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Residential grid storage technology battles: a multi-criteria analysis using BWM

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ABSTRACT

This article focuses on the battle for dominance between various battery technologies in the residential grid storage market (< 10 KWh) in the context of residential energy systems and the related home energy management systems. We focus on five major battery technologies that are available in the market (lithium-based batteries, lead-based batteries, flow batteries, nickel-based batteries, and sodium-based batteries). Based on a literature review and expert interviews, we study the factors for technology success in the residential grid storage market. By applying the best worst method (BWM), we assign the relative importance to the factors and predict which technology will have the highest chance of achieving success. We compare this to the technology that now has the highest market share and conclude that BWM is a useful method to indicate technology dominance in this market.

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Batteries; platforms; dominant designs; standards; grid storage market; electric energy storage; battery management systems; best worst method; BWM

1. Introduction

The energy transition encompasses four trends: de-carbonization towards a low carbon energy system; decentralisation steered by technology developments; electrification of transportation, heating, and industrial processes; and, digitisation as changes are all facilitated by information technology. Digitisation pertains to the fourth industrial revolution caused by cyber physical systems that also impact the energy sector. Residential energy systems are prone to this transition; the future home energy system can be characterised by electrification (electric automotive and reversible heat pumps) and home energy management systems governing the domestic energy system. These residential energy systems encompass the integrated governance of charging/discharging electric cars, space/tapwater heating and electric equipment for both usage and generation. It is estimated that in the Western world residential electricity usage can increase more than three-fold while feed-in, e.g. by solar PV can increase substantially. The result may be that the capacity of the current electricity distribution networks may not be sufficient, leading to a possible overload and thereby to instability. Thus, instability in the power grid is a major concern. The impetus by renewable energy sources, such as wind and solar, is growing due to sustainability concerns. These sources of energy, unlike traditional sources, are intermittent and discontinuous leading to substantial power fluctuations; the sun does not always shine and the wind does not always blow. In addition, wind and solar have a high simultaneity factor, e.g. when solar PV systems produce power, they all do this at the same time. A similar reasoning applies for charging electric vehicles and using heat

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pumps for space heating, both in the residential and utility domain. Therefore, both electricity generators, wind and solar, as well as large loads, electric vehicles and heat pumps, share the simultaneity factor leading to possible overload of the distribution network. Demand and supply management can prevent network overload. Demand management involves shifting large loads in time by use of energy management systems. Supply management involves shifting generation in time in which storage plays a major role - solar power generated midday can be stored for later use in the evening. Storage is thereby the tool to solve the intermittency issue by decoupling generation and usage. If this storage is utilised locally in combination with PV or small scale (urban) wind, this may circumvent network enforcement. With the expected downwards development of battery technology costs, this can be cheaper than enforcing the network, leading to a larger capacity grid to cope with overload (Quoilin et al. 2016; Bloomberg 2017; Hemmati and Saboori 2017; Xiaohua et al. 2017). Storage is therefore seen as a solution to intermittency because the combination of storage and renewable electricity sources allows control identical to traditional fossil fuel based electricity sources. Thus, to include intermittent renewables into the energy system, it is imperative to incorporate storage systems at various levels in the grid, from residential homes up to mid voltage substations, so to establish required stability of the grid. Indeed, batteries are increasingly combined with PV installations and are becoming commercially available for residential applications (Mulder, Ridder, and Six 2010; Cucchiella, D'Adamo, and Gastaldi 2016). Such grid storage systems cannot only improve grid stability in case of intermittency, but can also reduce load on the grid during peak hours by local feed-in as described above, which requires smart grid functionality for supply and demand control. The paramount component of these grid storage systems is the battery.

Currently five major battery technologies are available: lithium-ion batteries, lead-based batteries, flow batteries, nickel-based batteries, and sodium-based batteries. Which of these battery technologies will become the standard battery technology incorporated in the residential energy system of the future, hence the (residential) grid storage market? These battery technologies are in different stages of development. The lithium-ion technology seems to be gaining ground for residential storage applications mainly as spin-off from the lithium-ion automotive batteries. However, other battery technologies may better fit the energy characteristics associated with intermittent PV and residential load profiles. Sodium-based batteries (or other concepts), once further developed, may be an alternative for residential applications from a techno-economic perspective. Thus, battery technologies are vying for market dominance, and therefore, may be involved in technology battles (Suarez 2004). Several scholars have studied these battles for other purposes and have developed frameworks to explain their outcome (Gallagher and Park 2002; Suarez 2004). Few studies provide an understanding of the relative importance of factors that lead to technology dominance (Van de Kaa, De Vries, and Rezaei 2014; Van de Kaa, Kamp, and Rezaei 2017). We aim to close this gap. The objective of this paper is to explain the outcome of the battery technology battle in the grid storage market. We aim to assign weights to factors for technology dominance for battery technologies and to predict which technology has the highest chance of achieving market dominance. By doing so, this paper adds to the growing body of literature which focuses on technology battles.

2. Theory

Battles for dominance between different technologies emerge from time to time (Shapiro and Varian 1999). Various technology battles have been studied and attempts have been made to explain their outcome (Gallagher and Park 2002). These studies have been conducted from multiple perspectives and disciplines.

