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G. van de Kaa, Theo Fens, Jafar Rezaei, D. Kaynak ...+2 more authors

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G. van de Kaa[a,*], T. Fens[a], J. Rezaei[a], D. Kaynak[b], Z. Hatun[c], A. Tsilimeni-Archangelidi[a]

[a] Delft University of Technology, Jaffalaan 5, Delft 2600 GA, the Netherlands
[b] Statkraft, Derendorfer Allee 2a, 40476 Düsseldorf, Germany
[c] One IHC, Smitweg 6, 2961 AW Kinderdijk, the Netherlands

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ABSTRACT

The world is faced with various societal challenges related to e.g. climate change and energy scarcity. To address these issues, complex innovative systems may be developed such as smart grids. When these systems are realized challenges pertaining to renewable energy and sustainability may, in part, be solved. To implement them, generally accepted common standards should be developed and used by firms and society so that the technological components can be connected and quality and safety requirements of smart grids and their governance can be guaranteed. This paper studies a subcomponent of the smart grid. Specifically, the paper studies competing technologies for a standard means of interface between the smart meter and the concentration point for collecting meter data. Three types of communication technologies for the interface are currently battling for standard dominance: Power line communication, Mobile telephony, and Radio frequency. Nine relevant standard dominance factors were found: operational supremacy, technological superiority, compatibility, flexibility, pricing strategy, timing of entry, current installed base, regulator, and suppliers. The Best-Worst Method was applied to calculate the factors' relative weights. The results show that experts believe that Power line communication has a high chance of becoming dominant and that the most important factor affecting standard success is technological superiority. The relative weights per factor are explained and theoretical and practical contributions, limitations, and areas for further research are discussed.

1. Introduction

To realize smart grids, smart meters are essential as these devices can provide near continuous electricity measurements on every end point of the network [1]. Smart meters measure users' electricity consumption and provide supply companies with real-time electricity consumption information [2]. Detailed information on electricity consumption can help users to reduce their electricity consumption. This is especially the case when users participate in programs that promote behavioral change with respect to energy consumption [3]. Another advantage is that supplier companies can save manual reading efforts and detect fraud [4].

Clearly, there are various advantages attached to the smart metering technology and, therefore, these devices are being deployed in various countries [5]. However, to fully utilize smart meter capabilities in a dwelling, standards are needed to realize communication between the smart meter and external applications [6,7]. The focus of this paper lies on the connection between the smart meter and the central database which is established through a 'communication interface protocol' [8]. Unfortunately, currently, there is no single standard way of doing so. The selection of one common standard will in part enable the successful implementation of smart meters and smart grids [6,7], and, that will help in achieving the global emissions targets that are set [9] and, thus, contribute to a low carbon future and sustainability objectives. The goal of this paper is to explore factors that affect selection of these standards for smart meter connectivity.

Abbreviations: AMI, Advanced Metering Infrastructure; AMR, automatic meter reading; BWM, Best Worst Method; DSOs, Distribution System Operators; GPRS, General Packet Radio Service; GSM, Global System for Mobile communications; HD DVD, High Definition Digital Versatile Disc; LTE, Long-Term Evolution; MCDM, multi-criteria decision-making; PLC, Powerline Communication; RF, Radio Frequency; SMCG, Smart Meter Coordination Group; TSO, Transmission System Operator; UMTS, Universal Mobile Telecommunications System; USB, Universal Serial Bus; VHS, Video Home System

* Corresponding author.
E-mail address: g.vandekaa@tudelft.nl (G. van de Kaa).

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Three types of communication technologies are currently competing with each other: Power line communication (such as G.9902 or 1901.2), Mobile telephony (such as Universal Mobile Telecommunications System (UMTS), Global System for Mobile communications (GSM) / General Packet Radio Service (GPRS), Long-Term Evolution (LTE)) and Radio frequency (such as Meshnet3, Kamstrup Radio Frequency, 802.15.4 g-e, and Flexnet) [4,10]. For both users and firms, the uncertainty attached for choosing one or the other type of communication technology is high. These actors will wait until one technology has achieved dominance and then make a decision; as a result, there is no single common technology. The uncertainty can be reduced by giving an answer to the question which of these three technologies will achieve dominance. Indeed it may well be that the dominating technology depends on geographical conditions as stated later in the paper. In an urban environment, Power line communication may be dominant, while in a rural environment Radio Frequency may be the desired technology to fulfil needs. The underlying information transmission model (coding and information architecture) will mostly likely be a global standard to attain economy of scale and interoperability in smart meter data gathering.

