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The Battle between Battery and Fuel Cell Powered Electric Vehicles: A BWM Approach

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Abstract: The transition to a more sustainable personal transportation sector requires the widespread adoption of electric vehicles. However, a dominant design has not yet emerged and a standards battle is being fought between battery and hydrogen fuel cell powered electric vehicles. The aim of this paper is to analyze which factors are most likely to influence the outcome of this battle, thereby reducing the uncertainty in the industry regarding investment decisions in either of these technologies. We examine the relevant factors for standard dominance and apply a multi-criteria decision-making method, best worst method, to determine the relative importance of these factors. The results indicate that the key factors include technological superiority, compatibility, and brand reputation and credibility. Our findings show that battery powered electric vehicles have a greater chance of winning the standards battle. This study contributes to theory by providing further empirical evidence that the outcome of standards battles can be explained and predicted by applying factors for standard success. We conclude that technology dominance in the automotive industry is mostly driven by technological characteristics and characteristics of the format supporter.

Keywords: automotive; best worst method; BWM; standards battles; standards

1. Introduction

A battle is being waged in the personal transportation sector. Manufacturers are confronted with multi-billion Euro investment decisions. Will battery electric vehicles (BEVs) or hydrogen fuel cell powered vehicles (HFCVs) be the cars of the future? Betting on the wrong format could lead to bankruptcy. Toyota (Toyota, Japan), Honda (Tokyo, Japan), and Hyundai (Seoul, South Korea) are currently the strongest supporters of HFCVs, whereas BMW (Munich, Germany), General Motors (GM), and the alliance of Renault (Boulogne-Billancourt, France), Nissan (Yokohama, Japan), and Mitsubishi (Tokyo, Japan) support BEVs, with Tesla (Palo Alto, CA, USA) as the most vocal proponent. Plug-in hybrids are already part of many a manufacturer's line-up today. However, the most common strategy is to explore both options. Partnerships for developing fuel cells and batteries exist between e.g., GM and Honda; Toyota and BMW; and Daimler (Stuttgart, Germany), Ford (Dearborn, MI, USA), Nissan, and Renault. A compromising approach has also been launched in which battery electric vehicles use hydrogen fuel cells as range extenders. In other words, the technologies are complementary as well as competing.

Industries that are characterized by increasing returns to adoption often tend to result in single dominant designs due to the influence of network effects [1]. However, before such a dominant design emerges, fierce standards battles or platform wars are often fought, resulting in winner takes all situations [2]. While some scholars argue that the outcome of a platform war is the result of path dependency [3,4] and thus cannot be influenced directly, other scholars have shown that certain factors can influence which platform achieves market dominance [5–7]. Given the fact that the automotive industry has strong indirect network effects, it is likely that a dominant design will eventually emerge.

This paper focuses on which factors are most likely to affect the outcome of the battle between BEVS and HFCVs. We adopt the framework of Van de Kaa et al. [8], which includes factors for technology dominance and determine the relevant factors for this battle. Subsequently, we apply a multiple criteria decision-making method, the best worst method (BWM) [9], to determine the importance of these factors and give a first indication which of the two technologies has the best chance of winning the battle.

This paper contributes to the literature on standards wars in several ways. We apply the theoretical model of Van de Kaa et al. [8] and the BWM [9] to the automotive industry. Although the model has been applied to various cases [10–14], and the methodology has been used in various fields and context applications [12,15–24], they have never been applied jointly in the automotive industry. By employing both the model and the methodology for this specific case, we contribute to the growing evidence that factors for technology dominance can be determined [6,10–14,25,26], thereby contributing to the theory on standards battles. Finally, the practical contribution lies in reducing uncertainty for stakeholders involved in the process of choosing a technological alternative.

The rest of the paper is organized as follows. Section 2 presents the theoretical background which is followed by a discussion on the future of personal transportation in Section 3. Section 4 describes our method to determine the importance of the factors for dominance. Section 5 presents and discusses the results. We conclude in Section 6 with an interpretation of the results, contributions to the theory and a discussion on limitations and areas for further research.