Network economists focus on market mechanisms like learning effects and the existence of network externalities and switching costs which indirectly affect technology dominance. Network externalities refer to the notion that technologies increase in value the more consumers adopt them (Katz and Shapiro 1985). These scholars acknowledge the importance of accumulating an installed user base as, under the influence of network effects, this can lead to technology dominance. Such network externalities can result in winner takes all situations due to lock-in effects. Switching costs, either in terms of financial investments, time investments, or learning effects can lead to lock-in effects, and this makes it difficult to shift to an alternative technology. An example is the QWERTY keyboard layout format. Switching costs in the form of learning effects are so high that users cannot easily switch to alternative more easy to learn formats such as DVORAK (David 1985).

Various technology management scholars have focused on technology battles in markets with network effects. These scholars emphasise that, ceteris paribus, the technological superior alternative will have a higher chance of achieving success. However, there are also other factors at play. Technology management scholars emphasise the importance of an installed user base (Shapiro and Varian 1999) and study factors affecting it. First, markets in which network effects are apparent are generally accompanied with complementary goods (such as video games). Availability of a higher number of complementary goods can positively affect installed user base and this also works the other way around (Schilling 2002). Firms should therefore have close cooperation with suppliers of such goods. (Backwards) compatibility with a previous generation can also increase technology success as firms can tap into a (previous) installed base (Van de Kaa, Van den Ende, and De Vries 2015). Besides, in the literature it has been argued that technologies that are more flexible can better adapt to changing user requirements and will become more successful (Van de Kaa et al. 2011).

Scholars also emphasise strategic maneuvering to attempt to increase installed base (Suarez 2004). By pursuing marketing campaigns perceived installed base can be manipulated. By entering comparatively early, firms can pre-empt scarce resources, such as complementary goods, which can put other competitors at a disadvantage by stalling their speed of development (Suarez 2004). Then, a firm can develop an installed base at an early stage. Furthermore, A penetration pricing strategy can be applied whereby the product is offered to users at a low cost to increase adoption rate (Van de Kaa et al. 2011). For these strategies to work, firms should possess complementary resources such as financial resources (Gallagher and Park 2002). Reputation and credibility can help a firm develop its installed base relatively quickly, while operational supremacy (in terms of e.g. production capacity) can allow the firm to efficiently utilise its resources, thereby reducing production costs. Of course, if a large demand arises, a proper distribution system should be in place. Furthermore, by employing a proper learning strategy (e.g. whereby firms learn from previous mistakes), firms can increase the chances of achieving technology success (Van de Kaa et al. 2011). Finally, sometimes, a large company or regulatory institution will en masse adopt a technology. When such a big fish adopts the technology, the technology might gain dominance instantly.

Scholars have proposed multiple frameworks for studying technology dominance (Gallagher and Park 2002; Suarez 2004). However, most of these frameworks have not been applied to empirical cases of technology battles. We apply the framework that was developed by Van de Kaa et al. (2011), which has been successfully applied to various cases (Van de Kaa, De Vries, and Rezaei 2014; Van de Kaa, Kamp, and Rezaei 2017). This framework consists of 29 factors for format dominance categorised into five categories, namely, characteristics of the format, characteristics of the format supporter, format support strategy, other stakeholders, and market characteristics (Van de Kaa et al. 2011). The characteristics of the format (such as its technological superiority or the compatibility that it guarantees) are important for the chances that the format gains success. The characteristics of the format supporter are important and include complementary assets such as financial resources or reputation of the companies involved in the development and promotion of the technology. Such assets can be used to pursue a format support strategy such as a penetration pricing strategy or a timing of entry strategy. Also, other stakeholders often have an influence on the outcome of the technology battle, for example, a regulator can enforce a technology on the market. Finally, market characteristics such as network effects moderate the influence of firm level factors such as installed base. This paper takes a comprehensive approach based on the framework developed by Van de Kaa et al. (2011). We build on this framework by concentrating on the 23 firm level factors.

3. Battery types

A boundary condition for residential battery storage is the presence of decentral electricity generation sources such as PV, urban wind or micro CHP (Combined Heat and Power, a heating boiler that generates electricity by a Stirling engine of a fuel cell). Unfortunately, these sources generate electricity steered by time dependent events: PV and urban wind are driven by solar irradiation, and micro CHP systems are driven by seasons and daily temperature effects. From an electricity production perspective, these sources are intermittent. They often generate more electricity than is required in residential dwellings, and the surplus is then fed into the network. The simultaneity of these sources may then lead to grid overload due to feed-in. From a market perspective, the electricity fed back into the network may suffer from economic disadvantages: the feed-in price may be substantially lower than the supply price. This affects the yield on investments in PV/urban wind and micro CHP, resulting in longer pay back times. Local storage of surplus electricity thus maximises the yield on investments in PV/urban wind and micro CHP. This then gives ground to the development of a residential grid storage market for batteries. The emergence of such a market is further supported by the rapid development of automotive batteries, this leads to lower costs expressed in the price per kWh storage capacity.

