Strategies for the emergence of a dominant design for heat storage systems

Van de Kaa, Geerten

DOI
10.1080/09537325.2021.1884851

Publication date
2021

Document Version
Final published version

Published in
Technology Analysis and Strategic Management

Citation (APA)
Van de Kaa, G. (2021). Strategies for the emergence of a dominant design for heat storage systems. *Technology Analysis and Strategic Management*, *34*(1), 58-70.
https://doi.org/10.1080/09537325.2021.1884851

Technology Analysis & Strategic Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ctas20

Strategies for the emergence of a dominant design for heat storage systems

Geerten Van de Kaa

TECHNOLOGY ANALYSIS & STRATEGIC MANAGEMENT
https://doi.org/10.1080/09537325.2021.1884851

Routledge
Taylor & Francis Group

OPEN ACCESS   Check for updates

Strategies for the emergence of a dominant design for heat storage systems

Geerten Van de Kaa

Faculty of Technology, Policy, and Management, Delft University of Technology, Delft, Netherlands

ABSTRACT

An important component of sustainable home energy systems is the self-sufficient generation and usage of energy. Although sustainable solutions to both generation and usage of energy in homes have been extensively studied in the past, the storage of energy has only scarcely been studied. This paper focuses specifically on thermal energy storage. Three competing designs are currently available: sensible, latent and thermochemical heat storage systems. The question is which will become the dominant design. Relevant antecedents for design dominance are explored and applied to this case in order to determine their weights. Furthermore, it is assessed which of these three alternatives will have the highest chance of achieving market dominance. Technological characteristics are most important and latent heat storage technology has the highest likelihood of achieving design dominance. The paper contributes to ongoing research that attempts to assign weights to factors for technology dominance in different arenas.

ARTICLE HISTORY
Received 15 May 2020
Revised 2 December 2020
Accepted 26 January 2021

KEYWORDS
Dominant designs; strategy; heat energy storage; best worst method

1. Introduction

With the growing awareness of environmental protection and resources conservation over the last few decades, renewable energy sources have gained momentum in the energy systems globally. Despite the recent progress in reducing carbon emissions through adoption of renewables, the intermittency problem of these technologies constitutes a barrier for their wider availability as well as necessitating an effective solution in energy storage. Considering that the renewable energy solutions increasingly gain foothold, the significance of efficient energy storage systems is likely to persist, if not to increase, in the future. Indeed, the rising levels of CO_2 emissions in our atmosphere call for sustainable solutions to try to circumvent the resulting climate change issues. One of the sources of rising CO_2 emissions can be attributed to the buildings in which we work and live. Various solutions for sustainably generating, storing, and consuming energy have been documented and analysed in the literature. The focus in this paper lies on storing energy and, more specifically, on thermal energy storage. Here, various options can be used including sensible, latent and thermochemical heat storage systems.

Thermal energy storage is one of those technologies that promises great potential for storing thermal energy and for balancing the fluctuations in supply and demand caused by the intermittent nature of common renewable energy sources, especially when implemented in decentralised residential applications. Currently, thermal energy storage can be divided into three main categories:

CONTACT Geerten van de Kaa g.vandekaa@tudelft.nl

sensible, latent and thermochemical heat storage (Sharmaa et al. 2009). These categories differ with respect to the underlying principles on how they store thermal energy.

Although it is thus technically possible to realise thermal energy storage systems in buildings, many buildings have not yet implemented such systems and one of the reasons is that a single dominant design has not yet emerged. The phenomenon whereby multiple designs are developed and are competing is referred to in the literature as a dominance battle (Suarez 2004) and may result in a dominant design or de facto standard (Srinivasan, Lilien, and Rangaswamy 2006).

Scholars have come up with various factors that affect the outcome of these battles (Suarez 2004; Gallagher 2012) and that may be used in order to reach an understanding of which of the three alternatives will have the highest chance of achieving market dominance. They focus on factors such as direct network effects which refer to the phenomenon whereby technology increases in value the more it is being used by people (Farrell and Saloner 1985; Katz and Shapiro 1985). They also focus on indirect network effects which occur when the value of a technology increases as more complementary goods get adopted (Katz and Shapiro 1985).

The literature that focuses on battles for a dominant design or de facto standard mostly focuses on the consumer electronics and telecommunications industries because network effects traditionally play a role in these industries. However, with the gradual incorporation of ICT in different systems these systems become smarter and network effects may appear in the accompanying industries. For example, with the incorporation of ICT into the energy grid, two-way communication becomes possible between the nodes of the grid. Consumers can, e.g. exchange energy amongst themselves and large energy companies, and components that generate, store and use energy can become interconnected. Various scholars have shown that in such energy systems, indirect network effects may arise between components that generate energy, store energy and use energy (Heinz, Graeber, and Praktiknjo 2013; Giordanon and Fulli 2012; Bento 2008; Kublia and Ulli-Beer 2016; Kubli and Ulli-Beer 2015). Indirect network effects can for example be observed in electric vehicle and smart meter ecosystems (Giordanon and Fulli 2012) and hydrogen-based energy systems (Bento 2008). For example, for fuel cells that utilise hydrogen the demand for the latter depends on the number of fuel cells sold and, that, in turn, depends on the availability of the former (Heinz, Graeber, and Praktiknjo 2013). Indirect network effects may also be applicable to energy storage systems. For example, Kublia and Ulli-Beer (2016, 2015) emphasise the indirect network effects that are the result of the combination of complementary goods (e.g. solar panels) and the core product (storage technologies). Here, the increase in the availability of solar panels on a roof, increases the utility that one can get from adopting a storage technology. Using a similar argumentation, indirect networks may also apply for heat energy systems as their value may be dependent upon the availability of energy-generating technologies such as solar panels.