2. Theory

Battles for market dominance have been going on since the 1970s. Various generations of gaming consoles have been introduced and have fought for a share of the market [26,27]. In the 1970s, Japan Victor Company (JVC, Yokohama, Japan) battled with Betamax for market dominance in the video cassette recorder industry [28], and in the 1980s, Sun Microsystems (originally headquartered in Menlo Park, CA, USA) battled with Apollo Computer (Chelmsford, MA, USA) for a dominant workstation format [29]. In the 1990s and 2000s, there was a standards war between WiFi and HomeRF for wireless data communication [30] and between Blu-ray and HD-DVD for a high definition video format [25]. In the mid-1980s, scholars started to investigate the factors that affected the outcome of these battles. They approached the phenomenon from multiple scientific angles. Scholars with an evolutionary economics background argue that the result of a standards battle can only be explained by utilizing concepts such as path dependencies [3,4]. The idea here is that random idiosyncratic events determine the outcome of standards competition. This can lead to technologically superior standards such as QWERTY, the standard for the layout of computer keyboards [4].

Network economists stress the importance of market mechanisms such as network effects [31,32]. When network effects exist, the value of a technology increases the more people adopt that technology. We can distinguish between direct and indirect network effects. Direct network effects occur in markets that consist of physically interconnected systems, whereas indirect network effects occur in two-sided markets that consist of core technologies and complementary goods. Mobile telephony is an example of a market in which direct network effects are apparent. These effects relate to the physical interconnections that can be made by utilizing the mobile telecommunications network [33]. The market for video gaming consoles is characterized by indirect network effects that accrue from the value that people derive from using complementary goods in the form of games that are specifically made for the video gaming consoles; the more games available for a video gaming console, the higher the value of that console to users [34]. Network economists argue that, under the influence of network effects, the number of people that adopt a technology (the installed base) is a crucial factor for technology dominance. When markets are characterized by network effects, the installed base and the number of complementary goods reinforce each other and each become crucial for achieving standards success [5,6,26].

Strategy scholars argue that the outcome of standards battles can be explained and have identified factors that may affect the installed base. For example, firms can influence potential adopters' anticipations of the future installed base through marketing communications (e.g., through pre-announcements) [35]. When the war between Blu-ray and HD DVD was still raging, the promotors of Blu-ray launched the 'war is over' marketing campaign [36]. This led consumers to choose for Blu-ray, believing that the standard would eventually win the battle. Additionally, firms may apply a pricing strategy whereby they reduce the price of a product below cost in order to increase the installed base as quickly as possible [37]. Although applying this strategy does not lead to profits in the short term, it might lead to a large installed base of locked-in consumers in the long run, after which prices can be increased again [38]. Firms may also try to outcompete competitors by introducing their technology relatively early, resulting in first mover advantages [6,39,40]. Apart from strategies, complementary assets are crucial for winning standards battles. For example, financial resources are essential for pursuing lengthy marketing campaigns, and a certain amount of reputation and credibility among potential users is necessary for them to be committed to the technology [7].

Technology management scholars focused on the characteristics inherent to the technological artefact, including its technological superiority in terms of aesthetic qualities and its compatibility [35]. Sony, for example, purposely made its PlayStation 2 console backwards compatible with its PlayStation 1 console, so that there would be a large availability of complementary goods (i.e., PlayStation games). This led users to choose PlayStation 2 instead of competing game consoles including the Dreamcast or the Xbox [27]. Various scholars have developed frameworks to explain the outcome of platform wars or standards battles [5–8]. These scholars have integrated factors for technology dominance that are mentioned in the diverse streams of literature that have been discussed in this section.

3. The Future of Personal Transportation

Climate change concerns, fossil fuel depletion, and urban air pollution call for a more sustainable transportation sector. Existing transport fuel options, such as petrol, diesel, and natural gas fueled cars, are increasingly under pressure by newer, cleaner alternatives for passenger car and delivery van applications: biofuels, hybrid electric vehicles, plug-in hybrids, battery electric vehicles, and hydrogen fuel cell vehicles [41–45].