Smart meters have been studied by various scholars. For example, Zhou and Brown [11] studies the effect of policy intervention on smart meter rollout and Dehdarin [12] explores how the costs of that rollout should be distributed among the different actors involved. Other scholars study the (positive and negative) reactions of households to smart meters [13]. In this paper, a new perspective is taken on smart meters by studying factors that affect the success of communication technologies for smart meters. Previous research into the topic of factors for standard selection for smart metering has focused on various factors including e.g., technological characteristics, installed base, openness, and regulatory endorsement [4] and has concluded that no one single technology scores high on each of the criteria, so it is difficult to make a choice which technology should be chosen. The current study builds upon and extends this research by taking into account more factors (including factors that have hardly been studied in relation to the topic before) and establishes weights for the factors by applying a multi-criteria decision making approach called the Best Worst Method (BWM) [14,15]. This approach is chosen because pairwise comparison data can be collected in a structured way from experts, leading to more reliable results. It also requires fewer input data compared to similar methods. The BWM has been effectively used to investigate other cases such as supplier segmentation [16] and supplier selection [17], innovation management [18], university-industry collaboration [19], airline and airport evaluation [20,21], offshore outsourcing [22] and water resource management [23].

The objective of this paper is twofold. First, the aim is to determine which factors for technology dominance for smart metering communication are relevant and to assess their relative importance. Second, the aim is to identify which of the three technologies has the best chance of achieving dominance. In doing so, the focus lies on the Netherlands. The extant literature on technology dominance factors is first reviewed and it is determined which factors are applicable for smart metering communication, based upon secondary data. Then, the BWM is applied and results are presented and discussed.

Scholars who study standards battles and that take an evolutionary economics standpoint believe that path dependent processes determine the outcome of these battles and that the outcome therefore cannot be influenced beforehand but can be explained only when the (random) occurrences have unfolded [24]. Standardization and technology management scholars have argued and shown that these random occurrences are antecedents to known technology dominance factors [25,26]. This paper contributes to the latter idea by establishing weights for factors for technology dominance for the communication between the smart meter and the concentration point for collecting meter data. Thus, it provides more evidence that the standard selection process can indeed be modeled. In doing so, it builds upon prior research [27,28]. Furthermore, most scholars who study technology battles focus on the consumer electronics, information technology and telecommunications industry. This is one of the first studies that focuses on competing technologies for the energy sector. Third, this is the first study that applies the BWM to smart metering.

2. Theory

The outcome of technology battles can be explained by applying various theoretical lenses including technology management, network economics, and institutional economics [26,29]. Examples of such technology battles include the well-documented battle between Video Home System (VHS) and Betamax [30] and Blu-ray versus High Definition Digital Versatile Disc (HD DVD) [31]. Most of these scholars tend to agree on the relevance of quickly building up an installed base of users that adopts the standard [32]. Because of network externalities, a standard's value increases the more users adopt it [33,34]. Because of this, the installed base in itself becomes a factor that determines the success of a standard.

Given the fact that an installed base is so important, numerous strategic management and technology management scholars have studied the strategic determinants increasing a technology's installed base. For instance, when companies enter the market earlier compared to competitors, their installed base can be quickly increased and, effectively, these companies can pre-empt rivals from establishing a foothold [35]. Marketing communications such as pre-announcements may also be used to increase both expected and anticipated installed base [36]. Firms may apply a strategy of penetration pricing whereby products (implementing a standard) are priced below their cost price so that the installed base of users can be increased [37]. Later, when a sufficient installed base of users has been obtained (and networks effects can take over), the products may be priced at a normal level.

Of course, these strategies can only be applied properly if firms have sufficient complementary assets at their disposal [38]. These resources include financial resources, reputation, credibility, and operational supremacy. Such resources can be owned by individual firms, but the resources may also be gained by establishing inter-organizational relationships with key partners. However, these partners should all be sufficiently committed to the standard [39].

Scholars have also pointed towards the importance of other factors. For example, suppliers may provide complementary goods, which may be essential for reaching standard success [25]. Gallagher [38] studied the battles that have been fought in the video gaming industry and highlighted the importance of offering many complementary goods (i.e., video games) for achieving success with a video gaming console. Policies set by regulatory agencies can have an important influence on the establishment of common standards. For example, such agencies may enforce standards on the market, in which case a technology battle may end prematurely.

In prior cases (such as QWERTY versus Dvorak [40] or Moving Picture Experts Group 2 Audio versus Audio Codec 3 [41]), it can be observed that superior technological characteristics are not a sufficient condition for standard success. However, such characteristics still are important factors for standard success that should be taken into account. For example, if backwards compatibility with a previous generation can be guaranteed by a standard, it can tap into the previous installed base which may, effectively, increase the current installed base [41]. Furthermore, technological characteristics such as data rate or bandwidth capacity may be essential factors for standard success as was the case for WiFi versus Home Radio Frequency.