A knowledge gap can be identified here with respect to which factors for design dominance are important in these sectors. The main aim of the paper is to investigate the factors which, according to experts, influence the chance that thermal energy storage solutions for residential applications achieve a dominant position in the market and reflect on the findings by applying the best-worst method suggested by Rezaei (2015, 2016). This paper applies insights concerning factors for design dominance (Suarez 2004; Gallagher 2012; Van de Kaa et al. 2011) as a starting point to identify the factors that affect the technology battle under investigation.

This paper raises the question; for the case that is studied and according to key experts: what determinants of design dominance are relevant, what is their importance and which of the three alternative thermal energy storage systems will have the highest chance of achieving market dominance.

The paper can be considered novel and original in various ways. First, it contributes to a range of studies that has attempted to assign weights to factors for design dominance for systems that make up a sustainable home energy system (Van de Kaa et al. 2019; Van de Kaa, Fens, and Rezaei 2019; Van de Kaa et al. 2014). This paper focuses on technology battles for thermal energy storage systems; a case that has not been studied before in the literature. Second, the paper provides further evidence that the BWM can be successfully applied to determine the importance of criteria in a multi-criteria decision-making setting. Third, the paper provides practical implications for the thermal energy storage industry as it attempts to predict the chance of success for the three competing technological principles in residential applications. Gradually, relevance and importance of factors for specific components of the energy management system for homes emerge. Then, the uncertainty attached for firms and policymakers that have to make decisions in that industry decreases as they will have more knowledge on which factors they have to focus on and which solutions will have the highest chance to prevail. Finally, the paper provides a first indication that technological superiority as a factor for a standard's success remains important in the early stages of a technology battle.

2. Literature survey

The topic of technology battles has been studied by multiple scholars in various disciplines. It refers to the phenomenon whereby two or more designs have been developed by firms or other institutions and are available on the market and consumers have to make a decision for one or the other. Famous examples are VHS vs Betamax (Cusumano, Mylonadis, and Rosenbloom 1992) or Blu-ray vs HD DVD (Gallagher 2012). Scholars have mostly focused on the supply side of this phenomenon; the firms that develop and promote the designs. These scholars have come up with factors that might influence the outcome of so-called dominance battles, standards battles, or platform wars (Suarez 2004; Shapiro and Varian 1998; Shapiro and Varian 1999). Some scholars have focused on the demand side. For example, Chou et al. (Chou and Yutami 2014) focus on the reasons why consumers adopt smart meters.

Standardisation scholars that focus on standards battles have shown that technologies that are compatible with other technologies may have an advantage over technologies that do not offer the compatibility (Lee, Lee, and Lee 2003). This compatibility may exist between various technologies (horizontal compatibility) or between various generations of a single technology (vertical compatibility). Also, it has been shown that standards that are flexible have a favourable position (Van den Ende et al. 2012).

Scholars in the area of strategic management have pointed to the importance of characteristics of the supporter of the technology. Financial strength, reputation and credibility, production capacity and learning orientation are key complementary assets which are required to win a battle for a dominant design. Strategy scholars also point to various strategies including pricing, marketing, and timing of entry.

A platform is a concept that is very much related to the concept of a dominant design. Economists that study these platforms often visualise that concept as a two-sided market (Rochet and Tirole 2003). The function of the platform is to connect the supply side with the demand side. Therefore it is also very much related to the concept of an interface or compatibility standard. Examples of platforms include operating systems or video gaming consoles. Often, in two-sided markets, fierce competition occurs between platforms (Armstrong 2006) leading to winner-take-all situations (Hill 1997). Direct and indirect network effects may lead to a single platform that becomes the industry standard (Hill 1997).

Most of these scholars tend to agree on the importance of quickly establishing a sufficient amount of installed base (Shapiro and Varian 1998; Shapiro and Varian 1999). Indeed, because of the existence of the network effects, the platform that achieves a sufficient amount of installed base before its competitors, can pre-empt the market and establish platform success. Suarez (2004) introduces the notion of the technology dominance process. He acknowledges the fact that a technological field matures in various stages and that relevance of factors for technology dominance might change depending upon the stage within that process. He distinguishes five stages from the first idea up until the stage at which competition occurs based upon the dominant technology and assigns factors for design dominance to the separate stages.

Various scholars have attempted to develop all-encompassing frameworks consisting of factors that affect technology success (Suarez 2004; Van de Kaa et al. 2011; Schilling 2002). What these scholars have in common is that they focus mostly on industries that are traditionally characterised by increasing returns to adoption resulting from network effects (Farrell and Saloner 1985; Katz and Shapiro 1985). For example, battles for dominant designs for the various generations of the video gaming consoles (a consumer electronics industry product) are studied by multiple scholars in the literature (Gallagher and Park 2002; Schilling 2003). Other scholars have studied various standards battles for mobile telecommunications (Funk 1998; Funk and Methe 2001). Battles for dominant designs in the energy domain are only scarcely studied (an exception is, e.g. Van de Kaa, Fens, and Rezaei (2019)) but when they are studied, experts deem technological superiority as the most important factor for the dominance of a design. Thus, irrespective of the case that network effects appear to be apparent in these industries (Kubli and Ulli-Beer 2015; Kubli and Ulli-Beer 2016), technological superiority remains crucial. This research aims to contribute to these lines of research. In the remainder of this paper, the framework that was used in prior studies (Van de Kaa et al. 2011) will be applied to the case under investigation as, to date, that framework is the most complete framework with factors affecting design dominance.