We provide a brief introduction to the battery technologies available in the market, and discuss their advantages and disadvantages. It must be noted that these technologies are in various stages of development. Some technologies are already in widespread use (in other markets), whereas others have just recently been developed. This brings along various advantages and disadvantages for the technologies. For example, technologies that are in widespread use have a large installed base in other markets and people are thus more familiar with them, whereas newer technologies are technologically more advanced. However, no dominant technology has yet emerged for home energy management systems, and therefore each of the technologies could become dominant. Because these technologies are competing in the home energy management market, we assume that they are involved in a technology battle.

3.1. Lithium-Ion batteries

Lithium-ion batteries use lithium, the lightest metal available, as its primary material. This choice was very logical in the effort to reduce battery weight while improving power weight density. The foundation of the lithium-ion battery technology was first discovered by John Goodenough of the University of Texas in 1989 (Manthiram and Goodenough 1989). Lithium-ion batteries can be divided into two groups: lithium iron phosphate (also known as lithium ferrophosphate or LFP) batteries and metal oxides. Low weight, high energy density, high conversion efficiencies, and long cycle life are all favourable characteristics offered by lithium-ion batteries. But these batteries have the higher per kWh cost compared to all other batteries, are sensitive to both low and high temperatures, and may suffer from short lives (usually two to three years) at high discharge depths. However, research to solve issues like lifetime and discharge depths is making substantial progress. Specifically, complex metal alloy chemistries allow lithium-ion systems to be designed for specific charge/discharge profiles with longer lifetime up to a few 1000 cycles.

3.2. Lead-acid batteries

Since its development by Gaston Plante in 1859, the main components of the lead–acid batteries have remained consistent over the last 150 years. Recent developments on gel-type cells and absorbed glass-matt systems (valve regulated lead–acid batteries) have led to substantial improvements. Due to technology maturity, low production costs, low maintenance costs, proven reliability, and well-established distribution systems, lead–acid batteries are found ubiquitously within the technological field. However, their bulky size, heavy weight, and lack of operational data has meant that these batteries have not been widely applied in grid storage (Energy 2013). As they are losing ground to lithium-ion, the Advanced lead–acid Battery Compendium has set up research programmes to improve their performance (Blackman 2016).

3.3. Sodium-based batteries

Sodium-based batteries employ electrodes made of sodium compounds for electricity storage. They provide an attractive option for large-scale application as sodium is readily available at low cost. Sodium-based batteries have lower production costs than lithium-ion batteries, but they have lower energy weight and volume density, higher recharging time, and require high temperatures for optimal working, and have therefore not been widely adopted (Forum 2012). However, recent research shows that sodium-based battery chemistry may well outperform lithium-ion battery systems (Braga et al. 2017; UTnews 2017).

3.4. Flow batteries

Flow batteries provide electric storage functionality by using ion exchange between two electrolytes separated by a membrane with electrodes inserted in it. The capacity of the battery depends on the amount of electrolyte in the tanks and hence can be customised to provide any amount of electric power. Their life is not affected by the recharge-discharge cycles and they therefore provide a long cycle life. Various kinds of redox flow batteries are available, depending on the electrolytes used or the techniques used such as redox or hybrid types. These batteries have quite low energy density compared to lithium-ion batteries. However, the technology is very mature and they have fast charge and discharge times. Flow batteries can be built for very high power capacities, up to several MWs, making them suitable for network balancing, but less suited for residential applications.

3.5. Nickel-based batteries

Nickel-based batteries have been in the market for more than 50 years, with nickel metal hydride (NiMH) batteries being the most common configuration. Although research into NiMH batteries began in late 1960s to remove the toxicity issues with nickel cadmium batteries, (NiCd) the technology was not developed until the 1980s. NiMH and NiCd batteries are simple in technological structure, they are relatively inexpensive, recharge fast, and have a low operating temperature. However, they have high toxicity (though mild in case of NiMH), and low energy density compared to lithium-ion.

4. Methodology

4.1. Best worst method (BWM)

Multi-criteria decision analysis (MCDA) is used for analyzing a decision when there are multiple criteria involved. Explaining which factors (criteria) will affect the outcome of the battle between specific battery technologies in a grid storage market is a multi-criteria decision analysis (MCDA). This is because multiple factors contribute to the dominance of battery technologies, which is further compounded by the presence of multiple battery technologies. Multiple methods exist for solving these MCDA problems such as the Best Worst Method (BWM), Analytic Network Process (ANP), and Analytic Hierarchy Process (AHP). In this study, we use the BWM mainly due to its structured way of collecting data, its high reliability, and its high efficiency with respect to the amount of data needed, promising supporting philosophy and finally user-friendliness. BWM uses pairwise comparison to find weights of the criteria involved. It is a robust, vector-based method, which requires fewer comparisons (2*n*-3) compared to the other matrix-based methods such as AHP (n (n-1)/2) (Rezaei 2015). BWM is also easier to use and more reliable compared to other methods. It has been successfully applied in various fields such as supply chain management (Rezaei, Wang, and Tavasszy 2015; Rezaei et al. 2016), water resource management (Chitsaz and Azarnivand 2016), and innovation and technology management (Gupta and Barua 2016). In this study, the BWM is applied to assess the importance of factors for technology success for battery types in the residential grid storage market.