To guarantee that all the factors that may be relevant for the case of the competing technologies are considered, a framework comprising 23 firm-level factors for technology dominance [42] is applied. This framework has been effectively used in multiple contexts to assess its relevance and completeness [41] and it can thus be assumed that it is as complete as possible. The purpose of this paper is not to give a full overview of factors for technology dominance. For such an overview, one is referred to the extant literature on factors for technology dominance [25,26,29,42,43].

3. Smart metering industry

Due to the ICT revolution, the electricity supply system is facing a governance change and as a consequence, the electricity market is also undergoing substantial changes. Specifically, smart grids allow operators to gather detailed information on the amount of electricity supply and demand, so that demand can be matched to supply, i.e., the balancing mechanism. Transmission System Operators (TSOs), who are responsible for transmitting electric power on main high voltage electric networks, are already smart, as their governance is largely based on ICT. However, this is not the case for Distribution System Operators (DSOs), responsible for electric power transmission on lower voltage networks. With the advent of decentralized electricity generation, the balancing mechanism has also become more important in DSO networks. Smart meters can play a pivotal role in this governance change. In this way, the energy market and the world of information technology are gradually becoming intertwined [44]. A smart meter differs from traditional automatic meter reading (AMR) mainly because two-way communications can be realized. Advanced Metering Infrastructure (AMI) describes a smart grid set-up and consists among other of a smart meter and a data concentration point [45]. The focus of this paper is on the interface between these two components.

When a DSO makes the decision to invest in smart metering their complete meter park has to be replaced. Therefore, to decrease technological uncertainty, achieving system interoperability is key for such DSOs. To ensure interoperability, the EU Smart Meter Coordination Group (SMCG) is attempting to define common European standards, guidelines, functional requirements and specifications in cooperation with European Standardization organizations and industry and utility stakeholders. A detailed list of standards for smart metering is currently available.

The preferred communication infrastructure for smart metering differs per country. DSOs seem to have a decisive role in choosing a standard in a country. DSOs are responsible for realizing smart grids in Europe and guide Research and Development, policy and member state regulation to support this development around Europe [46]. DSOs need to ensure the long-term viability of the system so that demands for the electricity distribution can be met. DSOs are thereby the main players in the battle under consideration in this paper. Although various specifications to define the interface between the smart meter and the concentration point for collecting meter data have been developed over the past years, it appears that three standard technologies, are vying for market dominance: Power line communication, Mobile telephony and Radio frequency.

In Power line communication technology, the physical DSO network is used as a communication means. The signal containing the meter data is superimposed on the low voltage side of the DSO network and the data concentration point is generally located in the mid voltage substation. From this location either Internet (IP) or Power line communication on the mid voltage side of the DSO network is used to transfer meter data to the database. Mobile telephony can also be used to transfer data from the individual smart meter to the database. To this end, the smart meter is equipped with mobile telephony electronics. In case of Radio frequency, specific frequency bands are used to transfer the data. As the range of Radio frequency is limited, data collection is normally carried out with a mobile transmitter/receiver system that travels through a district for smart meter data collection in rural environments. For more continuous bidirectional communication in urban environments stationary transmitter/receiver systems are employed.

In the Netherlands, these communication technologies vary per region. In the central part of the country, Radio frequency is dominant since this technology was developed in-house by a DSO (Alliander). In the South and in the North of the country, powerline communication is applied by another DSO (Enexis), whereas in the West, Stedin is the main DSO offering a combination of communication standards: Mobile telephony and RF. While the smart meter market is currently growing, each technology and its related stakeholders have the opportunity to dominate the market. The European Commission recently published the first report measuring the progress of smart meter deployment across the EU against the 80% target by 2020 [47]. The member states' commitment represents a total potential investment of €45 billion.

4. Methodology

To determine which factors for technology dominance for smart metering are relevant, each of the 23 firm level factors for technology dominance offered by Van de Kaa et al. [42] are first evaluated by analyzing 14 secondary sources. Secondary sources include academic articles, reports, and online sources. An interview was also conducted with an expert with comprehensive knowledge on smart meter systems who was involved in the design of the smart meter architecture leading to the Dutch requirements on smart meters. He was, and still is, involved in projects concerning the realisation of smart grids with a focus on the underlying information architecture in which smart meters play a pivotal role, as from a regulatory perspective this is the only source on which financial settlement for energy can take place. In addition he is currently working on the system design of an integrated utility system (electricity, heat, hydrogen and water) in which metering is the core for financial settlement of these utilities. This system design constitutes the foundation for the actual realisation of a district sized pilot in the Netherlands in 2020. This expert has comprehensive knowledge on the competing technologies.