3. Thermal energy storage

Thermal energy storage systems store energy, that is generated at a given point in time, so that it can be used when there is demand for it, at a later point in time. This research specifically focuses on the storage of energy in the form of heat. Many solutions are available which can be divided into three main categories, based on rudimental differences in core concepts of the technology. Following prior research in the field, the categories used in this research are sensible, latent and thermochemical heat storage (Sharmaa et al. 2009). This section provides a general overview of these technologies through a short introduction in their fundamental working principles so that the reader will be familiar with the basics of each technology. For more specific details we refer to previously published research (Sharmaa et al. 2009; Sarbu and Sebarchievici 2018).

With sensible heat storage, through raising the temperature of a solid or liquid thermal substance, energy is stored. Water seems to be the best substance to use at temperatures below 100 degrees, while, at temperatures above 100 degrees, preference is given to other materials such as oils (Sharmaa et al. 2009). Sensible heat storage is the most developed of the three technologies, being the only one that offers actual commercial solutions for dwellings (Bortolotti). There are advantages and disadvantages that can be attributed to the use of sensible heat storage. Advantages for using sensible heat storage include that when compared to the other technologies, it is cheaper and it does not make use of toxic materials (Sarbu and Sebarchievici 2018). On the other hand, it requires significantly more space. It may therefore be a solution for rural dwellings or farm buildings, while less practical for urban dwellings.

The principles behind a latent heat storage system are pretty similar to that of a sensible heat storage. The main difference originates from the fact that in these systems a change of phase occurs (e.g. from solid to liquid or the other way around). Although one could think of such a system based on water, usually other substances such as paraffin are used. Prototypes have been developed for this technology (Niyas, Prasad, and Muthukumar 2017). The advantage of incorporating the phase change in the system is the fact that the substance can absorb or discharge heat while the temperature remains almost fixed. The loss of heat thus remains at a minimum. Furthermore, it requires less space when compared to sensible heat storage. However, the price for implementation is higher.

Thermo-chemical heat storage is based on a chemical reaction that takes place in the storage substance. Chemical reactions use the creation or breaking up of molecular bonds either to consume or generate heat energy. The technology is currently researched and prototypes have been developed (Zondag et al. 2013). The technology offers two main advantages over the other two technologies.

First, it requires a smaller storage size and nearly loss-free storage (Donkers 2015). On the other hand, it requires higher upfront investments (Aydinn, Casey, and Riffat 2015).

4 Methodology

To find out which determinants of design dominance are relevant, what their importance is and which of the three alternative thermal energy storage systems are most likely to achieve market dominance (all according to key experts) the study started with identifying the relevant factors for this specific case from the framework of Van de Kaa et al (2011). A literature review was conducted and one expert interview (expert #5 in Table 1) was carried out. Factors mentioned as relevant by either the literature or the expert are considered relevant. The possibility was left open to arrive at other factors than the ones mentioned in Van de Kaa et al (2011). The relevant factors were then used for the second step of the analysis. In this second step, weights were assigned to the factors to evaluate their importance according to 5 experts. All experts have comprehensive knowledge of the case. The characteristics of the experts can be found in Table 1.

To find the weights in the second step, the Best Worst Method (BWM) was applied. BWM is a multiple-criteria decision making (MCDM) method that was developed by Rezaei (2015) and was used in this study to give weights to factors for design dominance. This method is proven to be more reliable by requiring fewer comparison data (Rezaei 2015). The first step is to determine the most important factor and then compare the other factors with that most important factor. Next, the least important factor is determined and the other factors are compared with that factor. This provides a consistency check. For the comparisons, a scale of 1–9 is used.

To derive the weight for the criteria, five steps are followed. First, the criteria that are used will be specified. Second, the best (most important) and the worst (least important) factor is determined. Third, pairwise comparisons are performed. Here, the preference of the best criteria over the other criteria is determined by assigning a number from 1 to 9. 1 means the best criterion B is equally important to criterion *j*, and 9 means the best criterion B is extremely more important than criterion *j*. This results in the Best-to-Others vector:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$$

where a_{Bj} is the preference of best criterion B to criterion *j*. Next, the preference of other criteria over the worst criteria is determined also using a number between 1 and 9. This results in the Others-to-Worst vector:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$$

where a_{jW} is the preference of criterion *j* to the Worst criterion W. Then, optimal weight $(w_1^*, w_2^*, \ldots, w_n^*)$ for the criteria can be determined which will result in optimal weight and ξ^{L*}. ξ^{L*}

Table 1. Interviewee details.