The following steps are involved in the BWM for deriving weights (Rezaei 2015; Rezaei 2016).

1. Set the criteria for decision analysis. In this step, the decision-makers/experts identify the criteria important for decision analysis, denoted by c_j, $j = 1, \ldots, n$.
2. Identify the most important/most desirable criterion (best, denoted by *B*), along with the least desirable/least important (worst, denoted by *W*).
3. Express the preference of the Best over all the other criteria using a number from the range 1 to 9, where 1 means the Best is as preferred as the other criterion and 9 means that the Best is extremely preferred to the other criterion. This results in a vector which is termed as Best-to-Others vector (BO).

$$BO = (a_{B1}, a_{B2}, \ \ldots\ldots, \ a_{Bn}) \tag{1}$$

4. Express the preference of all the criteria over the Worst using a number from the range 1 to 9, where 1 means the criterion is as preferred (as important) as the Worst and 9 means that the criterion is extremely preferred (more important) to the Worst. This results in a vector which is termed as Others-to-Worst (OW) vector.

$$OW = (a_{1W}, a_{2W}, \ \ldots., a_{nW})^T \tag{2}$$

5. Calculate the optimal weights. The optimal weights can be obtained solving the following linear optimisation problem, which finds the weights such that the maximum deviation of the pairwise comparisons and their corresponding weight ratios (for all *j*) is minimised.

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

s.t.

$$\sum_j w_j = 1, \qquad w_j \geq 0, \ \text{for all } j. \tag{3}$$

The minmax model (3) is transferred to the following linear programming problem:.

$$\min \xi^L$$

s.t.

$$\begin{aligned} &|w_B - a_{Bj}w_j| \leq \xi^L, \quad \text{for all } j \\ &|w_j - a_{jW}w_W| \leq \xi^L, \quad \text{for all } j \\ &\sum_j w_j = 1 \\ &w_j \geq 0, \ \text{for all } j \end{aligned} \tag{4}$$

By solving this problem, the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ and the optimal objective function value ξ^{L^*} are found, which is defined as the consistency indicator of the pairwise comparison system. The closer ξ^{L^*} to zero, the more consistent the pairwise comparison system and the more reliable results.

4.2. Data collection

To explore the factors that affect technology success in the residential grid storage market and to determine which technology will have highest chance of achieving success, we used a three-step process (see Figure 1).

In the first step, we assess which factors of the framework developed by Van de Kaa et al. (2011) are relevant for our case by conducting a literature study and conducting one expert interview (expert 1). The interview in the first round was open ended and it was thus possible for the interviewee to suggest additional factors than the ones mentioned in Van de Kaa et al. (2011). The interview ended with a discussion of the framework of Van de Kaa et al. (2011), in which the interviewee assessed the relevance of each factor. A factor was deemed relevant when it was mentioned by the expert or was mentioned in the literature. The results of the literature study that was used for step 1 are available upon request.

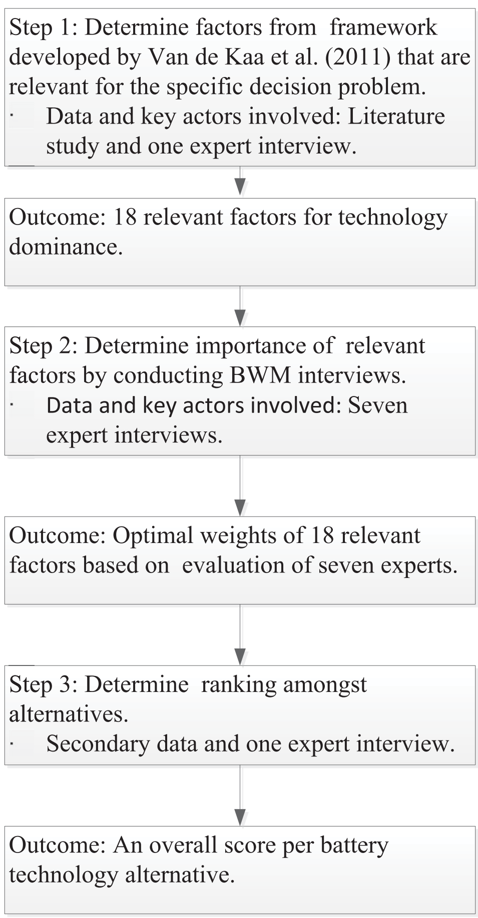

Figure 1. A three-step data collection process.

Table 1. Characteristics of interviewees.

Expert	Background	Function	Expertise
1	Academia and Industry	Energy sector consultant and researcher	Battery Technology and applications, active participant in development of grid storage processes.
2	Industry	Chairman of the board of a company in the area of renewable energy technology	Battery technology, micro grid storage.
3	Academia	Post doc researcher, technical university	Use of domestic battery storage to optimise electricity network design.
4	Industry	Consultant, institutional design of energy systems	Domestic storage supporting energy transition, institutional economics.
5	Industry	Head of CIO office at Distribution Network Operator	Operational impact domestic battery storage.
6	Academia and Industry	PhD candidate	Renewable energy systems, role local storage, institutional economics.
7	Industry	Innovation officer at a Distribution Network Operator	Impact of battery storage on electricity network investment strategy.

