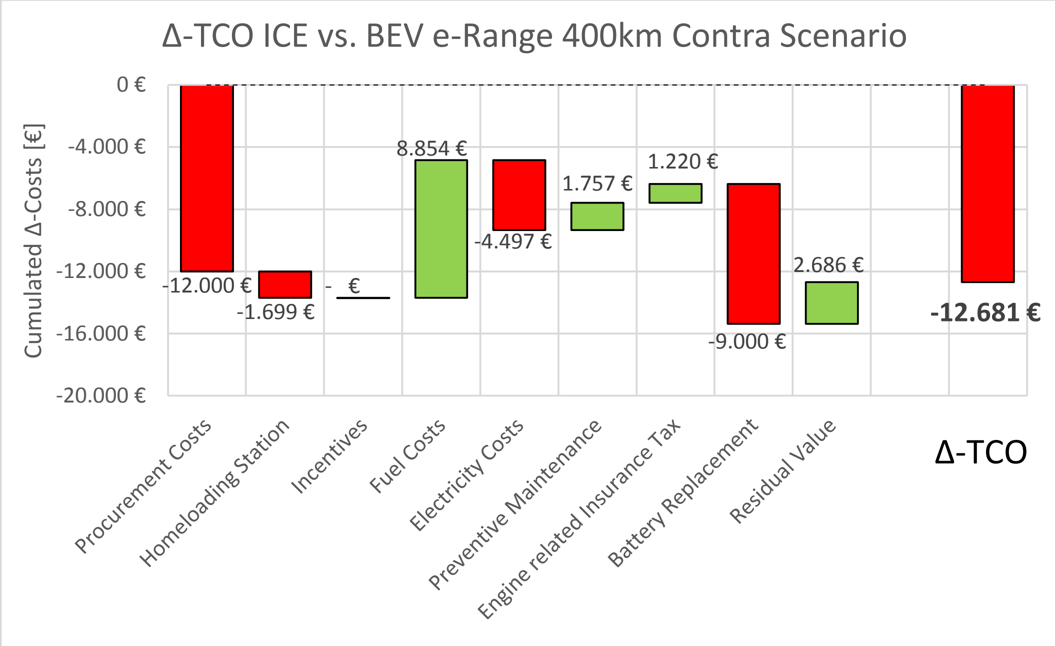


Figure 47: Delta-TCO BEV Contra Scenario

The technology of the BEV e-Range 400km, in particular the battery, accounts for the biggest amount of costs. In the Contra and Middle Scenario the 9.000€ cannot be compensated and result in negative Delta-TCO gaps.

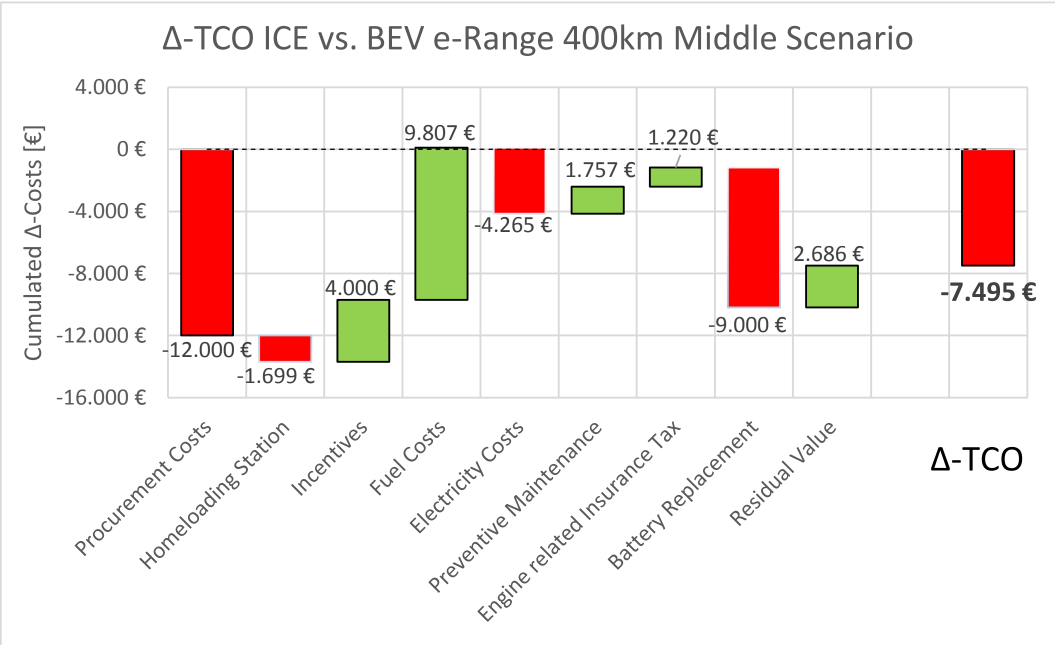


Figure 48: Delta-TCO BEV Middle Scenario

4.3.3 Conventional ICE vs. PHEV e-Range 50km

A Plug-in Hybrid Electric Vehicle represents benefits like low emissions, low fuel consumption and is approved to receive incentives (3.000€, if gCO_2/km is below 50). The main disadvantage is a more complex powertrain architecture, which leads to higher procurement costs.