#	Background	Expertise	Function
1	Academia/ Industry	Energy built environment, international cooperation, and renewables.	Programme Manager Energy Built Environment
2	Academia/ Industry	Aquifer thermal energy storage (ATES) technology and subsurface geothermal energy storage systems.	Part-time researcher
3	Academia	Engineering thermodynamics, refrigeration engineering and indoor climate control.	Associate Professor
4	Academia	Energy technology, turbulence, aeroacoustics and numerical simulation.	Chair, Energy Technology a department focusing on Process & Energy
5	Academia/ Industry	Energy market developments and its impact on the organisation and operation of energy companies. Strategic and tactical consultancy in the energy and utilities world.	Senior Research Fellow, Associated Partner

is an indicator of consistency, it shows a better consistency when the number is close to zero. To find the optimal weights ($w_1^*, w_2^*, \ldots, w_n^*$) are found by solving the model as specified in Rezaei (Rezaei 2015):

$$\begin{gathered} \min \xi \\ \text{s.t.} \\ |w_B - a_{Bj} w_j| \leq \xi, \text{ for all } j \\ |w_j - a_{jW} w_W| \leq \xi, \text{ for all } j \\ \sum_j w_j = 1 \\ w_j \geq 0, \text{ for all } j \end{gathered}$$

Finally, experts 1, 3, 4 and 5 rated how each alternative scores on each factor using numbers ranging from 1 to 9 and the average scores per factor were multiplied with the average weights and combined into an overall performance score per alternative. The interviews comprised the completion of the BWM questionnaire. Claims are made based on the results of the questionnaire. To support the claims, a follow up interview was conducted with expert 2.

5. Results

The first study resulted in 20 relevant factors for design dominance divided into 5 categories. The naming of the categories of the original paper (Van de Kaa et al. 2011) was slightly changed to let them fit better with the case under investigation. The first category, characteristics of the technology supporter, includes all aspects that make firms that are supporting a technology outcompete their rivals. This includes their financial and operational resources, reputation, and their learning orientation (e.g. the extent to which they can learn from prior mistakes). The second category; technological superiority, refers to all aspects pertaining to the technology itself that make it superior as compared to alternatives. The literature for this case emphasises the relevance of ‘technological superiority’ in terms of the level of trustworthiness, the safety, and the rate at which energy can be extracted from the device. One expert indicated that, apart from these aspects, a separate aspect ‘capacity’ is relevant and should also be mentioned separately. Since that aspect was not mentioned in the literature and the expert believed that it should be included separately we have done so. This results in a possibility to compare these different aspects that determine technological superiority and it may therefore result in an increased understanding of that particular category of factors. Capacity refers to (1) the absolute storage capacity, or the amount of heat that may be stored in a device and (2) the relative storage capacity or storage density (e.g. the amount of heat that may be stored in a device relative to its volume).

The technology support strategy includes all strategies that may be applied by technology supporters to gain market dominance. This includes pricing strategies (such as pricing below cost to quickly amass market share [Katz and Shapiro 1985]), appropriability strategies, timing of entry into a market, marketing communications and the technology supporter’s distribution strategy. The fourth category contains all (aspects of) stakeholders that are relevant in this arena and that might influence the outcome of the battle. This includes the regulator, suppliers of complementary goods, the effectiveness of the technology development process, and the network of stakeholders. Finally, the fifth category contains the relevant market mechanisms in this arena. For the case of heat energy storage, relevant mechanisms include the bandwagon effect, network externalities, the number of options available, the rate of change and the costs that users incur from switching from one technology to a competing one (switching costs). For a detailed elucidation of these factors the interested reader can refer to Van de Kaa et al. (2011) and Van de Kaa and De Vries (2015).

Table 2. Local and global average weights.

Categories/factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Local average weight	Global average weight[1]
Characteristics of the technology supporter	**0.18**	**0.04**	**0.11**	**0.05**	**0.11**	**0.10**	
Financial strength	0.18	0.05	0.07	0.05	0.18	0.10	0.01
Brand reputation and credibility	0.07	0.52	0.14	0.51	0.05	0.26	0.02
Operational supremacy	0.52	0.31	0.28	0.22	0.64	0.40	0.04
Learning orientation	0.23	0.12	0.51	0.22	0.13	0.24	0.02
Technological superiority	**0.45**	**0.22**	**0.19**	**0.48**	**0.44**	**0.36**	
Trustworthiness, safety, and energy extraction rate	0.83	0.25	0.90	0.25	0.88	0.62	0.22
Capacity	0.17	0.75	0.10	0.75	0.13	0.38	0.13
Technology support strategy	**0.14**	**0.49**	**0.50**	**0.11**	**0.05**	**0.26**	
Pricing strategy	0.45	0.46	0.43	0.17	0.11	0.33	0.08
Appropriability strategy	0.17	0.08	0.10	0.26	0.48	0.22	0.06
Timing of entry	0.13	0.12	0.05	0.04	0.27	0.12	0.03
Marketing communications	0.17	0.30	0.17	0.13	0.09	0.17	0.04
Distribution strategy	0.08	0.04	0.25	0.39	0.05	0.16	0.04
Other stakeholders	**0.05**	**0.13**	**0.05**	**0.09**	**0.29**	**0.12**	
Regulator	0.49	0.52	0.50	0.45	0.22	0.44	0.05
Suppliers	0.26	0.20	0.15	0.23	0.59	0.29	0.04
Effectiveness of the technology development process	0.07	0.20	0.06	0.09	0.10	0.10	0.01
Network of stakeholders	0.18	0.09	0.29	0.23	0.09	0.18	0.02
Market characteristics	**0.18**	**0.13**	**0.14**	**0.27**	**0.11**	**0.17**	
Bandwagon effects	0.47	0.22	0.16	0.43	0.55	0.37	0.06
Network externalities	0.18	0.13	0.24	0.16	0.05	0.15	0.03
Number of options available	0.14	0.13	0.06	0.16	0.17	0.13	0.02
Rate of change	0.07	0.04	0.12	0.07	0.14	0.09	0.01
Switching costs	0.14	0.48	0.42	0.16	0.10	0.26	0.04

