Advanced battery and materials supply development for electric vehicles

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Abstract: Several alternative vehicle and fuel options are under consideration to alleviate the triple threats of climate change, urban air pollution and foreign oil dependence caused by motor vehicles. This paper evaluates the primary transportation alternatives and determines which hold the greatest potential for averting societal threats. We developed a dynamic computer simulation model that compares the societal benefits of replacing conventional gasoline cars with vehicles that are partially electrified, including hybrid electric vehicles, plug-in hybrids fueled by gasoline, cellulosic ethanol and hydrogen, and all-electric vehicles powered exclusively by batteries or by hydrogen and fuel cells. 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 battle; standards transmission rate.*

I. 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]. 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., 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) [6], 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 [7] to the automotive industry. Although the model has been applied to various cases [8], and the methodology has been used in various fields and context applications [9], 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 [10], 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.

II. GENERAL COMPOSITION OF A PROTON EXCHANGE MEMBRANE FUEL CELL

In this PEM fuel cell was invented by Thomas Grubb and Leonard Kneidlach at General Electric in the early 1960s [11]. The first assignment was to develop a small fuel cell for the U.S. Navy's Bureau of Ships (Electronics Division) and the U.S. Army Signal Corps [12]. The fuel cell was fuelled by hydrogen generated by mixing water and lithium hydride. It was compact but the platinum catalyst was expensive. The initial idea was for NASA to develop a PEM fuel cell for Project Gemini in the early U.S. space program. Batteries were used for the preceding project mercury missions, but Project Apollo required a power source that would last a longer period of time. There were some challenges encountered during the manufacturing of the first PEM fuel cell. There were some internal cell contamination and leakage of oxygen through the membrane. General Electric modified the design and concept which worked perfectly for the rest of the Gemini flights. The designers of Project Apollo and the space shuttle ultimately chose to use alkali fuel cells. The work by General Electric on fuel cell continued till the 1970s and designed the PEM water electrolysis technology, which led to the U.S Navy oxygen generating plant. The British royal navy used PEM fuel cells in the early 1980s for their submarine fleet. The last decade has seen PEM fuel cells being researched extensively and made remarkable strides particularly in the transport industry.

The polymer electrolyte also called proton exchange membrane (PEM) fuel cell delivers high e power density while providing low weight, cost and volume. It is made up of a negatively charged electrode (anode), a positively charged electrode (cathode) and an electrolyte membrane as shown in Fig. 3. Hydrogen is oxidized on the anode and a reduction of oxygen occurs at the cathode. Protons are then moved from the anode to the cathode through the electrolyte membrane and the electrons are carried over an external load circuit. On the cathode, oxygen reacts with protons and electrons forming water and producing heat [13]. In PEM fuel cells, transport from fuel flow channels to the electrodes takes place through an electrically conductive carbon paper, which covers the electrolyte on both sides. The porosity of this backing layer is often 0.3 to 0.8 and functions as the medium for transporting the reactants and products to and from the bipolar plates to the reaction site [14]. An electrochemical oxidation reaction occurs at the anode producing electrons that flow through the bipolar plate often made of a metal or graphite and interconnect to the external circuit while the ions pass through the electrolyte to the opposing electrode. The electrons finally return from the external circuit while the ions pass through the electrolyte to the opposing electrode. The electrons return from the external circuit to participate in the electrochemical reduction reaction at the cathode. The reactions are shown in Eqs. (1)e(3):

$$\text{Anode}: H_2(g) \rightarrow 2H^+(aq) + 2e^- \quad (1)$$

$$\text{Cathode}: \frac{1}{2}O_2(g) + 2H^+(aq) + 2e^- \rightarrow H_2O(l) \quad (2)$$

$$\text{Overall}: H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l) \quad (3)$$

Fluorinated Teflon based material manufactured by DuPont is the standard electrolyte material currently being used today in PEM fuel cells. It was produced for space applications in the 1960s. The DuPont electrolytes have the generic name Nafion and the types used most often are 1135, 115 and 117. The Nafion membranes are fully fluorinated polymers having high chemical and thermal stability. The electrodes are designed to be thin films bonded closely to The Nafion membranes are fully fluorinated polymers having high chemical and thermal stability.