At present, all of the five alternatives are commercially available, albeit to different degrees. Gasoline and diesel dominate the market with a close to 98% share, (plug-in) hybrids and biofuels are well on their way of getting a foothold [46], while battery and fuel cell driven vehicles are just emerging. Nevertheless, the latter two are already the focus of a battle for market dominance. If we are to achieve greenhouse gas reductions of 80% below 1990 levels, all-electric vehicles powered by batteries or fuel cells are a necessity. There is no doubt that the transition to a sustainable transportation sector is expected to move from internal combustion engines to hybrids, plug-in hybrids, and biofuels in the mid-term, to all-electric vehicles (battery or fuel cell) in the long term.

Most car manufacturers are currently pursuing both BEVs and HFCVs to varying degrees but some seem to have already chosen sides [47–50]. BEV advocates include Tesla, BMW, GM, and Renault-Nissan-Mitsubishi. HFCV proponents include Toyota, Honda, and Hyundai. Typical arguments in favor of BEVs are the presence of a refueling infrastructure in the form of the electricity grid, energy efficiency considerations, and possibilities to extend the range. Arguments in favor of the HFCV are range, adaptability, refueling time and its applicability for heavier cars and trucks (more power). Nevertheless, these manufacturers are hedging their bets by forming partnerships to develop fuel cells and batteries, e.g., GM and Honda, Toyota and BMW, or the Daimler-Ford-Nissan-Renault fuel-cell partnership. Toyota and Tesla seem at the forefront of the standards battle. At present, BEVs seem to be off to a head start. Due to the increasing spread of plug-in hybrids, customers tend to be more accustomed to using electricity based vehicles. Then again, if hydrogen becomes the fuel of choice for heavy duty vehicles (trucks), shipping, and aviation, round two of the battle is waiting around the corner.

Academic literature has not yet adequately addressed the battery vs. fuel cell standards battle. Engineering literature has focused mostly on comparing BEVs with HFCVs along more objectively measurable criteria such as costs (vehicle cost, fuel cost per mile driven, W2W energy efficiency), infrastructure investments, and various performance indicators (life cycle/durability, reliability, range, power, engine volume, refuelling time, technical maturity, emissions, waste, safety, driving experience, and user friendliness) [41–45]. Alternatively, research focus has gone to the market deployment of both technologies, some investigating potential lead markets for electric vehicles [51], others presenting a multi-level perspective on introducing hydrogen and electric vehicles [52]. Standards battles literature has not yet addressed the battery vs. fuel cell case either. Sadly, popular press has seemingly more accurately put the finger where it matters, the car-tech battle. Headings such as Tesla vs. Toyota, or derivatively China vs. Japan, pinpoint the standards battle that has begun between BEVs and HFCVs for the domination of long-term future car manufacturer markets [47–50].

4. Methods

In order to understand which factors are most likely to contribute to the outcome of the battle between battery powered and fuel cell powered vehicles, we applied the factors for standard dominance presented in Van de Kaa et al. [8] that can be directly influenced by the firm. We apply this list of factors as it is the most complete list of factors that is available in the literature.

We used a linear model of the BWM to determine the importance or weights of the relevant factors. The BWM requires fewer comparisons with respect to other matrix-based Multi-Criteria Decision-Making (MCDM) tools, the final weights obtained from the BWM are highly reliable, and comparisons are more consistent than when using the full matrix-based methods [9,53]. Finally, the BWM is well known 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 that require comparison matrices with integers as well as with fractional numbers. Therefore, this research study serves as additional proof of the usability of this method for assessing technology dominance, and as unique proof that this method can be used to assess the technology battle between BEVs and HFCVs.

The linear model of the BWM used in this research study [53] consists of five steps:

Step 1

The expert determines the set of decision criteria. These criteria $\{c_1, c_2, c_3, \ldots\}$ 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 in 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-Other vector would be something like: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} refers to the preference of the best criterion B over the criterion j.

Step 4

The expert must determine the preference of all the criteria over the worst criterion by using a number between 1 and 9. This delivers the Others-to-Worst vector: $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$, where a_{jW} is the preference of factor j over the worst criterion W.

Step 5

According to Rezaei [53], 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 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:

$$\min \zeta^{\,L}$$

s.t:

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

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

$$\sum_j w_j = 1$$

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

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

To determine the set of decision criteria (Step 1), we first assessed which of the factors for technology dominance presented by Van de Kaa et al. [8] are relevant for this specific case. This was done through an analysis of secondary sources. A factor was included if it was mentioned in the secondary sources.