The remainder of this section provides the results of the BWM analysis. First, the weights of the relevant factors that are found in our analysis are presented in Table 2; the global average weights provide the importance of the factors according to the experts that were interviewed. From Table 2 it can be concluded that the experts deemed three factors to be especially important; 'Trustworthiness, safety, and energy extraction rate' received a global average weight of 0.22, capacity received a global average weight of 0.13, and pricing strategy received a global average weight of 0.08. The remainder of the factors scored relatively equally high. In order to analyse the reliability of the results, the consistency ratios are shown in Table 3. The closer these ratios are to zero, the higher the consistency level of the model. The model shows consistency ratios that are mostly below 0.20 and the average consistency ratios per category are all below 0.15. The highest consistency ratio in the model corresponds to respondent 5 with a consistency ratio of 0.26 for the category characteristics of the technology supporter. Overall it can be concluded that data collected are consistent and reliable.

In the final step of the analysis, experts ranked the alternatives in thermal energy storage technologies (see Table 4). The experts favoured latent heat storage with an overall highest score of 5.33.

Table 3. Consistency ratio results.

	Expert					
	1	2	3	4	5	Average
Categories	0.09	0.16	0.07	0.07	0.19	0.12
Characteristics of the technology supporter	0.18	0.10	0.05	0.15	0.26	0.15
Technological superiority	0.00	0.00	0.00	0.00	0.00	0.00
Technology support strategy	0.06	0.14	0.07	0.13	0.07	0.09
Other stakeholders	0.04	0.07	0.08	0.02	0.08	0.06
Market characteristics	0.08	0.17	0.07	0.06	0.14	0.10

Table 4. Ranking of alternatives.

	Sensible heat storage		Latent heat storage		Thermochemical heat storage	
	Performance score[2]	Weighted score**[3]	Performance score	Weighted score	Performance score	Weighted score
Characteristics of the technology supporter						
Financial strength	4.25	0.04	5.5	0.06	5.75	0.06
Brand reputation and credibility	4.25	0.11	4.25	0.11	4.25	0.11
Operational supremacy	5.25	0.20	5.5	0.21	5.5	0.21
Learning orientation	4.25	0.10	5.5	0.13	5.25	0.12
Technological superiority						
Trustworthiness, safety, and energy extraction rate	4.5	1.00	5.75	1.28	4.5	1.00
Capacity	2.75	0.37	6.25	0.84	4.75	0.64
Technology support strategy						
Pricing strategy	6.5	0.54	5	0.42	4.5	0.38
Appropriability strategy	4	0.22	5.75	0.32	6.75	0.38
Timing of entry	6.25	0.20	5.75	0.18	3.75	0.12
Marketing communications	5.25	0.23	5	0.22	5	0.22
Distribution strategy	5.75	0.24	5	0.21	4.5	0.18
Other stakeholders						
Regulator	5.5	0.29	5.5	0.29	4.5	0.24
Suppliers	6	0.21	5	0.18	4	0.14
Effectiveness of the Technology development process	5.5	0.07	4.5	0.06	4.75	0.06
Network of stakeholders	5.5	0.12	5	0.11	5.75	0.12
Market characteristics						
Bandwagon effects	3.75	0.23	3.75	0.23	5.5	0.34
Network externalities	2.5	0.06	2.75	0.07	4.5	0.12
Number of options available	3.75	0.08	3.25	0.07	5.25	0.12
Rate of change	3.5	0.05	4.75	0.07	4.25	0.06
Switching costs	4.75	0.21	6.5	0.28	4.75	0.21
		4.58		5.33		4.82

6. Discussion

6.1. Interpretation of the results

The importance of 'pricing strategy', 'Trustworthiness, safety, and energy extraction rate' and 'capacity' of thermal energy storage systems can be positioned in the literature as follows. First, concerning pricing strategy, network economists have argued that this is one important element of strategic manoeuvring during dominance battles (Katz and Shapiro 1986). For example, earlier research has shown that strategically pricing a product below its cost (penetration pricing) will increase market share (Katz and Shapiro 1985). These observations have mostly been done in consumer electronics and ICT industries. This paper suggests that they are also applicable to the residential energy context. One expert clarified the importance of pricing by pointing to the important role that consumers play in this particular battle. He argued:

> if you [consumers] have to buy a system it seems logical to me that price plays an important role. You need to have the money or you need to be able to borrow at cheap rates to purchase a certain system.

Both elements that determine the technological superiority of thermal energy storage systems are also important. Earlier research has shown that technological superiority is especially important in the early stages of the technology dominance process (Amankwah-Amoah 2016); this paper confirms that research as the battle is currently located in these early stages. As one expert noted: 'if you store heat, you also want to recover as much of it as possible, especially if that heat is not for free'. Experts rated capacity as one of the most important factors in this particular battle. As one expert noted:

we simply need a lot of heat in winter. Heat storage in sensible, latent or chemical systems takes up a lot of space. Land in cities is expensive, so technologies that have a high capacity and take up little space are desirable.

From Table 4, it can be inferred that, with the highest overall score of 5.33, latent heat storage technology has the highest chance of achieving technology dominance for heat energy system technologies. That technology, in fact, achieved the highest average performance score for the two most important criteria for design dominance, namely technological superiority and capacity. However, the sensible heat storage technology might very likely challenge the advantageous position of latent heat storage technology in the technology battle as it scores considerably higher in pricing strategy; another importance factor.