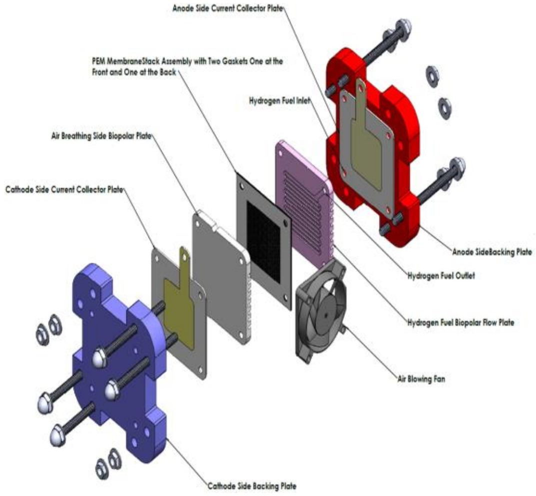

Figure 1. The polymer electrolyte membrane fuel cell (PEMFC).

The electrodes are designed to be thin films bonded closely to the membrane. The electrodes with low platinum loading are believed to perform better than that with high platinum loading. A soluble form of the polymer is incorporated into the porosity of the carbon support structure to sometimes improve the utilization of the membrane. This increases the interface between the electro-catalyst and the solid polymer electrolyte [15].

III. FUEL CELLS IN THE TRANSPORT INDUSTRY

One of the industries where fuel cell can play a critical role is the transport sector as explained earlier. This is simply because the transport sector accounts for 17% of the global greenhouse gas emissions yearly according to Cacciola et al. There has to be serious adjustment made in this industry if the sector wants to really meet the Kyoto protocol. The industry intends to offer both significant reductions in harmful emissions as well as better energy conversion efficiencies. The world has seen a massive boost in the transport industry over the last few decades. There has been a surge in innovative, economic and environmentally friendly transport system worldwide. According to Dias et al. [2], most vehicular systems are classified under three main categories: Internal combustion engine vehicles (ICEV), Hybrid electric cars and all electric cars. All electric cars utilize batteries, ultra-capacitors and fuel cells as their energy sources. The hybridization of ICEV and AEV gives rise to the hybrid system.

The shows the classification of cars while Eq. (4) shows the hybridization factor which is the ratio of the electric motor (EM) power to the total power:

$$H_F = \frac{P_{EM}}{P_{EM} + P_{ICE}} \qquad (4)$$

Vehicles are classified into different types depending on the hybridization factor. P_{EM} is the electric motor power and P_{ICE} is the internal combustion engine power. Sharing the shaft for both the EM and ICE and also using a power split path are some ways hybridization of electric motor is done. Hybridization of vehicle results in improvements of fuel economy often expressed as mile per gallon (MPG) or miles per gallon gasoline equivalent (MPGe). MPGe is used for EV or PHEV where 33.7 kWh electrical energy is same as the energy of one gallon of gasoline.

Internal combustion engine vehicle (ICEV) transforms chemical energy of fossil fuel into kinetic energy to run the car with the help of a combustion chamber. The by-product of the reaction is heat which is released directly into the atmosphere. The world currently has two types of ICEV. These are conventional ICEV with no assisting electric motors and 2 micro HEV with low voltage EM incorporated with it. The conventional ICEV functions as stand-alone thus it has the lowest fuel economy but produces the most exhaust gas and heat that are toxic to the environment. The micro e HEVs uses electric motor of around 12e14 V providing power of around 5 kW with the ICE. The internal combustion engine only uses the motor to start from cold start and does not play any active role in the car once it's in motion. This type of vehicle has the benefit of shutting down the ICE during coasting, braking or stopping which improves the fuel cell economy up to 5e15%. The Citroen C3 is an example of micro e HEV produced by Citroen.