In the second step of our research, we developed a structured questionnaire using the BWM to analyze the relative importance of the factors shortlisted in the first stage. We conducted seven semi-structured interviews using the questionnaire mentioned above. We interviewed both researchers and practitioners who could be considered objective outsiders, in other words, they did not favour one technology. This decreased the chances that they would have a bias for one technology. We also made sure that the experts had comprehensive knowledge of the topic. The characteristics of the interviewees are shown in Table 1.

We analyze the data obtained from the questionnaire using the BWM. The results of BWM calculations are the optimal weights of the relevant factors based on the evaluation of the experts.

In the third step (to establish a ranking amongst alternatives), we compare alternatives on the basis of factors by either using readily available information through secondary sources or by interviewing expert 1. We relied on company websites to determine the values for the factors financial strength, brand reputation and credibility, operational supremacy, and learning orientation. For example, company websites were used to evaluate the financial resources available to the supporters of the technologies as well as their reputation so as to assess the values for those factors. Also, we relied on http://batteryuniversity.com, and on https://techxplore.com to determine the value for the factor technological superiority, on https://www.solarquotes.com.au to determine the value for the factor complementary goods, on websites including https://en.wikipedia.org and an expert interview for the factors pricing strategy and timing of entry, on https://www.solarquotes.com.au to determine the value for the factor suppliers, on the report written by Gibson (2016) and on expert interviews to determine the value for the factor previous installed base. We relied on expert 1 to determine the value for the factors financial strength, brand reputation and credibility, operational supremacy, learning orientation, compatibility, flexibility, marketing communications, commitment, distribution strategy, current installed base, big fish, and network of stakeholders. We asked the expert to grade the alternatives from very low (2) to very high (8). This way we have a performance matrix, each row of which shows the performance of one battery with respect to all the factors. From the BWM analysis we obtained the weight of the factors. If we multiply the performance matrix by the weight vector, we come up with an overall score per battery technology based on which we can rank the battery technologies.

5. Results

The secondary data analysis and the expert interview resulted in four categories consisting of 18 relevant factors. For the case of battery technologies, we can distinguish characteristics of the format supporter (consisting of financial strength, brand reputation and credibility, operational supremacy and learning orientation), characteristics of the format (consisting of technological superiority, compatibility, complementary goods, and flexibility), format support strategy (consisting of pricing strategy, timing of entry, marketing communications, distribution strategy, and commitment), and other stakeholders (consisting of current installed base, previous installed base, big fish, suppliers, and network of stakeholders).

5.1. Weights of categories and factors for format success

Table 2 presents the weights of the categories and factors. The categories and their weights are presented in the first and second column. The underlying factors and their local weights are presented in the third and fourth column. The global weights[1] of each factor are shown in the last column.

5.1.1. Interpreting category weights

Our results show that the characteristics of the format is the most important category while the format support strategy is one of the least important ones. According to the interviewee, ' … if the product is really something customers want to buy that fits a specific purpose then the strategy is irrelevant … '. This can be seen in the case of the batteries. Although the lead-acid battery entered the market earlier and is cheaper than the lithium-ion battery the latter is more dominant due to its technological superiority, expressed in both its volumetric and gravimetric energy density, caused by massive research investments from the automotive industry. The lithium-ion battery also has superior characteristics for specific mobile applications, e.g. for mobile equipment (smart phones and laptops). In addition, the current generation of lithium-ion batteries have good characteristics for residential grid storage: a long lifetime of up to 8000 cycles, which leads to more than 20 years of use in a residential application (based on interviews by authors with home battery system providers).

5.1.2. Interpreting global weights of factors

From Table 2 we can conclude that technological superiority is the most important factor for technology success. High energy density, long life time expressed in a high number of charge/discharge cycles (up to 8000 in newer systems), high depth of discharge (down to a state-of-charge of 10%), are attributes of technological superiority. Specifically, lithium-ion has a best fit to domestic electricity usage, very low baseload (fewer than 100 Watts) with exceptional high load excursions (e.g. simultaneously running a water boiler and an oven that may rise to 5 kW load onto the network).

Table 2. Weights of categories and factors.

Category	Weight	Factors	Local Weights	Global Weight
Characteristics of the format supporter	0.196	Financial strength	0.184	0.036
		Brand reputation and credibility	0.229	0.045
		Operational supremacy	0.452	0.089
		Learning orientation	0.135	0.027
Characteristics of the format	0.513	Technological superiority	0.536	0.275
		Compatibility	0.184	0.095
		Complementary goods	0.145	0.074
		Flexibility	0.135	0.069
Format Support Strategy	0.178	Pricing strategy	0.414	0.074
		Timing of entry	0.190	0.034
		Marketing communications	0.162	0.029
		Commitment	0.104	0.019
		Distribution strategy	0.130	0.023
Other Stakeholders	0.111	Current installed base	0.177	0.020
		Previous installed base	0.383	0.043
		Big fish	0.187	0.021
		Suppliers	0.120	0.013
		Network of stakeholders	0.132	0.015

According to one interviewee 'high storage capacity' and 'high voltage' – both attributes of technological superiority, are the most important parameters for battery technology. Gibson (2016) mentions that 'Lithium-ion's high energy densities, both by volume and mass, have made it the chemistry of choice'.