A factor was found to be relevant if it was implicitly or explicitly mentioned in either one of the secondary sources that were analyzed [2,4,48–55,68–70] or in the interview that was conducted. In this analysis, the researchers were open to other factors then the factors included in [42]. The results of this analysis are available as a supplementary file.

To assess the relative importance of the factors and to evaluate which technology has the highest probability of achieving success, a multi-criteria decision-making (MCDM) approach was applied: BWM [14].

Here, the five steps of the BWM needed to arrive at the factor weights (criteria) are described.

Step 1. . *Determine a set of evaluation criteria.*

The factors (criteria) (C_1, C_2, …, C_n) need to be identified to evaluate the relative dominance level of a standard.

Step 2. *Determine the best and the worst criteria to be used for evaluating the technology's dominance.*

The best criterion is the most important one in identifying the technology's dominance. The worst is the least important.

Step 3. *Determine the preference of the best criterion over all the other criteria.*

An expert uses a number between 1 and 9 (1 shows that the best criterion is equally important to the other criterion, while 9 means that the best criterion is extremely more important than the other criterion) to indicate his/her preferences of the best criterion over other criteria. The resulting Best-to-Others vector would be:

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

where, a_{Bj} indicates the preference of the best criterion B over criterion j.

Step 4. *Determine the preference of each of the other criteria over the worst criterion.*

An expert uses a number between 1 and 9 here as well. The others-to-worst vector would be:

$$A_W = (a_{1W}, a_{2W}, \quad ..., a_{nW})^T,$$

where, a_{jW} indicates the preference of the criterion j over the worst criterion W.

Step 5. *Find the optimal weights.*

To find the optimal weights of the criteria, the maximum absolute differences were minimalized $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j, which is formulated as follows:

$$\min_j \max\{|w_B - a_{Bj}w_j|, \quad |w_j - a_{jW}w_W|\}$$

s.t.

$$\sum_j w_j = 1,$$

$$w_j \geq 0, \text{ for all} j. \tag{1}$$

The minmax model was then transfered to the following linear programming problem:

$$\min \xi^L$$

s.t.

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

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

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all} j \tag{2}$$

By solving this problem, the optimal weights ($w^*_1, w^*_2, ..., w^*_n$) and the optimal objective function value ξ^{L*} was obtained, which is defined as the consistency ratio of the pairwise comparison system. The closer ξ^{L*} to zero, the more consistent the pairwise comparison system, thus the more reliable the results.

In this study, seven experts in the communication technologies field were interviewed to find the weights of the factors (criteria) (see Table 1). Experts with comprehensive knowledge on the topic were selected.

After obtaining the weights of the criteria from each expert and aggregating the weights (by making an average), each technology can be evaluated with respect to each criterion and an additive model can be used to calculate the overall value of each technology as follows.

$$Value_{Technologyi} = \sum_j w_j^* T_{ij} \tag{3}$$

where w_j^* shows the optimal weight of criterion j, and T_{ij} shows the evaluation of technology i with respect to criterion j.

The following quantification method is used to find the values T_{ij}. If a technology performs very well, it is given the highest score of 3 (or $T_{ij} = 3$), if its performance is moderate, it is given a score of 2 (or $T_{ij} = 2$) and if it performs poorly, it is given the lowest score of 1 for that specific factor (or $T_{ij} = 1$). To determine these values, an expert interview was conducted with a practitioner who has over 15 years' work experience in the energy sector in the Netherlands. The values are checked for their consistency with secondary data [2,4,48–55].

5. Results

5.1. Determining the relevant factors for technology dominance for smart metering

Nine out of the 23 factors for technology dominance from van de Kaa et al. [42] were found to be relevant for the case of smart metering: operational supremacy, technological superiority, compatibility, flexibility, pricing strategy, timing of entry, current installed base, regulator and suppliers. The factors are explained and elaborated upon in Table 2.

In this specific case, the factor operational supremacy refers to the ownership of a network, adequate information architecture, network coverage, and superior resources compared to competitors. Technological superiority refers to quality of service, quality of data, end-to-end control, privacy, security, robustness, technological availability and durability. Compatibility refers to compatibility of technologies that are already embedded in smart meters, and to backward compatibility. Flexibility refers to the extent to which the end customer can switch to a different energy supplier or other smart metering type. Pricing strategy refers to the cost effectiveness of the communication technology. More specifically, this factor comprises cost effectiveness after roll-out, implementation and maintenance costs. Timing of entry refers to the point in time that the standard enters the market. Current installed base refers to the number of smart meters already installed that employs a particular communication technology. The DSOs are the major stakeholders for the competing technologies in Europe and thereby in the Netherlands. DSOs are the main decision makers in the adoption of a communication technology for smart meters in each of the European countries. DSOs can even be considered 'big fishes' [42]. At present, the EU directives, which have to be implemented into local legislation in EU member states, are technology neutral. Suppliers are the equipment sellers and service providers for a particular smart metering communication technology. The fact that there is a variety of suppliers can help a smart metering technology to become dominant in the market which includes the communication technology.