In fact, a closer examination of the data reveals that the technology battle is far from being an open-and-shut case, and each alternative possesses a chance of becoming the dominant technology; the total scores of each technology were found relatively close to each other meaning that we could also infer that, currently, three designs are co-existing and each of these designs thus still has a chance to become the de facto standard in the market. Situations in which multiple designs co-exist often can be observed in markets where network effects are either non-existent, extremely low or in situations where customers attain a desired level of benefits accruing from network effects at lower market share levels (For example, for video gaming consoles, there are sufficient number of complementary goods (games) available for each console and a sufficient number of people to play the games with) (Schilling 2020).

In smart grids, indirect network effects can be observed more and more (Heinz, Graeber, and Praktiknjo 2013; Giordanon and Fulli 2012; Bento 2008; Kublia and Ulli-Beer 2016, 2015). As argued before, it may be the case that these effects are also apparent for the systems that are studied in the current paper. Then, according to the extant literature on network effects, it could be the case that a single dominant design would emerge for these systems (Farrell and Saloner 1985; Katz and Shapiro 1985). On the other hand, all technologies are still in the first stages of the technology dominance process (Suarez 2004). An early front runner has not appeared and, therefore, a single dominant design has also not yet emerged in this market; the technology battle has not yet really started. It is at this stage that the technology battle gradually will take off and actors involved can still affect its outcome. For example, radical innovation for thermo chemical heat storage might result in a better technological performance in terms of, e.g. the capacity of the solutions utilising that particular design. This together with a drop in the overall cost to invest in this technology may lead to a significant increase in the performance score of thermo chemical heat storage systems over the competing designs. That might lead to that design becoming dominant. Alternatively, these technologies might find their own unique applications and niche markets and may continue to co-exist. There are various examples, such as in the video gaming industry (Gallagher and Park 2002), where designs co-exist as they have found specific niches in the market.

6.2. Theoretical contributions, limitations and practical implications

The main theoretical contribution of this paper to the existing literature on technology battles is that it applies factors for design dominance on the selection of heat energy storage technologies; a case that has never been studied using factors for technology success. Where evolutionary economists state that the establishment of dominant designs is a path dependent process this paper provides evidence that this process can in fact be modelled and that factors for the establishment of dominant designs can be determined; thereby a contribution is made to the existing literature in which this is stated and shown (Suarez 2004; Schilling 2002; Van de Kaa et al. 2017). More specifically, the paper contributes to the ongoing research that attempts to establish weights for factors for technology success in the residential realm (Van de Kaa et al. 2019; Van de Kaa, Fens, and Rezaei 2019; Van de Kaa et al. 2014).

Several contributions go beyond that research. First, the research offers new relevant factors for design dominance related to technological superiority; trustworthiness, safety, energy extraction rate, and capacity. Second, whereas previous research has focused specifically on the fourth stage of the dominance process as defined by Suarez (2004), this research specifically focuses on the third stage and can be considered one of the first empirical studies that specifically focuses on establishing weights for design dominance in that stage. It finds first empirical support for the importance of strategic manoeuvring in the form of pricing strategy in that stage. Furthermore, Suarez (2004) believed that technological superiority is not relevant in the third stage while this paper's results indicate that several aspects of technological superiority including trustworthiness, safety, energy extraction rate and capacity are most important. Thus the technological superiority of a design appears to be an important determinant for design dominance after a commercial product has arrived but before an early front runner has appeared in the market.

Furthermore, the study reveals that the actual weights for the factors and the comparison of the alternatives in terms of their likelihood of becoming dominant can be estimated by using the best-worst method (Rezaei 2015, 2016), providing an evidence for the applicability of the method in this context.

The research is of practical merit for firms and policy makers as it hints to the buttons that can be touched and the levers that can be pulled in order to achieve design dominance in the early stages of the dominance process; a practical insight that might be much welcomed for these specific actors. For example, for consumers, heat energy technologies immediately result in a lower energy bill, but the initial investment is still very high. The lower the costs, the faster the return on investment, and the more profitable the purchase for consumers. Therefore, pricing might also be so important. However, as one respondent noted: 'With fossil energy prices being low, high capital expenditures causes the payback period to be too long.' This could be one of the reasons why these technologies are still not used that much in our daily lives. Government subsidies could help in bringing the prices down; a recommendation for public policy makers is too incorporate such subsidies for the preferred technology in their policy. The results of the paper allow for evaluating whether certain policy or managerial interventions could result in one of the technologies achieving a dominant position according to the experts. For example, when government subsidies would be given for a certain technology, the value that is assigned to the factor 'pricing strategy' for that technology would go up (lower prices result in a higher score for that factor) with a maximum value of 9. This would result in a new total weighted score. This procedure would result in a total weighted score of 4.79 for sensible heat storage, and 5.19 for thermochemical heat storage. It can be concluded that these numbers are lower than the original value for latent heat storage which was 5.33. Therefore, it can be concluded that, although incorporating such subsidies would result in higher total weighted scores, it would not be sufficient to achieve design dominance for the particular technologies; apparently, other interventions are needed.