Compatibility (with the various invertors and battery management systems in the market) is the second most important factor. The physio-chemical characteristics of lithium-ion batteries require careful cell management as cells can differ in charge/discharge characteristics. This brought about the need for advanced battery management systems. Compatibility is supported by the standardisation of invertors and battery management systems, and is hence partially related to the installed base criterion.

Looking at the category characteristics of the format supporter, we find that operational supremacy is the most important factor which is directly related to the maturity and controllability of the production process. The growing abundance of lithium-ion in portable equipment (smart phones, laptops, tools) and in the automotive industry (electric cars) has resulted in a rapid improvement in production technology processes. This, in turn, led to a reduction in production costs. Specifically, quality assurance processes are the main drivers for this.

The fourth and fifth most important factors are complementary goods and pricing strategy. Complementary goods concern the earlier mentioned Home Energy Management Systems that are required to optimise battery governance to facilitate battery longevity. Pricing strategy may help introducing residential storage systems as being exemplified by for instance Tesla with its Powerwall.

The sixth most important factor is flexibility. In the literature it has been argued that standards that are more flexible can better adapt to changing user requirements and will become more successful (Van de Kaa, Van den Ende, and De Vries 2015). This also seems to be important in the battle for residential grid storage battery types. Flexibility concerns the size of the battery unit that can be assembled into battery packs if varying geometry that fit the space in domestic dwellings, for example a battery pack sized such that is fits the space in the attic or the basement.

5.2. Comparing the alternatives

In the final phase of our analysis, we rank the battery alternatives. Table 3, shows the evaluation of the five batteries with respect to the various factors, and the final column shows the weights of the

Table 3. Ranking of the battery alternatives.

	Batteries					
Factors	lithium ion	lead–acid	nickel-based	sodium-based	flow batteries	Local weights
Financial strength	8	7	7	3	3	0.036
Brand reputation and credibility	8	7	7	3	3	0.045
Operational supremacy	8	7	7	3	3	0.089
Learning orientation	8	7	7	3	3	0.027
Technological superiority	8	2	6	6	5	0.275
Compatibility	7	7	7	7	7	0.095
Complementary goods	8	2	3	3	3	0.074
Flexibility	7	7	7	3	3	0.069
Pricing strategy	2	8	2	3	5	0.074
Timing of entry	7	8	5	2	3	0.034
Marketing communications	8	7	2	5	4	0.029
Distribution strategy	8	6	4	7	7	0.023
Commitment	9	4	2	8	8	0.019
Current installed base	9	5	3	5	5	0.020
Previous installed base	8	8	5	2	2	0.043
Big fish	9	7	3	5	5	0.021
Suppliers	8	2	3	3	3	0.013
Network of stakeholders	9	4	3	7	6	0.015
Total score	7.430	5.171	5.321	4.510	4.373	

criteria. The multiplication results in an overall score for each battery (final row) which can be used for our ranking purpose.

From the results (Table 3), we can conclude that lithium-ion has the best chance of achieving success (7.430) followed by nickel-based batteries (5.321). Lithium-ion ranks high for all factors except for pricing strategy as it is the most expensive of all alternatives. Nickel-based batteries are distant second. Compared to lead–acid, they have much better storage density, which explains their ascendancy. Although lead-acid is clearly an inferior technology, it comes third mainly because of its incumbent nature. With major companies still involved in the lead-acid battery, it ranks high on the various factors underlying the characteristics of the format supporter and factors underlying the format support strategy, but rank quite low on the characteristics of the format itself. Among the two newer technologies, sodium-based batteries have a slight edge over the flow batteries. Note, however that the BWM is based on a snapshot of the interviewees' opinion. Further development of the sodium-based battery or the flow battery may well result in these two outperforming current lithium-ion systems. One major disadvantage of lithium-ion is fire (or even explosion) hazard caused by dendrite forming in the charge process, and intrinsic property of the fluid electrolytes in lithium-ion batteries. Solid state electrolytes, for instance, in sodium-based systems do not suffer from dendrite forming, but these systems are under development and currently in an embryonic state.

6. Discussion and conclusion

In this paper, we have analysed 18 factors for technology dominance and five technological alternatives available in the market. Our analysis shows that technological superiority is the most important factor for achieving dominance. It appears that, currently, lithium-ion has the best chance of achieving market dominance.

