Explaining Technology Dominance in the Standards Battle between Battery Electric Vehicles and Hydrogen Fuel Cell Electric Vehicles by Means of Using the Multi-Criteria Decision-Making Tool Known as the Best Worst Method

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Executive Summary

During the last decade, the personal transportation vehicle market has experienced a remarkable transformation that is far from being over. Unprecedented technological innovation and an increasing concern about pollution and climate change have pushed society towards a search for sustainable solutions. These efforts have materialized into two main alternatives to conventional fossil-fuel based personal transportation options: Battery Electric Vehicles (BEVs) and Hydrogen Fuel Cell Electric Vehicles (HFCEVs). The study of such a challenging endeavour like the renewal of the worldwide car stock by emerging technologies can lead to valuable insights about the drivers behind technology dominance for the standards battle between the BEV and the HFCEV.

This research study was performed in three different phases. The first stage consisted of determining which factors are relevant for this technology battle according to the most up-to-date framework of factors for standards battles. The second phase consisted of analysing the data collected by surveying experts in economics of technology and innovation as well as in the automotive sector to determine the importance of pre-selected factors. In addition, in this second stage, it was found that, out of the two alternatives – BEVs and HFCEVs –, there is one which will most likely achieve market dominance according to experts. The third and final stage of this research study consisted of discussing the findings obtained from the data analysis in light of literature to answer the main research question: *"which factors affect technology dominance in the standards battle between BEVs and HFCEVs according to experts?"*.

Out of the 29 factors from the framework by van de Kaa, van den Ende, de Vries and van Heck (2011), 11 were considered to be relevant for this particular technology battle. The analysis of the collected data by means of a Multi-Criteria Decision-Making method known as the Best Worst Method allowed to find the importance of each of these factors according to experts. Results show that key factors for this technology battle are *technological superiority*, *compatibility* and *brand reputation and credibility*. Factors with moderate importance are *pricing strategy*, *financial strength* and *network of stakeholders*, and factors with the lowest importance were found to be *regulator*, *commitment*, *learning orientation*, *complementary goods* and *marketing communications*. In addition, according to experts, it was determined that BEVs have a substantial higher likelihood of achieving technology dominance in comparison to HFCEVs. Based on the results, it can be concluded that, according to experts, all relevant eleven factors affect technology dominance in this standards battle, since none of the factors turned out to have a negligible or extremely low level of importance in comparison to the rest of the criteria.

The results of this research study has implications for both policy makers as well as executives of firms involved in this technology battle. The outcome of this analysis suggests that policy makers should focus all efforts on incentivizing BEVs as a means of personal transportation. Regarding the automotive industry, the results of this study encourage executives of firms involved in this technology battle to orient the efforts of their companies towards the BEV, and to do so by focussing on technological innovation while taking care of the brand image. In addition, the outcome of this study suggests the importance of collaboration between firms and policy makers for the sake of improving *compatibility* between vehicles and complementary products.

This research study contributes to scientific literature by sharpening the understanding of what drives a technology battle by showing the relevance that several factors have to determine technology dominance in the standards battle between BEVs and HFCEVs. In addition, a first indication that some of these results might be generalizable to achieve technology dominance in the automotive and adjacent industries is provided. Moreover, the outcome of this study contributes to determine which factors tend to be relevant for technology dominance in standards battles in general. Finally, this thesis delivers useful insights for the practical field, which is currently debating which alternative should be supported.

Future research is encouraged to analyse more technology battles in different types of industries in order to determine which factors affect technology dominance in each market, and therefore, to be able to make further generalizations about what factors tend to drive technology battles in general.

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List of Acronyms

BEV: Battery Electric Vehicle

BWM: Best Worst Method

HFCEV: Hydrogen Fuel Cell Electric Vehicle

ICEV: Internal Combustion Engine Vehicle

MCDM: Multi-Criteria Decision-Making

ZEV: Zero Emissions Vehicle

1. Introduction

During last decades, markets and society have shown an increasing interest in electric mobility. The main reasons for this claim are the unprecedented technological innovation and development of sustainable solutions. These reflect how important sustainability has become for the clear majority of developed nations, which witness with concern the advent of the consequences of an increasingly palpable climate change. Such concept of electric mobility was initially introduced in the market as 'hybrids', which consist of reciprocating engine vehicles assisted by electric motors powered by batteries. Nowadays, the development of electric transportation has resulted in the appearance of 100% electric cars, which depend exclusively on electric motors to run. These electric motors obtain the required electricity from lithium-ion batteries or hydrogen fuel cells. The former type is called Battery Electric Vehicle (BEV), while the latter is known as Hydrogen Fuel Cell Electric Vehicle (HFCEVs).

During the last couple of years, governments from all over the world have tried to incentivise the adoption of electric vehicles in an attempt to adopt a more sustainable and environmentally friendly approach to light-duty transportation (Bjerkan, Nørbech & Nordtømme, 2016; Masiero, Ogasavara, Jussani & Risso, 2016). In fact, for the European Union, preventing climate change has become a priority. Consequently, targets towards the reduction of greenhouse gas emissions have been established by the European Commission. These targets imply a 20% reduction in greenhouse gas emissions by 2020, and a 40% cut by 2030 in comparison to 1990 emission levels. Eventually, the emissions by 2050 are expected to be cut between 80-95% in comparison to the mentioned reference baseline. In addition, the demands of the European Commission do not only cover greenhouse gas emissions, but energy consumption from renewable energies as well. In fact, EU countries agreed to achieve a 20% of the total energy consumption from renewable energy by 2020, and at least a 27% by 2030 (EU climate action, 2017). However, it is worth mentioning that actions regarding the production and usage of clean energy go beyond meeting the demands of the European Commission. They represent a necessary step towards the reduction of pollution in cities, the improvement of living standards and a responsible and sustainable use of energetic resources.

Electric transportation represents a cornerstone in the fight against climate change, even if electricity employed by electric vehicles comes from non-renewable energy sources. This is because energy conversion efficiency of non-renewable energy sources in industrial generation plants is substantially higher than in internal combustion engine vehicles. In fact, on average, internal combustion engines efficiency is 20% (Sierens & Rosseel, 2000), while industrial energy generation efficiency can reach 85% (Worrell, Bernstein, Roy, Price & Harnisch, 2009). Therefore, it can be concluded that the substitution of the current reciprocating engine vehicle stock by electric cars would be part of the solution to mentioned challenging problems. It is then expected that electric mobility will be the future of personal transportation.

Battles like the one between BEVs and HFCEVs are generally between specification of interfaces (Van de Kaa, van den Ende, de Vries & van Heck, 2011). In literature, many authors decide to use the term 'standard' in order to refer to this specification of interfaces (Van de Kaa et al., 2011). However, since there are many categories of standards (Blind, 2004), such term may lead to confusion. According to Krechmer (1996), a compatibility standard is a set of specifications that "define the interface between two or more mating elements that are compatible" (p. 7). In addition, there is some overlap in literature between the concept of 'dominant design' and standard (Den Uijl, 2015). As explained by van de Kaa et al. (2011), 'dominant' has several meanings. According to them, the most complete definition of 'dominant design' is a new product or system that achieves more than 50% of the market share for a significant amount of time in a certain product category. Another concept that has certain meaning overlap with the concepts of standard and dominant design is the concept of 'platform'. A platform is defined as a product, service or technology consisting of core components and interfaces that are compatible with complements as one system (Gawer, 2011). The reason for this meaning overlap is due to the fact that the concepts of standard and dominant design became intertwined into the term 'platform technology' (Kim & Kogut, 1996). Platforms do not necessarily imply technological dominance, although compatibility of components with other platforms tends to attract customers (Schilling, 2000). In addition, platforms may appear on several levels of a product architecture, just like in the case of dominant designs (Den Uijl, 2015). In order to find a solution to this overlapping of meaning among complementary standard, dominant design and platform, den Uijl (2015) uses the term 'de-facto standard' to cover them all under one single concept. According to den Uijl (2015), a de-facto standard is a "compatibility standard, platform, or product design specification that has obtained widespread acceptance (>50% market share in terms of worldwide yearly unit sales) through market competition" (p. 6). In this research, the focus will be on the concept of de-facto standards, and therefore, on a combination of compatibility standards, dominant designs and platforms. The reason why the concept of de-facto standards is considered for this research study is due to the fact that the three concepts of compatibility standard, dominant design and platform play a role in the context of the technology battle between BEVs and HFCEVs. Figure 1 below shows how a de-facto standard can have, but does not necessarily need to have, the three facets. Instead, it is possible that a de-facto standard only has one or two of them:

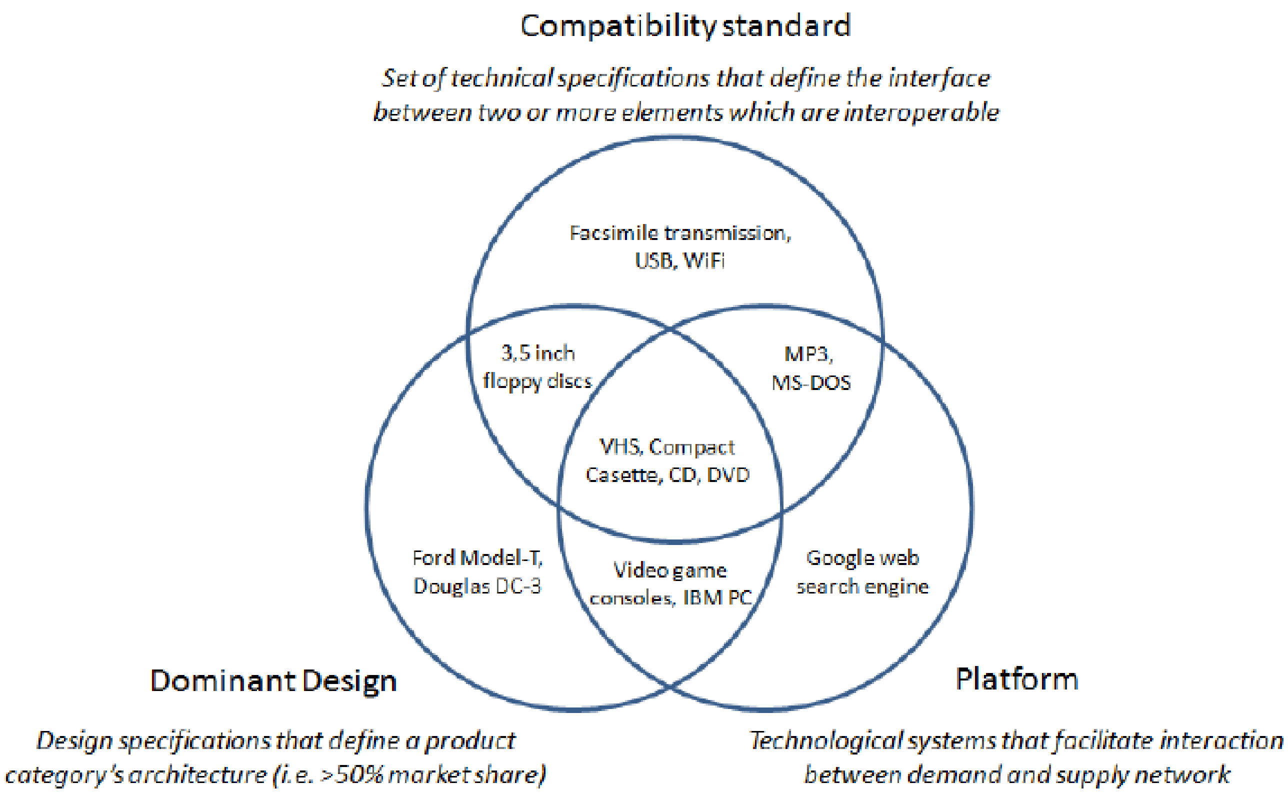

Figure 1. Overlap among concepts of compatibility standards, dominant designs and platforms (Den Uijl, 2015, p. 6)

The main scientific contribution of this research study consists of determining which factors are relevant for the technology battle between BEVs and HFCEVs. These findings may be relevant for other technology battles in the automotive and similar industries. In addition, this thesis contributes to find out which factors tend to be relevant for technology dominance in standards battles in general.

1.1. Research Problem

To assess technology dominance in the standards battle between BEVs and HFCEVs, it is necessary to use the most complete framework of factors for technology dominance. This framework, developed by van de Kaa et al. (2011), has been used in several studies in the field of dominant designs and standardization (Van de Kaa, de Vries & Rezaei, 2014; Van de Kaa, Rezaei, Kamp & de Winter, 2014; Van de Kaa, van Heck, de Vries, van den Ende & Rezaei, 2014). However, despite the societal importance of this topic, this model has never been used in the context of the standards battle between the BEV and the HFCEV. Consequently, there is no extensive analysis about which factors are relevant for this battle, and therefore, no indication about the degree of importance of each of them. Without this, it is not possible to explain technology dominance in the context of this technology battle. In addition, although there is scientific literature about the analysis of standards battles by means of using Multi-Criteria Decision-Making (MCDM) methods (Van de Kaa at al., 2014; Van de Kaa, Rezaei et al., 2014; Van de Kaa, van Heck et al. 2014), the analysis performed in these scientific articles is based on the Analytic Hierarchy Process (AHP) and not on the recently developed Best Worst Method (BWM). However, despite the lack of literature employing MCDM methods to assess technology battles, such methods, and in particular the BWM, allow for the gathering of plenty of insights that can be translated into a simple final result.

Therefore, it can be concluded that there is a need for a comprehensive analysis that determines which factors are relevant, and how important they are, for this particular battle. This will bring light into this standards battle from a technology dominance perspective, and thus, contribute to the research field of technology dominance. In addition, performing this analysis by means of the BWM will allow to assess this standards battle with a different approach to the one present in existing scientific literature.

1.2. Research Objective

The aim of this research is to determine which factors affect technology dominance in the standards battle between BEVs and HFCEVs according to experts. To study technology dominance in this context, it is necessary to determine which factors of the framework developed by van de Kaa et al. (2011) are relevant and how important they are according to experts. In order to determine the importance of relevant factors for this technology battle, the MCDM tool known as the BWM will be employed. By using this method, the weights for each of the relevant factors will be computed. As a by-product of such analysis, it will be possible to obtain a final value for each of the alternatives – BEV and HFCEV – giving an indication about which type of vehicle has the highest likelihood of achieving technology dominance according to experts. In addition, it is worth mentioning the possibility that the analysis based on the insights of experts might not reveal a scenario in which the balance tips towards a certain alternative. This would indicate that, according to experts, there would be a high probability that both technologies are bound to coexist, and therefore, there would be no technology dominance.

The notion of assigning weights to factors to assess technology dominance in standards battles can be found in existing literature (Van de Kaa at al., 2014; Van de Kaa, Rezaei et al., 2014; Van de Kaa, van Heck et al. 2014). However, this has not been done for the technology battle between BEVs and HFCEVs. Furthermore, determining final values for each alternative will be valuable to deliver advice regarding which design will most likely achieve market dominance according to experts. This has not been done for this particular technology battle either, and thus, it represents a practical implication of this research.

1.3. Research Questions

To accomplish the research objective explained in previous section and fulfil the research gap presented in section 1.1, it is necessary to answer the next main research question:

"Which factors affect technology dominance in the standards battle between Battery Electric Vehicles and Hydrogen Fuel Cell Electric Vehicles according to experts?"

To give an answer to this, it is necessary to answer the next three sub-research questions:

"Which factors are relevant for the technology battle between the Battery Electric Vehicle and the Hydrogen Fuel Cell Electric Vehicle according to experts?"

"What is the importance of each of the relevant factors for the standards battle between the Battery Electric Vehicle and the Hydrogen Fuel Cell Electric Vehicle according to experts?"

"Which alternative, either the Battery Electric Vehicle or the Hydrogen Fuel Cell Electric Vehicle, will most likely achieve technology dominance according to experts? "

1.4. Research Approach

This research will be performed in three differentiated phases. The first phase consists of determining the answer to the first sub-research question: "which factors are relevant for the technology battle between the Battery Electric Vehicle and the Hydrogen Fuel Cell Electric Vehicle according to experts?". To find out which factors from the framework developed by van de Kaa et al. (2011) must be included as criteria in the BWM linear model, a literature review will be performed. This is done under the assumption that relevant aspects for this technology battle are most probably already present in literature. To find such literature, search engines like Google Scholar, Scopus and ScienceDirect among others will be employed. However, in order to reduce the risk of not considering a relevant aspect for this standards battle in the analysis, the literature review will be complemented by two interviews with two different experts in the field . In case both of these experts agree that a certain factor is relevant despite not finding scientific literature supporting such relevance, then the factor will be included in the model. However, if literature supporting the relevance of a certain factor is not found, and only one of the two experts considers it relevant, such factor will not be included in the analysis. This approach is followed to guarantee that only relevant factors for the technology battle between BEVs and HFCEVs are included in the model, since otherwise, the presence of too many factors in the analysis will lower the discrimination power of the BWM, and therefore, the quality of the results.

The second phase targets the second and third sub-research questions: “what is the importance of each of the relevant factors for the technology battle between the Battery Electric Vehicle and the Hydrogen Fuel Cell Electric Vehicle according to experts?” and “which alternative, either the Battery Electric Vehicle or the Hydrogen Fuel Cell Electric Vehicle, will most likely achieve technology dominance according to experts?”. To give answer to these questions, a linear model of the MCDM tool known as BWM is employed. This method starts by identifying the best and worst criteria (Rezaei, 2015; Rezaei, 2016). Eventually, pairwise comparisons between each of these two criteria against all other factors result in obtaining weights for each of the factors. The final results for each vehicle type are obtained by aggregating the weights of the factors and the scores of the alternatives (BEV and HFCEV), giving an indication about which alternative will most likely achieve technology dominance according to experts. It is worth mentioning that the BWM has been employed in several research studies before, and in this sense, this can be considered a replication of other studies. However, the notion of assigning weights to factors to determine technology dominance for this particular standards battle is not present in existing scientific literature, what makes this thesis more than just a mere replication study.

To make proper use of the BWM, experts from academia as well as from industry will be surveyed to obtain the preference values for each of the relevant factors so that the pairwise comparisons of the criteria can be performed. Three groups of experts will be surveyed to accomplish the data acquisition. These are academics from the Delft University of Technology, academics from other universities around the world and industry practitioners. These contacts will be provided by faculty professors and PhD candidates with extensive networks in other universities as well as in the automotive industry. In addition, interviewees and respondents will be asked to provide the contact information of other potential candidates. Finally, additional experts will be contacted via professional networks on the Internet or directly by email.

Finally, based on the data analysis performed, conclusions will be drawn in the third phase of this research study in order to give an answer to the main research question: “which factors affect technology dominance in the standards battle between Battery Electric Vehicles and Hydrogen Fuel Cell Electric Vehicles according to experts?”.

1.5. Structure of the Thesis

After the introduction of this research study, several streams of theoretical literature related to technology battles will be discussed in section 2. This will be followed by the research methodology in section 3, where the framework to be employed will be presented, the factor selection procedure will be discussed, details about the BWM will be delivered, and further insights about data collection and the application of the BWM linear model will be specified. Section 4 delivers the description of the technology battle between the BEV and the HFCEV. In addition, the case analysis is presented and the results of the data analysis are delivered. Section 5 consists of the interpretation of results, in which the outcomes of the data analysis are discussed in light of the theory. Finally, section 6 delivers the theoretical and practical contributions of this research study, a reflection about how this study adds to the master's degree in engineering and policy analysis and the conclusions.

2. Theoretical Background

In order to give answer to the main and sub-research questions, it is necessary to understand which factors can explain the emergence of de-facto standards as a result of a technology battle. Several authors have tried to synthesize relevant aspects of technology battles in frameworks of factors. Among the most cited, it is worth mentioning the ones by Lee, O'Neal, Pruett and Thomas (1995), Schilling (1998), and Suarez (2004). However, there is more literature available about the aspects that influence the outcome of technology battles. In this chapter, the different existing frameworks and scientific literature about the emergence of de-facto standards and technology dominance are discussed.