IV. ELECTRIC VEHICLES

It took over sixty years and six generations of gasoline engines for the Chevy Corvette to develop an electric car that can accelerate the speed to sixty mph within 4 s. The journey of developing electrical car engines from idea to market hasn't been an easy path. The poor performance of earlier electric cars developed led to the low patronage by users. Cost was also another determining factor that made people lose interest committing funds and resources in that venture. With the improvement of battery technology and automotive technology advancement over the last two decades, the new generation of high-performance electric cars might soon become the latest choice of car for buyers around the globe. It is therefore clear that Electrical vehicles driven by energy stored in batteries or fuel cell units are the most likely option for reducing emissions from the transport sector. The world is generally coming up with lots of policies to encourage automobile industry manufacturers to shift their internal combustion engines to (EVs).This is because the world is doing everything possible to reduce emissions but at the same time boost regional economic development. Hydrogen,

Electric and Hybrid cars have been developed and demonstrated in several exhibitions. The future trends in green vehicle have been a subject of discussion in recent times. Major car makers have interest in developing future green vehicle markets. Green vehicles use renewable. Energy sources as their main source of fuel. The current developments of green vehicles are listed in Table 1. These models were at developmental stages between 2009 and 2012. This publication seeks to explore the current technology status and potential developments of green vehicles are reviewed and the developments of the technology applications are thoroughly analysed to understand the move towards cleaner energy systems.

An alternative power source recently considered and still under intense investigation to replace or complement the internal combustion engine in recent times is Electricity. Hickman, 2009 described the three types of electrically powered cars as pure -electrics (such as the Tesla): hybrids (the Prius) and plug e in hybrids (the Karma). Battery is often used by the pure electric to power the motor engine instead of petrol in the pure electrics. Pure electric cars that depend on battery as source of power have a range of 30e50 miles only. This clearly shows that it has some limitations in terms of range and lifetime though aid in the reduction of CO_2 emissions. Hybrid vehicles are designed to use both an electric motor and an internal combustion engine. The battery often used in hybrid is small compared to that used in all e electrics. It also allows the vehicle to travel longer distance compared to the puree electrics on one battery charge. Hybrids with plug in capabilities use a combination of grid electricity, regenerative energy from braking, and power from another on board source such as internal combustion engine or fuel cell. The engines can be designed to operate serially and applied to a variety of vehicles. The ideal scenario is to charge the plug-in e hybrids electric vehicles at night during off peak grid use with power from renewable energies such as wind, solar and biomass. The Obama's administration stimulus Bill granted $14.4billionfor plug in hybrids. Electric cars are estimated to have about 35% of the car market by 2025 with 10% pure electric cars and 25% of hybrid cars according to Harrop and Das, 2009.

In contrast to vehicles powered by a conventional fossil fuel or biofuel-based ICE, the energy storage system is of crucial importance for electric vehicles. As explained earlier using batteries to store electrical energy is one options for the manufacturing of electric cars. The other is the storage of energy in the form of hydrogen. The history of Electrical cars can be dated back years ago when Opel and General Motors first conceptualize the idea. General Motors first developed the world's first fuel cell EV called the GM Electron in 1966. The idea was revisited in the 1990s where the technology was revisited and reintroduced within the framework of a large e scale development program. The work done during the development program led to the current HydroGen4 fuel cell car being manufactured. This is a mid e sized cross over vehicle based on the Chevrolet Equinox. The 1990s also experienced huge progress in the development of pure battery electric vehicles. These were mainly built to large scale project purposely for demonstrations. Example is the Opel Impulse and the Rugen e Project. It is also worth noting that mass e produced Electric Vehicles were designed and brought to the market on lease basis, namely the GM EV1.

The depletion of the fossil fuels resources and climatic change caused by anthropogenic CO_2 emissions all contributed to the desire for electric cars to be commercialized. Most projects later carried out by Opel and GM in relation to this were actively supported by the GM Alternative Propulsion Centre Europe in Mainz-Kastle.

Automotive technology development

There are over 900 million vehicles worldwide on the road today. The fuel used for propulsion purposes for about 96% of these vehicles are produced from fossil fuel. It is estimated on record that this number of vehicles on the road is likely to increase appreciably to 1.1 billion vehicles by 2020 due to high economic expansion in China and India. This likely situation would have a detrimental effect on global crude oil demand and for the worldwide CO2 emissions. Since an increase in demand of oil and CO2 production proportional to the projected number of vehicles is not sustainable for financial, ecological and political reasons, every implementation strategy must aim at the replacement of fossil fuel as a source of energy for automotive applications. One strategy that was used by General Motors is the electrification of the automobile, the displacement of gasoline by alternative energy carriers as shown in Fig. 5. This will lead to a drastic reduction in fuel consumption, reduced emissions and also increased energy security through geographic diversification of the available energy sources.