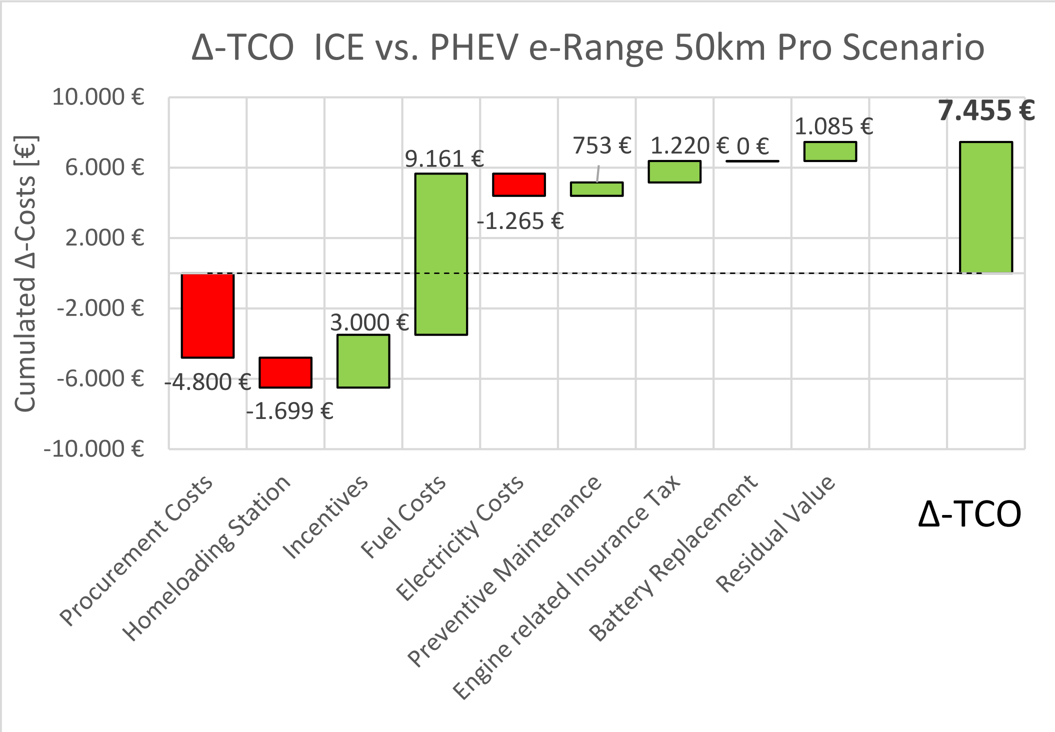


Figure 49: Delta-TCO PHEV 50km Pro Scenario

The Pro Scenario for the PHEV e-Range 50km displays the best alternative to a conventional powertrain in this TCO forecast. Low procurement costs and the one-time payment for the loading infrastructure compared to great savings in the fuel consumption result in a positive Delta-TCO of nearly 7.500€. This almost doubles the costs of necessary measures for the electrification.

The more interesting outcomes are displayed in Figure 50 and Figure 51. Even under difficult conditions, like in the Contra Scenario (no incentives and battery replacement) and Middle Scenario (higher fuel prices and battery replacement), the PHEV e-Range 50km has positive Delta-TCOs.

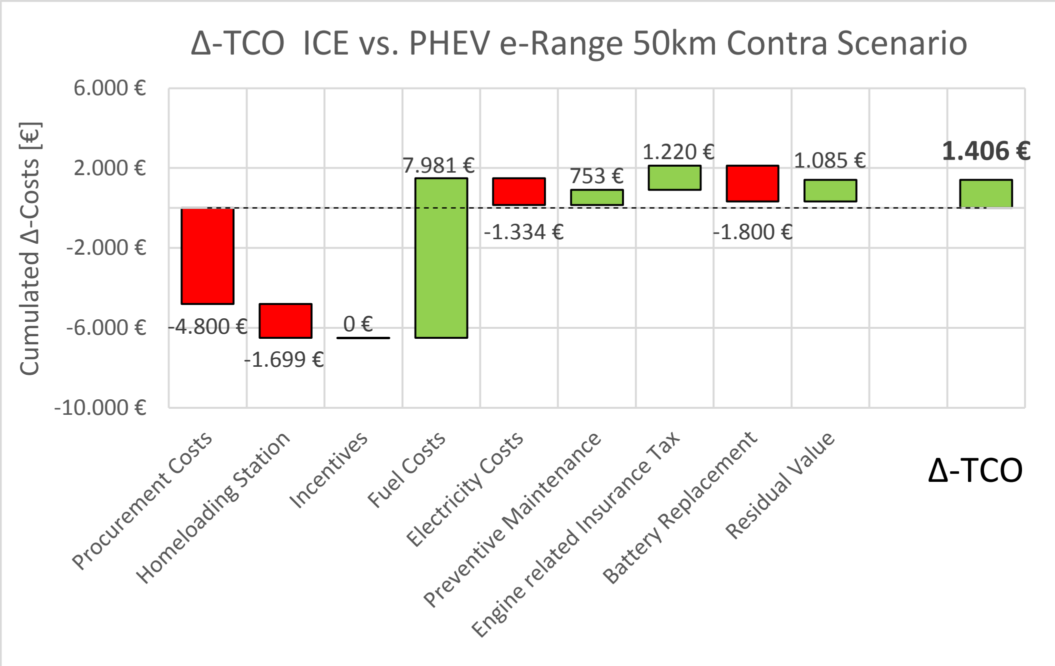


Figure 50: Delta-TCO PHEV 50km Contra Scenario

Furthermore, the PHEV e-Range 50km opens up a cost advantage in fuel costs of 7.981€ in the Contra Scenario. Savings in the preventive maintenance and the engine related insurance tax also ensure a positive outcome.

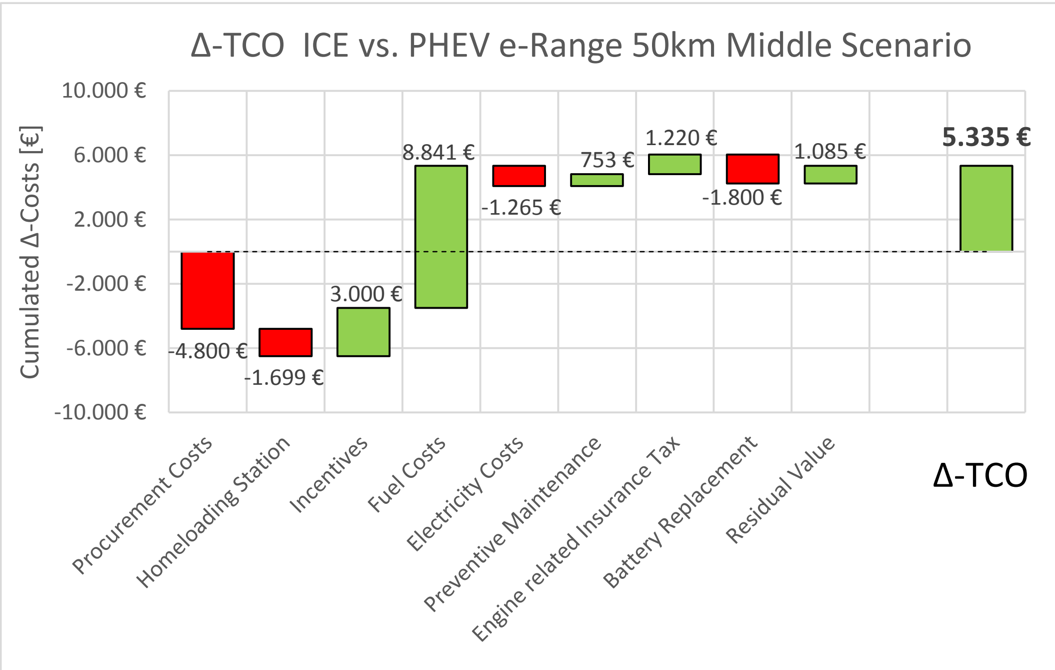


Figure 51: Delta-TCO PHEV 50km Middle Scenario

4.3.4 Conventional ICE vs. PHEV e-Range 100km

The second PHEV in the comparison differentiates itself through the ability to drive 100km electrically. That doubles the driving range of the PHEV from 4.3.3. On the one hand that saves fuel costs but on the other hand requires a bigger battery to cover the longer distance. Therefore, the delta in the procurement price, due to the costs for electrification, increases to 7.800€, which is almost double the costs from the PHEV e-Range 50km.