As explained in Chapter 1, according to den Uijl (2015), a de-facto standard is a "compatibility standard, platform, or product design specification that has obtained widespread acceptance (>50% market share in terms of worldwide yearly unit sales) through market competition" (p. 6). Therefore, winning or losing a technology battle can be understood as a synonym of achieving the establishment of a de-facto standard. To understand how this emerges, many authors from the fields of evolutionary economics (Utterback & Abernathy, 1975; Anderson & Tushman, 1990), network economics (Farrel & Saloner, 1985; Katz & Shapiro, 1985; Arthur, 1989; Liebowitz & Margolis, 1994), institutional economics (Willard & Cooper, 1985; Cusumano, Mylonadis & Rosenbloom, 1992; Garud & Kumaraswamy, 1993; Khazam & Mowery, 1994) and technology management (David, 1985; Lee et al., 1995; Schilling, 1998; Schilling, 2002; Suarez, 2004) have designed models, and have come up with factors that may have an influence on the emergence process. This literature contributes to debunk the past prevailing notion that considers technological superiority as the most important aspect to achieve technology dominance.

Based on the work of Anderson and Tushman (1990), the reasons why a design achieves market dominance is in many occasions not related to technological superiority. One of the most famous cases for such apparent incongruence is the market dominance of the VHS instead of the technologically superior Sony Beta format. Building on scientific literature that assumes that the emergence process of a de-facto standards is not a 'black box' in which it is not possible to know what happens inside, Lee et al. (1995) debunks the conception that the emergence of dominant designs is due to interactions that are too sophisticated to be understood. Such demystification brings with it the possibility of developing heuristics and models that can be employed to increase the likelihood of technology dominance.

Apart from the mentioned frameworks by Anderson and Tushman (1990) and Lee et al. (1995), there are several other frameworks that attempt to synthesise relevant aspects of the process of emergence of de-facto standards. Among these, it is worth mentioning the frameworks by Utterback (1994), in which strategies for mastering innovation are delivered from the lens of technological change, the model of economic and strategic factors that lead to success or technological lockout by Schilling (1998), the framework for technological dominance by Suarez (2004), the model for the probability and time of emergence of dominant designs by Srinivasan, Lilien and Rangaswamy (2006) and the framework developed by de Vries, de Ruijter and Argam (2011), which contemplates the combination of factors that may lead to the coexistence of several designs.

Utterback (1994) considers the capacity to innovate as the most relevant aspect in a technology battle. According to him, innovation is a sine qua non for market dominance. Such focus on innovation also stands out in the work of other scholars. Among them, it is worth mentioning the work by Lee et al. (1995), which brings out the importance of the learning capacity of an organization. This is related to the research study on organizational learning by Levitt and March (1988), which focuses on the learning orientation by pointing out the importance of competency traps, in which organizations tend to perform at a sub-optimal level by sticking to old routines that have shown to work in the past, leading organizations to specialize on the wrong skills (Levitt and March, 1988). This important aspect has also been discussed by Cohen and Levinthal (1990) and Leonard-Barton (1992). Cohen and Levinthal (1990) states that “the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends is critical to its innovative capabilities” (p. 128). Following the same line of thought, Leonard-Barton (1992) concludes that “technology-based organizations have no choice but to challenge their current paradigms” (p. 123). Another theoretical aspect linked to the learning orientation of format supporters is the rate of change of the market itself, which is of great importance for the technology battle between BEVs and HFCEVs due to the rapid rate of technological improvement within the industry. Utterback (1994) emphasized the concepts of ‘periods of continuity’ and ‘periods of discontinuity’. During the former, improvements to technology are incremental, and therefore, non-revolutionary. However, during periods of discontinuity, big leaps forward are achieved, making previous technology obsolete. Schilling (2002) exemplifies this idea by stating that “a firm’s technology can be locked out of the market simply because the firm is unable to keep up with the rate of technological change in the industry” (p. 389). Therefore, according to existing literature, it can be concluded that, without predisposition of firms to harness new information and adapt to new market conditions, the likelihood that a certain technology achieves market dominance and maintains such position dramatically decreases.

Building on previous literature, Schilling (1998) takes a more comprehensive approach by performing an exhaustive analysis of the aspects that lead to technology dominance. With this framework, and in the same line of thought as Lee et al. (1995), she claims that technology adoption processes are not fully random and that firms can exert certain control to influence the outcome. Her model revolves around strategies that lower the risk of 'technological lockout', which stands for the inability of a firm to compete in the market due to slow investment strategies in new product developments. In fact, Schilling (1998) is more precise than Lee et al. (1995), since she takes into consideration two main possible negative scenarios for firms. Her model consists of two types of technological lockouts. In the first type, "the firm produces products, in the absence of a dominant product design, that are subsequently rejected by the market as the market moves toward a dominant design" (p. 271). The second type of technological lockout occurs when there is a dominant design already in the market, and the firm is incapable of producing products conforming to the standard (Schilling, 1998). To avoid falling into the first type of technological lockout, the already discussed learning capacity of technology supporters plays an essential role. In addition, other aspects like complementary goods, installed base, timing of entry, margin of technological improvement, presence of entry barriers and network externalities are considered essential factors to take into account to avoid the first type of technological lockout. On the other hand, the chances of entering a type II technological lockout are in function of the firm's learning capabilities, as well as the presence and effectiveness of competitor intellectual property strategies. In addition, Schilling (2002) proves how essential some of these factors are for industries with high network externalities. Factors that are especially important for industries with high network externalities are the installed base, presence of complementary goods, learning orientation of the firm and timing of entry.

Suarez (2004) approached technology dominance from a different perspective in comparison to previous literature. He provides a new approach by distinguishing between 'firm-level' and 'environmental' factors. As Lee et al. (1995) did, Suarez (2004) considers factors that cannot be controlled by technology supporters as essential in the final outcome of a technology dominance process. However, Suarez (2004) shows the dependence between the relevance of factors and the stage of the technology dominance process. While frameworks by Lee et al. (1995) and Schilling (1998) show which factors may be relevant in a technology battle, Suarez (2004) goes beyond by showing that the importance of factors varies depending on the phase of the dominance process. In his words: "success in each phase seems to respond to a different mix of firm and environmental-level factors" (p. 283).

In comparison to the already discussed frameworks, Srinivasan et al. (2006) brings light into the relationships between well-known important factors in technology battles and the probability and time of emergence of technology dominance. The model by Srinivasan et al. (2006) is based on a statistical model that shows that dominant designs are more likely to emerge in markets with low intellectual property constraints, weak network externalities, low product ‘radicalness’ and high R&D intensity. The fact that the emergence of dominant designs is more likely to occur in environments of low technological rate of change is consistent with Utterback (1994) model, since periods of continuity in which there are low levels of innovation are generally followed by leaps forward that lead existing technology down the path of obsolescence. In addition, Srinivasan et al. (2006) offers a complementary view of the models about technological lockout by Schilling (1998) and technology dominance by Suarez (2004). This is due to the fact that several aspects considered as relevant by Schilling (1998) and Suarez (2004) to avoid technology lockout or achieve technology dominance are portrayed in the market conditions that favour the emergence of de-facto standards.

So far, literature reviewed about technology battles suggests that only one alternative will eventually achieve the position of de-facto standard. However, the research study by de Vries et al. (2011) offers empirical proof that this does not necessarily have to be the case for all technology battles. To debunk this exclusive conception, de Vries et al. (2011) shows the results of an extensive literature review in which factors are grouped into two categories: factors that favour the existence of a dominant alternative and factors that favour the co-existence of multiple designs. Many of the factors from both categories are compiled from literature that has already been discussed in this chapter. The main factors that favour the emergence of a dominant design are the installed base, the availability of complementary goods and the lock-in effect, which are relevant aspects for technology dominance according to Katz and Shapiro (1985), Arthur (1989), Schilling (1998) and Suarez (2004). Other aspects that favour the dominance of one design are the network externalities, as already identified by Katz and Shapiro (1985) and Liebowitz and Margolis (1994), the inter-organizational linkages that the group of format supporters have with potential allies, the appropriability strategy, as discussed by Anderson and Tushman (1990), Suarez (2004) and Srinisvasan et al. (2006), the timing of entry, considered by Schilling (2002) and Suarez (2004), pricing strategies, the reputation of the format supporters, governmental regulation, and finally, technological superiority (Vries et al., 2011). On the other hand, factors that favour the existence of multiple designs in the marketplace are the presence of different features that encourage the formation of consumer communities, the existence of technologies that enable compatibility between both competing technologies, and finally, the arrogance of firms whose attitude of superiority might lead them to compete in battles they cannot win.

No model can perfectly predict what will happen in the future marketplace. However, frameworks can be used ex-ante as valuable heuristics that narrow down the range of outcomes (Lee et al., 1995) of the technology battle between BEVs and HFCEVs. However, in order to increase the reliability of the analysis to be performed, it is crucial to employ the most complete framework of factors available. All models discussed above offer valuable insights and unique perspectives to assess the emergence of de-facto standards. Nevertheless, none of them are as comprehensive as the framework developed by van de Kaa et al. (2011). This framework, based on an extensive literature review, gathers all the factors known until now that might have an influence on the outcome of a technology battle. This is the reason why such model will be employed in this research study.

The framework developed by van de Kaa et al. (2011) gathers and classifies all know factors for interface format battles in five categories: *characteristics of the format supporter*, *characteristics of the format*, *format support strategy*, *other stakeholders* and *market characteristics*. The first category is rooted in institutional economics theory, and it alludes to the strength of actors supporting a certain format. The stronger the actors behind a certain technology, the higher the likelihood that this technology achieves market dominance in the future. The second category, *characteristics of the format*, is based on management and standardization literature, and it consists of aspects that show that a superior format has a higher likelihood of achieving market dominance. The third cluster is based on institutional economics, and it consists of the strategies that corporations can adopt to win a standards battle. The category *other stakeholders* highlights the importance of stakeholders that do not belong to the group of technology supporters. Finally, the category *market characteristics* is rooted in network economics literature. This group of factors takes into consideration those characteristics that are out of the control of corporations, but that nonetheless, have an impact on the results of a technology battle. The list and explanation of the 29 factors gathered in van de Kaa et al. (2011) are given in Appendix 1. For the sake of terminological simplicity and accuracy, the terms 'design', 'technology', 'technological design' and 'standard' will be used interchangeably to refer to the alternatives of the technology battle – BEV and HFCEV –, and they will replace the terms 'format' and 'interface format' used in the framework by van de Kaa et al. (2011) in the remainder of this research study.

3. Research Methodology

This section delivers an explanation about the application of the framework of factors to be used in this research study. In addition, the procedure to determine which factors are relevant for this particular technology battle is presented and insights about the MCMD method known as the BWM are delivered. Finally, the data collection procedure as well as the application of the BWM are described.

3.1. Framework

In order to carry out this research, the framework of factors for winning interface format battles developed by van de Kaa et al. (2011) is used. As explained in previous chapter, this framework consists of 29 factors. These are grouped into five categories, namely *characteristics of the design supporter*, *characteristics of the design*, *design support strategy*, *other stakeholders*, and *market characteristics*. Out of these five categories, only the first four will be used in this research study. This is due to the fact that only the factors in these four categories can be directly affected by the stakeholders involved in the technology battle. The fifth category consists of factors that have the same values for both of the alternatives (Van de Kaa, Rezaei, et al., 2014), and therefore, since these factors do not differ for both designs, they are of no relevance for explaining technology dominance. Thus, out of the 29 original factors from the model by van de Kaa et al. (2011), only the first 23 will be initially considered for this research study.

3.2. Relevant Factors

A linear model of the MCDM tool known as the BWM will be employed to explain technology dominance in the context of this specific technology battle. To accomplish this task, it is necessary to determine the level of importance of each of the relevant factors according to experts. However, before using this method to determine the level of importance of each factor, it is essential to find out which factors are relevant for this technology battle. This was done by means of performing an extensive literature review, which was complemented by information gathered during two interviews with two different experts in the field of economics of technology and innovation. In this literature review, reports from design supporters, academic articles and news articles were analysed. Despite the relevance of this technology battle, there is no extensive theoretical and practical literature that studies this topic from a similar perspective, what led to the necessity of complementing the literature review with two interviews with experts from academia in order to make sure that no relevant factor was discarded from the analysis. As explained in section 1.4, the use of insights collected during these two interviews is complementary to the literature review and the main purpose for it is nothing more than to make sure that relevant factors for which no literature was found were included in the model. However, factors not found in literature would only be included in the analysis when both interviewees agree on their high relevance for this technology battle. Otherwise, these factors would be discarded to make sure that the discrimination power of the BWM is as high as possible, allowing for more precision, and therefore, more conclusive results. This is due to the fact that the higher the number of non-relevant factors included in the analysis, the lower the discrimination power of the tool, making very important factors "stand-out" less in comparison to the rest. All in all, the explained factor selection procedure was designed to make sure that all relevant factors were included in the model while not being too conservative by including an excess of criteria. If we do not make sure that all relevant factors are included in the analysis, then the model will not be complete, leading to false conclusions. On the other hand, the power of the BWM will be reduced if the factor selection procedure is too conservative and variables that are almost certainly not relevant are included in the model.

3.3. BWM

As mentioned in previous paragraph, a linear model of the BWM will be employed to determine the importance or weights of the relevant factors. The reason why the linear model of the BWM is used to determine which factors affect technology dominance is because, according to Rezaei (2015), the BWM requires fewer comparisons with respect to other matrix-based MCDM tools such as the Analytical Hierarchy Process (AHP). In addition, final weights obtained from the BWM are highly reliable and comparisons are more consistent than when using the AHP. Finally, the BWM excels for its simplicity, since comparisons are performed by only using integer numbers between one and nine. This represents a clear advantage with respect to other MCDM methods, which require comparison matrices with integers as well as with fractional numbers. Therefore, this research study serves in a certain way as another proof of the usability of this method for assessing technology dominance, and as a unique proof that this method can be used to asses this particular technology battle.

According to Rezaei (2015) the linear model of the BWM to be used in this research study consists of several steps:

Step 1

The set of decision criteria must be determined. These criteria $\{c_1, c_2, c_3, \dots\}$ are the relevant factors that must be used to come to a decision.

Step 2

The expert must determine the best (e.g. the most important) and the worst (e.g. the least important) factor per each of the clusters or categories of factors. At this point, no comparison with other criteria is required.

Step 3

The expert must determine the preference of the best criterion with respect to the rest of the criteria within the same cluster. This is done by means of using scores between 1 and 9, where 1 implies equal importance and 9 means extreme importance. The Best-to-Others vector would be something like: $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$, where a_{Bj} refers to the preference of B (best criterion) with respect to criterion j.

Step 4

The preference of all the criteria with respect to the worst criterion must be determined by using an integer between 1 and 9. This delivers the Others-to-Worst vector: $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})$, where a_{jW} is the preference of factor j with respect to the worst criterion W.

Step 5

According to Rezaei (2016), by minimizing the maximum of the set of $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}W_W|\}$ the formulation to find the unique solution becomes:

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$$

s.t:

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{for all j}$$

This can be translated into the following linear programming problem:

$$\min \xi^L$$

s.t:

$$|w_B - a_{Bj}w_j| \leq \xi^L, \text{for all j}$$

$$|w_j - a_{jW}w_W| \leq \xi^L, \text{for all j}$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{for all j}$$

Such linear problem has a unique solution, which are the optimal weights $(w_1{}^*, w_2{}^*, \dots, w_n{}^*)$ and the consistency indicator ξ^L. The closer to zero ξ^L is, the higher the level of consistency of the model, and the more reliable the data used for the analysis is.

3.4. Data Collection

To gather all necessary data to perform the BWM analysis, it was necessary to obtain the opinion of experts in the field of research. To accomplish such task, experts in the case of this research study were contacted and asked to fill out a questionnaire. Such questionnaire consisted of an online survey, since this was the most convenient option to gather data from experts from all over the world. The obtained data set consists of data provided by 18 respondents from different geographical regions. To be more specific, these respondents were from the United States, the Netherlands, Spain, Portugal, Germany, Austria and China. The group of experts consists of industry practitioners, scholars from several prestigious universities as well as the director of a prestigious energy research institute. Since the results of this research study depend on the opinion of these experts, it was necessary to make sure that respondents had enough knowledge on the topic to be considered experts. Therefore, only academics and researchers with several published scientific publications or years of research, and practitioners with several years of experience in topic-related areas were consulted. In addition, to reduce the presence of bias from a certain group of respondents, data from both experts in technology battles as well as in BEV and HFCEV technical aspects were collected.

The scientific survey was developed via SoSci Survey software package, and hosted on the servers of this German company. To make filling out the survey the least laborious and time-consuming possible for the respondent, dynamic functionality as well as skip logic were implemented by means of using PHP programming language and HTML. By doing so, pages seen by the respondent depended on previous answers. In other words, depending on the answer given by the expert, the survey showed tailored questions in subsequent pages. The survey consisted of two main parts. In the first part, respondents were asked to determine the best factor for the first category. After this, they were asked to determine the preference values of each of the factors with respect to the already selected most important one. Finally, the expert was asked to provide the preference value for the factor that was chosen neither as the best nor as the worst criterion in comparison to the worst criterion. After doing this for the four categories or clusters of factors, the respondents were asked to do the same they have had to do for each category, but now taking the categories, and not the factors within the categories, as criteria. In the second part of the survey, respondents were asked to score both technologies for each of the factors. In this part, experts had to determine which alternative – either the BEV or the

HFCEV – performs better for each of the relevant factors and how much better it performs in comparison to the other technological design.

3.5. BWM Application

In the BWM application process, first, the weights for each criteria or factor within a category are computed. This is done by following the five-step process described in section 3.3. The obtained weights represent the importance of a certain factor within the category it belongs to. Therefore, such weight can only be compared to weights of other criteria belonging to the same category, which is the reason why they are called "local weights". In other words, factor local weights can only be compared within categories, but not across categories. These factor local weights can be seen in Table 8 in Appendix 3 with a yellow cell background. However, since for the analysis in this research study it is required to compare all factors irrespectively of the category they initially belong to, it is necessary to "normalize" the local weights (weights of factors that can only be compared to the weights of other factors within a category) by multiplying them by the weight of the corresponding categories. By doing so, the so-called "global weights" (importance of factors that can be compared to the weights of any other factor irrespectively of which category this factor belongs to) for the technology battle are determined. These can be found in Table 9 in Appendix 3 with a red cell background. To make sure that all calculations have been done properly, the sum of all these global weights must be equal to 1.

Once the global weights of each of the relevant criteria is known, data obtained from the second part of the survey is used to compute the average scores of each factor for each of the alternatives, namely BEVs and HFCEVs. These average scores for each of the alternatives are a reflection of how well each type of vehicle performs for each criterion or factor. However, they do not take into account the level of importance of each factor, namely the global weights mentioned above. By multiplying the average scores for each type of technology by the global weight per factor found before (column with averages on the right-hand side of red cells in Table 9 in Appendix 3), the weighted scores for each of the alternatives are determined. These weighted scores for each vehicle configuration show how well each vehicle type performs for each relevant factor taking into account the weight of the factors (factor weight scaled). In addition, by adding all the weighted scores of each alternative, two final figures that must sum up to one are obtained. These two last figures give the answer to the third sub-research question (see section 1.3). The alternative with the highest value corresponds to the type of vehicle that, according to experts, has the highest likelihood of achieving technology dominance.

Finally, it is worth mentioning that in order to make sure that all computations were performed correctly and that the results of the analysis are consistent from a methodological point of view, the sum of the last two figures that deliver the answer to the third sub-research question must be equal to one.