We first conducted a survey to gather all the necessary data to perform the BWM (Steps 2 to 5). The questionnaire in the survey was developed by using the SoSci Survey software package. We implemented dynamic functionality as well as skip logic by using the programming languages PHP and HTML to ensure a relatively easy process for the respondents to fill out the questionnaire. Pages seen by the respondent depended on previous answers. In other words, depending on the answer given by the respondent, the survey showed tailored questions in subsequent pages.

The anonymized survey was sent to over 100 experts in the field. We contacted both researchers and practitioners (engineers and managers) with comprehensive knowledge of the topic. A researcher/academic was considered to have comprehensive knowledge of the topic if he or she had either published on the topic or had several years of experience in the topic. A practitioner was considered to have comprehensive knowledge of the topic if he or she had several years of experience in topic-related areas. We also ensured that experts had a background both in BEVs and HFCVs to decrease the bias towards a certain standard. To find potential respondents who met these criteria, we searched among research institutes, universities, company websites, and via LinkedIn. This resulted in a total of 18 respondents from the Unites States, the Netherlands, Spain, Portugal, Germany, Austria, and China. The group of experts comprised industry practitioners (engineers with a technical viewpoint and managers with a business/management viewpoint), scholars from several prestigious universities as well as the director of a prestigious energy research institute.

5. Results

We found 11 factors from the framework by Van de Kaa et al. [8] to be relevant for the case of BEVs vs HFCVs. Relevant factors include “financial strength”, “brand reputation and credibility”, "learning orientation", "technological superiority", "compatibility", "complementary goods", "pricing strategy", "marketing communications", "commitment", "regulator" and "network of stakeholders". These factors are briefly explained in Table 1.

Table 1. Factors for standard success [adapted from 8].

Main Factors (Criteria)	Sub-Criteria	Description
Characteristics of the format supporter	Financial strength	The financial means with which a strategy may be pursued. Firms need financial resources to pursue marketing campaigns or a penetration pricing strategy [30].
	Brand reputation and credibility	A firm's reputation and credibility are important as they may affect people's intention to adopt standards.
	Learning orientation	Learning orientation entails learning from failures that were made in previous battles and the extent of R&D investments in the technology.
Characteristics of the technology	Technological superiority	Technological superiority refers to all technological characteristics allowing the technology to outperform the competing technology [54].
	Compatibility	A technology that is compatible with other technologies increases the chances that the technology is adopted. For example, this refers to compatibility with an infrastructure that is already present (refuelling stations and vehicles).
	Complementary goods	A higher availability and variety of complementary products has a positive effect on the installed base of a technology [30].
Strategy	Pricing strategy	Pricing strategy can be used to increase the installed base of a technology. For example, the technology can be priced below cost (penetration pricing) which will increase the installed base.
	Marketing communications	Marketing communications has a positive effect on the installed base. Firms can pursue marketing campaigns and thereby increase expected and perceived installed base.
	Commitment	When firms are more committed to a technology, this has a positive effect on the chances that this technology achieves success [10].
Other stakeholders	Regulator	The regulator may be very important in standards competition. When it enforces a standard, the standards battle may end prematurely as the enforced standard achieves success.
	Network of stakeholders	Network of stakeholders can be crucial. For example, when the standard is promoted by a diverse network of stakeholders and thus by firms that represent different industries, the standard can make use of the installed base in each of these industries [25].

Table 2 shows the global weights (importance) of the eleven relevant factors for this technology battle according to the 18 experts (The full dataset is available upon request). The first column shows the categories and factors for standard success (explained in Table 1), and columns 2–19 show the results by applying the BWM method for individual respondents. The last column shows the average weights. Based on these data, we can conclude that the three key factors influencing standard dominance are "technological superiority" (0.160), "compatibility" (0.150), and "brand reputation and credibility" (0.126). The three least important factors are "marketing communications" (0.051), "availability of complementary goods" (0.059), and "learning orientation" (0.059).

Table 2. Importance of the factors.