Although the costs in the preparation phase are that high, the PHEV e-Range 100km can justify the investments in electrification with later savings in fuel consumption, seen in Figure 52. That results finally in a cost advantage of 5.690€ against the conventional vehicle in the Pro Scenario.

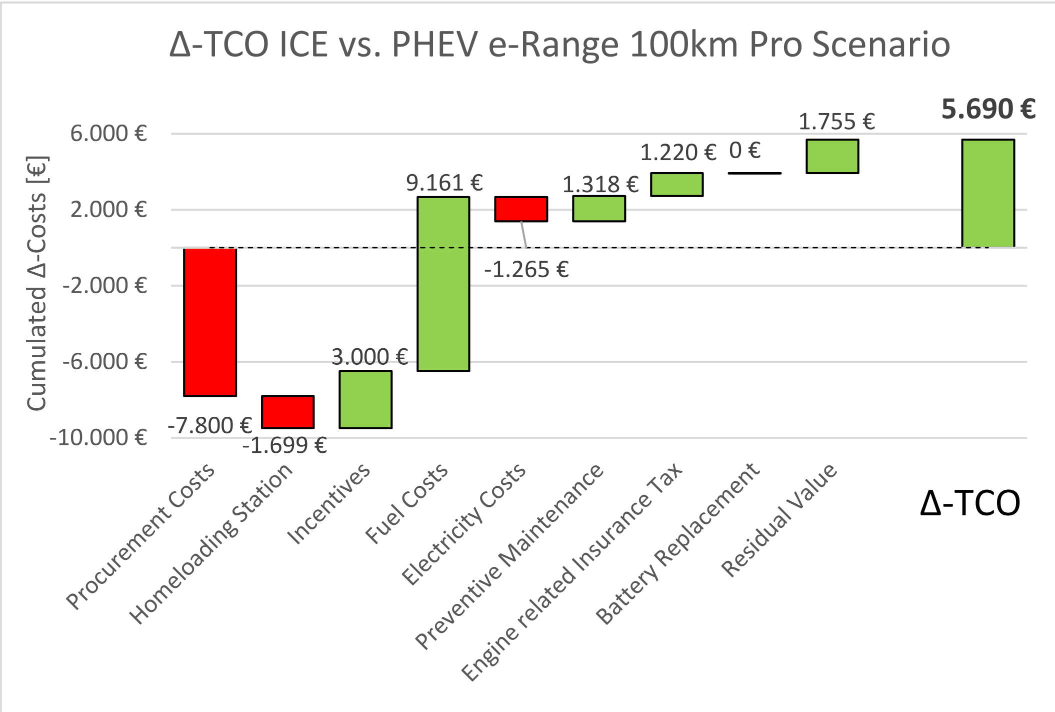


Figure 52: TCO-Delta PHEV 100km Pro Scenario

The Contra Scenario, seen in Figure 53, simulates almost constant fuel prices over the years and therefore shrinks the cost advantage for fuel costs. Main cost drivers in this scenario are the procurement costs, the home loading station and the battery exchange. In the Delta-Cost accumulation, the battery exchange has, after the procurements costs, the biggest impact on the result.

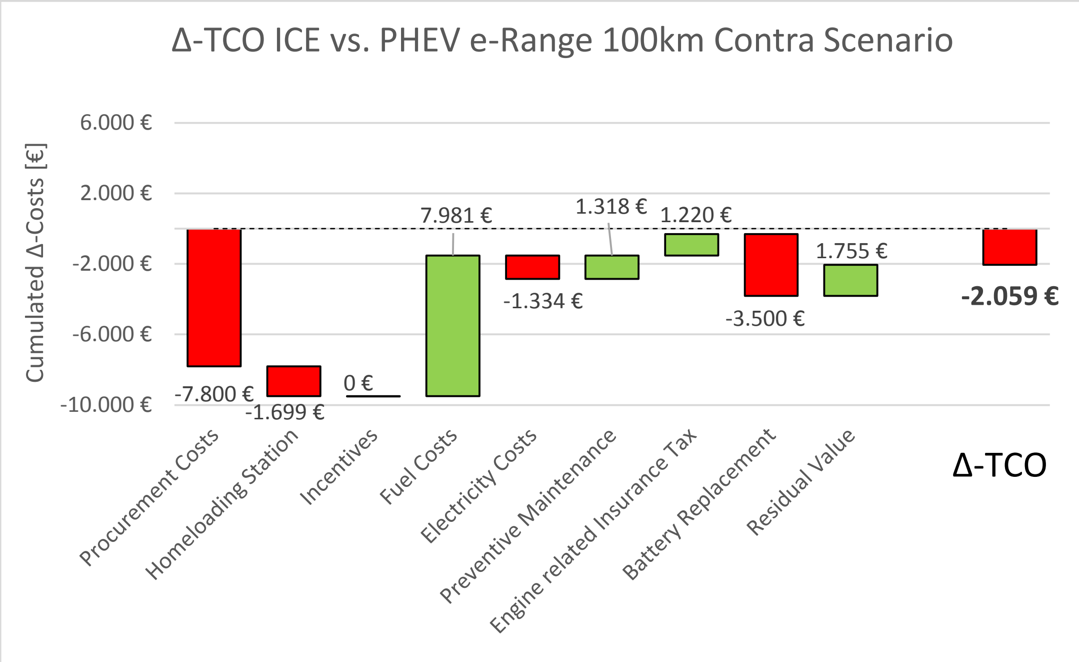


Figure 53: TCO-Delta PHEV 100km Contra Scenario

The battery exchange is compared to the PHEV e-Range 50km even more expensive, due to the bigger battery. A bigger size is necessary to cover an electric driving range of 100km. However, these costs need to be covered twice. One time the battery is included in the procurement cost and one time as spare part exchange – battery replacement. Therefore, only the Pro Scenario and the Middle Scenario (see Figure 54) have a postive outcome.