5.2. Assessing the importance of factors for technology dominance

Table 3 shows the importance (weights) of the relevant factors by applying the BWM based on interviews with seven experts.

As can be seen from Table 3, the consistency ratio of each interviewee is very close to zero, which shows the veracity between the weights obtained from the method (BWM) for each expert and the pairwise comparisons provided by that expert, which in turn shows the

Table 1
List of interviewed experts.

Expert #	Background	Field of expertise	Years of working experience
1	Academia	Electrical & electronics engineering / smart grid communications	9 years
2	Industry	Smart energy systems / sustainability / utilities industry / smart city / electric mobility	4 years
3	Academia	Innovation & entrepreneurship specialized in energy sector	1 year
4	Industry	Actively involved in smart metering industry. Fundamental studies on socio-technical aspects of smart metering and energy management systems in the framework of smart grids.	> 15 years
5	Academia	Digital platform architecting in engineering systems / e-mobility / smart energy	6 years
6	Policymaker	Smart electricity system and interoperability / electrical & computer engineering / mobile & communication systems	4 years
7	Industry	Smart metering / electrical & electronics engineering / management of technology / telecommunications & ICT insights	2 years

Table 2
explanation and elaboration of relevant factors.

Factors	Explanation and elaboration
Operational supremacy	The extent to which a group of standard supporters has organized its resources in an efficient manner so that the resources can be better utilized [42]. Production capacity is a typical example of such a resource [56]
Technology superiority	All technological aspects inherent to the standard that determine its technological stand-alone value [36]. The sum of these aspects determine whether the standard is technologically superior over its competitors [42]. Examples of such technological aspects are its data rate or ease of use [41].
Compatibility	Compatibly refers to the extent of which the standard is designed in such a way that it defines interoperability between different similar technologies so that these technologies can work together [57]. It also refer to interoperability with a previous technological generation (backwards compatibility). If so, it can tap into the installed base of the previous generation [58]. For example, the Universal Serial Bus (USB) 2.0 standard was compatible with the USB 1.0 standard, and, therefore, producers of goods that support USB 2.0 could easily sell those products to the many users that owned a personal computer that still supported the USB 1.0 standard.
Flexibility	The extent to which the standard is changed during the entire lifetime according to user requirements. When a standard is more flexible, it has a higher chance of achieving success [59,60].
Pricing strategy	Pricing strategy refers to the price that is set for the product that implements the standard. Generally it can be concluded that the lower the price (which can be lower than the cost price), the more users will buy the product, and the higher the market share of the standard [37].
Timing of entry	The point in time at which the product in which the standard is implemented is introduced in the market. If the product is introduced before a competing product, it may quickly amass installed base [61]. This increases the chances that the standard achieves dominance [42].
Current installed base	Installed base concerns the number of products in which the standard is implemented and that are used [42]. In standards based markets that are characterized by increasing returns to adoption, network effects exist [33,34]. In these markets, the value of products increases the more users adopt the products. Therefore the installed base of users is an important factor for standard dominance.
Regulator	When a regulator enforces a standard on the market it may instantly achieve dominance.
Suppliers	'Suppliers' refers to the companies that offer complementary products in which the standard is implemented such as VHS tapes or Video games. As the availability of complementary products and the installed base are interrelated [25,29], the more companies offer complementary products, the higher the demand for the core product in which the standard is implemented [62], increasing the standard's installed base.

Table 3
The weights of the criteria after applying the BWM.

Factors	Interviews							Average weight
Operational supremacy	0.13	0.03	0.15	0.09	0.04	0.09	0.13	**0.09**
Technology superiority	0.31	0.10	0.08	0.30	0.17	0.11	0.31	**0.20**
Compatibility	0.10	0.30	0.15	0.13	0.07	0.09	0.10	**0.13**
Flexibility	0.08	0.15	0.10	0.19	0.04	0.34	0.19	**0.16**
Pricing strategy	0.19	0.04	0.08	0.06	0.17	0.17	0.04	**0.11**
Timing of entry	0.03	0.04	0.03	0.02	0.03	0.04	0.03	**0.03**
Current installed base	0.06	0.08	0.31	0.05	0.04	0.04	0.06	**0.09**
Regulator	0.05	0.10	0.04	0.10	0.35	0.07	0.08	**0.11**
Suppliers	0.05	0.15	0.04	0.05	0.09	0.06	0.06	**0.07**
Consistency ratio of the interviewee	0.01	0.04	0.04	0.01	0.03	0.04	0.01	

Table 4
Overview of the scores of the alternative technologies.