Criteria Experts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Avg.
Characteristics of the format 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
ξ^*	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 format																			
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
ξ^*	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
Format 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
ξ^*	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																			
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
ξ^*	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

The consistency ratios ζ^* are also shown in Table 2. The closer this ratio is to zero, the higher the level of consistency of the model. The obtained model shows ζ^* values close to zero for each single category of factors per respondent as well as for the total consistency per respondent. The highest value of ζ^* in the model corresponds to respondent 5, with a ζ^* of 0.194. The highest category average ζ^* belongs to the category "characteristics of the format supporter", with an average ζ^* of 0.108. Overall, we can conclude that data collected are consistent and reliable.

Table 3 presents the results of the analysis of the two technologies. We compared the factor score of each technology. For example, BEV scored 0.093 for technological superiority compared to a score of 0.066 for HFCV. Summing up the individual scores results in the total factor score for each technology (sum of global weights). The total factor score for BEV was 0.709 compared to 0.291 for HFCV. This implies that, according to our experts, BEV has a substantial advantage in terms of achieving technology dominance. In fact, the results show that BEV is superior to HFCV in every single factor.

Table 3. Final results of the analysis of both types of technologies.

Factor	BEV	HFCV
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 global weights	0.709	0.291

6. Discussion and Conclusions

The transition to a more sustainable personal transportation sector requires the widespread adoption of electric vehicles powered by batteries or fuel cells. Automotive manufacturers are now confronted with decisions to invest in technologies that will become adopted in the future. While some manufacturers have chosen to invest in either BEVs or in HFCVs, most companies have invested in both and/or have formed partnerships to develop both batteries and fuel cells, thereby hedging their bets.

Academic literature has not yet sufficiently addressed the battle between BEVs and HFCVs. This paper focused on determining the factors that are most likely to influence which of the two technologies will become dominant. Based on insights from the technology management literature, where scholars have developed frameworks integrating factors for technology dominance, we applied a multi-criteria decision-making method, the best worst method, to determine the relative importance of a range of factors and have provided a first indication of the outcome of the battle.

6.1. Interpretation of the Results

The results indicate that technological superiority, compatibility, and brand reputation and credibility are the most influential factors for standard success in the market for electric vehicles. What are the reasons and implications?

The importance of technological superiority in explaining technology dominance comes as no surprise. Technical performance has always been an important aspect in the automotive sector. Traditional internal combustion vehicle manufacturers invest heavily to maintain technological superiority in terms of range, power, operative ease, and maintenance. Consumers simply demand the highest performance in exchange for their money. The importance of technological superiority is confirmed in the literature on the technology battle between BEVs and HFCVs. HFCVs are considered to suffer from hydrogen storage and safety issues [55–58]. BEVs face challenges in range, i.e. battery capacity, and long charging times [59–64]. These limitations to technological performance make BEVs and HFCVs less attractive in the eye of potential buyers, posing a barrier to market acceptance. The difference in favour of BEVs vis-à-vis HFCVs can be attributed to the familiarity of both technologies as well as technical specifics. Regarding the former, batteries are widely used in a wide variety of appliances, whereas fuel cells remain relatively unknown to the broader audience. Batteries are simply a proven technology. Moreover, BEVs have attracted more R&D and Tier 1 investments. Concerning the latter, academic literature ([41–45], among others) indicates many technical specifics that determine superiority, ranging from fuel costs and battery/fuel cell life cycle to the performance indicators mentioned above and more advanced factors such as possibilities to use the car for energy storage. An additional consideration worth mentioning at this point is whether technological superiority will remain important. According to Suarez [7], when the first commercial product has been introduced within a product category, technology related factors for standard dominance become less important and marketing and business strategies become increasingly relevant. In other words, once both options have proven themselves in the market, other factors may become more important. This implies that it may be necessary to further specify our research question for the various phases of market deployment (introduction, expansion, and saturation).