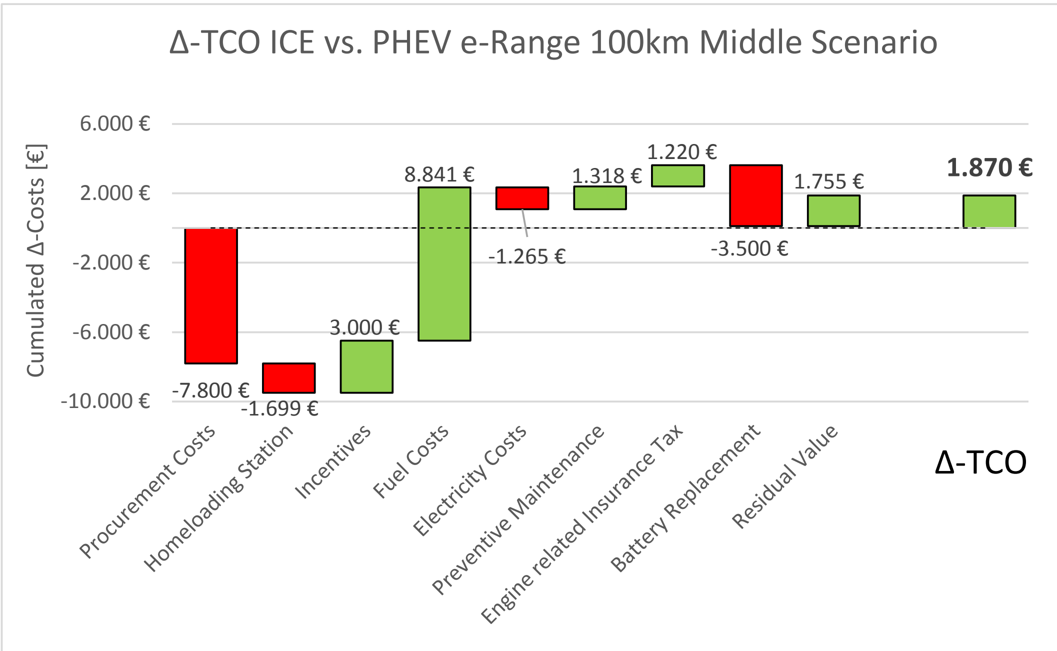


Figure 54: Delta-TCO PHEV 100km Middle Scenario

4.4 Summary of the Results

This chapter sums up the results of the cost comparison in the recent chapter. In the end it provides a purchase recommendation relying on the outcome of the TCO tool.

4.4.1 Comparison of the Different Results

The MHEV has the lowest degree of electrification and the lowest investment costs to electrify a conventional powertrain. With a low investment, the MHEV can justify a potential purchase in every calculated scenario, seen in Figure 55. However, the cost differences are still very little compared to a conventional powertrain. 631€ in the Contra Scenario can be compensated very fast when market conditions change.

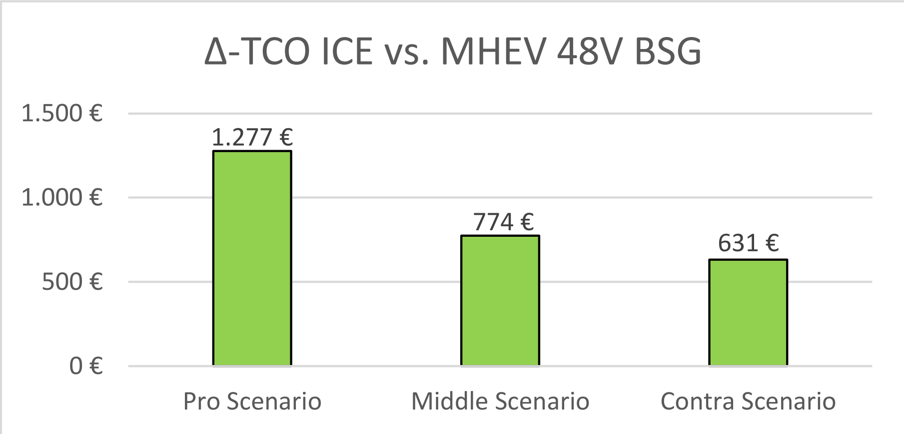


Figure 55: Summary Delta-TCO MHEV 48V BSG

In contrast to that, the BEV e-Range 400km can only display a positive Delta-TCO result in the Pro Scenario. For the other two scenarios, Figure 56 shows some major disadvantages against the conventional powertrain. The cost difference in the Contra Scenario is even bigger than the electrification investment in the procurement phase. That shows, that under these conditions the cost gap in the operation phase doesn't get smaller but even bigger over time.

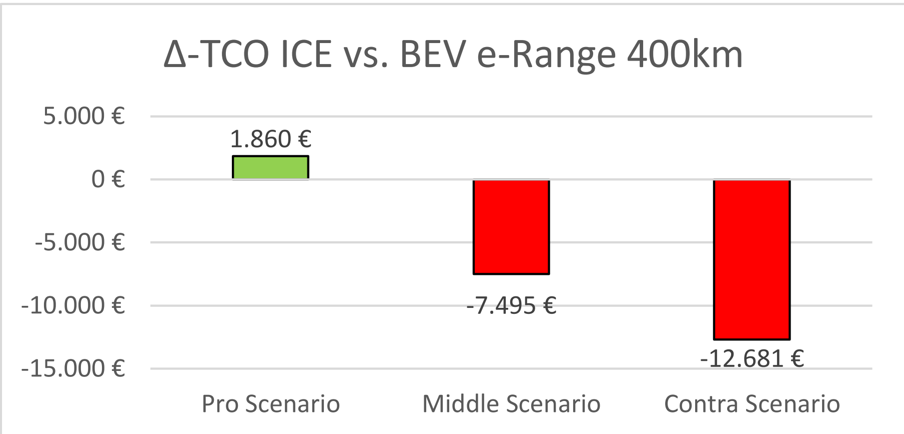


Figure 56: Summary Delta-TCO BEV e-Range 400km

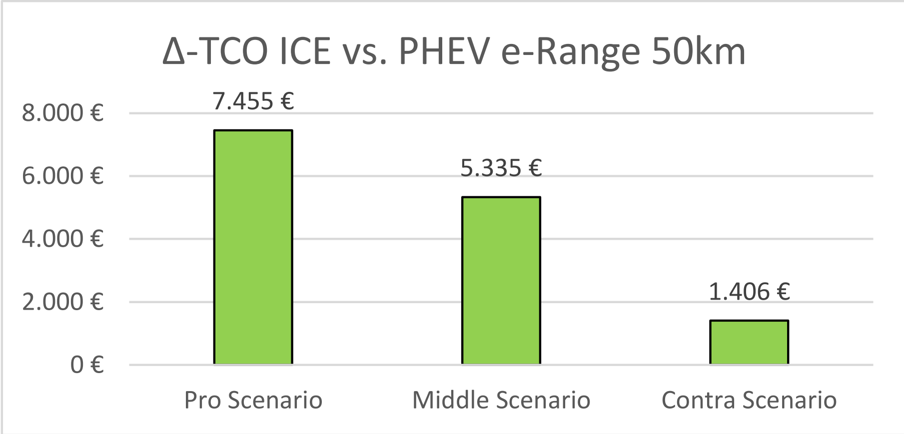


Figure 57: Summary Delta-TCO PHEV e-Range 50km

The best option of the alternative powertrain configuration is the PHEV e-Range 50km. Next to the MHEV, its results also provide positive Delta-TCOs throughout the different scenarios (see Figure 57). The differences are the significantly higher positive Delta-TCOs. The savings in costs in the Pro Scenario nearly double the investments for the electrification of the powertrain, as can be seen in Figure 49.