Factors	Power line communication	Mobile telephony	Radio frequency
Operational supremacy	0.04	0.01	0.04
Technology superiority	0.03	0.06	0.09
Compatibility	0.06	0.06	0.02
Flexibility	0.07	0.02	0.07
Pricing strategy	0.05	0.03	0.03
Timing of entry	0.01	0.01	0.00
Current installed base	0.04	0.03	0.01
Regulator	0.05	0.02	0.04
Suppliers	0.01	0.03	0.01
Total score	**0.38**	**0.29**	**0.33**

reliability of the results. The results show that technological superiority is the most important factor with an average weight of 0.20, followed by flexibility (0.16) and compatibility (0.13). Pricing strategy and regulator are both ranked fourth (0.11), and operational supremacy and current installed base have a joint fifth place (0.09). Suppliers is ranked sixth with an average weight of 0.07, and timing of entry is the least important factor with an average weight of 0.03.

5.3. Identifying the dominant standard

Finally, the scores obtained in the final step of the analysis were multiplied with the average weights in Table 4, and the values were normalized to fit into the scale of 0–1. The results indicate that Power line communication has a score of 0.38. This means that according to the 7 experts that participated in the BWM study, power line communication is in the best position to win the battle. This is based upon the values that were given by the experts to the 9 factors that the experts deemed important in this specific battle.

6. Conclusion and discussion

The realisation of the smart grid will in part support the transition to a low carbon future and achieve the global emissions targets [9]. However, for a smart grid to be realized smart meters are needed [8,12] and have to be rolled out. This will be hastened when common interface protocols for interconnection between smart meter and external applications are chosen as these are needed to fully utilize smart meter capabilities in a dwelling [6,7].

Competing technologies for the communication between the smart meter and the concentration point for collecting meter data between three technologies: Power line communication, Mobile telephony, and Radio frequency were studied. Nine factors for technology dominance were found to be relevant: operational supremacy, technological superiority, compatibility, flexibility, pricing strategy, timing of entry, current installed base, regulator, and suppliers. The relative factor weights were calculated and it was found that experts believe that Power line communication has a high chance of becoming dominant. The results show that in this case, the most important factor affecting standard success appears to be technological superiority, whereas, in this case, the least important factor appears to be timing of entry.

6.1. Interpretation of the results

The results show that technological superiority, flexibility, and compatibility are the most important factors for technology dominance. Indeed, 87% of the respondents ranked either technological superiority or flexibility as the most important factor. All interviewees ranked compatibility as an important factor, with a standard deviation of 7%

among the respondents. Thus, it appears that the outcome of this battle is mainly affected by the characteristics of the technology rather than by the market, by industry or by firm characteristics. In addition, all interviewees ranked timing of entry as the least important factor, with a standard deviation of 0.5%.

The question arises why these three factors are so important? Technological superiority is important because it corresponds to long-term viability. As the smart metering communication technology is part of a complex infrastructure (the smart grid), the fulfillment of the specific aspects underlying technological superiority is a main prerequisite for a standard to be adopted for such complex infrastructures. Flexibility is important because the communication technology should be flexible enough to cope with the rapid changes in the energy supply infrastructure. Compatibility is important because the communication technology has to be compatible with the technologies already embedded in smart meters, with the existing big scale infrastructure and communication services, next to possible future developments, without requiring large extra investment. These three factors are also often mentioned in other studies both in the energy domain and in other domains. For example, Erlinghagen et al. [4] mention several technical criteria that affect smart metering communication standard adoption including, the range, the reach inside buildings, data rates, frequency bands, interoperability and robustness. Also, in the competition between hydrogen fuel cell and battery powered electric vehicles the two most important factors were technological superiority (in terms of e.g. the range offered by the technology) and compatibility (with e.g. an existing charging station infrastructure) [28]. Technological superiority also appears to be the key factor for technology success in the battle for photovoltaic technological systems. The solar cell's efficiency offered by the technology appeared to be a crucial factor for success [63]. Flexibility did not appear to be essential in cases of standards battles for energy systems but it was a crucial factor for success in other markets such as the consumer electronics industry. For example, one of the key factors that led to the success of USB over Firewire in the battle for a standard interface protocol between the computer and peripheral devices was the fact that USB was more flexible; more changes were incorporated into the standard in response to user requirements [41,64].