6.1. Theoretical contributions and practical implications

This research contributes to the literature in several ways. First, extant literature claims that the outcome of technology battles is not merely a result of path dependencies, but that factors for technology success are applicable. Although this claim was put forth in earlier research (Schilling 2002; Suarez 2004), empirical evidence that supports the claim is scarce. We provide evidence of the claims for the case of residential grid storage. We show that factors for technology success can be used to explain and predict the outcome of such battles, thus building on earlier research (Van de Kaa, De Vries, and Rezaei 2014; Van de Kaa, Kamp, and Rezaei 2017).

We also apply the BWM method developed by Rezaei (2015, 2016) to a real-life world problem to check its robustness. It appears that the technology that has the highest chance of achieving success according to our method is also the technology that currently is dominant. Although the market for grid storage is still growing, lithium-ion based batteries have a 90% market share in the grid storage sector (Congress 2015; Gifford 2015; Harrop 2016), so it does not seem realistic that the favourable position of lithium-ion will fade anytime soon (Gibson 2016). In fact, currently users might be locked into the lithium-ion battery technology and, then, it is difficult to switch to another technology. This serves as a proof that the BWM method is indeed a useful method and that it can predict technology success.

The outcome of this research can be used by practitioners in various ways. First, we decrease the uncertainty attached to choosing a technology for firms that are currently in the market and that have not yet decided for a certain battery system. We advise these firms to choose for the lithium-ion technology. Furthermore, we recommend newcomers in this market to focus on the factors that have received the highest weights. This may help them to become successful and possibly even overtake the position of the incumbents.

6.2. Limitations and areas of future research

One of the limitations of our study is that it was difficult to find experts with sufficient expertise to participate in the BWM. Future research should continue this research and interview more respondents. We advise a focus on the two newer technologies. Although our results showed that lithium-ion batteries have the highest ranking, one of our interviewees suggested that flow batteries (which have the lowest ranking) could challenge the dominance of lithium-ion batteries in the future (albeit for stationary applications). One reason for this discrepancy is the nature of technology development of flow batteries itself. Currently, flow batteries are inferior to lithium-ion batteries in terms of technological superiority, but this could change in the future. Future research could attempt to explain which of the two newer technologies have the highest chance of achieving success once they are sufficiently mature.

Another limitation is that respondents may have known the outcome of the battle and that this could have resulted in retrospective bias. This retrospective bias may have influenced the results in the direction of the winning technology.

Although our study indicates that the experts think that lithium-ion has the best chance of achieving market success, we cannot say with 100 percent certainty that this will be the outcome of the battle. The technologies could co-exist. Indeed, the numbers in Table 3 are also close together; experts also gave a high ranking to nickel-based and lead–acid. Technologies may co-exist when users gain network externality benefits at lower levels of market share (Schilling 2016). Future research could study whether this is indeed the case in this particular market. If so, the technologies may indeed co-exist.

We believe that the relevance and importance of factors for technology success differs depending on the arena in which the technology battle takes place. We therefore believe it is essential to study factors for technology success for different technology battles. We recommend future research to study more cases using the same or other methods and to apply the framework of Van de Kaa et al. (2011) or other frameworks to various cases of technology battles. Eventually it might be possible to combine new results and prior results and arrive at a framework which can be used to explain and predict technology success for various situations.

Note

1. The global weight of a factor is obtained by multiplying the local weight of that factor by the weight of its corresponding category. For instance, the global weight of financial strength is obtained as follows: Global weight of financial strength = local weight of financial strength * weight of category characteristics of format supporter or: 0.036 = 0.196*0.184.

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No potential conflict of interest was reported by the authors.

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References

Blackman, James. 2016. “Lead Battery Group Calls for Funds to Battle Lithium-ion’s Dominance of Energy Storage Market | Energy Storage News.” *Energy Storage News*.

Bloomberg. 2017. "The Latest Bull Case for Electric Cars: The Cheapest Batteries Ever." https://www.bloomberg.com/news/articles/2017-12-05/latest-bull-case-for-electric-cars-the-cheapest-batteries-ever.

Braga, M. H., N. S. Grundish, A. J. Murchison, J. B. Goodenough, and A. Ginsberg. 2017. "Alternative Strategy for a Safe Rechargeable Battery." *Energy & Environmental Science* 10: 331–336.

Chitsaz, N., and A. Azarnivand. 2016. "Water Scarcity Management in Arid Regions Based on an Extended Multiple Criteria Technique." *Water Resources Management* 31 (1): 1–18.

Congress, Green Car. 2015. "Li-ion Dominating Grid Storage Market with 90% of 2014 Proposals." *Green Car Congress*. http://www.greencarcongress.com/2015/03/20150305-luxgrid.html.

Cucchiella, Federica, Idiano D'Adamo, and Massimo Gastaldi. 2016. "Photovoltaic Energy Systems with Battery Storage for Residential Areas: an Economic Analysis." *Journal of Cleaner Production* 131: 460–474. doi:10.1016/j.jclepro.2016.04.157.

David, Paul A. 1985. "Clio and the Economics of QWERTY." *American Economic Review* 75 (2): 332–337.

Energy, U.S. Department of. 2013. Grid Energy Storage.

Forum, MIT Enterprise. 2012. *Energy Storage for the Grid: Watchful Waiting or the Perfect Storm?* Cambridge. https://www.mitefnorthwest.org/sites/default/files/files/MITEF_NW_Energy_Storage_Companion_Paper.pdf.