4. Results

In this chapter, the history of significant events in the technology battle between BEVs and HFCEVs is described. In addition, the reader can find the current state as well as future prospects of such battle. The second section of the chapter provides the case analysis, in which the relevant factors for the technology battle between BEVs and HFCEVs are presented. Finally, the results of the application of the BWM are delivered.

4.1. Case Description

As Schott, Puttner and Muller (2015) state, the "history of the electric car is long and unsteady" (p. 35). Although the concept of such machine was developed well over a century ago, it was not until recently when this type of vehicle started to obtain certain presence in the market place (Tuttle & Baldick, 2015).

The first commercially successful electric vehicle appeared in the 1890s, and during the following years, several car manufacturers targeted their efforts at advancing electric car technology. However, the fact that electric cars were less noisy, easier to drive and environmentally cleaner were not good enough qualities against the affordability of the mass-produced Ford Model T, what caused the electric vehicle to completely disappear from the picture. The dark ages of the electric car continued as a consequence of cheap oil and rapid technological advancements in ICEVs (Internal Combustion Engine Vehicles) until the late 1960s, when the United States Energy Department started to incentivize research and development of electric vehicles (Matulka, 2014). However, it was not until 1996 when General Motors presented a compelling electric car that attracted the attention of the American public: the EV1 (Edwards, 2006). This can be considered as the first mass-produced all-electric car of the modern era (Davies, 2017), delivering a respectable performance with a range of 80 miles and a great acceleration (Matulka, 2014). Nevertheless, once again, high hopes for BEVs ended in vain when, after having produced about 1100 EV1s (Edwards, 2006), General Motors decided to cancel the program due to the lack of economic feasibility of the project (Matulka, 2014).

In spite of all the misfortunes suffered by the BEV, the market started to change at the end of the second half of the 1990s. This stepping point coincides with the introduction of the Toyota Prius and the Honda Insight, which were the first mass-produced Hybrid Electric Vehicles (HEVs) by the giant Japanese automakers. Together with the increase of oil price and an ever-growing concern about climate change, this event put the seed that took the market to its current scenario (Matulka, 2014). Seven years after the start of the modern Hybrid Electric Vehicle (HEV) era in the United States in 1999

(Tuttle & Baldick, 2015), a Silicon Valley start-up named Tesla Motors – now named Tesla (O'Kane, 2017) – announced a luxury high performance sports car with a range of more than 200 km (Matulka, 2014). The announcement of such car, named the Tesla Roadster, attracted the interest of big car manufacturers, which started to invest large sums of capital in the development of mass-production BEVs. This led to the presentation of two additional BEVs and one plug-in hybrid electric vehicle in the following years. These cars were the Tesla Model S, the Nissan LEAF and the Chevrolet Volt (Boudreau, 2012; Matulka, 2014). With this, automakers gave the general public the chance to choose between different options of compelling electric vehicles. In addition, since the Tesla Model S and the Nissan LEAF were all-electric and the Chevrolet Volt was a plug-in hybrid electric car (Matulka, 2014), the consumer had the possibility to choose between a fully electric option and an 'in between' alternative between gasoline and electric, which was more appealing in the eyes of more conservative customers.

It is worth mentioning the relevant role of the government of the United States in this car 'electrification' process. In order to incentivize the electrification of personal transportation, the US government injected 51 billion US dollars to save General Motors from bankruptcy (Healey, 2013) and granted a loan of more than 400 million US dollars to Tesla Motors (Matulka, 2014) as well as to other manufacturers (ATVM, n.d.). These actions certainly helped General Motors, Tesla and other automakers to develop and produce their electric car models.

The HFCEV has had a different historical background compared to the BEV. Despite the fact that fuel cell technology is more than a century and a half old, its development and use in road vehicles has occurred in the last few decades (FuelCellToday, n.d.).

From the development of the first usable fuel cell system back in the late 1950s to the 1970s, fuel cell development was mostly linked to military and space applications, being the United States and the Soviet Union the main promoters (FuelCellToday, n.d.). The first road vehicle equipped with an operational fuel cell system came from the hand of General Motors in 1966. Its name was the 'Electrovan' (Kantola, n.d.) and it was limited to demonstration purposes (FuelCellToday, n.d.). However, the development of such van can be considered as the introduction of hydrogen powered fuel cell technology into the automotive field. Soon after this, in the 1970s, European countries and the United States started to implement air pollution policies with the target of reducing harmful ICEV exhaust gases. This, added to the Organization of the Petroleum Exporting Countries (OPEC) oil embargoes, strengthened the energy efficiency standards, leading German, Japanese and US automakers to explore the possibilities of hydrogen powered fuel cells (FuelCellToday, n.d.). Later in 1990, the California Zero Emission Vehicle (ZEV) rule provided additional support, making carmakers like Daimler-Chrysler, General Motors and Toyota to further implement hydrogen fuel cell technology in their designs (FuelCellToday, n.d.). Despite the economic recession at the verge of the year 2000, the concern of governments and society about climate change translated into a higher capital investment in fundamental research with the aim of reducing the costs and increase the performance of fuel cells (FuelCellToday, n.d.). Such interest in finding new ZEVs led the European Union, Canada, Japan, South Korea, the United States, China and Australia to carry out programs on stationary and transportation fuel cells as well as on the required hydrogen storage and distribution infrastructure (FuelCellToday, n.d.). In spite of these efforts, it is not until recent years when several automakers have released HFCEV models for sale and leasing. Among them, it is worth mentioning the Toyota Mirai, the Honda Clarity Fuel Cell and the Hyundai Tucson Fuel Cell.

As it can be observed, both BEVs and HFCEVs have suffered and benefited from several kinds of circumstances. Generally, concerns about the advent of climate change, environmental pollution and oil prices have benefited both types of cars. However, HFCEVs started to lose the lead in favour of batteries after hybrid electric vehicles were presented (Bakker, 2010). This can be seen in the fact that most car manufacturers are, either moving away from hydrogen or keeping HFCEVs as a back-up plan in case there is a trend break in the future (Lambert, 2016; Wuttke, 2016; Morris, 2017). This, summed to the fact that the number of BEVs sold until now is incomparably greater than the number of HFCEVs, draws a trend in which the BEV would take over the vast majority of the market, giving the HFCEV the possibility of only having certain presence in niche markets.

As mentioned, the BEV dominates the current ZEV market. To be more specific, in 2015, the number of BEVs amounted to 70,000 in California, 25,000 in Germany, 31,000 in France, 608,000 in Japan and 3,000 in Denmark. In comparison, HFCEVs amount to 300 in California, 125 in Germany, 60 in France, 7 in Japan and 21 in Denmark (Brunet, Kotelnikova and Ponssard, 2015). This means that, in 2015, there were more than 1,400 BEVs for each HFCEV on the road. In fact, even though BEVs currently only represent about a 1% of the worldwide car sales (DeBord, 2016), this trend does not seem to stop, since big car automakers are investing large sums of capital in the development of all-electric cars as well as infrastructure for such vehicles ("These Six Automakers", 2016; Bell, 2016). Regarding the latter, it is worth mentioning the advantage that BEVs have had in comparison to HFCEVs, since the former can benefit from the already existing infrastructure of charging stations as a direct consequence of the presence of hybrid electric cars. However, this is certainly not the case for hydrogen. This is exemplified in the more than 16,000 electric charging sites for BEVs only in the United States ("Electric Vehicle Charging", n.d.) versus the 214 hydrogen refuelling stations worldwide (STORAGE, 2016).

4.2. Case Analysis

Based on secondary sources, out of the initially considered 23 factors from the framework by van de Kaa et al. (2011), 11 of them were found to be relevant for the technology battle between BEVs and HFCEVs. In Appendix 2, a list of literature sources and quotes for each of these 11 factors can be found.

Complementing the performed literature review (Appendix 2), interviews with two experts in the field of economics of technology and innovation were conducted to reduce the odds of leaving a relevant factor out of the analysis. As explained in section 3.2, a factor for which no literature about its importance could be found would be added to the analysis if, and only if, both experts agree on its relevance for this technology battle. However, these two interviews did not reveal the necessity to include any additional factors apart from the 11 already included in the model. In other words, experts' opinion did not coincide in the relevance of any factor for which no evidence of relevance was found in literature. Appendix 4 shows a table in which the opinion of both experts regarding the relevance of each factor for the technology battle is presented together with the results of the literature review. In addition, Figure 2 below shows the scheme of factors in which those marked with a green "v" are those included in the model and the ones marked with a red "x" correspond to those discarded from the analysis. The factors that were found to be relevant for this technology battle are *financial strength*, *brand reputation and credibility*, *learning orientation, technological superiority*, *compatibility*, *complementary goods*, *pricing strategy*, *marketing communications*, *commitment*, *regulator* and *network of stakeholders*.

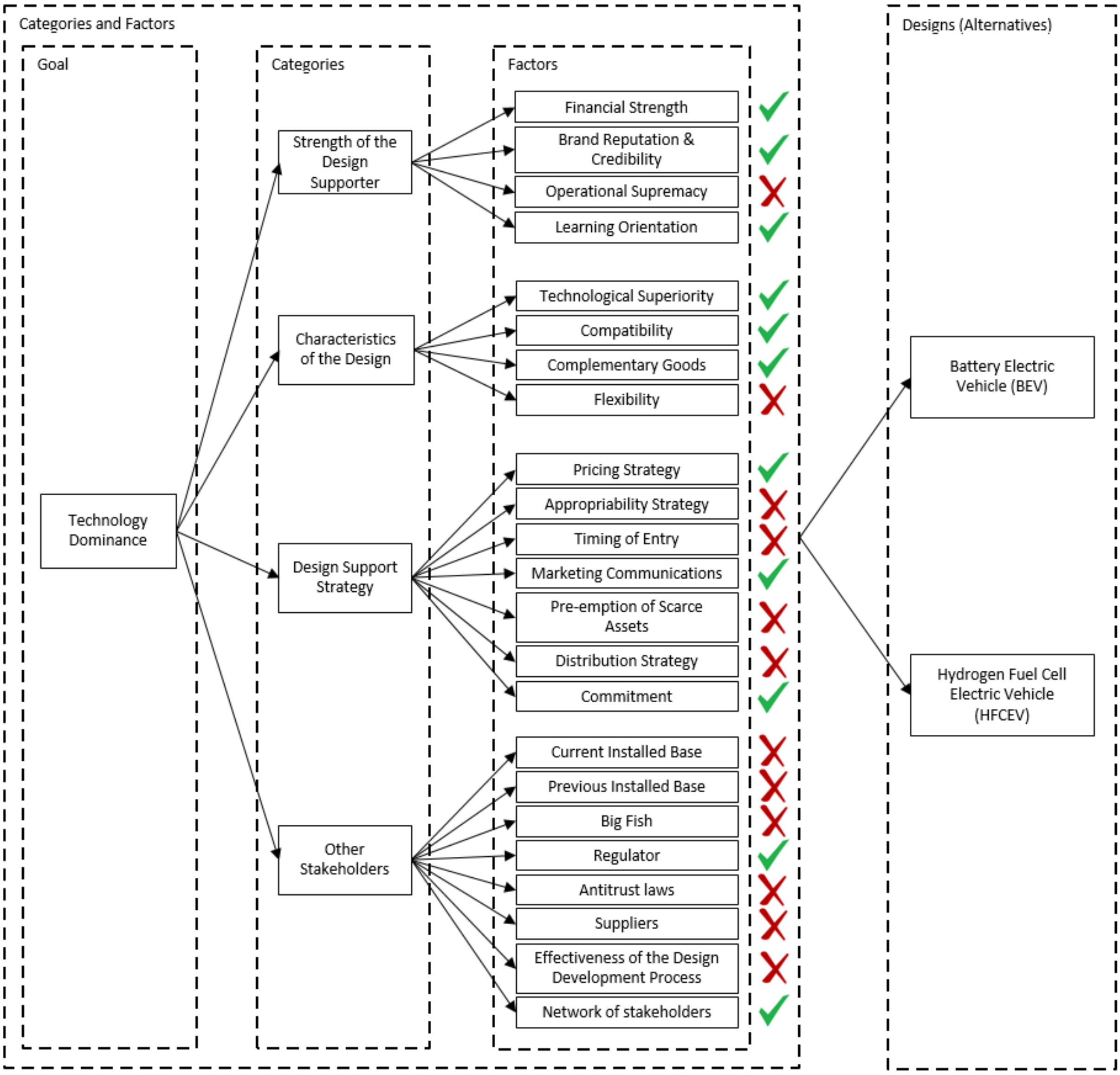

Figure 2. Goal, categories of factors and final list of factors for the BEV vs. HFCEV technology battle.

Once the relevant factors for this technology battle were known, the application of the MCDM method known as the BWM was employed to determine the importance of these factors. This importance is represented by the final weights of the factors obtained after the analysis (see last column of Table 9 in Appendix 3) in such a way that the higher the weight, the more important the relevant factor is for this particular technology battle according to experts.

4.3. Results of the Analysis

After performing the analysis by means of employing the BWM, the weights of each of the relevant factors for the technology battle are determined. These are called global weights, since they can be compared to each other in terms of importance no matter which category of factors they belong to. This is due to the fact that the importance of the category they belong to has already been included in the analysis. Figure 3 below shows the global weights or importance of the 11 relevant factors for this technology battle according to experts. As shown, the most important factor is *technological superiority*, closely followed by *compatibility* and *brand reputation and credibility*. Regarding the factors that have a "moderate" importance, these are *pricing strategy*, followed by *financial strength* and *network of stakeholders*. Finally, the five least relevant factors are *regulator*, *commitment*, *learning orientation* and *complementary goods*, and *marketing communications*.

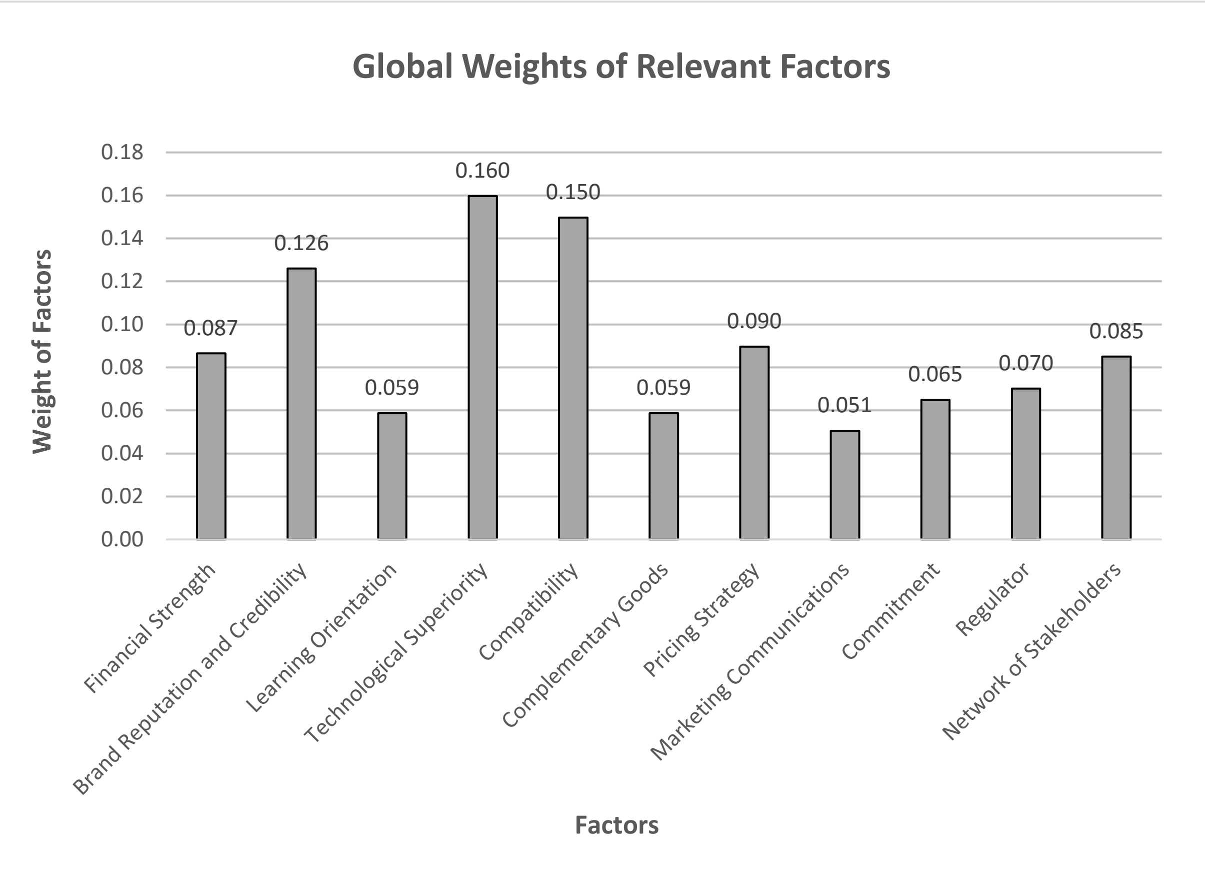

Figure 3. Global weights of the relevant factors for the technology battle between BEVs and HFCEVs according to experts.

Before computing the global weights shown above in Figure 3, the local weights had to be determined (see last columns of Table 8 in Appendix 3). Table 1 below shows the local weights and ranking of importance of each of the factors in each of the categories. Since these are local weights, they can only be used to compare the importance of factors that belong to the same category. As it can be seen in Table 1 below, *brand reputation and credibility* is the most important factor in the category *characteristics of the design supporter*, *technological superiority* is the most important factor in the category *characteristics of the design*, *pricing strategy* turned out to be the most important factor in the *design support strategy* category and *network of stakeholders* was found to be the factor with the highest importance in the fourth category, namely *other stakeholders*.

Table 1. Average local weights and rankings of each factor within each category for the technology battle between BEVs and HFCEVs according to experts.

Category	Factor	Average Local Weight	Ranking within Category
Characteristics of the Design Supporter	Financial Strength	0.297	2
Characteristics of the Design Supporter	Brand Reputation and Credibility	0.460	1
Characteristics of the Design Supporter	Learning Orientation	0.242	3
Characteristics of the Design	Technological Superiority	0.433	1
Characteristics of the Design	Compatibility	0.408	2
Characteristics of the Design	Complementary Goods	0.160	3
Design Support Strategy	Pricing Strategy	0.362	1
Design Support Strategy	Marketing Communications	0.300	3
Design Support Strategy	Commitment	0.339	2
Other Stakeholders	Regulator	0.486	2
Other Stakeholders	Network of Stakeholders	0.514	1

Regarding the weights of each of the categories of factors, these can be seen in Figure 4 below. As it can be observed, the category *characteristics of the design* is the most important one. This is because the two most important factors for this technology battle, *technological superiority* and *compatibility*, belong to this category. The second most important category is *characteristics of the design supporter*, which is related to the strength of the technology supporters (Van de Kaa et al., 2011). *Design support strategy* holds the third place. Such category is related to the strategies that technology supporters can follow in order to win the technology battle (Van de Kaa et al., 2011). Finally, the least important category corresponds to *other stakeholders*, which is related to the stakeholder that do not belong to the group of technology supporters (Van de Kaa et al., 2011).