Interestingly, although technological superiority is regarded as the most important factor, Power line communication scores the lowest in terms of technological superiority based on primary and secondary sources. However, Power line communication is expected to become the dominant technology as it has one major advantage: the required infrastructure is already present so no major communication technology specific investments are required. This shows that the technologically superior standard does not always achieve dominance. For example, in the standards battle between Firewire and USB, Firewire was technologically superior, but USB became the dominant standard [41].

Pricing strategy, the regulator, operational supremacy and current installed base are considered moderately important in this battle. Pricing strategy has a moderate effect on the outcome of the battle because the prices for electronic hardware for Power line communication, Mobile telephony, and Radio frequency do not differ much; smart meters concern in essence a mass market as every dwelling needs to have one to be connected to the electricity network. The regulator also plays a moderate role. This is because the EU directives on smart metering have to be implemented into EU member state legislation, and is thereby a kind of regulatory standard on its own. Moreover, the EU directives are technology neutral and therefore have a minor effect.

Operational supremacy is of moderate importance because there is little difference in production capacity requirements between Power line communication, Mobile telephony, and Radio frequency. For example, bandwidth requirements are not a major concern as only small amounts of data have to be transferred. Installed base has little effect because the choice of communication technology is not made by the consumer, but partly depends on the given geographical infrastructure, and partly on the DSOs' governance preferences. With respect to infrastructure, in a rural environment, Radio frequency or Mobile telephony are a more likely choice, because Power line communication is less suitable for larger distances between the smart meter and the concentration point for collecting meter data. In contrast, in an urban environment, Power line communication is most probably the preferred technology because of shorter distances between the smart meter and the concentration point for collecting meter data. With respect to governance, some DSOs may not want to be dependent on a communication service provider such as telephony, and may therefore prefer either Power line communication (urban) or Radio frequency (rural).

Suppliers can be an important factor in countrywide roll-outs. If vendors of a particular communication technology are found to be incompetent or insufficient in number, it may be difficult to proceed with the technology. However, this is not considered a major issue by the experts, because this is a big scale deployment with high potential earnings and therefore dedicated suppliers will be available once deployment starts. It was generally accepted that the least important factor is timing of entry. This can be attributed to the aspect that the smart meter roll-out is a fully regulated process. Indeed, smart meter installation and governance are regulated in the Netherlands. However, the smart meter equipment is a fully free market and thereby open for a standards battle. Also, DSOs are free to choose for one of the three communication technologies to support in the smart meters that the DSOs roll out. After all, the introduction of the smart meter is set by EU directives, the timing of which is determined by the regulators in the EU member states.

Erlinghagen et al. [4] mention both installed base and regulator as relevant non-technical factors for smart meter communication standard adoption but the authors do not assign weights to these factors. Most of the factors that were found to be of moderate importance were also of moderate or low importance or not relevant in the battle for photovoltaic technological systems [63] and in the battle between battery and hydrogen fuel cell powered electric vehicles [28]. There is one exception; pricing strategy was the most important factor in the battle for photovoltaic technological systems [63]. This is because the choice of a solar cell that is to be installed is primarily made by consumers.

The results indicate that Power Line Communication has the best chance of achieving success, which is in line with the literature. For example, Kabalci [65] provides an extensive listing of possible wireline and wireless communication technologies for smart grids from a wider perspective. This paper's limited perspective concerns smart meter communication between the smart meter and the concentration point for collecting meter data. In the above paper only two technologies are eligible for smart meter communication: Mobile telephony (GSM/GPRS) and Powerline Communication (PLC). Radio Frequency (RF) is not considered in this paper. In the context of smart meter communication technology to date no real standard could be established due to novelty and ongoing and converging developments. The BWM showed the capability to distinguish PLC as dominant primarily based on the advantage that the existing electricity network infrastructure can be used and no separate data transport infrastructure is required as is the case with the two competing technologies. Also, Erlinghagen, et al. [4] identified 17 possible smart meter communication standards and evaluated these using focused interviews with stakeholders. These 17 possible standards can, at a higher abstraction level, be grouped into the three technologies that are investigated with the BWM: Mobile telephony, RF (wireless), and PLC (wireline). The authors indicate that "The pre-dominant use of narrowband PLC standards in Europe currently limits the use cases for smart metering and the possibilities for leveraging this communication infrastructure for broader smart grid solutions. The preference of many utilities for low costs and ownership of the communication network may therefore create future bottlenecks."(page 1260). The pre-dominance of PLC is in line with the insights from the current study.