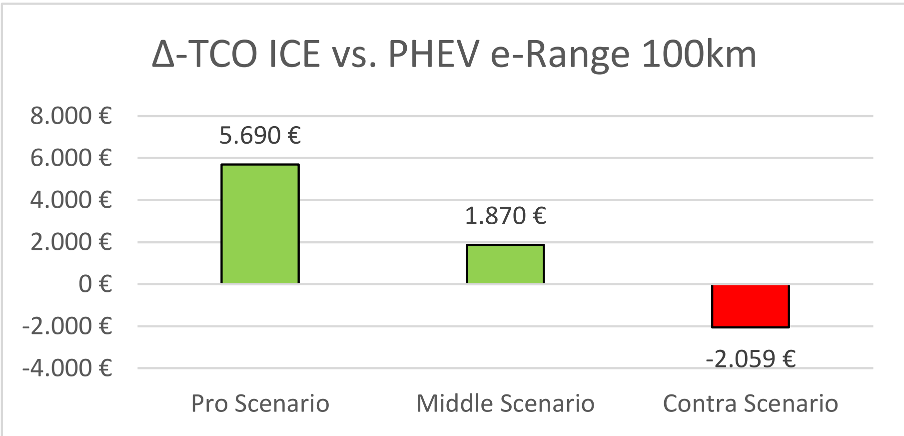


Figure 58: Summary Delta-TCO PHEV e-Range 100km

Although the characteristics of the PHEV e-Range 100km are almost identical to the PHEV e-Range 50km, this variant fails to be a justifiable investment option in every scenario, seen in Figure 58. As already mentioned, the costs for a bigger battery are just too high currently to be compensated in the observed holding period.

4.4.2 Conclusion of the Results

Finally only two electrified powertrains, the MHEV 48V BSG and the PHEV e-Range 50km, are justifiable powertrain alternatives to the conventional architecture from today's perspective. However, the TCO tool shows also positive Delta-TCOs for the remaining two options, but only for certain boundary conditions. That leads to the conclusion that electrified powertrains are really worth the investments in the beginning, in case of the MHEV 48V BSG and PHEV e-Range 50km. Further, also the BEV and the second PHEV could become better options in the near future. The requirements are minimized electrification costs, respectively lower costs for batteries, and battery warranties for the holding period. If both these costing blocks could be covered and incentives are still accessible, these architectures become considerable options too.

5 Conclusion

In contrast to the heavy machinery industry, where the operation phase is definitely the time frame when major costs are created, the passenger vehicle industry shows different characteristics. The biggest amount of money is still paid for procurement and purchase of the vehicle, which is at the beginning of the lifecycle. Additionally, acquiring equipment for infrastructure (e.g. a home charging station) increases the costs in the preparation phase even further.

As a result of that, it is still a long way to go, to provide competitiveness for electrified powertrains to sustain the pressure on the free market and to provide the edge to compete against cheaper conventional powertrains. Significant cost differences at purchase prices can't be offset through low operation costs (fuel consumption, maintenance & repair) in the near future. Therefore, in the author's opinion, the industry still has no other choice than filling up the cost gaps to conventional vehicles with incentive systems and overall benefit programs like free home charging infrastructure and free of charge parking and loading at sought-after parking spots in central areas.

In the near to middle future, technology is expected to develop, which probably decreases prices for batteries, respectively battery cells. Both, new technology and price competitive batteries will benefit pure electric vehicles (BEVs) the most. Combining with expected higher prices of fossil fuels due to running out resources, BEVs will be the best option for future mobility, cf. 2.2.4. However, significant uncertainties still prevail. Not only the already mentioned oil price is an unknown factor, but also the development of the electricity price is uncertain, due to the further rising demand of electricity.

A medium term plan for electric cars is to promote it to a broader population and to make it a more attractive investment. To achieve that, exchanging whole vehicle fleets of state departments, public corporations and companies (e.g. company cars with possibility of input tax deduction) would establish a usual street scene and create the image of affordability for everyone.

Ultimately new foundations need to be laid to clarify how purchase prices can catch up to those of conventional ones to establish a long-term potential of sustainable development on the vehicle market. Purchase incentives can't therefore be successful in the long run, because environmental and for that reason also fuel consumption regulations will not be reached without any kind of electrified powertrain architecture.

6 Forecast

The created TCO model is established and prepared for usage in practice. However, different uncertainties still exist. For a further development of the Excel environment, a more detailed cost structure on the BOM level is strongly recommended. Only then, the direct influence of potential cost drivers (e.g. batteries) and other electrified measures, can be illustrated in means of the life cycle.

A more complex and problematic issue will be the implementation of real driving profiles of end consumers, since the established values for this thesis still base on the results of the NEDC. The real ratio between pure electric and pure conventional driving will be particularly interesting. Further, a possibility to calculate costs for commercialized vehicles could be established. Due to the governmental incentives and tax benefits, this customer group will cover high purchase costs the fastest.

To calculate potential resale and residual values, valid data is non-existent or not available so far. The accessible regression parameters are not yet accurate enough to provide a reliable value development for the future (parameters base on conventional vehicles). The big unknown for electrified powertrains will be batteries. Cell price, design strategies and potential driving ranges will influence the competitiveness of these vehicles the most in comparison with future prices of fossil fuels and electricity.

Reference List

ADAC Online (2016). *Diesel and Gasoline Prices.* Retrieved September 28, 2016, from https://www.adac.de/infotestrat/tanken-kraftstoffe-und-antrieb/kraftstoffpreise/.

Albrecht, V., & Wetzel, P. (2009). M-TCO - Daimler AG. In S. Schweiger (Ed.), *Lebenszykluskosten optimieren. Paradigmenwechsel für Anbieter und Nutzer von Investitionsgütern* (1st ed., pp. 84–85). Wiesbaden: Gabler.

Allgemeiner Deutscher Automobil-Club (2010-2011). *Autokosten: Plus … ADAC-Auto-Tests ; über … Modelle im Kostenvergleich.* Haar: New Look Electronic Publ.

Asiedu, Y., & Gu, P. (1989). Product Life Cycle Analysis: State of the Art Review. *International Journal of Production Research*. (36), 883–908.

AUDI AG (2011). *Audi A3 e-tron.* Retrieved August 10, 2016, from http://www.turbo.fr/actualite-automobile/410726-concept-audi-a3-tron/.

AVL List GmbH (2016). *AVL Facts.* Retrieved August 18, 2016, from https://www.avl.com/avl-facts.

Back, A. (1988). *Lebenszyklusorientiertes Produktcontrolling, Ansätze zur computergestützten Realisierung mit einer Rechnungswesen-Daten- und -Methodenbank*. Erlangen, Nürnberg, Univ., Diss., 1988.

Bernhart, W. (2010a). *Electromobility - The only way forward? 22nd International AVL Conference "Engine & Environment".* Graz.