Technological characteristics appear to be important. However, it has to be noted that many technologies that were once technologically superior compared to their alternatives eventually did not achieve dominance. Though Betamax was technological superior compared to VHS, the latter eventually won in part due to the existence of complementary goods (indirect network effects) (Cusumano, Mylonadis, and Rosenbloom 1992). Also, the DVORAK keyboard layout was technologically superior compared to the QWERTY layout but the latter was the dominant keyboard layout design as the costs to switching from QWERTY to DVORAK were too high for users (David 1985). Once an early front runner will appear in the market and the market enters stage 4 of the dominance stage, installed base, (hidden) network effects and switching costs could become more important (Suarez 2004) and the initial technological advantage of a certain design might dissipate. Then, other factors might become more important.

Despite the insights the research offers, some limitations are applicable. Firstly, the focus of the research is the residential market in the Netherlands. Factors for technology dominance as well as their relative importance may vary from one context to another and as a result the generalisability of the results of this research to other contexts may be limited. Future research is encouraged that focuses on factors for design dominance for other components of energy and ICT systems. Furthermore, future research could apply other methods such as a quantitative approach which could lead to an even better understanding of the problem at hand. In fact, some well-known examples of technology battles have been analysed applying other methods which also resulted in valuable insights (Schilling 2002; Shankar and Bayus 2003). Second, one of the reasons why technological superiority was mentioned as being especially important by the experts could be that the experts that were interviewed mostly had a technical background and either are or have been actively working in the R&D of these technologies. This, therefore, might have led the participants of the study to have slight preference on the technical characteristics of the design over the other aspects of the design. Future research could follow a similar approach but by conducting interviews with people that also have a non-technical background.

All three technologies are still considered to be under development let alone reached the maturity, especially latent heat storage and thermochemical heat storage lack commercial applications. Therefore, the results of this study can be subject to change as these technologies develop over time. As the outcome of this battle is not known yet, it is unknown whether our prediction is close to reality. Also, the opinions of the experts concerning importance of criteria might change in hindsight when they know which technology will achieve success. It might e.g. be the case that due to a random event that cannot be explained beforehand a certain design will achieve dominance. When the outcome of this battle is known, a future study could follow a similar approach and evaluate whether the predictions made and the weights assigned to the factors hold. Then we can test whether the results hold.

7. Conclusion

In this paper, the technology battle of thermal energy storage technologies for residential applications in the Netherlands is investigated and the most influential factors for the selection of three competing designs, namely sensible heat storage, latent heat storage, and thermochemical heat storage, are identified. After a literature review and multiple interviews with experts, the study has identified 20 factors of influence that affect the technology battle in this field. The relative weights of the factors are then calculated by gathering inputs from experts and applying the BWM. Most influential factors for the selection of thermal energy storage technologies are found to be *trustworthiness, safety, energy extraction rate*, *capacity*, and *pricing strategy*. The study concludes that latent heat storage has the highest chance of becoming the dominant design among thermal energy storage solutions, although differences are small.

Notes

1. The local average weights are the average weights for the subcriteria (factors) within a category while the global average weights are the overall weights of factors. So the global average weight of a sub-criterion is obtained by multiplying the local average weight of the sub-criterion by the weight of the criterion to which it belongs. For instance the global average weight of ‘‘financial strength’’ (.01) is obtained by multiplying the weight of ‘‘Characteristics of technology supporter’’ (0.10) by the local average weight of ‘‘financial strength’’ (0.10).
2. Average performance score.
3. Average performance score multiplied by average global weight.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributor

Geerten van de Kaa is Associate Professor of Standardization and Business Strategy at Delft University of Technology. He holds a PhD from Rotterdam School of Management, Erasmus University. His research focuses on a better understanding of the standardization process in order to enable complex innovations and solve societal and business challenges. He has published in high ranking international journals including *Organization Studies, IEEE Transactions on Engineering Management, Technovation, and Technological Forecasting and Social Change*. He is editor-in-chief of the *International Journal of Standardization Research*.

References

Amankwah-Amoah, J. 2016. "Competing Technologies, Competing Forces: The Rise and Fall of the Floppy Disk, 1971–2010." *Technological Forecasting & Social Change* 107: 121–129.

Armstrong, M. 2006. "Competition in Two-Sided Markets." *The RAND Journal of Economics* 37 (3): 668–691.

Aydinn, D., S. P. Casey, and S. Riffat. 2015. "The Latest Advancements on Thermochemical Heat Storage Systems." *Renewable & Sustainable Energy Reviews* 41: 356–357.

Bento, N. 2008. "Building and Interconnecting Hydrogen Networks: Insights from Theelectricity and Gas Experience in Europe." *Energy Policy* 36: 3019–3028.

Bortolotti, M. 2016. *Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap 2017 Update*. https://eera-es.eu/wp-content/uploads/2016/03/EASE-EERA-Storage-Technology-Development-Roadmap-2017-HR.pdf.

Chou, J.-S., and G. A. N. Yutami. 2014. "Smart Meter Adoption and Deployment Strategy for Residential Buildings in Indonesia." *Applied Energy* 128: 336–349.

Cusumano, M. A., Y. Mylonadis, and R. S. Rosenbloom. 1992. "Strategic Maneuvering and Mass-Market Dynamics: The Triumph of VHS Over Beta." *Business History Review* 66 (1): 51–94.

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

Donkers, P. A. J. 2015. *Experimental Study on Thermochemical Heat Storage Materials*. 's-Hertogenbosch: BOXPress.

Farrell, J., and G. Saloner. 1985. "Standardization, Compatibility, and Innovation." *The Rand Journal of Economics* 16 (1): 70–83.