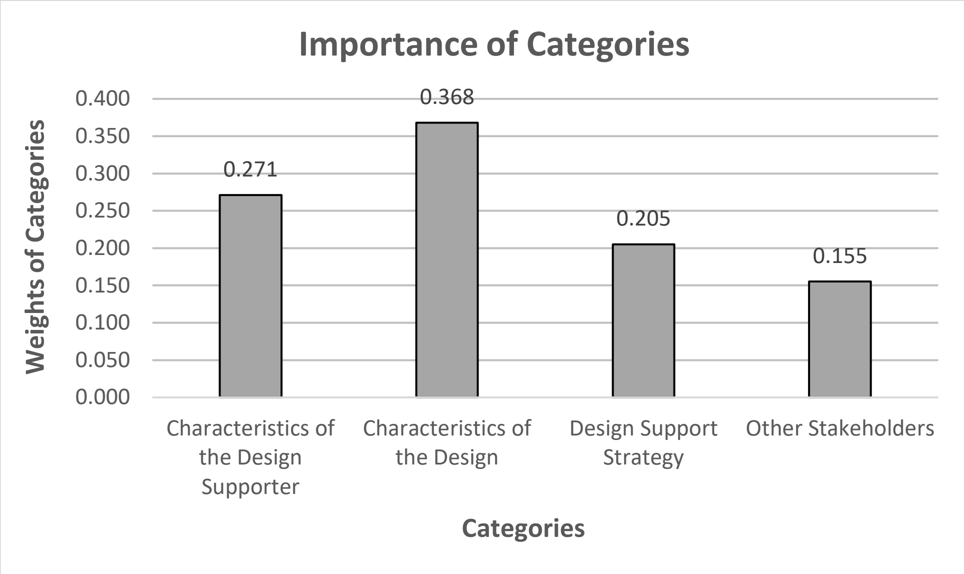

Figure 4. Weights of the categories of factors for the technology battle between BEVs and HFCEVs according to experts.

Regarding the average scores of each of the alternatives, 17 out of the 18 respondents had an overall favourable opinion of the BEV in comparison to the HFCEV. This can be observed in Table 2 below, in which the average scores of both technological designs for each of the respondents is shown. Such average scores were determined by computing the averages of the scores given by each respondent for each technology (see "Avg. Score per Alternative per Respondent" row of Table 10 in Appendix 3)

Table 2. Average score for BEVs and HFCEVs and alternative with highest average score per respondent.

Respondent	Average Score for BEV	Average Score for HFCEV	Technology with Highest Score
1	0.705	0.295	BEV
2	0.878	0.122	BEV
3	0.572	0.428	BEV
4	0.637	0.363	BEV
5	0.892	0.108	BEV
6	0.419	0.581	HFCEV
7	0.536	0.464	BEV
8	0.808	0.192	BEV
9	0.808	0.192	BEV
10	0.728	0.272	BEV
11	0.650	0.350	BEV
12	0.708	0.292	BEV
13	0.760	0.240	BEV
14	0.735	0.265	BEV
15	0.757	0.243	BEV
16	0.673	0.327	BEV
17	0.781	0.219	BEV
18	0.888	0.112	BEV

Table 10 in Appendix 3 (blue background cells) shows the average scores of each technology for each of the relevant factors without taking into account the importance or weight of each factor. There, the reader can observe the advantage of the BEV compared to the HFCEV, since according to experts, the BEV performs better for every single factor. In addition, as shown in Table 3 below, the final result of the BWM analysis – which is the sum of the weighted scores for each type of technology – were found to be 0.709 for the BEV and 0.291 for the HFCEV. This implies that, according to experts, the BEV has a substantial advantage with respect to the HFCEV in terms of eventually achieving technology dominance. Figures in this table show how better each alternative or design performs in comparison to the competing technology. Results in Table 3 show that, according to experts, the BEV is superior to the HFCEV in every single factor. In addition, it can be observed that adding up the sum of the final results equals one, which serves as a proof that all calculations where performed correctly from a methodological standpoint. Finally, it seems reasonable to take the license to remind the reader that figures in Table 3 are ratios, and not probabilities. Therefore, they represent the advantage of one alternative compared to the other technology according to experts.

Table 3. Weighted scores per factor and sum of weighted scores for each technology.

	BEV	HFCEV
Financial Strength	0.065	0.021
Brand Reputation and Credibility	0.087	0.039
Learning Orientation	0.037	0.022
Technological Superiority	0.093	0.066
Compatibility	0.112	0.038
Complementary Goods	0.041	0.017
Pricing Strategy	0.067	0.023
Marketing Communications	0.039	0.011
Commitment	0.048	0.017
Regulator	0.054	0.016
Network of Stakeholders	0.065	0.020
Sum of Weighted Scores	**0.709**	**0.291**

Figure 5 below depicts how well the BEV performs in comparison to the HFCEV by showing the weighted scores percentage difference between both technologies per factor. As it can be observed in Figure 5, the factor for which the BEV is most superior compared to the HFCEV is *marketing communications*. The next seven factors for which the difference between weighted scores is larger are, in descending order of magnitude, *regulator*, *network of stakeholders*, *financial strength*, *compatibility*, *commitment*, *pricing strategy* and *complementary goods*. The factors for which the difference between both technologies is the lowest are *brand reputation and credibility*, *learning orientation* and *technological superiority*.

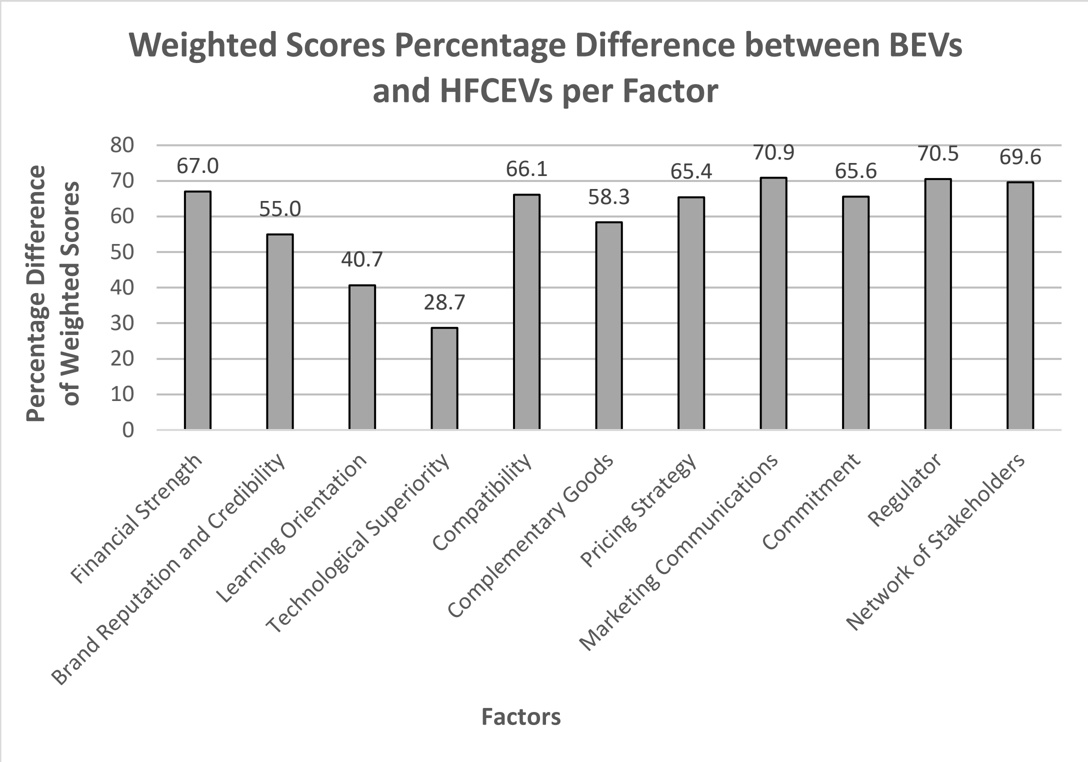

Figure 5. Percentage difference of weighted scores between the BEV and the HFCEV according to data collected from experts.

Finally, as explained in section 3.3, the closer to zero the consistency indicator ξ^{L} is, the higher the level of consistency of the model. The obtained model shows ξ^{L} values lower than 0.2 for each single category of factors per respondent as well as for the total consistency per respondent. As it can be seen in Table 8 in Appendix 3, the highest value of ξ^{L} in the model corresponds to respondent 5, with a ξ^{L} of 0.194. Regarding the highest category average ξ^{L}, this belongs to the category *characteristics of the design supporter*, with an average ξ^{L} of 0.108. Overall, it can be concluded that data collected is reliable, and therefore, it delivers consistent results.

5. Interpretation of Results

In this section, the interpretation of results delivered in 4.3 is performed. Such interpretation is done factor by factor in a decreasing order of importance according to the results obtained based on the opinion of experts.

5.1. Key Factors

As explained in section 4.3, the most important factors for this technology battle according to experts are: *technological superiority*, *compatibility* and *brand reputation and credibility*. In this sub-section, the results for these factors are interpreted in light of theoretical and practical literature.

5.1.1. Technological Superiority

In the automotive market, technical performance has always been a very relevant aspect. In fact, traditional ICEV manufacturers have always invested large amounts of money with the objective of developing the finest pieces of engineering. The BEV and HFCEV industry are certainly not different, since consumers are the same, and they still demand the highest performance in exchange for their money. Among other aspects, *technological superiority* can be translated in terms of more range, more power, higher overall operative easiness and lower maintenance.

Technology management literature shows the relevance of *technological superiority* in a standards battle. As Suarez (2004) stated, this term reflects “how well a given technology performs vis a vis competing alternatives”. It is no surprise that Suarez (2004) claims that technology superiority is very relevant to achieve market dominance. Apart from him, there are many other authors who defend a positive relation between this aspect and the chances of eventually winning a standards battle. Among them, it is worth mentioning Wade (1995), Schilling (1998), Schilling (2002), De Vries et al. (2011), van den Ende et al. (2012) and van de Kaa (2014). In addition, van de Kaa et al. (2011) found 39 studies explicitly suggesting a positive relation between this factor and technology dominance.

However, as results of this research study show, technology superiority, despite being the most relevant, is far from being the only factor that explains market dominance in this particular standards battle. In fact, there are several other factors that, according to experts, are of extreme importance for this case (*compatibility* and *brand reputation and credibility*). This coincides with the work performed by several scholars in the fields of technology management and standardization, evolutionary economics and network economics. Several scientific articles show that, despite being an important factor, a better product from a technical standpoint is no guarantee of success in a technology battle. Among these authors, it is worth mentioning David (1985), Rosenbloom and Cusumano (1987), Anderson and Tushman (1990) and Lee et al. (1995), who have shown cases in which the most advanced alternative from a technological point of view did not achieve market dominance as a consequence of network externalities and excess inertia effects among other reasons.

For the technology battle between BEVs and HFCEVs, the importance of *technological superiority* has also been confirmed by practical literature. Chalk and Miller (2006), Ross (2006), Edwards, Kuznetsov, David and Brandon (2008) and Mori and Hirose (2009) all mention the importance of technical performance to achieve a wide market penetration of HFCEVs. These authors blame the issues on hydrogen storage and safety as the main challenges faced by HFCEV technology to achieve market dominance. On the other hand, the BEV faces different challenges. Among the main ones, it is worth mentioning the current range – and thus energy capacity of batteries – limitations (Chau & Wong, 2002; Nemry & Brons, 2010; Axsen, Kurani & Burke, 2010; Elkind, 2012; Brown, 2013; Adepetu & Keshav, 2017), as well as long charging times (Tsang, Pedersen, Wooding & Potoglou, 2012; Boulanger, Chu, Maxx & Waltz, 2011; Perujo, van Grootveld & Scholz, 2012; Steinhilber, Wells & Thankappan, 2013; Windisch, 2014). According to Perujo et al. (2012), Cluzel, Lane and Standen (2013) and Steinhilber et al. (2013), these limitations in terms of technological performance make BEVs less attractive on the eye of potential buyers, and therefore, limit market penetration possibilities. Therefore, it seems reasonable to conclude that *technological superiority* is certainly a key factor to explain technology dominance in the standards battle between BEVs and HFCEVs.

One of the reasons why *technological superiority* has been rated by experts with such high importance might be due to availability heuristics[1]. In other words, experts see technical feasibility as a very important aspect at the present time, and therefore, it is easy for them to project such present scenario into the future without realizing that, in two decades from now, both technologies might be fully developed and delivering very similar performance. In such hypothetical future scenario, *technological superiority* might not be so important for the consumer. This can be compared to the case of ICEVs, in which gasoline and diesel vehicles are already fully developed, and in most cases, potential buyers do not give too much attention to technical differences.

5.1.2. Compatibility

Until recently, no *compatibility* problems have arisen with the use of ICEVs, since all cars are compatible with fuel pump connections from any gas station. With the introduction of BEVs and

[1] Events that are easier to remember or imagine are perceived to be more probable.

HFCEVs, the problem of establishing *compatibility* standards to make sure all vehicles are compatible with charging points and hydrogen refuelling stations arise. Due to the time and geographically scattered process of development of the BEV and the current lack of compatibility standards, automakers have been producing their own vehicles with their own electricity connection types for DC fast charging[2], therefore limiting *compatibility* (Wittenberg, 2016).

Compatibility cannot be understood without the idea of a network. This is why most literature defending the importance of *compatibility* comes from the field of network economics. In addition, technology management and standardization literature also treat the concept of *compatibility*. It is worth remembering that, according to Suarez (2004), "no technology works in isolation", and therefore, some degree of coordination and *compatibility* with other products is essential.

Based on the work of Arthur (1989), institutional economists like Anderson and Tushman (1990), network economists like Farrel and Saloner (1985) and institutional economists like Garud and Kumaraswamy (1993), it is demonstrated that the benefits of *compatibility* make firms and consumers converge into the adoption of single compatible standards. According to Schilling (2002), *compatibility* plays a key role in avoiding that a standard enters into technological lockout. Furthermore, there is a relation between the idea of 'increasing returns to adoption', and the concept of *compatibility* and the emergence of de-facto standards (David and Greenstein, 1990; Schilling, 1998). According to Schilling (1998), complex technologies – like the BEV and the HFCEV – exhibit increasing returns to adoption, since the more a certain type of vehicle is used, the more attracted new potential players will be, and thus, the more capital that will be invested in that particular technological design, leading to a higher development rate. In order to maximize the number of BEVs or HFCEVs in the road, *compatibility* is essential, since consumers want their personal mode of transportation to be compatible with any complementary product that might add extra value – like fast charging stations. Therefore, since a link between *compatibility* and improvement of the design can be established, it makes sense that the results of this research study show the importance of *compatibility* for this particular standards battle.

Results obtained in this research study suggesting that *compatibility* is a key factor to explain technology dominance in this standards battle is also confirmed by practical literature. On one hand, Brown, Pyke & Steenhof (2010) argue that internationally consistent compatibility standards are critical for the success of the BEV. By taking care of this from an international point of view, it is possible to make sure that the BEV does not show a deceleration of its market growth due to the presence of technical incompatibilities between systems. In addition, authors like Nemry and Brons (2010),

[2] Charging station type that can charge the battery of a vehicle within half an hour (Wittenberg, 2016).

Boulanger et al. (2011) and Steinhilber et al. (2013) argue that the lack of *compatibility* of charging systems slows down the attractiveness, and therefore, the adoption of BEVs.

On the other hand, practical literature revealing the importance of *compatibility* in the case of the HFCEV is very limited. This might be due to the fact that HFCEVs all consist of compatible standards for refuelling mechanisms. After all, all information found on *compatibility* of fuel dispensers seem to show that hydrogen dispensing nozzles adapt to car receptacles, avoiding *compatibility* issues ("Toyota Mirai", n.d.; Toyota, 2015). Certainly, it seems interesting that experts believe that BEVs have a substantial advantage with respect to the HFCEV regarding *compatibility* (Figure 5), when the only literature found about *compatibility* problems comes from the BEV side. This might be the result of a bias by experts caused by the predominant presence of BEVs and charging stations in comparison to the few HFCEVs and hydrogen refuelling stations. In other words, the patent superior presence of BEVs on the roads might make experts to unwittingly believe that BEVs have substantially less problems from a *compatibility* point of view. In summary, it can be stated that, if the importance of *compatibility* is well backed by theoretical and practical literature, the substantial superiority of BEVs regarding this factor is not supported by literature.

5.1.3. Brand Reputation and Credibility

Brand reputation and credibility has always been an extremely important aspect in the traditional automotive industry. For many drivers, a car is not just a mode of transport, but an expression of their preferences and values (Steg, 2005). Therefore, purchasing a car cannot be considered to be a fully rational decision. If this has been the case for a long time with ICEVs, there is no reason to think that it will be different for ZEVs.

Theoretical literature supports the importance of this factor in the context of a technology battle. Suarez (2004) identifies reputation and credibility as one of the most important firm-level factors that positively affect technology dominance. In addition, scholars like Teece (1986), Klepper and Simons (2000) and Gallagher and Park (2002) argued the importance that *brand reputation and credibility* has in a battle of standards, proving that an excellent *brand reputation and credibility* of the design supporters increases the chances of that technology achieving market dominance. In addition, Axelrod, Mitchell, Thomas, Bennett, and Bruderer (1995) show how past performance of the group of technology supporters has a positive influence on the prospects of new projects, and Foray (1994) shows that brand reputation has a calling effect of new players that may join the group of technology supporters. This is especially important for the technology battle between BEVs and HFCEVs, since the presence of large prestigious automakers supporting one specific design might be a sufficient argument to convince other players in the industry to support the same design. This can be seen in the initial presence of Tesla, General Motors and Nissan in the BEV market. The efforts and success of these companies in developing and profit from the development of BEVs has attracted the interest of many other players in the industry, substantially increasing the chances of technology dominance by the BEV. Whether Toyota and Honda will have the same effect with the HFCEV is something that only the future can tell. Following the same line as the results of this research study, technology management literature shows how important this factor is for a technology battle.

For the technology battle between BEVs and HFCEVs, the relevance of the credibility and reputation of a brand can also be seen in practical literature. In fact, the brand image and reputation of companies like Tesla has had a positive effect on the prospects of the company ("Why Tesla", 2016), and by extension, of the BEV. In addition, as mentioned above, the purchase of a car depends on factors different from just technical performance, like the customer perceptions of quality, reliability and social desirability (Fox, Axsen, & Jaccard, 2017). Therefore, *brand reputation and credibility* can be used as a differentiation factor, which if properly used, can benefit firms, and thus, designs supported by these firms (Mangram, 2012). From the performed analysis, *brand reputation and credibility* comes out as a factor with a significant difference in favour of the BEV (Figure 5). This is probably due to the fact that experts have had the chance to see the positive influence that brands like Tesla have had in the acceleration of BEV adoption.

5.2. Factors with Moderate Importance

Section 4.3 shows that the three factors with moderate importance for this technology battle according to experts are: *pricing strategy*, *financial strength* and *network of stakeholders*. Below, theoretical and practical literature will be used to interpret these results.

5.2.1. Pricing Strategy

The moderate importance of this factor seems to make sense from the point of view of network economics, strategic management and institutional economics. Penetration pricing is one of the strategies that supporters of a certain technology can use to sell more units of a certain product (Katz & Shapiro, 1986). This is important for this particular technology battle, since initial prices of BEVs have been substantially higher than those of ICEVs as a consequence of the high costs of batteries (Axsen et al., 2010). In addition, according to Suarez (2004), pricing strategies can be considered to have a strong effect in technology battles like the one between BEVs and HFCEVs, a battle in which no design – especially the HFCEV – has achieved a very large installed base yet. To increase the rate of adoption of the design, and therefore, the installed base, making more affordable cars by reducing prices below costs for some period of time may help. Penetration pricing can also be used to undermine the efforts of competing technologies, since lowering the prices can be used as a temporary deterrence to discourage supporters behind competing technologies (Katz & Shapiro, 1985; Farrell & Saloner, 1986)

The moderate importance of the *pricing strategy* can also be found in practical literature as well. According to Axsen et al. (2010), potential car buyers choose among different vehicle technologies mainly based on the purchase price. There are several articles considering pricing as a very important aspect for the BEV, and by extension, for this technology battle. However, it is worth mentioning that these articles were published more than a decade ago (Garling & Thogersen, 2001, Chalk & Miller, 2006), and therefore, they cannot be considered representative of the current state of the technology battle, since BEV prices have dropped substantially as a consequence of an 80% decrease in battery costs during the last six years (Lambert, 2017).