Although power line communication received the highest score

(0.38), the scores of the other two technologies was also relatively high (0.33 and 0.29) indicating that, in the future, multiple technologies may co-exist depending on geographical indicators. Indeed, dominance of power line communication does not exclude the use of the other two communication technologies: RF and Mobile telephony. It may, e.g., be that power line communication becomes the dominant technology in urban environments, while RF and mobile telephony may prove to be better applicable in rural environments. If so, this could be attributed to the characteristics of the communication technologies next to techno-economic considerations. Similar battles where multiple technologies co-exist have occurred in consumer electronics (video gaming consoles [38]) and in information technology (memory cards [66]). The geographical indicator (urban or rural) is an underlying determinant of the technological field in which the standard is used. Besides, the technological field is determined by other aspects such as the industry sector in which the battle is fought, the number and power of actors involved, and the extent to which the actors cooperate. In the model of Van de Kaa [42] the latter two determinants are included as separate factors. However, it could also be argued that the determinants that affect the technological field are in fact pre-cursors of the factors for technology dominance. Then, the nine factors found mediate between underlying determinants and technology dominance. It may also be the case that the factors that affect the technological field moderate the influence of the factors for technology dominance [26].

6.2. Theoretical contributions, practical contributions, limitations and future research areas

The paper contributes to the technology competition literature in several ways. First, weights for technology dominance factors in the case of the smart metering communication technology were established. So, further empirical evidence that the process of standard selection can be modeled and that weights for factors for technology dominance for particular cases can be established is provided, thus building on prior research in this area [27,67]. Second, this paper arrives at a new factor for technology dominance that affects the technological field in which the standard is used; the extent to which this is a rural or urban setting. This new factor may also be important in other arena's where technologies are competing with each other. Third, the paper illustrates a case of competing technologies in a business to business context. In this context it appears that technology buyers (DSOs) are mostly determining the outcome of technology competition and not the technology suppliers. In most cases of competing technologies (mostly studied in the information technology sector and in a business to consumer context) this is the other way around. Finally, this is the first time that weights for factors for technology dominance for smart metering communication have been established by means of the BWM. Thus, this study provides an application of the method.

This research may also be beneficial for the firms and policymakers by providing a first indication of which factors are relevant and by assessing their relative importance. These factors may also be relevant for technology battles that are currently being waged for smart energy system components and for future technology battles, for example, for charging technology for electric vehicles, vehicle to grid applications, fuel cell applications, heat pump technology and heat storage technology that are presently all researched intensively. Finally, the experts believe that Power line communication may become the dominant technology. Although from a functional and concept perspective Powerline can be seen as an obvious winner, from a governance perspective (operational expenditures and capital expenditure) it may well be that geographical indicators (urban, semi-urban, rural, extra-rural) exert an influence on the technology choice due to applicability of the technology for this purpose. For decision makers within DSOs, this might decrease the uncertainty attached to the decision which of the three technologies to support. It is foreseen that standardization of power line communication in other EU member states will result in lower costs for implementation. In addition, the network infrastructure (power lines), fully controlled by the DSOs, is used as carrier leading to both lower governance costs and a more effective use of assets. These arguments are expected to lead to a dominance of power line communication for urban environments but supporting evidence is still missing at the moment. However, This study was conducted in the Netherlands early 2017 and to date (mid 2018) one of the three major DSOs has opted for power line communication for smart meters, while the other two DSO are moving from Mobile telephony towards RF. It can be argued, in the end, that power line communication may well be the dominant technology due to economies of scale and governance perspectives (use of the network infrastructure). The newest developed standards within this category are G.9902 and 1901.2 [4]. Based upon the results DSOs are advised to choose to incorporate either one of these two standards into their products.

In the case that is studied, the core player is the DSO. The main decision that this DSO is confronted with is to choose a technology to communicate between the smart meter and the concentration point for collecting meter data. DSOs manage the powerline grids in countries and thus have a large amount of control over that technology. It might be the case that because the DSOs have control of the Powerline technology this is a reason for them to choose that technology for other purposes. Indeed, control by a core player of a technology might be a factor for adopting that technology. In future research this new factor may be taken into consideration in similar situations.

One of the limitations of this study is that the focus in solely on the Netherlands. The importance (weights) of the relevant factors may be different in other EU countries although the countries all have to comply with the same directives concerning smart meters. Future research could examine the reasons for these differences.

Furthermore, the focus is on competing technologies for a standard means of data communication between the smart meter and the concentration point for collecting meter data and the paper finds that powerline communication will have the highest chance to become the standard way of data communication. Still, a choice has to be made between the various standards that apply this means such as G.9902 and 1901.2. Future research could study this battle in depth.

Furthermore, studying the role of the technological field in relation to standard dominance is an area for future research. Another question for future research is how much time ahead each factor can predict support for a technology. The nine factors that were used in this study may constitute a short or medium predictive model which may explain that each standard receives an approximately equal value in Table 4. Future research could study which factors can predict support for a technology in the long run and could apply those factors for this case in order to find which technology has the best chance to achieve dominance.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2018.12.035.

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