Gallagher, S. R., and Seung H. Park. 2002. "Innovation and Competition in Standard-Based Industries: A Historical Analysis of the U.S. Home Video Game Market." *IEEE Transactions on Engineering Management* 49 (1): 67–82.

Gibson, Peter. 2016. "Dawn of the Lithium-Ion Battery Era." *American Society for Mechanical Engineers*. https://www.asme.org/careereducation/early-career-engineers/me-today/dawn-the-lithiumion-battery-era.

Gifford, Jonathan. 2015. "Report: Lithium ion Batteries Dominate Emerging Grid Storage Market: pv-Magazine." *PV Magazine*.

Gupta, H., and M. K. Barua. 2016. "Identifying Enablers of Technological Innovation for Indian MSMEs Using Best–worst Multi Criteria Decision Making Method." *Technological Forecasting and Social Change* 107: 69–79.

Harrop, Peter. 2016. "Lithium-ion Batteries Will Dominate the Battery Business | IDTechEx Research Article." *IDTechEx*. https://www.idtechex.com/research/articles/lithium-ionbatteries-will-dominate-the-battery-business-00009486.asp.

Hemmati, Reza, and Hedayat Saboori. 2017. "Stochastic Optimal Battery Storage Sizing and Scheduling in Home Energy Management Systems Equipped with Solar Photovoltaic Panels." *Energy and Buildings* 152: 290–300.

Katz, Michael L., and Carl Shapiro. 1985. "Network Externalities, Competition, and Compatibility." *American Economic Review* 75 (3): 424–440.

Manthiram, A., and J. B. Goodenough. 1989. "Lithium Insertion Into Fe2(SO4)3 Frameworks." *Journal of Power Sources* 26 (3–4): 403–408.

Mulder, G., F. Ridder, and D. Six. 2010. "Electricity Storage for Grid Connected Household Dwellings with PV Panels." *Solar Energy* 84 (7): 1284–1293.

Quoilin, Sylvain, Konstantinos Kavvadias, Arnaud Mercier, Irene Pappone, and Andreas Zucker. 2016. "Quantifying Self-consumption Linked to Solar Home Battery Systems: Statistical Analysis and Economic Assessment." *Applied Energy* 182: 58–67.

Rezaei, Jafar. 2015. "Best-worst Multi-Criteria Decision-Making Method." *Omega* 53: 49–57.

Rezaei, J. 2016. "Best-worst Multi-Criteria Decision-Making Method: Some Properties and a Linear Model." *Omega* 64: 126–130.

Rezaei, J., T. Nispeling, J. Sarkis, and L. Tavasszy. 2016. "A Supplier Selection Life Cycle Approach Integrating Traditional and Environmental Criteria Using the Best Worst Method." *Journal of Cleaner Production* 135: 577–588.

Rezaei, J., J. Wang, and L. Tavasszy. 2015. "Linking Supplier Development to Supplier Segmentation Using Best Worst Method." *Expert Systems with Applications* 42 (23): 9152–9164.

Schilling, M. A. 2002. "Technology Success and Failure in Winner-take-all Markets: The Impact of Learning Orientation, Timing, and Network Externalities." *Academy of Management Journal* 45 (2): 387–398.

Schilling, M. A. 2016. *Strategic Management of Technological Innovation*. New York: McGraw-Hill.

Shapiro, Carl, and Hal R. Varian. 1999. "The art of Standards Wars." *California Management Review* 41 (2): 8–32.

Suarez, F. F. 2004. "Battles for Technological Dominance: An Integrative Framework." *Research Policy* 33 (2): 271–286.

UTnews. 2017. "Lithium-Ion Battery Inventor Introduces New Technology for Fast-Charging, Noncombustible Batteries." https://news.utexas.edu/2017/02/28/goodenough-introduces-new-battery-technology.

Van de Kaa, G., H. J. De Vries, and J. Rezaei. 2014. "Platform Selection for Complex Systems: Building Automation Systems." *Journal of Systems Science and Systems Engineering* 23 (4): 415–438.

Van de Kaa, G., L. M. Kamp, and J. Rezaei. 2017. "Selection of Biomass Thermochemical Conversion Technology in the Netherlands: A Best Worst Method Approach." *Journal of Cleaner Production* 166: 32–39.

Van de Kaa, G., J. Van den Ende, and H. J. De Vries. 2015. "Strategies in Network Industries: The Importance of Inter-organisational Networks, Complementary Goods, and Commitment." *Technology Analysis & Strategic Management* 27 (1): 73–86.

Van de Kaa, G., J. Van den Ende, Henk J. De Vries, and E. Van Heck. 2011. "Factors for Winning Interface Format Battles: A Review and Synthesis of the Literature." *Technological Forecasting & Social Change* 78 (8): 1397–1411.

Xiaohua, Wu, Hu Xiaosong, Yin Xiaofeng, Zhang Caiping, and Qiand Shide. 2017. "Optimal Battery Sizing of Smart Home via Convex Programming." *Energy* 140 (1): 444–453.