Bernhart, W. (2010b). *Powertrain 2020: The Li-Ion Battery Value Chain - Trends and Implication. Presentation at EV Battery Forum Asia.* Shanghai.

Bernhart, W. (2012). *The Lithium-Ion Battery Value Chain.* Munich/Tokyo/Seoul/Shanghai.

Bernhart, W., Schlick, T., Olschewski, I., Thoennes, M., & Garrelfs, J. (2014). *E-mobility index for Q1/2014.* Roland Berger Strategy Consultants – Automotive Competence Center & Forschungsgesellschaft Kraftfahrwesen mbH Aachen.

Blanchard, B. S. (1978). *Design and manage to life cycle cost.* Portland, Or.: M/A Press.

BmF (2016). *Website des Bundesministerium für Finanzen: Steuern - Fahrzeuge.* Retrieved August 08, 2016, from Bundesministerium für Finanzen: https://www.bmf.gv.at/steuern/fahrzeuge/motorbezogene-versicherungssteuer.html.

BMW AG (2016). *BMW i3: Antrieb & Technik.* Retrieved August 10, 2016, from http://www.bmw.de/de/neufahrzeuge/bmw-i/i3/2015/antrieb-technik.html.

Bode, M., Bünting, F., & Geißdörfer, K. (2011). *Rechenbuch der Lebenszykluskosten: Ein Leitfaden mit Rechenmodell und Arbeitshilfen. Betriebswirtschaft.* Frankfurt, M.: VDMA-Verl.

Boussabaine, H. A., & Kirkham, R. J. (2004). *Whole life-cycle costing: Risk and risk responses* (1. publ). Oxford u.a.: Blackwell Publ.

Brown, R. J. (1979). A New Marketing Tool: Life Cycle Costing. *Industrial Marketing Management, Vol. 8 No. 2*(8), 109–113.

Bünting, F. (2009). Lebenszykluskostenbetrachtungen bei Investitionsgütern. In S. Schweiger (Ed.), *Lebenszykluskosten optimieren. Paradigmenwechsel für Anbieter und Nutzer von Investitionsgütern* (1st ed., pp. 36–50). Wiesbaden: Gabler.

Carr, L. P., & Ittner, Christopher, D. (1992). Measuring the Cost of Ownership. *Journal of Cost Managment*, 42–51.

Cavinato, J. L. (1991a). A Total Cost/Value Model for Supply Chain Competitivness. *Journal of Business Logistics, 32*(4), 42–51.

Daimler AG (2016). *Homepage.* Retrieved August 29, 2016, from https://www.daimler.com/de/.

Delucchi, M., & Lipman, T. (2001). An analysis of retail and lifecycle cost of battery powered vehicle. *Transportation Research Part D, 6*.

Delucchi, M., & Lipman, T. (2006). A retail and lifecycle cost analysis of hybrid electric vehicles. *Transportation Research Part D, 11*, 115–132.

Deutscher Bundestag (2009). Gesetz zur Neuregelung der Kraftfahrzeugsteuer und Änderung anderer Gesetze.

Dexheimer, V. (2003). *Hedonic Methods of Price Measurement for Used Cars.*

Edwards, R., Godwin, S., Krasenbrink, A., Huss, A., Maas, H., Hass, H., et al. (2013). *Well-to-wheels analysis of future automotive fuels and powertrains in the European context: Tank-to-wheels (TTW) report, version 4, July 2013. EUR, Scientific and technical research series: Vol. 26027.* Luxembourg: Publications Office.

Ehrlenspiel, K., Kiewert, A., & Lindemann, U. (2014). *Kostengünstig Entwickeln und Konstruieren: Kostenmanagement bei der integrierten Produktentwicklung* (7. Aufl. 2014). *VDI-Buch.* Berlin Heidelberg: Springer Berlin Heidelberg.

Ellram, L. M. (1993c). Total Cost of Ownership: Elements and Implementation. *International Journal of Purchasing and Material Management, 29*(4), 3–12.

Ellram, L. M. (1993). A Framework for Total Cost of Ownership. *International Journal Logistics Management, 4*(2), 49–60.

Ellram, L. M. (2002). Total Cost of Ownership. In D. Hahn & L. Kaufmann (Eds.), *Handbuch Industrielles Beschaffungsmanagement. Internationale Konzepte - Innovative Instrumente - Aktuelle Praxisbeispiele* (2nd ed., p. 661). Wiesbaden, s.l.: Gabler Verlag.

Ellram, L. M., & Siferd, S. P. (1993b). Purchasing: The Cornerstone of the Total Cost of Ownership Concept. *Journal of Business Logistics, 14*(1), 163–184.

Ellram, L. M., & Siferd, S. P. (1998). Total Cost of Ownership: A Key Concept in Strategic Cost Management Decisions. *Journal of Business Logistics, 8*(1), 55–84.

Ferrin, B. G., & Plank, R. E. (2002). Total Cost of Ownership Models: An Exploratory Study. *Journal of Supply Chain Management, 8*(3), 18–29.

Fischer, R., Kücükay, F., Jürgens, G., & Pollak, B. (2016). *Das Getriebebuch* (2., überarb. Aufl. 2016). *Der Fahrzeugantrieb.* Wiesbaden: Springer Fachmedien Wiesbaden.

Ford, D., & Ryan, C. (1981). Taking technology to market. *Harvard Business Review, 59*(2), 117–126.

Fröhlich, O., & Reichmann, T. (1994). Produktlebenszyklusorientierte Planungs- und Kontrollrechnung als Bausteine eines dynamischen Kosten- und Erfolgscontrolling. In K. Dellmann (Ed.), *Neuere Entwicklungen im Kostenmanagement.* Bern, Stuttgart, Wien: Haupt.

Geißdörfer, K. (2009). *Total cost of ownership (TCO) und life cycle costing (LCC): Einsatz und Modelle ein Vergleich zwischen Deutschland und USA. Controlling und Management: Vol. 7.* Berlin [u.a.]: Lit.

Geißdörfer, K., & Gleich, R. (2009). Standardisierungspotentiale lebenszyklusbasierter Modell des strategischen Kostenmanagements. *Zeitschrift für Betriebswirtschaft, 79*(6), 693–715.

Graham, R. (2001). *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.* Palo Alto, California.

Heilala, J., Helin, K., & Montonen, J. (2006). Total Cost of Ownership analysis for modular final assembly systems. *Total Cost of Ownership analysis for modular final assembly systems, 44*(18-19), 3967–3988.

Herrmann, C. (2010). *Ganzheitliches Life Cycle Management: Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen. VDI-Buch.* Berlin, Heidelberg: Springer.

Herrmann, C., & Spengler, T. (2006). *Industriearmaturen: Was kosten sie wirklich.*

Hofmann, P. (2014). *Hybridfahrzeuge: Ein alternatives Antriebssystem für die Zukunft* (2. Aufl.). Wien, Heidelberg, New York, NY, Dordrecht, London: Springer.