5.2.2. Financial Strength

Financial strength is especially important for capital intensive industries like the automotive field, since car manufacturers require large sums of capital – in the order of billions of US dollars – to develop their products (Ayre, 2017; Hammerschmidt, 2014). According to institutional economists like Willard and Cooper (1985), a strong financial muscle is one of the aspects that distinguishes 'survivors' from 'non-survivors'. For this particular technology battle, such aspect becomes even more important, since the frontiers of BEV and HFCEV technology have to be taken beyond and the effects of economies of scale will be not be noticeable until a large number of vehicles are manufactured. Therefore, without a significant amount of capital, BEV and HFCEV manufacturers would not have the possibility to perform the necessary investments in R&D to develop the technology to create compelling products. In addition, they would not be able to withstand periods of low profits or even losses due to penetration pricing strategies to promote an installed base increase (Ehrhardt, 2004), nor to perform intense marketing campaigns (Schilling, 1999).

According to practical literature, inadequate battery performance does not meet the requirements for large scale commercialization yet (Axsen et al., 2010; Elkind, 2012). As a consequence, neither BEV nor HFCEV producers could achieve economies of scale with these types of cars, what leaves penetration pricing as the only formula to reduce vehicle prices. Furthermore, investors do not generally invest in charging points until there is a market for them (Green, Skerlos & Winebrake, 2014) – the same can be assumed for HFCEVs and hydrogen refuelling stations. Since big investments are expected to come once a large market already exists (Orbach & Fruchter, 2011), financial efforts to tip the market towards one technology or the other belongs to the design supporters.

5.2.3. Network of Stakeholders

According to Gomes-Casseres (1994), a technological design that counts with the support of a large group of stakeholders has a higher likelihood of achieving market dominance. This has been proven for other standards battles in the past (Dranove & Gandal, 2003), and there is no reason to think that it will be different for the technology battle between the BEV and the HFCEV. Technology management scholars also show a link between a large network of committed stakeholders and the probability of achieving technology dominance. Schilling (2002) acknowledges the fact that bundling partnerships positively influence the adoption of technology and Suarez (2004) considers the level of cooperation with other actors as an important environmental factor that contributes to technology dominance. After all, the more stakeholders interested in the success of a certain technology, the higher the support to make that technology achieve market dominance. In this particular standards battle, electricity companies and other actors need to make sure that the electric grid and infrastructure is designed to withstand a high number of BEVs recharging simultaneously (Eberle, Müller & Von Helmolt, 2012; Mangram, 2012). In the case of HFCEVs, stakeholders responsible for the production, distribution and storage of hydrogen are also essential for the successful commercialization of this type of vehicle.

The results obtained in this research study show that the factor *network of stakeholders* has a moderate importance for this technology battle (Figure 3). In addition, according to experts, BEVs have a substantial advantage regarding this specific aspect (Figure 5). This can be seen in practical literature as well, since most of the articles found reveal clear disadvantages for the HFCEV due to serious limitations regarding the production, distribution, storage and utilization of hydrogen. (Edwards et al., 2008; Ball & Wietschel, 2009; Marbán & Valdés-Solís, 2007; Schulte, Hart & Van der Vorst, 2004; Barreto, Makihira & Riahi, 2003; Yu, Silva, Chu, Nascimento & Camargo, 2011). Regarding the BEV, the presence of a large number of charging stations has a positive impact on the adoption of BEVs (Sierzchula, Bakker, Maat & van Wee, 2014). Therefore, a strong *network of stakeholders* providing part of these charging points prove the importance of this factor for this technology battle.

5.3. Least Important Factors

As shown in section 4.3, *regulator*, *commitment*, *learning orientation*, *complementary goods* and *marketing communications* have the lowest importance weights according to experts. However, this does not imply that these aspects are not relevant for this technology battle, since the lowest score, belonging to *marketing communications* (0.051) has approximately one third of the weight of *technological superiority* (0.160), which is the most important factor. However, these results show that, according to experts, the importance of these five aspect for this technology battle is limited in comparison to the influence of the rest of factors.

5.3.1. Regulator

There is plenty of theoretical literature that can explain the relevance of this factor for this technology battle. Schilling (1998, 2002) acknowledges the importance of governmental regulation on the adoption of a dominant design. In fact, according to Schilling (1998) and Suarez (2004), regulators have the power to impose a single standard for a certain industry, making a specific technology automatically achieve market dominance. However, one of the reasons why *regulator* turned out to be one of the five least important factors might be due to the fact that, according to experts, most governments are looking for alternatives to fossil-fuel modes of transportation and it does not seem likely that regulators will take action to enforce one of the alternatives. Nevertheless, the apparent unwillingness of regulators to enforce a certain technological design does not mean that governments do not play a role in incentivizing a certain alternative. This can be clearly seen for the case of the BEV in the United States, in which car companies like Ford, Nissan, Fisker and Tesla were given loans by the United Stated Department of Energy ("Electric Vehicles", n.d.; O'Connell, 2013). In addition, there is plenty of practical literature acknowledging the relevance that regulation and governments have in the adoption of BEVs (Garling & Thogersen, 2001; Mangram, 2012; Yu et al., 2011; Van Mierlo, Maggetto & Lataire, 2006; Bjerkan, Nørbech & Nordtømme, 2016; Brown et al., 2010) as well as HFCEVs (Edwards et al., 2008; Eberle et al., 2012; Edwards, Mahieu, Griesemann, Larivé and Rickeard, 2004; Ball & Wietschel, 2009; Van Mierlo et al., 2006; Zhang, L., Yu, Ren, Ma, Zhang, W. & Liang, 2016).

Figure 5 shows that surveyed experts give a clear advantage to the BEV for this factor. This might be because the BEV has been intensively promoted by governments all over the world ("Electric Vehicles", n.d.; O'Connell, 2013; Tietge, Mock, Lutsey & Campestrini, 2016). However, it is worth mentioning that most incentives are not only for BEVs, but for ZEVs in general, and therefore, for HFCEVs as well ("Japan's measures", 2009).

5.3.2. Commitment

The importance of *commitment* in this technology battle can be seen in the work of institutional economists like Willard and Cooper (1985), who show a positive relationship between business survival and *commitment* of the design supporters. Following the same line, Adner (2006) shows how important it is for a certain technology to receive sufficient attention from the group of design supporters, especially during the early stages of development characterized by losses or scarce profits. In addition, Tegarden, Hatfield and Echols (1999) show how divided simultaneous attention to several standards might have a negative effect on the rest of technology supporters, reducing the odds of that technology achieving market dominance. However, results show that, according to experts, *commitment* is not one of the most important factors. The most probable explanation why *commitment* might not be such an important factor for this technology battle is because the group of supporters behind both technologies is currently composed of large incumbents with plenty of resources. Therefore, some of the companies behind one technology might be capable of changing sides if necessary, since they have the necessary resources to 'catch-up' after some time (Yu et al., 2011). In other words, in a scenario where most players have the capacity to switch sides and catch-up easily, commitment does not provide a large advantage, since there is always the risk of being easily caught-up by new entrants. However, it is worth mentioning that it seems obvious that the *commitment* of Tesla and Elon Musk to the BEV has put this technology in the lead of the ZEV market. Such lead can be seen in the results of this research study (Figure 5), which show a 65.6% advantage of the BEV with respect to the HFCEV.

5.3.3. Learning Orientation

The relative importance of *learning orientation* has been extensively discussed by Anderson and Tushman (1990), Utterback (1994), Suarez and Utterback (1995) and Gallagher (2007), who argue that experimentation and learning capacity of the technology supporters has a very positive influence on the outcome of a technology battle. In addition, Srinivasan et al. (2006) shows how the chances of the emergence of a dominant design are positively correlated to the intensity of R&D efforts. Another author who has defended the relationship between *learning orientation* and technological progress is Melissa Schilling. She considers the 'absorptive capacity' of technology supporters as an essential driver to deliver products that meet customer requirements (Schilling, 1998). In addition, *learning orientation* can imply production costs reductions, which have a positive impact on the final price (Weiss, Patel & Junginger, 2012; Palencia, Furubayashi & Nakata, 2014; Contestabile, Offer, Slade, Jaeger & Thoennes, 2011), and thus, on overall vehicle sales. However, the analysis of data collected from respondents shows that this aspect is not among the most important for this technology battle. One of the possible reasons lie in the fact that experts might see small differences in R&D orientation between BEV and HFCEV automakers. In addition, the difference between the *learning orientation* of both groups of supporters is considerable lower than for the rest of factors – with the exception of *technological superiority*. This can be explained by the fact that both sides have shown remarkable innovations during the last decade.

5.3.4. Complementary Goods

According to evolutionary and network economics, *complementary goods* increase the value of a product (David, 1985; Teece, 1986; Khazam & Mowery, 1994; Smit & Pistorius, 1998; Funk, 2003; Adner, 2006; Gallagher, 2007). It is also worth mentioning that de Vries et al. (2011) considers the existence of *complementary goods* as one of the factors that favour the emergence of dominant designs, since it contributes to the creation of demand-side economies of scale (Farrell & Saloner, 1986). In addition, scholars from the field of technology management also state the positive relation between the availability of complementary products and the chances of achieving technology dominance. Among them, it is worth mentioning Schilling (1998), Schilling (2002) and Suarez (2004). Schilling (1998) describes the lack of *complementary goods* as one of the factors influencing technological lockout. In addition, Schilling (2002) shows how network externalities research links the value of a technology to the availability of *complementary goods*. This is confirmed by Cluzel at al. (2013) as well as Nemry and Brons (2010), who show that the availability of charging stations is essential to achieve wide BEV adoption. After all, if there are no sufficient charging or hydrogen refuelling stations, it would not be surprising that consumers opt for another alternative. Furthermore, there is plenty of literature mentioning the importance of electricity and hydrogen related infrastructure for this technology battle (Edwards et al., 2008; Mori and Hirose, 2009; Eberle et al., 2012), what supports the idea that efficient and sufficient production and distribution of electricity and hydrogen must be achieved to improve the odds of success of a certain technological design.

One of the possible reasons why results show a low importance of *complementary goods* in comparison to other factors might be due to the fact that they are often present in products that show a high level of direct network externalities. The BEV and HFCEV markets certainly show network effects. However, the level of these is not the same as in other industries, and in addition, such network effects tend to be indirect. In order to understand this seemingly counterintuitive result, an interview with an expert in economics of technology and innovation was conducted. According to this expert, infrastructure related issues seem to be of extreme importance for this particular technology battle. Based on his opinion, one of the plausible reasons why surveyed experts did not consider the availability of *complementary goods* as a crucial factor might be due to the notion that "electricity is everywhere". Therefore, finding a charging point, either in the road or at home seems to be almost guaranteed. On the other hand, the potential of hydrogen for other modes of transportation like shipping, heavy-duty vehicles and aerospace applications prove the existence of hydrogen distribution and storage infrastructure that can be easily adapted for personal transportation purposes. Therefore, according to this interviewee, It seems probable that the lack of concern by respondents about the availability of charging and hydrogen refuelling stations might be due to the fact that electricity is easily available and hydrogen infrastructure will be present everywhere where electricity is not available.

5.3.5. Marketing Communications

According to network economists, a proper consumer expectation management can increase the odds of market dominance (Katz & Shapiro, 1985; Shapiro & Varian, 2013). In addition, as Suarez (2004) explains, consumer expectation management consists of brand image, pre-announcements and availability of information (Arthur, 1989; David, 1987; Farrell & Saloner, 1985). Specially, pre-announcements seem to be a strategy used by many automakers in order to create 'hype' about a model with the objective of increasing the number of orders. In addition, *marketing communications* does not only have an effect on customers, but on socio-political forces as well (Smit & Pistorius, 1998), what might allow BEV and HFCEV manufacturers to benefit from influencing policy makers decisions. *Marketing communications* can also be used to increase the public knowledge of both technological designs. This aspect is regarded as essential for authors like Elkind, (2012), since public ignorance about BEV technology – and therefore about HFCEVs – has a detrimental effect in terms of adoption rate.

The explanation of why *marketing communications* turned out to be the least important of all the pre-selected relevant factors might be in the concept of availability heuristics. It might be possible that, since respondents see technical aspects as extremely important at the moment, they might make an extrapolation of this thinking scheme into the future without realizing that, in a few decades, *technological superiority* might not be as important as *marketing communications*. In fact, van de Kaa et al. (2011) argues that aspects like marketing remain relevant even during later stages of a standards battle.

6. Discussion and Conclusion

This chapter delivers insights regarding conceptual contemplations as well as aspects that can be of use for the practical field. In addition, the limitations of this study are discussed and a reflection about how this research study adds to the engineering and policy analysis Master of Science is delivered. Finally, this chapter ends with the conclusion.

6.1. Theoretical Contributions

This research study contributes to existing scientific literature by sharpening the understanding of what drives a technology battle by assessing the standards battle between BEVs and HFCEVs. Therefore, this study represents a minor step towards the refinement of theories and frameworks employed to assess technology battles. To help show the theoretical contribution of this research study, Table 12 in Appendix 5 was elaborated. This table, based on a literature review, gathers which of the 23 initially considered factors from the framework by van de Kaa et al. (2011) have been found to be relevant for technology dominance in other standards battles. In this table, it can be observed that most studies only identify a few factors as relevant. In addition, none of the factors are relevant in all of the cases, which indicates the non-existence of necessary factors for technology dominance in standards battles. Apart from this, the combination of the gathered publications together with the results of this study shows that the factors that more often tend to influence technology dominance in standards battles are *complementary goods*, *technological superiority* and *pricing strategy*. Therefore, sharpening the image of which factors tend to be relevant for technology dominance in standard battles in general is certainly one of the contributions of this study. However, it is worth mentioning that the more studies like this one that are performed, the sharper this image will become. This is why further research aiming at determining which factors affect technology dominance in other standards battles is encouraged. In addition, it is worth mentioning that future researchers may benefit from the use of the most up-to-date framework of factors – currently the model by van de Kaa et al. (2011) –, since that would increase the thoroughness and completeness of these future studies, leading to more trustworthy results. Another aspect shown in Table 12 is the fact that all technology battles in the video game industry were driven by the factors *complementary goods*, *pricing strategy* and *marketing communications*. In addition, it shows that technology dominance in all standards battles in the video recording industry (videocassette and digital video disc industries) seems to be driven by the factor *complementary goods*. This serves as a first indication of the existence of necessary factors for technology dominance in standards battles within certain industries. Following this indication, this research study contributes to determine which factors are necessary for technology dominance in the automotive industry. However, in order to find them, further research analysing other technology battles in this industry is required. Another aspect to take into account from Table 12 is the fact that all technology battles in the video game and video recording industry share one common relevant factor for technology dominance: *complementary goods*. This means that the existence of necessary factors for technology dominance within a certain sector might be an indication of the importance of that same factor in a similar industry – like in the case of the video game and the video recording industry. In other words, it might be the case that technology battles in similar industries might require some of the same necessary factors to achieve technology dominance. In relation to this observation, this study shows which factors are relevant for technology dominance in the standards battle between BEVs and HFCEVs according to experts, and therefore, it contributes to prove whether technology dominance in standards battles in the automotive and adjacent industries is driven by one or more of the same factors. In addition, future research studies about factors that drive technology dominance in this and other industries will allow for the creation of more refined frameworks of factors. By accomplishing this task, a sharper image of what drives technology battles in each industry will emerge. Certainly, this research study represents a minor step towards the realization of that accomplishment. However, it is necessary to encourage the realization of future research that might allow to make generalizations that cannot be withdrawn from a single case-specific study.

This research study also represents a contribution to literature about dominant designs. According to Suarez (2004), technology battles in phase III of the dominant process are characterized by the fact that the different designs "start to accumulate a sizable installed based [sic] of users" (Suarez, 2004, p. 283). Therefore, It seems safe to assume that this is the case in the current situation of the technology battle assessed in this research study. Suarez (2004) claims that, in this phase, strategic manoeuvring – consisting of *timing of entry*, *pricing strategy*, *appropriability strategy* and marketing and public relations intensity – of the design supporters is the most important factor. At the same time, Suarez (2004) claims that "technological differences between both alternatives" (p. 282)become less important once the technology battle enters phase III. However, the outcome of this study seems to contradict this claim, since according to experts, *technological superiority* turned out to be the most important factor, while *timing of entry* and *appropriability strategy* were concluded to be non-relevant, *pricing strategy* turned out to have moderate importance and *marketing communications* turned out to be the least important of the relevant factors. Therefore, this research study shows that, according to experts, the model developed by Suarez (2004) does not adapt to this particular technology battle. In addition, some of the most important factors for this technology battle – like *compatibility* – are not even present in his model. Thus, future research following the same 'stage' approach as Suarez (2004) with a more complete framework of factors and for different technology battles based on different product categories is encouraged. Such recommended research would allow to create more precise models that take into account the characteristics of different markets.

6.2. Practical Contributions

The main contributions of this research study are theoretical, since the main focus of this thesis is conceptual. However, this research study also provides interesting practical contributions. Among them, it gives an overview of how experts view the technology battle between BEVs and HFCEVs. One of the results of this analysis is the fact that the BEV will most likely emerge victorious in the field of personal transportation according to the analysis performed based on the opinion of experts. Therefore, the outcome of this analysis might be useful for actors interested in the outcome of this technology battle.

The results of the analysis of the opinion of experts might be of help for the practical field in order to adjust their strategies and interests. After all, the outcome of this research study poses the question of whether the industry should follow with the development of both technologies, or whether they should focus on only continuing the development of the BEV. A 70-30 distribution between both types of vehicles (Table 3 in section 4.3) suggests a substantial difference, and therefore, it seems reasonable to assume that experts are likely to be correct. However, it is important to keep in mind that experts are also vulnerable to bias, and therefore, they could also be wrong. In addition, as Suarez (2004) shows, technology battles are very time dependent and different factors are important in different phases. Therefore, it is possible that important aspects in the present might not be so important in the future.

Another practical contribution of this research study can be found in Appendix 6. There, the reader can find implications and recommendations from a corporate entrepreneurship perspective for firms involved in the development of either BEVs or HFCEVs in light of the results obtained in this study.

6.3. Limitations

The selection of relevant factors for this research study was based on a literature review as well as on two interviews with two different experts in the technology battle between BEVs and HFCEVs. However, it seems appropriate to mention that research was subjected to time constraints. The pre-selected relevant set of factors for this study should be considered as preliminary and a more exhaustive selection of factors is encouraged for future research. This implies performing a more comprehensive literature review as well as conducting more interviews with experts to validate the list of relevant factors obtained from such literature review.

Another limitation is the picture that this technology battle might be time sensitive, and thus, as explained in previous section, the importance of factors varies depending on the stage of the battle. In addition, the experience of experts is tied to the present stage of the battle, and therefore, their vision of the future might be shaped by current events. In other words, experts might make a projection of what they currently see into the future, ignoring that factors that are relevant for this stage of the technology battle might not be as important in future phases. Apart from this, it is also worth taking into consideration the presence of illusory correlation[3], context dependence, confirmation bias[4] and, last but not least, availability heuristics as aspects that may reduce the credibility of expert opinion.

Another limitation of this research study is the fact that it focuses only on personal transportation (cars), and therefore, it does not take into account other modes of transportation like aircraft, ships and heavy-duty vehicles, for which hydrogen fuel cells might have better prospects. A holistic approach taking into consideration all possible applications for both technologies is encouraged for future research.