Funk, J. L. 1998. "Competition Between Regional Standards and the Success and Failure of Firms in the World-Wide Mobile Communication Market." *Telecommunication Policy* 22 (4/5): 419–441.

Funk, J. L., and D. T. Methe. 2001. "Market- and Committee-Based Mechanisms in the Creation and Diffusion of Global Industry Standards: The Case of Mobile Communication." *Research Policy* 30 (4): 589–610.

Gallagher, S. R. 2012. "The Battle of the Blue Laser DVDs: The Significance of Corporate Strategy in Standards Battles." *Technovation* 32 (2): 90–98.

Gallagher, S. R., and S. 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.

Giordanon, V., and G. Fulli. 2012. "A Business Case for Smart Grid Technologies: A Systemic Perspective." *Energy Policy* 40: 252–259.

Heinz, B., M. Graeber, and A. J. Praktiknjo. 2013. "The Diffusion Process of Stationary Fuel Cells in a Two-Sided Market Economy." *Energy Policy* 61: 1556–1567.

Hill, C. W. L. 1997. "Establishing a Standard: Competitive Strategy and Technological Standards in Winner-Take-all Industries." *Academy of Management Executive* 11 (2): 7–25.

Katz, M. L., and C. Shapiro. 1986. "Technology Adoption in the Presence of Network Externalities." *The Journal of Political Economy* 94 (4): 822–841.

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

Kubli, M., and S. Ulli-Beer. 2015. "Transition patterns of Distributed Energy Generation Concepts Considering Network Effects." In *Proceedings of International Conference CISBAT*, Lausanne, Switzerland.

Kublia, M., and S. Ulli-Beer. 2016. "Decentralisation Dynamics in Energy Systems: A Generic Simulation of Network Effects." *Energy Research & Social Science* 13: 71–83.

Lee, J., J. Lee, and H. Lee. 2003. "Exploration and Exploitation in the Presence of Network Externalities." *Management Science* 49 (4): 553–570.

Niyas, H., S. Prasad, and P. Muthukumar. 2017. "Performance Investigation of a Lab–Scale Latent Heat Storage Prototype – Numerical Results." *Energy Conversion and Management* 135: 188–199.

Rezaei, J. 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.

Rochet, J. C., and J. Tirole. 2003. "Platform Competition in Two-Sided Markets." *Journal of the European Economic Association* 1 (4): 990–1029.

Sarbu, I., and C. Sebarchievici. 2018. “A Comprehensive Review of Thermal Energy Storage.” *Sustainability* 10 (191): 1–32.
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. 2003. “Technological Leapfrogging: Lessons from the U.S. Video Game Console Industry.” *California Management Review* 45 (3): 6–32.
Schilling, M. A. 2020. *Strategic Management of Technological Innovation*. New York: McGraw-Hill.
Shankar, V., and B. L. Bayus. 2003. “Network Effects and Competition: An Empirical Analysis of the Home Video Game Industry.” *Strategic Management Journal* 24 (4): 375–384.
Shapiro, C., and H. R. Varian. 1998. *Information Rules, a Strategic Guide to the Network Economy*. Boston, MA: Harvard Business School Press.
Shapiro, C., and H. R. Varian. 1999. “The Art of Standards Wars.” *California Management Review* 41 (2): 8–32.
Sharmaa, A., et al. 2009. “Review on Thermal Energy Storage with Phase Change Materials and Applications.” *Renewable & Sustainable Energy Reviews* 13: 318–345.
Srinivasan, R., G. L. Lilien, and A. Rangaswamy. 2006. “The Emergence of Dominant Designs.” *Journal of Marketing* 70 (2): 1–17.
Suarez, F. F. 2004. “Battles for Technological Dominance: An Integrative Framework.” *Research Policy* 33 (2): 271–286.
Van de Kaa, G., et al. 2011. “Factors for Winning Interface Format Battles: A Review and Synthesis of the Literature.” *Technological Forecasting & Social Change* 78 (8): 1397–1411.
Van de Kaa, G., et al. 2014. “Photovoltaic Technology Selection: A Fuzzy MCDM Approach.” *Renewable and Sustainable Energy Reviews* 32: 662–670.
Van de Kaa, G., et al. 2017. “The Battle Between Battery and Fuel Cell Powered Electric Vehicles: A BWM Approach.” *Energies* 10: 1707–1720.
Van de Kaa, G., et al. 2019. “Realizing Smart Meter Connectivity: Analyzing the Standards Battle Between Power Line Communication, Mobile Telephony, and Radio Frequency Using the Best Worst Method.” *Renewable & Sustainable Energy Reviews* 103: 320–327.
Van de Kaa, G., and H. De Vries. 2015. “Factors for Winning Format Battles: A Comparative Case Study.” *Technological Forecasting & Social Change* 91 (2): 222–235.
Van de Kaa, G., T. W. Fens, and J. Rezaei. 2019. “Residential Grid Storage Technology Battles: A Multi-Criteria Analysis Using BWM.” *Technology Analysis & Strategic Management* 31 (1): 40–52.
Van den Ende, J., et al. 2012. “The Paradox of Standard Flexibility: The Effects of co-Evolution Between Standard and Interorganizational Network.” *Organization Studies* 33 (5–6): 705–736.
Zondag, H., et al. 2013. “Prototype Thermochemical Heat Storage with Open Reactor System.” *Applied Energy* 109: 360–365.