Hofstätter, H. (1977). *Die Erfassung der langfristigen Absatzmöglichkeiten mit Hilfe des Lebenszyklus eines Produktes. Modernes Marketing : Bd. 2, Die Marketingstrategie der Unternehmung: Teil 2.* Würzburg, Wien: Physica-Verlag.

Höft, U. (1992). *Lebenszykluskonzepte: Grundlage für das strategische Marketing- und Technologiemanagement*. Zugl.: Berlin, Freie Univ., Diss. *Technological economics: Bd. 46.* Berlin: Erich Schmidt.

Hurkens, K., van der Valk, W., & Wynstra, F. (2006). Total Cost of Ownership in the Service Sector: A case study. *Journal of Supply Chain Management, 42*(1), 27–37.

Institut für angewandte Sozialwissenschaft GmbH (2010). *Mobilität in Deutschland (MiD).* Bonn/Berlin: Bundesministerium für Verkehr, Bau und Stadtentwicklung.

International Energy Agency (2012). *World Energy Outlook 2012.* Paris: OECD Publ.

Jackson Jr., D. W., & Ostrom, L. L. (1980). Life Cycle Costing in Industrial Purchasing. *Journal of Purchasing and Materials Management, 16*(4), 8–12.

Kaufman, R. J. (1969). Life Cycle Costing: Decision Making Tool for Capital Equipment Acquisitions. *Journal of Purchasing*, 16–31.

Kemminer, J. (1999). *Lebenszyklusorientiertes Kosten- und Erlösmanagement*. Zugl.: Duisburg, Univ., Diss., 1999. *Gabler Edition Wissenschaft : Markt- und Unternehmensentwicklung.* Wiesbaden, Wiesbaden: Dt. Univ.-Verl.; Gabler.

Kiel, E. (Ed.) (2007). *VDI-Buch. Antriebslösungen: Mechatronik für Produktion und Logistik.* Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

Klima- und Energiefond (2016). *Bundesförderungen für Private Österreich.* Retrieved August 25, 2016, from http://e-connected.at/content/f%C3%BCr-private.

Kloess, M., Rechberger, J., Haas, R., & Ajanovic, A. (2008). Szenarien der Elektrifizierung des Antriebsstrangs individueller PKW bis 2050 in Österreich. *e & i Elektrotechnik und Informationstechnik, 125*(11), 367–371.

Kölscheid, W. (1999). *Methodik zur lebenszyklusorientierten Produktgestaltung: Ein Beitrag zum life cycle Design*. Zugl.: Aachen, Techn. Hochsch., Diss., 1999 (Als Ms. gedr). *Berichte aus der Produktionstechnik: Bd. 99,17.* Aachen: Shaker.

Krämer, S. (2007). *Total cost of ownership: Konzept, Anwendung und Bedeutung im Beschaffungsmanagement deutscher Industrieunternehmen*. Zugl.: Erlangen-Nürnberg, Univ., Diplomarbeit. Saarbrücken: VDM Verlag Dr. Müller.

Kreyenberg, D. (2016). *Fahrzeugantriebe für die Elektromobilität: Total Cost of Ownership, Energieeffizienz, CO2-Emissionen und Kundennutzen* (1. Aufl. 2016). Wiesbaden: Springer Fachmedien Wiesbaden GmbH; Springer Vieweg.

Linz, S., Dexheimer, V., & Kathe, A. Hedonische Preismessung bei Gebrauchtwagen. *Wirtschaft und Statistik, 2003*, 538–542.

Lorenzen, L. E., Rudzio, H., & Blümel, P. (2006). Die totale Kostenkontrolle. *wt Werkstattstechnik*. (7/8), 489–494.

Mock, P. (2015). *European Vehicle Market Statistics: Pocketbook 2015/16.* Berlin.

Neumann, N. R., Eckstein, L., & Olschewski, I. (2013). *TCO-Related Strategies for Stakeholders to Promote Electric Vehicles.* Aachen: RWTH Aachen.

NPE (2011). *Fortschrittsbericht der nationalen Plattform Elektromobilität (Zweiter Bericht).* Berlin.

NPE (2012). *Fortschrittsbericht der nationalen Plattform Elektromobilität (Dritter Bericht).* Berlin.

NPE (2014). *Fortschrittsbericht der nationalen Plattform Elektromobilität (Vierter Bericht) - Bilanz der Marktvorbereitung.* Berlin.

Osten-Sacken, D. v. d. (1999). *Lebenslauforientierte, ganzheitliche Erfolgsrechnung für Werkzeugmaschinen*. Univ., Diss.--Stuttgart, 1999. *IPA-IAO-Forschung und Praxis: Vol. 299.* Heimsheim: Jost-Jetter.

Petring Energietechnik GmbH (2016). *Home loading stations.* Retrieved August 15, 2016, from http://www.wallb-e.net/.

Pfohl, M. (2002). *Prototypengestützte Lebenszykluskostenrechnung: dargestellt an einem Beispiel aus der Antriebstechnik.* München.

Pistoia, G. (2014). *Lithium-ion batteries: Advances and applications.* Amsterdam: Elsevier.

Plötz, P., Gnann, T., Kühn, A., & Wietschel, M. (2013). *Markthochlaufszenarien für Elektrofahrzeuge.* Karlsruhe: Studie im Auftrag der acatech.

Propfe, B., Redelbach, M., Santini, D. J., & Friedrich, H. (2012). *Cost analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values.* Los Angeles, California.

Randelhoff, M. (2010). *Produktionskosten des Chevrolet Volt.* Retrieved October 05, 2016, from http://www.zukunft-mobilitaet.net/2190/zukunft-des-automobils/elektromobilitaet/produktionskosten-elektroauto-chevrolet-volt/.

Razum, J. (2003). *Introducing Industrial Total Cost of Ownership.* Greenville, South Carolina.

Reif, K. (2010). *Konventioneller Antriebsstrang und Hybridantriebe.* Wiesbaden: Vieweg+Teubner Verlag / GWV Fachverlage GmbH Wiesbaden; SpringerLink (Online service).

Riezler, S. (1996). *Lebenszyklusrechnung: Instrument des Controlling strategischer Projekte*. Zugl.: Bochum, Univ., Diss., 1995. *Bochumer Beiträge zur Unternehmungsführung und Unternehmensforschung: Vol. 48.* Wiesbaden: Gabler.

Rückle, D., & Klein, A. (1994). Product Life Cycle Cost Management. *Neuere Entwicklungen im Kostenmanagement*, 335–367.

Ruth, M., Timbario, T., & Laffen, M. (2011). *Methodology for Calculating Cost per Mile for Current and Future Vehicle Powertrain Technologies, with Projections to 2024.* USA: Renewable Energy Laboratory (NREL).