Finally, it is worth reminding the reader that the results obtained from the data analysis based on the opinion of experts should not be interpreted as an attempt to predict the future of the technology battle between the BEV and the HFCEV. After all, the main goal of this research study is to determine which factors affect technology dominance in this standards battle according to experts.

6.4. Reflection

This research study has important implications from the point of view of the engineering and policy analysis Master of Science. One of the fundamental pillars of such master programme is the approach of grand societal challenges, and what greater challenge than attempting to understand the development of sustainable personal transportation?

The performed research has relevant implications for the design of transportation policies. Based on the outcome of the analysis, it is fair to say that, according to experts, it seems that BEVs will most likely achieve technology dominance. If, according to experts, the BEV will most probably dominate the personal transportation market, it seems reasonable to open the debate about whether

[3] Mistaken impression that two unrelated variables are correlated.
[4] Preference for information that confirms one's beliefs or hypothesis.

governments and policy-makers should continue to subsidize the HFCEV for this specific mode of transportation. Perhaps it would be beneficial for regulators and society as a whole to focus all efforts on incentivizing the BEV and design policies to adapt inner cities and main roads for the use of this type of vehicle. These policies would imply planning the creation of new charging stations located all over inner cities and main intercity routes. In addition, it would require the planning and design of powerful and robust electric grid systems capable of delivering enough electricity to allow the simultaneous charging of large numbers of BEVs during peak times. Overall, the possible policy ramifications and future research built on this study would imply the assessment of economics of infrastructures, policy analysis of multi-actor systems, actor and strategy models, regulation, systems modelling, decision-making in networks and technology development and impact assessment for technology selection, all core disciplines in the engineering and policy analysis master's degree.

6.5. Conclusion

The main goal of this research study was to determine which factors affect technology dominance in the standards battle between BEVs and HFCEVs according to experts. To accomplish this task, it was first necessary to find out which factors are relevant for the mentioned technology battle. This was done by means of a literature review and two interviews with two different experts in the field of economics of technology and innovation. In addition, the importance of each of these relevant factors was determined to be able to find out which alternative will most likely achieve technology dominance according to experts. In this section, the main findings and conclusions of this research study are presented question by question.

The first sub-research question consisted of determining which factors are relevant for the technology battle between the BEV and the HFCEV according to experts. Out of the initially considered 29 factors from the framework by van de Kaa et al. (2011), only eleven of these were found to be relevant for such technology battle. These were *financial strength*, *brand reputation and credibility*, *learning orientation*, *technological superiority*, *compatibility*, *complementary goods*, *pricing strategy*, *marketing communications*, *commitment*, *regulator* and *network of stakeholders*.

To answer the second sub-research question, it was necessary to find the importance of each relevant factor for this technology battle according to experts. This was done by means of surveying industry practitioners and academics with an in-depth knowledge of the subject. The results obtained show the factors *technological superiority*, *compatibility* and *brand reputation and credibility* as the most important for this specific standards battle. Factors found to have moderate importance were *pricing strategy*, *financial strength* and *network of stakeholders*. Finally, aspects that were determined to have the least importance were *regulator*, *commitment*, *learning orientation*, *complementary goods* and *marketing communications*.

By further analysing the data collected by experts, the answer to the third sub-research question was found. The third sub-research question consisted of finding which alternative will most likely achieve market dominance according to experts. After data analysis, the BEV was concluded to be such alternative, since the sum of weighted scores for the BEV was found to be 0.709, which is substantially superior to the sum of weighted scores for the HFCEV (0.291).

Finally, in relation to the main research question consisting of determining which factors affect technology dominance according to experts, it is concluded that all relevant factors have a significant influence on technology dominance for this particular standards battle. This is due to the fact that the most important factor (*technological superiority*) was approximately only three times more important than the least important factor (*marketing communications)*. However, it is also concluded that, according to experts, the three key factors affecting technology dominance the most are *technological superiority*, *compatibility* and *brand reputation and credibility*.

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Appendix 1

Explanation of Factors for Winning Technology Battles

In this appendix, all factors presented in van de Kaa et al. (2011) framework are explained. Definitions below are based on explanations from van de Kaa et al. (2011) and van de Kaa and de Vries (2015).

<u>Characteristics of the Design Supporter:</u>

Related to the strength of the technology design supporters.

1. Financial strength: current financial condition and future prospects of the group of design supporters.
2. Brand reputation and credibility: public opinion of the group of design supporters based on past events.
3. Operational supremacy: characteristics of the group of technological design supporters that give them an advantage to "exploit resources better than their competitors" (Van de Kaa & de Vries, 2015, p. 224).
4. Learning orientation: inclination of the group of design supporters towards expanding "their knowledge and skills base and improve their ability to assimilate and utilize future information" (Van de Kaa & de Vries, 2015, p. 224).

<u>Characteristics of the Design:</u>

Aspects that show that a superior design has a higher likelihood of achieving market dominance.

5. Technological superiority: a design can be considered to be technologically superior if it can perform better than other designs.
6. Compatibility: "compatibility concerns the fitting of interrelated entities with each other so that they can function together" (Van de Kaa & de Vries, 2015, p. 224). An example for the technology battle between BEVs and HFCEVs would be the compatibility of BEVs and charging stations equipment.
7. Complementary goods: goods that are necessary to commercialize a design.
8. Flexibility: the level to which a design "can be changed to suit new conditions or situations" (Van de Kaa & de Vries, 2015, p. 224).

<u>Design Support Strategy:</u>

Strategies that design supporters can use to win a technology battle.

9. Pricing strategy: "the technique of offering low prices to early customers to build up an installed base and influence the choices of later adopters (Van de Kaa & de Vries, 2015, p. 224)".

10. Appropriability strategy: actions that organizations can take to prevent their design from being copied by competitors.
11. Timing of entry: the point in time when a particular design “is introduced in the market” (Van de Kaa & de Vries, 2015, p. 224).
12. Marketing communication: actions undertaken to influence the expectations of customers.
13. Pre-emption of scarce assets: “the extent to which the actor is able to gain advantage by controlling assets before another can control them” (Van de Kaa & de Vries, 2015, p. 224).
14. Distribution strategy: methods used to strengthen the distribution scheme.
15. Commitment: the pledge to stick to the development of a specific design.

<u>Other stakeholders:</u>

Related to stakeholders that do not belong to the group of technological design supporters.

16. Current installed base: number of users of a particular technological design.
17. Previous installed base: users of previous technological design generations that might upgrade to the new design.
18. Big fish: an actor with plenty of power to support a design and that can have an important positive influence on the market position of that design.
19. Regulator: an actor with enough power to prescribe a design in the marketplace (a government for instance).
20. Antitrust laws: the judiciary of a country can keep a particular design from achieving technology dominance by means of anti-trust policies.
21. Suppliers: actors that support a certain design by offering complementary products and services.
22. Effectiveness of the format development process: technological designs “can be developed in different ways, for instance, by a single company, in a consortium of different companies, or in committees of an official standardization organization. Differences in, for instance, decision rules, process management and stakeholder involvement impact the effectiveness of the process, for example, in terms of its duration or the quality of the resulting specifications” (Van de Kaa et al., 2011, p. 1405).
23. Network of stakeholders: a design has a higher likelihood of achieving technology dominance if it is supported by a diverse network of stakeholders from strategic industries.

<u>Market Characteristics:</u>

24. Bandwagon effect: the stimulating effect that the adoption of a design by a group users has on other users to adopt the same design.

25. Network externalities: measure of the positive effects experienced by the user of a design due to the use of that same design by other consumers.
26. Number of options available: number of technological designs competing for market dominance.
27. Uncertainty in the market: related to risk averse behaviours of consumers when uncertainty in the market is too high.
28. Rate of change: speed of development of a certain industry, both from a technology and from a market perspective.
29. Switching costs: costs to be paid by the consumer to switch to a different technological design.

Appendix 2

Sources and Quotes from Literature Review Arranged by Factor.

Table 4. Sources and quotes that show the relevance of factors belonging to the category *characteristics of the design supporter*.

Characteristics of the Design Supporter	Sources and Quotes
1. Financial Strength	"The two most important challenges for fuel cells are cost and durability. The cost for automotive (ICE) power plants is about \$25–35 kW^{-1}. Current fuel cell systems are estimated to be about a factor of five higher in cost, even when cost savings for high-volume manufacturing are applied." (Chalk & Miller, 2006, p. 78) "Fuel cells are projected to have energy efficiency twice that of internal combustion engines. However before fuel cells can realize their potential, significant challenges remain. The two most important are cost and durability for both automotive and stationary applications." (Chalk & Miller, 2006, p. 73) "On the other hand, market incumbents restricted by their existing assets, which reflect past investments, often react to pressure, making the business less likely that they engage in these types of innovation entrepreneurship. However, given their superior market power and investment capabilities, incumbents can play catch-up quickly once they decide to become fast followers." (Yu, Silva, Chu, Nascimento and Camargo, 2011, para. 56) "In a recent study, Hockerts and Wüstenhagen [20] sustain that, while incumbents tend to lag behind start-ups concerning the primary innovation, they do nonetheless have a tendency to invest in more encompassing sustainability management systems, addressing multiple environmental and social issues where new entrants focuses on only a few issues." (Yu et al. , 2011, para. 69)
2. Brand Reputation and Credibility	"[C]onsumers choose among vehicle technologies according to a function that considers financial costs, namely purchase price, maintenance costs and fuel costs, as well as intangible costs, which monetizes all non-financial factors such as consumer perceptions of quality, reliability, availability of supporting infrastructure (e.g. refueling), and social desirability." (Fox, Axsen & Jaccard, 2017, p.135) "Tesla's longer-term success is highly contingent upon overall consumer adaptation of electric vehicles and the company's ability to broaden its brand." (Mangram, 2012, p. 296) "Branding is a tool used by marketers to help differentiate products in a concrete manner (Savary & Elberse, 2006). It is important for marketers to effectively manage the local, regional and global characteristics of their brands. This is critical for companies such as Tesla who understand the importance of product expansion into lucrative foreign markets." (Mangram, 2012, p. 306)

3. Learning Orientation	"The advancement of the BEV market is highly contingent upon continued improvements in core technologies including vehicle batteries and overall vehicle performance. This includes improvements in battery characteristics such as range/power, production costs, safety and reliability. It also comprises vehicle performance improvements such as torque, efficiency and reliability." (Mangram, 2012, p. 291) "It is important to note that this battery technology was a result of more than ten years of R&D by the Argonne National Laboratory" (Yu et al., 2011, para. 51) "EV1 looked very similar to Impact but this new prototype incorporated many improvements based on the learning accumulated by GM." (Yu et al., 2011, para. 44) "It was also found that, at the firm level, the *probe and learn* process, theory proposed by Lynn, Morone and Paulson [25], was a present and relevant process in the observable phases of the technological battle. The learning gained through the prototypes generated by the various divisions of GM, offered information that could be used in different models, testing different architectures over time." (Yu et al., 2011, para. 75) "The importance of the probe and learn process for GM may suggest an adaptation in the framework proposed by Suarez [34]: include such learning process as the most influential factor in all phases of the technological battle." (Yu et al., 2011, para. 78) "It is well known that China has successful promotion and adoption of EVs (BEVs) in a nationwide scale...A lot of lessons and experiences can be learned from the previous EVs promotion, which can help FCVs promotion open the market." (Zhang, Yu, Ren, Ma, Zhang and Liang ,2016, p. 17190)

Table 5. Sources and quotes that show the relevance of factors belonging to the category *characteristics of the design*.

Characteristics of the Design	Sources and Quotes
4. Technological Superiority	"While the challenges for batteries are technical and economic in nature, for fuel cells, they are rather economic." (Ball & Wietschel, 2009, p. 619) "The evaluation of hydrogen worldwide is positive if… there is no major technological breakthrough in vehicle batteries." (Ball & Wietschel, 2009, p. 626) "Automotive fuel cell systems will also be required to be as durable and reliable as current automotive engines." (Chalk & Miller, 2006, p. 78) "Hydrogen storage on-board the vehicle is considered key to achieving market success for fuel cell vehicles. To be competitive with ICE vehicles, hydrogen fuel cell vehicles should have a similar driving range. The major challenge is storing enough hydrogen on board for an equivalent driving range of 300 miles while meeting the performance (weight, volume, kinetics, etc.), safety and cost requirements without compromising passenger or cargo space. The energy density is critical. … No current hydrogen storage technology meets these targets." (Chalk & Miller, 2006, p. 79)

	“Parallel efforts in the area of advanced batteries will improve cost, efficiency, and durability and enhance the penetration of battery hybrid vehicles. This will result in reduced fossil fuel usage during the transition to fuel cell vehicles operating on hydrogen derived from domestic renewable sources.” (Chalk & Miller, 2006, p. 80) “For the electric vehicle application … calendar life, operating temperature range, and selling price remain challenges. Additional challenges for the EV application include energy density and specific energy. A breakthrough in the development of advanced electrodes (e.g. a higher capacity density positive electrode material) is needed to achieve the energy goals.” (Chalk & Miller, 2006, pp. 77-78) “Technical challenges for hydrogen fuel cell systems for transportation include cost, durability, and hydrogen storage capacity. Battery systems face challenges in battery cost, performance, life, and tolerance to abuse.” (Chalk & Miller, 2006, p. 74) "[T]he battery powered EV (BEV) cannot commercially compete with the ICEV in terms of driving range and initial cost." (Chau & Wong, 2002, p. 1966) “Ultimately, the degree of electrification and the displacement of fossil energy carriers are a function of energy prices, technology progress … , infrastructure availability, the regulatory framework, vehicle performance, and, finally, the vehicles' total cost of ownership for the end customer.” (Eberle, Müller & Von Helmolt, 2012, p. 8797) “At the present time, there are three major technological barriers that must be overcome for a transition from a carbon based (fossil fuel) energy system to a hydrogen-based economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Second, new generations of hydrogen storage systems for both vehicular and stationary applications must be developed. Finally, the cost of fuel cell and other hydrogen-based systems must be reduced.” (Edwards, Kuznetsov, David & Brandon, 2008, p. 4356). “The safety of hydrogen is also critical, encompassing not only scientific and technological aspects but also psychological and societal issues. Despite its perceived reputation, hydrogen has an extraordinary safety record during many decades of use in industrial applications. However, hydrogen is significantly different from today’s common fuels because of its ability to migrate through very small channels, and also in its combustion properties—again very different from carbon-based fuels. These aspects demand diverse safety precautions and an appropriate (new) culture for operations in which customers will interact directly with hydrogen and fuel cell technologies.” (Edwards at al., 2008, p. 4357). “One of the crucial technological barriers to the widespread use of hydrogen as an effective energy carrier is the lack of a safe, low-weight and low-cost hydrogen storage method with a high energy density” (Edwards at al., 2008, p. 4357). “To achieve a significant penetration of hydrogen into future energy systems, the methods of hydrogen production, distribution, storage and utilisation must be dramatically improved beyond their present performance, reliability and cost.” (Edwards at al., 2008, p. 4360). “The challenges are substantial and require scientific breakthroughs and significant technological developments coupled with continued social and political commitment.” (Edwards at al., 2008, p. 4361).

	"The most serious barriers to 'take-off' for the EV market are the current uncertainty regarding the development of the EV technology, car manufacturers' and oil companies' pushing of technologies to reduce the environmental impacts of the ICV and insufficient governmental support." (Garling & Thogersen, 2001, p. 64) "However, due to the low density, hydrogen gas limits the amount of hydrogen stored on board. This restriction also prevents wide penetration of fuel cells." (Mori and Hirose, 2009, p. 4569) "However, although the development of fuel cell technology appears to be progressing smoothly towards eventual commercial exploitation, a viable method for storing hydrogen on board a vehicle is still to be established. The US Department of Energy (DoE) has taken what is perhaps an extreme view of what the technology needs to deliver. By rejecting taxation as a means of persuading the public to change their fuel, the DoE starts from the position that the hydrogen-fuelled vehicle must be able to match the performance of a hydrocarbon-fuelled car and must do so at a comparable cost (based on the costs of oil in the recent past). This has led them to establish a series of targets which, given the remarkable advantages of petrol and diesel for this purpose, will be very tough to meet." (Ross, 2006, p. 1084) "The search for a material that is capable of storing hydrogen in the amounts necessary to make a hydrogen fuelled fuel cell car a practical proposition has become a major objective of materials research." (Ross, 2006, p. 1089) "In the long run, depending on the evolutions of technology and environmental factors [34], some of these niches may expand and therefore reshape the EV industry as a whole." (Yu et al., 2011, para. 72)
5. Compatibility	"The impacts of the EV in regards to public health and safety, environmental sustainability, as well as how quick this technology is adopted will be greatly influenced by the standards to which the EV and related infrastructure are designed" (Brown, Pyke and Steenhof, 2010, p. 3798) "Internationally consistent standards will also be critical for ensuring compatibility between jurisdictions, a pivotal point underpinning international trade within the globally interconnected automotive and automotive parts markets and also the compatibility of EV-related infrastructure (Castaldo, 2009)." (Brown et al., 2010, p. 3798) "The importance for adequate and consistent standardization in supporting the broad-based uptake of the EV can be illustrated by considering technologies where standardization processes played a role in their respective uptake. One example in this regards is the uptake of the VHS relative to the uptake of Betamax technology." (Brown et al., 2010, p. 3798) "Such compatibility and standardization across EV-related technologies and infrastructure will be a crucial enabling force that will drive the uptake of the EV into the future… These standards will have to be international in scope, going beyond national boundaries to ensure the market is not inhibited by incompatible options. This will be important not only in terms of the EV itself but also in terms of the infrastructure and the skills of those who charge and potentially service these vehicles." (Brown et al., 2010, p. 3798)

	"The risk is that without adequate standardization, fractured development of these various components of the EV market could ultimately undermine the uptake of the EV and the societal benefits that could otherwise be achieved with the widespread adoption of the EV." (Brown et al., 2010, pp. 3790-3800) "Ultimately, the degree of electrification and the displacement of fossil energy carriers are a function of energy prices, technology progress … , infrastructure availability, the regulatory framework, vehicle performance, and, finally, the vehicles' total cost of ownership for the end customer." (Eberle et al., 2012, p. 8797)
6. Complementary Goods	"The impacts of the EV in regards to public health and safety, environmental sustainability, as well as how quick this technology is adopted will be greatly influenced by the standards to which the EV and related infrastructure are designed" (Brown et al., 2010, p. 3798) "Uncoordinated charging of one million EVs (from a total German car parc [sic] of 40 million vehicles) at a single point in time in the early morning or the evening would create a power demand of 3.5 GW when using standard German home sockets (at maximum 3.5 kW) and infrastructure installations. Obviously, even this modest fleet would cause a very substantial challenge when the charging takes place without coordination by the grid operator" (Eberle et al., 2012, p. 8791) "Another challenge emerges also for the public infrastructure: a standard public charging point becomes blocked for hours by just one customer." (Eberle et al., 2012, p. 8791) "At the present time, there are three major technological barriers that must be overcome for a transition from a carbon based (fossil fuel) energy system to a hydrogen-based economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Second, new generations of hydrogen storage systems for both vehicular and stationary applications must be developed. Finally, the cost of fuel cell and other hydrogen-based systems must be reduced." (Edwards at al., 2008, p. 4356). "Some of the key scientific and technical challenges for the hydrogen economy are … lowering the cost of hydrogen production to a level comparable to the energy cost of petrol" (Edwards at al., 2008, p. 4360). "The prevailing theory is that in order for the BEV industry to gain significant global market share, a supportive charging station infrastructure needs to be developed that is on a similar scale as that of the gasoline powered vehicle infrastructure (Hardester, 2010). This translates into a viable network of quick-charging stations which are capable of rapid charging a BEV" (Mangram, 2012, p. 293) "[S]torage technologies must meet several requirements simultaneously, including the infrastructure, cost and charging capabilities." (Mori and Hirose, 2009, p. 4570)

Table 6. Sources and quotes that show the relevance of factors belonging to the category *design support strategy.*

Design Support Strategy	Sources and Quotes
7. Pricing Strategy	"For the electric vehicle application … calendar life, operating temperature range, and selling price remain challenges." (Chalk & Miller, 2006, p. 77) "Ultimately, the degree of electrification and the displacement of fossil energy carriers are a function of energy prices, technology progress … , infrastructure availability, the regulatory framework, vehicle performance, and, finally, the vehicles' total cost of ownership for the end customer." (Eberle et al., 2012, p. 8797) "[C]onsumers choose among vehicle technologies according to a function that considers financial costs, namely purchase price, maintenance costs and fuel costs, as well as intangible costs, which monetizes all non-financial factors such as consumer perceptions of quality, reliability, availability of supporting infrastructure (e.g. refueling), and social desirability." (Fox et al., 2017, p. 135) "No doubt, promotional pricing and tax relief will still be important" (Garling & Thogersen, 2001, p. 63)
8. Marketing Communication	"Tesla's primary goal is to increase the number of electric vehicles available to mainstream consumers in three ways: sales of its vehicles through its expanding network of company-owned showrooms and online; 2) sales of its patented electric powertrain components to other automakers to stimulate overall electric vehicle interest and sales; and 3) serve as a catalyst and positive example of how 'fun' and 'social responsibility' driving are mutually compatible. (Logan, 2011)" (Mangram, 2012, p. 296) "To achieve Tesla's primary goal of increasing the number of electric vehicles – preferably Tesla BEVs – available to mainstream consumers, the company must weave a focused, consistent marketing communications message throughout all communications media." (Mangram, 2012, p. 307) "A powerful public national and European support is still necessary as well as an effective marketing approach." (Van Mierlo, Maggetto and Lataire, 2006, p. 2749)
9. Commitment	"Since the mid-1990s the vast majority of the automotive industry has embraced the electric vehicle technology, leading to large development and testing activities in preparation for commercialization in the coming years." (Yu et al., 2011, para. 55) "The first mass-produced HEV was the Toyota Prius model, launched in Japan in 1997, and followed by the Honda HEV Insight model, launched in 1999. As the Fig. 3 shows, only in the late 2000s others automakers released hybrids; all of them are incumbent companies: the big three US automakers (GM, Ford, Chrysler), as well as the European groups (Volkswagen, Daimler, BMW, Porsche, Peugeot-Citroen PSA) and the Asian Nissan, Hyundai, Mazda, Mitsubishi. Until 2010, around fifty hybrid models (passenger cars, sport utility vehicles and pick-up trucks) have been introduced in world market, while some of the biggest automakers offer HEV as option on all models. The total cumulative world sales of hybrid vehicles reached in 2010 approximately 3.7 million units" (Yu et al., 2011, para. 64)

Table 7. Sources and quotes that show the relevance of factors belonging to the category *other stakeholders*.