This strategy was first established in 1996 during the development of the first electric vehicle GM EV1. This design was a pure battery electric vehicle (BEV) but failed to rise or compete on the market hence the need for its modification in the subsequent years. EV1 drivers coined the term range anxiety describing their omnipresent concern or the fear of becoming stranded with a discharged battery in a limited e range vehicle away from an electric infrastructure. These concerns remain one of the main challenges which still hinder the progress of the BEV on the market even till now. However, most of the EV e enabling electric components and systems have found utility in the meantime by adapting them for the usage in mild and fully hybrid electric vehicles (HEV's). These vehicles often do not provide power by exclusively using electric motor and therefore the power and energy level requirements for the system components are reduced in comparison with a conventional BEV. The conventional hybrid (both mild and full) improves vehicle efficiency thus reduces power generated from an onboard liquid medium. The onboard electrical engine and the storage system are only used to shift the operating point of the ICE to a more favourable point on the efficiency map and to enable recuperation. Thus, HEVs provide unfortunately not any additional pathways to utilize CO_2-neutral renewable energy sources. Partially, these drawbacks may be resolved by introducing so-called extended-range electric vehicles (EREVs) that are discussed in the following sections. Zero-emission vehicles using an electric powertrain system based on hydrogen fuel cells or purely battery electric systems that are fully competitive to conventional vehicles regarding performance and ease-of-use represent the ultimate target of the GM strategy as shown in Fig.5. A further important step into this direction is the start of mass production of the Chevrolet Volt at the end of 2010, as well as the introduction of other vehicles like the Opel Ampera which are also based on the VOLTEC technology.

V. BATTERY ELECTRIC VEHICLES (BEV) (ALL ELECTRIC CAR)

All electric cars are designed to use only battery to power the motor instead of petrol. They normally utilize electrical power for the vehicle propulsion. Six types of power transfer systems in all electric vehicles have been explained into details in literature.

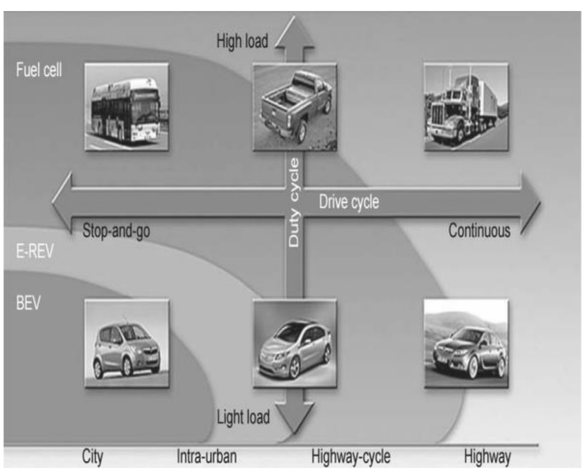

Figure 2. Application map for various EV technologies.

They are classified into three compared to the recent lithium e ion batteries. Many car makers have applied this better battery technology in their electric powered cars. Tesla is the first powered lithium battery car. It is a pure electric roadster vehicle. This magnificent edifice was first unveiled to the public in 2006 but by 2009 a profit margin of nearly 5% was being made by the company. The Tesla can travel a distance of 244 miles on lithium e cobalt battery.

Sections:

Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicles (FCEV's) and Fuel cell hybrid electric vehicles (FCHEV's). There are similarities between the BEV and FCEV but FCHEV is different. The FCHEV involves hybridization of battery and fuel cell. The BEVs use energy storage systems while the FCEVs use fuel cells. The FCHEVs use both the fuel cell and energy storage system to power the vehicle. The battery electric vehicle is classified under the all-electric vehicles (AEV) which rely on battery as its primary energy source. The battery placed in the car gains its energy from the grid hence it is charged very often. The charging system is normally placed on board or off board. The mechanical drivetrain of this configuration is very low making it highly advantageous. This leads to the weight of the vehicle being very low hence loss from transforming energy from electrical to mechanical is very low. High torque traction motors for accelerating the vehicle is the main requirement for this type of configuration but also reduces the efficiency. High torque traction motors have high current flow in the armature winding, leading to heat loss in the motor. Battery electric vehicles travel short distance and the speed is also limited making it conducive for stop and run driving situations. BEVs are best preferred for inequity driving due to their low mileage, low weight and low top speed. A modification of the vehicle power train is one approach to increase the vehicle driving range and top speed. An additional gear box in the vehicle is one effective way of getting this done. The function of the gear box is for the BEVs to run in both city and highway; however, this modification compromises the efficiency of the vehicle. BEVs without gear box (motor to wheel) has higher efficiency due to lower number of moving parts, has low rotational inertia and no energy loss in gear and differential mechanism [16].