Our results suggest that compatibility is another key factor in explaining technology dominance. In this case, compatibility refers to the 'connection' between vehicles and charging points and hydrogen fueling stations. The literature is well-aware of the challenges that arise with respect to compatibility issues. For example, Brown et al. [65] stress that international compatibility is considered critical for the success of BEVs; the difference in charging systems reduces the attractiveness, and therefore, the adoption of BEVs [61,63,66]. The scattered process of development (in time and space) and the current lack of compatibility standards have led car manufacturers to produce vehicles with their own electricity connection types for DC fast charging [67]. In contrast, HFCVs hardly have any compatibility issues between HFCVs and fuel dispensers as hydrogen dispensing nozzles adapt to car receptacles [68,69]. In the future, a hydrogen infrastructure is likely to be set up for heavy duty vehicles, and in the shipping and aviation sector, which might enable an easy addition of fuel stations for personal transportation. However, as this infrastructure still needs to be built, and the electricity grid and an increasing number of charging stations are already in place, it is not surprising that experts believe that BEVs still have a substantial advantage over HFCVs regarding compatibility. In addition, the relative presence of BEVs on the road compared to relatively few HFCVs could be responsible for a bias among experts that BEVs have substantially fewer problems related to compatibility.

Finally, brand reputation and credibility has always been an extremely important aspect in the automotive industry. For many drivers, a car is not just a mode of transport, but an expression of their preferences and values [70]. Purchasing a car is more than a rational decision on technical performance; customer perceptions of quality, reliability, and social desirability matter [71]. Brand reputation and credibility can hence be used as a differentiation factor by firms and for designs supported by these firms [72]. The presence of big prestigious car manufacturers supporting one specific design can be a sufficient argument to convince other players in the industry to follow. The efforts and success of Tesla, GM, and Nissan in developing and profiting from the development of BEVs have attracted the interest of many other players in the industry, substantially increasing the chances of technology dominance by BEVs. The reputation of Tesla especially has had a positive effect on BEVs and on the prospects of the company itself [73]. Only the future can tell whether Toyota and Honda will have the same effect with HFCVs. This explains why experts believe BEVs performs substantially better than HFCVs with respect to brand reputation and credibility. Of course, experts have had the chance to see the positive influence of Tesla in the acceleration of BEV adoption, and the HFCV has not yet provided us with a similar case.

6.2. Contributions

This paper contributes to the research on standards battles and design dominance [1,5–7] in several ways. First, we contribute to the growing evidence that the outcome of standards battles is not merely a result of path dependency, but that the process can be modelled and that factors for technology dominance can be determined [6,10–14,25,26,74]. More specifically, we contribute to an emerging body of literature that assigns weights to factors for standard dominance in various fields [11,13]. These contributions argue that the outcome of standards battles can be explained and predicted by applying factors for standard dominance, by determining their weights, and by applying them to specific cases. We corroborate this notion in this paper.

Our respondents scored 11 factors for standard dominance. They gave the highest scores to technological superiority (0.160), compatibility (0.150) and brand reputation and credibility (0.126). Thus, the likely dominance of BEVs or HFCVs hinges mostly on technology related factors for standard dominance (e.g., technological superiority and compatibility) and on the reputation and credibility of the manufacturer and its brand. Our results showed that BEVs are superior to the HFCV in every single factor, indicating that according to the experts we interviewed, BEVs have a substantial advantage for becoming the dominant technology.

Although both the BWM method and the list of factors for standard dominance have previously been analysed and applied, they have never been applied jointly in the automotive industry. More specifically, this is the first time that factors for standard dominance have been applied to the case of electrics cars. We prove that the BWM can be successfully applied to this specific case.

The results may also be beneficial for practitioners and might be applied by firms to reduce the uncertainty attached to choosing a particular standard in this battle and in future standards battles in this arena.

6.3. Limitations and Areas for Future Research

Unfortunately, the BWM does not require experts to further elaborate which technical specifications of BEVs and HFCVs make them conclude in favour of BEVs. Future research could study which specifications were at the core of our results. For example, technological superiority appears to be crucial in this battle. Many aspects underlying this factor were discussed in Section 6.1. These and other aspects may be studied in subsequent research using a similar approach so that more detailed knowledge about the technical factors for standard success can be established. Future research could study why some factors are ranked higher for one standard compared to the other. We also recommend future research to study more standards battles in other fields using the same or a similar approach to further increase our knowledge about weights for factors for standard dominance in various field.

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