Other Stakeholders	Sources and Quotes
10.Regulator	"Hydrogen and fuel cells are unlikely to emerge in future energy markets without decisive and favourable policy support and incentives." (Ball & Wietschel, 2009, p. 626) "Up-front price reduction is the most powerful incentive in promoting [BEV] adoption." (Bjerkan, Nørbech & Nordtømme, 2016, p. 169) "Exemptions from purchase tax and VAT are critical incentives … in promoting EV adoption." ." (Bjerkan at al., 2016, p. 169) "[I]f the market is to expand to include a significant share of EVs, standards and regulation will need to be expanded in order to incorporate the entirety of the system impacts of the EV, from generation impacts, to the vehicle-to-grid ''smart grid'', to the end-user." (Brown et al., 2010, p. 3806) "Ultimately, the degree of electrification and the displacement of fossil energy carriers are a function of energy prices, technology progress … , infrastructure availability, the regulatory framework, vehicle performance, and, finally, the vehicles' total cost of ownership for the end customer." (Eberle et al., 2012, p. 8797) "The challenges are substantial and require scientific breakthroughs and significant technological developments coupled with continued social and political commitment." (Edwards at al., 2008, p. 4361). "[P]lug-in electric vehicles (PEVs), hydrogen fuel cell vehicles (HFCV), and biofuel vehicles (85% ethanol). These technologies have failed to substantively displace fossil fuels despite several decades of intermittent media hype, optimistic government goals and innovation activity—largely due to a lack of effective climate policy." (Fox et al., 2017, p. 133) "Consider the example of a vehicle regulation that forces automakers to develop and sell PEVs. There is considerable uncertainty regarding future cost reductions in the technology, the evolution of consumer preferences, and the rollout of recharging infrastructure. With imperfect information about the future, there is risk that a transition to PEVs might end up being more costly for society than a transition to another low-carbon technology, such as biofuel or hydrogen-fuel cell vehicles." (Fox et al., 2017, p. 133) "In the transportation sector, a carbon tax also has an advantage in potentially prompting a wider variety of abatement actions, including mode switching and decreased travel demand, in addition to switching to low carbon vehicle technologies." (Fox et al., 2017, p. 133) "No doubt, promotional pricing and tax relief will still be important" (Garling & Thogersen, 2001, p. 64) "The most serious barriers to 'take-off' for the EV market are the current uncertainty regarding the development of the EV technology, car manufacturers' and oil companies' pushing of technologies to reduce the environmental impacts of the ICV and insufficient governmental support." (Garling & Thogersen, 2001, p. 65)

	"More certainty about governments' commitment to support implementation of EVs on a larger scale would surely help" (Garling & Thogersen, 2001, p. 65) "A significant degree of governmental support is necessary because of private sector underinvestment in critical areas such as electric vehicle R&D and infrastructure development" (Mangram, 2012, p. 294) "A powerful public national and European support is still necessary as well as an effective marketing approach." (Van Mierlo et al., 2006, p. 2749) "The framework proposed by Suarez [34] highlights some factors which are most relevant at the firm level and at the level of the environment. It was observed through the data collected that, in terms of environmental protection, the regulatory interventions had significant relevance throughout the process. Government involvement has had a direct relationship with the actions taken by GM in the development of electric vehicle technology over the five decades studied." (Yu et al., 2011, para. 75) "This difficult mission [lack of infrastructure] has to be overtaken by the government, or accomplished by companies led by the government." (Zhang et al.,2016, p. 17190)
11.Network of Stakeholders	"[T]he introduction of hydrogen would largely require a new dedicated pipeline transportation and distribution infrastructure." (Ball & Wietschel, 2009, p. 622) "This highlights the multiple ways in which a "hydrogen economy" can evolve, depending, among other factors, on the infrastructure available in a particular region." (Barreto, Makihira, and Riahi, 2003, p. 281). "The impacts of the EV in regards to public health and safety, environmental sustainability, as well as how quick this technology is adopted will be greatly influenced by the standards to which the EV and related infrastructure are designed." (Brown et al., 2010, p. 3798) "[I]t is important that trans-national and cross-industry working groups be formed in order to create an environment of interaction and co-operation." (Brown et al., 2010, p. 3806) "Uncoordinated charging of one million EVs (from a total German car parc [sic] of 40 million vehicles) at a single point in time in the early morning or the evening would create a power demand of 3.5 GW when using standard German home sockets (at maximum 3.5 kW) and infrastructure installations. Obviously, even this modest fleet would cause a very substantial challenge when the charging takes place without coordination by the grid operator" (Eberle et al., 2012, p. 8791) "Another challenge emerges also for the public infrastructure: a standard public charging point becomes blocked for hours by just one customer." (Eberle at al., 2012, p. 8791) "[T]he generation of renewable energy and green hydrogen by electric utilities or completely new companies will play an important role." (Eberle at al., 2012, p. 8794)

	“Ultimately, the degree of electrification and the displacement of fossil energy carriers are a function of energy prices, technology progress … , infrastructure availability, the regulatory framework, vehicle performance, and, finally, the vehicles' total cost of ownership for the end customer.” (Eberle at al., 2012, p. 8797) “At the present time, there are three major technological barriers that must be overcome for a transition from a carbon based (fossil fuel) energy system to a hydrogen-based economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Second, new generations of hydrogen storage systems for both vehicular and stationary applications must be developed. Finally, the cost of fuel cell and other hydrogen-based systems must be reduced.” (Edwards et al., 2008, p. 4356) “To achieve a significant penetration of hydrogen into future energy systems, the methods of hydrogen production, distribution, storage and utilisation must be dramatically improved beyond their present performance, reliability and cost.” (Edwards et al., 2008, p. 4360) “The prevailing theory is that in order for the BEV industry to gain significant global market share, a supportive charging station infrastructure needs to be developed that is on a similar scale as that of the gasoline powered vehicle infrastructure (Hardester, 2010). This translates into a viable network of quick-charging stations which are capable of rapid charging a BEV” (Mangram, 2012, p. 293) “Even a partial shift from gasoline to electricity as a transportation fuel will have major ramifications on the demands and operation of electric grid power systems. One potential solution to these issues is the development of smart-grid technologies which incorporate advanced distribution, transmission, metering and consumer technologies (Ashtiani et al., 2011). Smart-grid technologies include two-way communications processes between electricity users and energy providers, enhanced electricity load monitoring and management of two-way electricity flows.” (Mangram, 2012, p. 294) “However, this is not the only condition that needs to be accomplished for the success of a hydrogen-based society. Technological development must bring about a reduction in the costs of H2 production, distribution, storage and utilisation.” (Marbán & Valdés-Solís, 2007, p. 1636) “Innovative technical strategies, such as establishing local networks of storage-based stations, designing modular station components, or the installation of “virtual” hydrogen stations, will be important in reducing the capital costs of early hydrogen stations. In addition, scenario analysis suggests that initial cost burdens can be significantly reduced if a high degree of coordination is attained between all involved stakeholders, including fuel providers, vehicle manufacturers, vehicle purchasers and government.” (Melaina, 2003. p. 754) “[I]ntroducing hydrogen fuel requires facing two fundamental necessities: firstly, consumer acceptance and, secondly, a working infrastructure.” (Schulte, Hart & Van der Vorst, 2004, p. 678). “The key problem with FCEV is still the development of a costly infrastructure.” (Yu et al., 2011, para. 47)

Appendix 3

Tables Containing BWM Analysis.

Table 8. Local weights for pre-selected relevant factors for the 18 respondents.

	Local Weights																		
Factors (↓) / Respondents (→)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Average**
Characteristics of the Design Supporter	0.059	0.259	0.466	0.172	0.259	0.218	0.545	0.259	0.259	0.466	0.103	0.092	0.466	0.290	0.300	0.055	0.151	0.466	**0.271**
Financial Strength	0.260	0.204	0.683	0.100	0.694	0.169	0.154	0.292	0.111	0.313	0.111	0.100	0.125	0.100	0.787	0.100	0.745	0.306	**0.297**
Brand Reputation and Credibility	0.100	0.685	0.217	0.640	0.222	0.740	0.769	0.167	0.685	0.563	0.583	0.640	0.688	0.660	0.083	0.660	0.071	0.111	**0.460**
Learning Orientation	0.640	0.111	0.100	0.260	0.083	0.091	0.077	0.542	0.204	0.125	0.306	0.260	0.188	0.240	0.130	0.240	0.184	0.583	**0.242**
Consistency (ξ^L)	0.140	0.130	0.183	0.140	0.194	0.104	0.154	0.042	0.130	0.063	0.028	0.140	0.063	0.060	0.120	0.060	0.173	0.028	**0.108**
Characteristics of the Design	0.546	0.466	0.259	0.259	0.466	0.536	0.207	0.466	0.466	0.259	0.466	0.169	0.172	0.548	0.510	0.475	0.189	0.172	**0.368**
Technological Superiority	0.327	0.542	0.625	0.353	0.286	0.808	0.111	0.644	0.111	0.281	0.325	0.100	0.662	0.167	0.575	0.583	0.745	0.542	**0.433**
Compatibility	0.596	0.292	0.250	0.529	0.571	0.083	0.644	0.244	0.667	0.594	0.575	0.575	0.262	0.542	0.325	0.111	0.184	0.292	**0.408**
Complementary Goods	0.077	0.167	0.125	0.118	0.143	0.108	0.244	0.111	0.222	0.125	0.100	0.325	0.077	0.292	0.100	0.306	0.071	0.167	**0.160**
Consistency (ξ^L)	0.058	0.042	0.125	0.176	0.000	0.058	0.089	0.089	0.000	0.031	0.075	0.075	0.123	0.042	0.075	0.028	0.173	0.042	**0.072**
Design Support Strategy	0.226	0.103	0.172	0.466	0.103	0.163	0.155	0.103	0.172	0.103	0.259	0.254	0.103	0.097	0.070	0.282	0.604	0.259	**0.205**
Pricing Strategy	0.542	0.292	0.250	0.708	0.325	0.286	0.229	0.685	0.125	0.204	0.644	0.167	0.167	0.542	0.160	0.275	0.745	0.167	**0.362**
Marketing Communications	0.292	0.167	0.125	0.083	0.575	0.143	0.143	0.204	0.563	0.685	0.111	0.542	0.292	0.292	0.640	0.063	0.184	0.292	**0.300**
Commitment	0.167	0.542	0.625	0.208	0.100	0.571	0.629	0.111	0.313	0.111	0.244	0.292	0.542	0.167	0.200	0.663	0.071	0.542	**0.339**
Consistency (ξ^L)	0.042	0.042	0.125	0.125	0.075	0.000	0.057	0.130	0.063	0.130	0.089	0.042	0.042	0.042	0.160	0.163	0.173	0.042	**0.085**
Other Stakeholders	0.169	0.172	0.103	0.103	0.172	0.084	0.094	0.172	0.103	0.172	0.172	0.485	0.259	0.065	0.120	0.188	0.057	0.103	**0.155**
Regulator	0.333	0.333	0.200	0.800	0.333	0.333	0.167	0.750	0.800	0.800	0.100	0.333	0.125	0.111	0.833	0.833	0.889	0.667	**0.486**
Network of Stakeholders	0.667	0.667	0.800	0.200	0.667	0.667	0.833	0.250	0.200	0.200	0.900	0.667	0.875	0.889	0.167	0.167	0.111	0.333	**0.514**
Consistency (ξ^L)	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	**0.000***
Group Consistency (ξ^L)	0.131	0.052	0.052	0.052	0.052	0.117	0.075	0.052	0.052	0.052	0.052	0.023	0.052	0.032	0.090	0.088	0.151	0.052	**0.068**

*Note that the consistency ratio of the category *other stakeholders* is equal to zero. This is due to the fact that it is not possible to have inconsistencies when applying pairwise comparisons between only two criteria or factors.

Yellow cells correspond to the local weights computed by using the data collected from each of the experts. Weights in these yellow cells correspond to the importance of each of the factors for the technology battle between BEVs and HFCEVs according to experts. However, these weights can only be compared within categories. For instance, the weight of *financial strength* for respondent 1 can only be compared to the weights of the factors belonging to the same category (*characteristics of the design supporter*), namely *brand reputation and credibility* and *learning orientation*. To be able to compare the weights of factors irrespectively of the category they belong to, global weights in Table 9 were obtained. Coming back to the previous example, in Table 9, the weight of *financial strength* according to data obtained from respondent 1 can be compared to the weight of any other factor – as long as these weights belong to the same respondent or column. In addition, last column on the right-hand side of Table 9 (column under "Average") shows the aggregated global weights of the factors for all 18 respondents. These values in the last column on the right-hand side are the importance of each of the relevant factors according to the aggregated opinion of experts. Finally, Table 10 – which was divided in two due to limited space – delivers the results of the computations performed based on the preferences given by experts regarding which alternative – either the BEV or the HFCEV – performs better for each of the factors. By calculating the average of the scores given by all respondents for each alternative, the average scores per factor for each type of vehicle configuration are found (see blue cells in Table 10). However, these average scores do not take into account the importance or global weights of the factors. By multiplying the average scores (blue cells in Table 10) by the importance of factors found in Table 9 (global weights in "Average" column), the weighted scores per factor for each of the alternatives are found (see Table 3). By summing the weighted scores for each of the alternatives, the technology with the highest likelihood of achieving technology dominance according to experts is determined (see last row of Table 3). As it can be observed in Table 3, the BEV obtains a result of 0.709, which is higher than the result obtained for the HFCEV (0.291). Therefore, according to experts, the BEV has higher chances of achieving technology dominance. Finally, it is worth mentioning that all consistency indicators (ξ^L) are very close to zero, since the highest consistency indicator in the model is 0.194. Such ξ^L corresponds to the category *characteristics of the design supporter* of respondent number 5. Due to the low values of the consistency indicators, it can be concluded that data collected from experts is consistent and reliable.

Table 9. Global weights for pre-selected relevant factors for the 18 respondents.

	Global Weights																		
Factors (↓) / Respondents (→)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	**Average**
Characteristics of the Design Supporter																			
Financial Strength	0.015	0.053	0.318	0.017	0.180	0.037	0.084	0.075	0.029	0.145	0.011	0.009	0.058	0.029	0.236	0.006	0.112	0.142	**0.087**
Brand Reputation and Credibility	0.006	0.177	0.101	0.110	0.057	0.161	0.419	0.043	0.177	0.262	0.060	0.059	0.320	0.192	0.025	0.036	0.011	0.052	**0.126**
Learning Orientation	0.038	0.029	0.047	0.045	0.022	0.020	0.042	0.140	0.053	0.058	0.032	0.024	0.087	0.070	0.039	0.013	0.028	0.272	**0.059**
Characteristics of the Design																			
Technological Superiority	0.178	0.252	0.162	0.091	0.133	0.433	0.023	0.300	0.052	0.073	0.151	0.017	0.114	0.091	0.293	0.277	0.141	0.093	**0.160**
Compatibility	0.325	0.136	0.065	0.137	0.266	0.045	0.133	0.114	0.310	0.154	0.268	0.097	0.045	0.297	0.166	0.053	0.035	0.050	**0.150**
Complementary Goods	0.042	0.078	0.032	0.030	0.067	0.058	0.050	0.052	0.103	0.032	0.047	0.055	0.013	0.160	0.051	0.145	0.013	0.029	**0.059**
Design Support Strategy																			
Pricing Strategy	0.122	0.030	0.043	0.330	0.034	0.047	0.035	0.071	0.022	0.021	0.167	0.042	0.017	0.052	0.011	0.077	0.450	0.043	**0.090**
Marketing Communications	0.066	0.017	0.022	0.039	0.059	0.023	0.022	0.021	0.097	0.071	0.029	0.138	0.030	0.028	0.045	0.018	0.111	0.075	**0.051**
Commitment	0.038	0.056	0.108	0.097	0.010	0.093	0.097	0.011	0.054	0.011	0.063	0.074	0.056	0.016	0.014	0.187	0.043	0.140	**0.065**
Other Stakeholders																			
Regulator	0.056	0.057	0.021	0.083	0.057	0.028	0.016	0.129	0.083	0.138	0.017	0.162	0.032	0.007	0.100	0.157	0.050	0.069	**0.070**
Network of Stakeholders	0.113	0.115	0.083	0.021	0.115	0.056	0.078	0.043	0.021	0.034	0.155	0.323	0.226	0.057	0.020	0.031	0.006	0.034	**0.085**

Table 10. Scores for pre-selected relevant factors for each alternative for the 18 respondents.