There are absolutely no tail-pipe emissions. They depend strictly only on batteries that are often recharged from the grid or by regenerative braking (utilizing brake energy as fuel). The old battery technology is less efficient compared to the recent lithium e ion batteries. Many car makers have applied this better battery technology in their electric powered cars. Tesla is the first powered lithium battery car. It is a pure electric roadster vehicle. This magnificent edifice was first unveiled to the public in 2006 but by 2009 a profit margin of nearly 5% was being made by the company. The Tesla can travel a distance of 244 miles on lithium e cobalt battery pack and is able to accelerate to 60 mph in 4 s.

The high level of redundancy and multiple layers of battery protection in the Tesla roadster proved safe to be used in cars. The battery pack of the Tesla is 900 pounds in weight and there is a cooling system to constantly keep the lithium battery at optimum temperature. In 2011, the group received a US government loan guarantees and huge collaborations with the German auto manufacturer Daimler to produce a pure electric Sedan. As of 2009 the Sedan model was nearly $49,000 which was less than the Tesla roadster ($109,000) but very speedy. Tesla has made remarkable progress between 2009 and 2016. Today prices for Tesla cars vary between $80,000e1,300,000 depending on the size of the battery and the model. The company currently produces model S and model X. It also comes with autopilot capabilities designed to make highway driving safer and stress free.

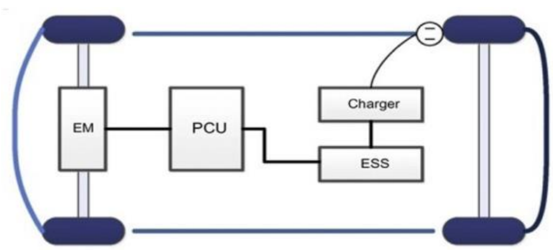

Figure 3. Drive train schematic diagram of BEV's.

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 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. 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 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, by minimizing the maximum of the set of

$$\left\{ \left| w_B - a_{Bj} w_j \right|, \left| w_j - a_{jW} W_W \right| \right\}$$

the formulation to find the solution becomes:

$$\min max_j \left\{ \left| w_B - aBjwj \right|, \left| w_j - ajWwW \right| \right\} \text{s.t:}$$

$$\sum_j w_j = 1$$

$w_j \geq 0$, for all j

This can be translated into the following linear programming problem:

min ζL s.t:

$$wB - a_{Bj} w_j \right| \leq \zeta_L, \text{ for all } j \left| w_j - a_{jW} w_W \right| \leq \zeta_L, \text{ for all } j$$

$$\sum_j w_j = 1$$

$w_j \geq 0$, 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 ζ^*. The closer to zero ζ^* 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 So Sci 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.

VI. RESULTS

We found 11 factors from the framework by Van de Kaa et al. 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.
	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.
	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.
	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.
Strategy	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.
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.

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 $\zeta *$ 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 2. 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 2. 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

VII. 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.

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. BEVs face challenges in range, i.e. battery capacity, and long charging times. 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 (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.

VIII. CONCLUSION

CR networks face unique security problems not encountered by conventional wireless networks. In this paper a novel authentication protocol for CR networks, *CoG-Auth*, has been proposed by taking into account the security threats and constraints of the CR devices. The protocol is implemented using RSA/AES and its performance is analyzed and compared with the standard IEEE 802.16ePKMv2. It is found that *CoG-Auth* is secure and efficient enough, and gave better results for several performance indicators such as authentication time, successful authentication and transmission rate. The *CoG-Auth* also fulfils the fundamental security requirements, does not require the provision of any resource enriched base station or CAs, thus enabling it to be applicable to both Infrastructure an ad hoc CR network.

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