Sams, C. (2015). *Entwicklung einer Total Cost of Ownership (TCO) Methodik für AVL List: Modellimplementierung in ein TCO Berechnungswerkzeug für Antriebsstränge gewerblicher Nutzung*. Diplomarbeit. Leoben: Montanuniversität Leoben.

Schwarzer, C. (2016). *So funktioniert die Kaufprämie für Elektroautos.* Retrieved September 29, 2016, from http://www.zeit.de/mobilitaet/2016-04/elektroauto-kaufpraemie-bestseller.

Schweiger, S. (2008). Nachhaltige Wettbewerbsvorteile für Anbieter und Nutzer von Maschinen/Anlagen durch Lebenszykluskostenoptimierung schaffen. *Lebenszykluskosten optimieren*, 15–34.

Schweiger, S. (Ed.) (2009). *Lebenszykluskosten optimieren: Paradigmenwechsel für Anbieter und Nutzer von Investitionsgütern* (1. Aufl.). Wiesbaden: Gabler.

Schweiger, S. (Ed.) (2011). *Serviceinnovationen in Industrieunternehmen erfolgreich umsetzen: Neue Geschäftspotenziale gezielt durch Dienstleistungen ausschöpfen* (1. Aufl.). Wiesbaden: Gabler.

Shields, M. D., & Young, S. M. (1991). Managing Product Life Cycle Costs: An Organizational Model. *Journal of Cost Management for Manufacturing Industry, 5*(3), 39–52.

Siegwart, H., & Senti, R. (1995). *Product life cycle Management: Die Gestaltung eines integrierten Produktlebenszyklus.* Stuttgart: Schäffer-Poeschel Verlag.

Stan, C. (2012). *Alternative Antriebe für Automobile: Hybridsysteme, Brennstoffzellen, alternative Energieträger* (3., erw. Aufl.). Berlin, Heidelberg: Springer Vieweg.

Stratmann, J. (2001). *Bedarfsgerechte Informationsversorgung im Rahmen eines produktlebenszyklusorientierten Controllings*. TU Berlin., Diss., 2000. *Reihe: Bd. 71.* Lohmar, Köln: Eul.

Tschöke, H. (2012). Informationsreihe MTZ Wissen Die Elektrifizierung des Antriebsstrangs. *MTZ - Motortechnische Zeitschrift, 73*(5), 413–419.

Tschöke, H. (2015). *Die Elektrifizierung des Antriebsstrangs: Basiswissen. ATZ/MTZ-Fachbuch.* Wiesbaden: Springer Vieweg.

van Vliet, O., Kruithof, T., Turkenburg, W., & Faaij, A. (2010). Techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars. *Journal of Power sources, 195*, 9570-6585.

Wallentowitz, H., & Freialdenhoven, A. (2011). *Strategien zur Elektrifizierung des Antriebsstranges: Technologien, Märkte und Implikationen* (2., überarbeitete Auflage). Wiesbaden: Vieweg+Teubner Verlag / Springer Fachmedien Wiesbaden GmbH Wiesbaden; SpringerLink (Online service).

Welle, R., & Neugebauer, E. (2007). Die TCO-Maschine kommt. *Fertigung, Januar/Februar*, 58–60.

Wildemann, H. (2010). *Total Cost of Ownership: Leitfaden zur Optimierung der Gesamtkostenposition in Beschaffung, Produktion und Logistik* (4. Aufl.). *Leitfaden / Transfer-Centrum für Produktions-Logistik und Technologiemanagement: Vol. 98.* München: TCW-Verl.

Williamson, S. S. (2013). *Energy management strategies for electric and plug-in hybrid electric vehicles.* New York, Heidelberg, Dordrecht, London: Springer.

Wouters, M., Anderson, J. C., & Wynstra, F. (2005). The adoption of total cost of ownership for sourcing decisions - a structural equations analysis. *Accounting, Organizations and Society, 30*(2), 167–191.

Wübbenhorst, K. L. (1984). *Konzept der Lebenszykluskosten: Grundlagen, Problemstellungen und technologische Zusammenhänge*. Zugl.: Darmstadt, Techn. Hochsch., Diss., 1984. *Reihe Betriebswirtschaft: Vol. 12.* Darmstadt: Verlag für Fachliteratur.

Wynstra, F., & Hurkens, K. (2005). Total Cost and Total Value of Ownership. In M. Eßig & U. Arnold (Eds.), *Perspektiven des Supply Management. Konzepte und Anwendungen ; Festschrift für Ulli Arnold* (pp. 463–482). Berlin u.a.: Springer.

Zehbold, C. (1996). *Lebenszykluskostenrechnung. krp Edition, Schriftenreihe der krp.* Wiesbaden, s.l.: Gabler Verlag.

Zsidisin, G. A., Ellram, L. M., & Ogden, J. A. (2003). The Relationship between Purchasing and Supply Management's perceived Value and Participation in Strategic Supplier Cost Management Activities. *Journal of Business Logistics, 24*(2), 129–154.

List of Figures

List of Tables

List of Equations

List of Abbreviations

ADAC	Allgemeiner Deutscher Automobil-Club
AFC	Annual Fuel Consumption
BEV	Battery Electric Vehicle
BOM	Bill Of Material
BSFC	Brake Specific Fuel Consumption
BSG	Belt Starter Generator
CD	Charge Depleting
CNG	Compressed Natural Gas
CS	Charge Sustaining
DC	Direct Current
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DME	Dimethyl Ether
E85	Ethanol
E-CVT	Electrically Continuous Variable Transmission
EREV	Extended Range Electric Vehicle
EUCAR	European Council for Automotive R&D
EV	Electric Vehicle
FAME	Fatty Acid Methyl Esther
FCEV	Fuel Cell Electric Vehicle
FT-Diesel	Fischer-Tropsch Synthesis Diesel
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HVO	Hydro-treated Vegetable Oil
ICE	Internal Combustion Engine
LCC	Life Cycle Costing
LiB	Lithium Ion Batteries
LPG	Liquefied Petroleum Gas
M&R	Maintenance & Repair
MCRP	Mean Costs of Replacement Parts
MHEV	Mild Hybrid Electric Vehicle
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NCM	Nickel Manganese Cobalt Oxide
NEDC	New European Driving Cycle
NGV	Next Generation Vehicle
NPE	Nationale Plattform Elektromobilität

OEM	Original Equipment Manufacturer
PHEV	Plug-In Electric Vehicle
PISI	Port Injection Spark Ignition
PKW	Personenkraftwagen
REEV	Range Extended Electric Vehicle
RV	Resale Value
SME	Small and Medium Enterprises
SOC	State Of Charge
TCO	Total Cost of Ownership
TTW	Tank To Wheel
VAT	Value Added Tax
VDMA	Verband Deutscher Maschinen- und Anlagenbau
VersStG	Versicherungssteuergesetz
WB	Wallbox