	Scores																	
Factors (↓) / Respondents (→)	1		2		3		4		5		6		7		8		9	
Characteristics of the Design Supporter	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV
Financial Strength	0.800	0.200	0.900	0.100	0.200	0.800	0.833	0.167	0.900	0.100	0.667	0.333	0.750	0.250	0.667	0.333	0.875	0.125
Brand Reputation and Credibility	0.833	0.167	0.900	0.100	0.200	0.800	0.667	0.333	0.900	0.100	0.143	0.857	0.250	0.750	0.857	0.143	0.889	0.111
Learning Orientation	0.750	0.250	0.667	0.333	0.167	0.833	0.250	0.750	0.900	0.100	0.167	0.833	0.200	0.800	0.667	0.333	0.875	0.125
Characteristics of the Design																		
Technological Superiority	0.800	0.200	0.900	0.100	0.125	0.875	0.200	0.800	0.900	0.100	0.143	0.857	0.800	0.200	0.857	0.143	0.333	0.667
Compatibility	0.333	0.667	0.900	0.100	0.833	0.167	0.875	0.125	0.889	0.111	0.125	0.875	0.667	0.333	0.900	0.100	0.900	0.100
Complementary Goods	0.667	0.333	0.900	0.100	0.833	0.167	0.667	0.333	0.889	0.111	0.143	0.857	0.667	0.333	0.900	0.100	0.900	0.100
Design Support Strategy																		
Pricing Strategy	0.833	0.167	0.900	0.100	0.800	0.200	0.857	0.143	0.900	0.100	0.800	0.200	0.200	0.800	0.833	0.167	0.833	0.167
Marketing Communications	0.857	0.143	0.900	0.100	0.800	0.200	0.800	0.200	0.900	0.100	0.750	0.250	0.667	0.333	0.667	0.333	0.875	0.125
Commitment	0.800	0.200	0.900	0.100	0.833	0.167	0.200	0.800	0.889	0.111	0.667	0.333	0.200	0.800	0.875	0.125	0.857	0.143
Other Stakeholders																		
Regulator	0.750	0.250	0.900	0.100	0.833	0.167	0.857	0.143	0.875	0.125	0.250	0.750	0.750	0.250	0.833	0.167	0.667	0.333
Network of Stakeholders	0.333	0.667	0.889	0.111	0.667	0.333	0.800	0.200	0.875	0.125	0.750	0.250	0.750	0.250	0.833	0.167	0.889	0.111
Avg. Score per Alternative per Respondent	0.705	0.295	0.878	0.122	0.572	0.428	0.637	0.363	0.892	0.108	0.419	0.581	0.536	0.464	0.808	0.192	0.808	0.192

	Scores																			
Factors (↓) / Respondents (→)	10		11		12		13		14		15		16		17		18			
Characteristics of the Design Supporter	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	BEV	HFCEV	**Avg. BEV**	**Avg. HFCEV**
Financial Strength	0.333	0.667	0.875	0.125	0.875	0.125	0.857	0.143	0.800	0.200	0.714	0.286	0.833	0.167	0.750	0.250	0.900	0.100	**0.752**	**0.248**
Brand Reputation and Credibility	0.875	0.125	0.667	0.333	0.250	0.750	0.857	0.143	0.833	0.167	0.667	0.333	0.889	0.111	0.833	0.167	0.900	0.100	**0.689**	**0.311**
Learning Orientation	0.857	0.143	0.750	0.250	0.857	0.143	0.750	0.250	0.857	0.143	0.667	0.333	0.143	0.857	0.875	0.125	0.900	0.100	**0.628**	**0.372**
Characteristics of the Design																				
Technological Superiority	0.333	0.667	0.143	0.857	0.857	0.143	0.857	0.143	0.667	0.333	0.667	0.333	0.857	0.143	0.167	0.833	0.900	0.100	**0.584**	**0.416**
Compatibility	0.875	0.125	0.833	0.167	0.889	0.111	0.875	0.125	0.667	0.333	0.833	0.167	0.250	0.750	0.900	0.100	0.900	0.100	**0.747**	**0.253**
Complementary Goods	0.875	0.125	0.250	0.750	0.833	0.167	0.667	0.333	0.667	0.333	0.800	0.200	0.250	0.750	0.900	0.100	0.900	0.100	**0.706**	**0.294**
Design Support Strategy																				
Pricing Strategy	0.333	0.667	0.750	0.250	0.667	0.333	0.667	0.333	0.667	0.333	0.800	0.200	0.800	0.200	0.833	0.167	0.900	0.100	**0.743**	**0.257**
Marketing Communications	0.875	0.125	0.750	0.250	0.167	0.833	0.833	0.167	0.667	0.333	0.833	0.167	0.889	0.111	0.833	0.167	0.875	0.125	**0.774**	**0.226**
Commitment	0.889	0.111	0.800	0.200	0.889	0.111	0.667	0.333	0.667	0.333	0.800	0.200	0.833	0.167	0.750	0.250	0.875	0.125	**0.744**	**0.256**
Other Stakeholders																				
Regulator	0.889	0.111	0.667	0.333	0.833	0.167	0.667	0.333	0.800	0.200	0.800	0.200	0.800	0.200	0.875	0.125	0.857	0.143	**0.772**	**0.228**
Network of Stakeholders	0.875	0.125	0.667	0.333	0.667	0.333	0.667	0.333	0.800	0.200	0.750	0.250	0.857	0.143	0.875	0.125	0.857	0.143	**0.767**	**0.233**
Avg. Score per Alternative per Respondent	0.728	0.272	0.650	0.350	0.708	0.292	0.760	0.240	0.735	0.265	0.757	0.243	0.673	0.327	0.781	0.219	0.888	0.112		
																		Average:	**0.719**	**0.281**

Appendix 4

Combined Results of Literature Review and Interviews with Experts to Determine Which Factors are Relevant for the Technology Battle between BEVs and HFCEVs.

Table 11. Results of the selection of relevant factors for the technology battle between the BEV and the HFCEV.

	Literature Review	Interview with Expert A	Interview with Expert B	Included in the Model (YES/NO)
Characteristics of the Design Supporter				
Financial Strength				YES
Brand Reputation and Credibility				YES
Operational Supremacy				NO
Learning Orientation				YES
Characteristics of the Design				
Technological Superiority				YES
Compatibility				YES
Complementary Goods				YES
Flexibility				NO
Design Support Strategy				
Pricing Strategy				YES
Appropriability Strategy				NO
Timing of Entry				NO
Marketing Communications				YES
Pre-emption of Scarce Assets				NO
Distribution Strategy				NO
Commitment				YES
Other Stakeholders				
Current Installed Base				NO
Previous Installed Base				NO
Big Fish				NO
Regulator				YES
Antitrust Laws				NO
Suppliers				NO
Effectiveness of the Design Development Process				NO
Network of Stakeholders				YES

Green implies the factor was found to be relevant.
Red implies the factor was not found to be relevant.

Appendix 5

Literature Review with Case-Based Research Studies That Identify Relevant Factors for Technological Dominance in a Technology Battles.

Table 12. Results of literature review of technology battles case studies.

	1 Computer Industry (Langlois & Robertson, 1992)	2 Stereo Component Industry (Langlois & Robertson, 1992)	3 Videocassette Industry (Cusumano et al., 1992)	4 Computer Industry (Khazam & Mowery, 1994)	5 Computer Industry (Wade, 1995)	6 Computer Industry (Christensen & Rosenbloom, 1995)	7 Telecom. Industry (Majumdar & Venkataraman, 1998)	8 Computer Industry (Tegarden et al., 1999)	9 Banking Industry (De Vries & Hendrikse, 2001)	10 Video Game Industry (Gallagher & Park, 2002)	11 Computer Industry (Garud, Jain & Kumaraswamy, 2002)	12 Video Game Industry (Shankar & Bayus, 2003)	13 Digital Video Disk Industry (Dranove & Gandal, 2003)	14 Telecom. Industry (Funk, 2003)	15 Video Game Industry (Schilling, 2003)	16 Digital Video Disk Industry (Gallagher, 2012)	17 Photovoltaic Industry (Van de Kaa et al., 2014)	Automotive Industry (This Study)	Sum
Characteristics of the Design Supporter																			
Financial Strength							X			X					X	X		X	5
Brand Reputation and Credibility	X		X	X						X				X	X			X	7
Operational Supremacy																			0
Learning Orientation			X	X		X								X	X			X	7
Characteristics of the Design																			
Technological Superiority		X	X	X	X				X	X				X	X		X	X	10
Compatibility	X									X					X			X	4
Complementary Goods	X	X	X	X					X	X	X	X	X		X	X		X	13
Flexibility	X																		1
Design Support Strategy																			
Pricing Strategy		X						X	X	X		X			X	X	X	X	10
Appropriability Strategy		X								X	X				X				4
Timing of Entry	X		X	X				X	X	X					X	X			9
Marketing Communications										X	X	X			X	X		X	6
Pre-emption of Scarce Assets																			0
Distribution Strategy																			0
Commitment						X		X										X	4
Other Stakeholders																			
Current Installed Base			X	X			X			X	X				X	X			7
Previouss Installed Base							X												1
Big Fish																			0
Regulator																		X	1
Antitrust Laws																			0
Suppliers			X			X			X	X				X	X	X			8
Effectiveness of the Design Development Process																			0
Network of Stakeholders			X	X						X					X	X		X	6

Relevant factors for this research study are marked with a [grey] background

Blue	Videocassette Industry
Orange	Computer Industry
Light yellow	Telecommunications Industry
Green	Video Game Industry
Teal	Digital Video Disc Industry
White	Other Industries

X (grey)	Relevant Factor for Tecnology Dominance
X (yellow)	Relevant Factor for Technology Dominance That Is Also Relevant in the Same or Similar Industry

Appendix 6

Implications and Recommendations for Firms Involved in the Development of BEVs or HFCEVs in Light of the Results of This Study and Corporate Entrepreneurship Literature.

This section elaborates on the implications and recommendations for existing corporations involved in the development of either BEVs or HFCEVs in light of the results obtained from the performed analysis in this thesis. Some of the factors that, according to experts, are relevant for this technology battle will be considered in light of corporate entrepreneurship related literature to sharpen the understanding about how companies should behave and which corporate strategies these companies should adopt to identify and seize opportunities and increase the probabilities of playing an important role in the non-fossil fuel based personal transportation market.

The automotive field is a very capital-intensive industry (Kallstrom, 2015). Therefore, it seems fair to assume that the future of this market will partially depend on the performance and decisions of large corporations that own the resources to carry out the necessary efforts to push the boundaries of technology. However, the fact that this is a capital-intensive industry does not imply that startups cannot emerge. In fact, it is worth mentioning the positive impact that the automaker Tesla – a company founded in 2003 (Kumparak, Burns & Escher, 2015) – has had on the development of BEVs and the acceleration of the transition towards sustainable means of transport. However, despite the undeniable role that startups may have in the development of BEVs and HFCEVs, it seems reasonable to claim that this industry will be mostly developed by ICEV incumbents that will adapt to these new technologies in an attempt to capture part of the market share. This is the reason why it would be beneficial to assess the corporate strategies that companies behind this technology battle might have to adopt in light of the obtained results and corporate entrepreneurship related literature.

It seems logical to claim that, sooner or later, the transition towards sustainable mobility is bound to happen, either due to concerns about pollution and climate change, or due to prohibitively high future fossil fuel prices as a reflection of their increasing scarcity. However, established automakers have organizational schemes optimized for the development of ICEVs, and therefore, it seems opportune to perform a renewal or adjustment of these corporate structures to navigate through this transition phase. There are two main types of corporate venturing strategies that companies can adopt to re-organize themselves to increase their chances of playing a relevant role in the development of BEVs and HFCEVs. These strategies are known as 'internal' and 'external' corporate venturing. Internal corporate venturing is the strategy by which a new business is created inside the umbrella of the existing organization. On the other hand, external corporate venturing involves the creation of a new business outside the domain of the parent company or main core business organization (Covin & Miles, 2007).

According to experts, *technological superiority* is the most important factor to achieve technology dominance in the technology battle between BEVs and HFCEVs. Although many revolutionary innovations come from market entrants (Cooper & Schendel, 1976; Foster, 1988), authors like Ahuja and Lampert (2001) argue that incumbents are also capable of organizing themselves in a way that allows for the accomplishment of technical breakthroughs. This hints the importance of innovation within and outside the firm. For ICEV manufacturers, this implies the creation of a corporate structure capable of encouraging R&D and seizing and benefiting from opportunities in the marketplace. This relates to the concept of organizational ambidexterity. ICEV organizations attempting to play an important role in the future of the automotive industry must be willing to become ambidextrous organizations. This is, firms capable of innovating to come up with technological breakthroughs while protecting their traditional businesses (O'Reilly & Tushman, 2004).

Regarding in-house innovation, it is essential for ICEV manufacturing companies to carefully decide how R&D efforts are executed, either in a new business unit inside the firm (internal corporate venture), or outside the parent organization in a new corporation (external corporate venture). From a *technological superiority* and *learning orientation* standpoint, it seems beneficial for automakers to opt for internal corporate venturing, since although many elements in BEVs and HFCEVs are completely different to those in ICEVs – like energy storage systems and powertrains –, there are many others that are equal or similar – like the chassis and the body of the car. The creation of an internal corporate venture would allow car manufacturers to harness synergies between the new and the main core business units by means of close collaboration. The new business unit would benefit from the knowledge obtained throughout many years of experience in vehicle design by the traditional part of the firm, giving the new unit the chance to focus on the development of new technologies – like battery and powertrain technology – leaving the other well-known elements to be co-developed by both the new and the main core business units. In addition, in contrast to setting this new business inside already existing units, having an autonomous internal corporate venture would decrease the probability of learning traps, since the predominant line of thought of the main core business would not affect the original thinking and innovative efforts performed by the new independent business unit. Among the different learning traps that ICEV manufacturers should be aware of, it is worth mentioning the familiarity trap[5], the maturity trap[6] and the propinquity trap[7] (Ahuja & Lampert, 2001).

[5] Trap in which some companies fall due to their tendency to invest only in familiar technologies (Ahuja & Lampert, 2001).
[6] Tendency of some organizations to favour mature technologies to the detriment of emerging ones (Ahuja & Lampert, 2001).
[7] Affinity for using solutions found in the past as a starting point to solve new problems (Ahuja & Lampert, 2001).

Furthermore, granting certain autonomy to the new business unit in charge of the development of novel technologies would allow it to work at a certain distance from the ailments that some corporations might suffer from, like "bureaucracy, arrogance, tired executive blood, poor planning and short-term investment horizons" (Bower & Christensen, 1996). However, the creation of an internal corporate venture unit comes with some constraints. Among them, it is worth mentioning the fact that the main core business might feel cannibalized[8]. In order to avoid this, it seems reasonable to keep competition between the new business unit and the traditional part of the firm as low as possible. To accomplish this, close interaction and easy mobility of employees between units must be achieved. After all, although cannibalization would most probably occur at the expense of the ICEV part of firms, this does not necessarily imply that the main core business would slowly become useless. Instead, the ideal scenario would be one in which the complementary knowledge, capabilities and human capital of the ICEV part of the company are employed and progressively transferred to the new business unit, which would most likely become the future main core business. However, this transition process must occur at the right pace. Being too slow at increasing the capabilities of the new business unit would most likely lead the company to show a low competitiveness in the future marketplace. At the same time, moving the company towards this new business too fast would result in the loss of sales in internal combustion technology related products.

Large ICEVs automakers should remain aware of market opportunities that can increase their chances of achieving *technological superiority*. To accomplish this, *financial strength* becomes essential to address the acquisition of innovation occurring outside the walls of the firm. The main strategy to absorb external innovation consists of so-called Corporate Venture Capital (CVC) activities. These consist of ways to obtain access to innovation and opportunities in market entrants like startups (Hasenpusch & Baumann, 2017). According to Chesbrough (2002), these CVC activities should be seen "as important ways for a company to fuel the growth of its business". These activities are normally carried out by venture capital funds that remain alert to interesting opportunities. However, these CVC funds should be able to work in close cooperation with the internal corporate venture department in order to acquire the right technology at the right moment. Moreover, it is worth mentioning that having a strong financial muscle should not be seen as the panacea. It is essential for large automakers to realize that their size and resources are no guarantee of technological supremacy. Furthermore, success will most likely not occur unless companies can identify and adapt to the demands of future customers. After all, even large commercial organizations must be resilient and flexible enough to adapt to unanticipated changes (Hamel & Valikangas, 2003). Among the main efforts to adapt and

[8] Cannibalization due to product similarity is the process by which two different products meet the demands of the consumers in a similar way (Kim & Chhajed, 2000), increasing the sales of a new product to the detriment of the sales of an existing one.

absorb cutting-edge innovation, automotive companies like BMW and General Motors among others have their own venture capital arms (Taylor III, 2011; "Big Auto's Startup", 2016), responsible for seizing business opportunities in smaller companies that might increase their potential technological capabilities in the future.

Other factors that proved to be relevant for the technology battle between BEVs and HFCEVs according to experts are *network of stakeholders* and *complementary goods*. Many *complementary goods* for these types of vehicles can only be produced or placed by or in collaboration with other stakeholders. It seems fair to claim that a dense network of compatible charging or hydrogen refueling stations can only be placed with the collaboration of governmental institutions and other companies. Therefore, a good relationship between firms and other stakeholders is essential for the outlook of the companies involved. Following this line of thought, McEvily and Zaheer (1999) stress how important it is for firms to develop connections with other stakeholders, since these might become the source of "new information, ideas, and opportunities" for future business. In relation to *network of stakeholders* and *complementary goods*, it is worth mentioning the importance of the factor *brand reputation and credibility*. After all, the better the reputation of a company, the easier it is for a firm to establish a network of actors that is willing to engage and collaborate in vital aspects for the success of the business. The size and strength of the *network of stakeholders* can be positively influenced by a good brand reputation, and therefore, it can be concluded that it is essential for firms to enjoy a good reputation in order to increase the likelihood of succeeding in these markets. The connection between brand reputation and corporate venture strategies is industry-specific, since while for certain types of products the weight of the brand is an essential factor, for other types, this factor might not be particularly important. However, it seems reasonable to claim a relationship between the type of corporate venture strategy chosen by company and its brand reputation, and by extension, the factors *network of stakeholders* and *complementary goods*. As explained above, the better the *brand reputation and credibility*, the larger the *network of stakeholders* and the more *complementary goods* produced. Therefore, it seems crucial for car manufacturers to choose the right corporate venture strategy to use and protect their present and future *brand reputation and credibility*. As mentioned above, there are two main corporate venture strategies: internal and external. The latter has the advantage that a potential failure of the new business would not have major negative repercussions on the brand image of the parent company. However, this type of strategy poses some important limitations as well. The main one is the fact that the new corporation would not be under the name of the main core business, and therefore, the new corporation would not enjoy the same visibility, making it more difficult to establish connections with other stakeholders. On the other hand, if the new corporate activities are established within a new business unit inside the parent corporation, such new business would be able to use the name of the brand in its own benefit to increase its visibility and attract interested stakeholders. On the downside, a failure of the new business unit may have a negative influence on the image of the parent company. However, this strategy seems to be safer than directly implementing the new activities within the main core business. It is worth mentioning that the adoption of internal venturing strategies can already be observed in some prestigious automaker companies like BWM with the ‘i’ (Taylor III, 2011; Reed, 2011) and Mercedes-Benz with the ‘EQ’ (Bubbers, 2016; Savov, 2016) sub-brands.

Taking into account the different aspects treated along this discussion, it seems that, at first glance, one of the most suitable corporate venturing strategies for existing ICEV manufacturers to enter the BEV or HFCEV market consists of a combination of internal corporate venturing and CVC strategies. An internal venturing strategy would allow the new business unit to harness technology developed by the parent corporation with more ease while maintaining certain independence from the traditional parent corporation attitude. In addition, internal venturing would allow the new business unit to lie behind the brand reputation of the firm, what is expected to have a positive influence in the ability to capture an extensive network of stakeholders that might improve the outlook of the new business. Furthermore, in case of failure of the new business, the firm reputation would not result as damaged as it would if the new activities were directly implemented within the main core business.

Bibliography of Appendix 6

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