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Gearbox versus direct drive - opening up the black box of technology characteristics

van de Kaa, Geerten; van Ek, Martijn; Kamp, Linda M.; Rezaei, Jafar

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Wind turbine technology battles: Gearbox versus direct drive - opening up the black box of technology characteristics

Geerten van de Kaa[a,*], Martijn van Ek[b], Linda M. Kamp[a], Jafar Rezaei[a]

[a] *Delft University of Technology, Jaffalaan 5, 2628BX, Delft, Netherlands*
[b] *Croonwolter&dros, Marten Meesweg 25, 3068AV, Rotterdam, Netherlands*

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ABSTRACT

This paper studies the battle between two types of wind turbines, the gearbox wind turbine and the direct drive wind turbine. Applicable determinants that affect technological dominance for the wind turbine drive trains case are identified. By applying the Best-Worst Method, the relative importance to the determinants to understand which of the two wind turbine drive train types has the highest chance of achieving success are allocated. The results show that energy cost and reliability are the most important determinants, and that at this moment both drive train types still have the potential to become dominant. A contribution is made to the literature on dominant designs by focusing on the energy sector; a sector that has only scarcely been studied before with respect to design dominance. Furthermore, weights for factors for the technology dominance for the case of technology battles for wind turbine technology were established.

1. Introduction

Often, when new innovative and high-tech sustainable technologies are developed, multiple technological options are developed simultaneously by competing (groups of) firms. For example, when the first wind turbines were being developed, both horizontal-axis wind turbines and vertical-axis wind turbines were being developed for about a decade until the horizontal-axis wind turbine became the dominant design (Gipe, 1991; Kamp et al., 2004). Such a process in which more than one option are being developed and ultimately one of them wins is called a 'technology battle', a 'battle for a dominant design' or 'market-based standardization' (Muto, 2017). Developing several options at the same time is inescapable as multiple companies might be working on competing technologies at the same time. This costs extra time and money. Actors who have invested in the option that did not become the winner, have to change to the other option. This involves so-called 'switching costs'. And policy makers that subsidize the development of sustainable technologies may find out that they have subsidized the 'wrong option'. Therefore, it is important to have insight at an early stage into which of the competing options is most likely to become the dominant design. A whole scientific field (Suarez, 2004; Schilling, 2002; Schilling, 1998; Garud and Kumaraswamy, 1993; Gallagher and Park, 2002; Gallagher, 2012) has developed around this issue. This scientific field does not make profound technical comparisons but assesses the competing technical options using a broad range of variables, including technical, economic, managerial and institutional variables. Both the selection of the relevant variables for the case under study and the assessment of the competing technical options using these variables are most often based for a large part upon interviews with experts. This paper describes such a research. It focuses on the battle between gearbox wind turbines and direct drive wind turbines.

This research contributes in several ways. Other studies that focus on technology dominance in relation to the wind turbine industry differ from this paper in a number of respects. These other studies are descriptive in nature, they focus on the first (entrepreneurial) stages of the technology dominance process as defined by Suarez (Suarez, 2004) and they do not focus on the question which are the determinants that explain the outcomes of these battles. Furthermore, in these studies the specific battle between the gearbox and direct drive has not been described yet. This specific battle occurs in the fourth stage of Suarez' technology dominance process. Instead, the focus in these studies has been on two topics. Part of the studies have focused on how wind power technologies became established in countries as a whole (Gipe, 1991; Nielsen and Heymann, 2012; Garud et al., 2019; Kamp, 2004). Thus, these studies focus on dominance of renewable energy technologies in general and its determinants. Other studies have focused on battles for design dominance resulting in technological paths that emerge within the early stages of the wind turbine industry (Kamp et al., 2004;

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

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Garud and Karnøe, 2003; Karnøe and Garud, 2012; Heymann, 1998; Kamp, 2002; Kamp, 2007), for example vertical-axis wind turbines versus horizontal-axis wind turbines and two-bladed wind turbines versus three-bladed wind turbines.

This paper analyses the battle between wind turbine drive trains and uses a quantitative multi-criteria decision making methodology to investigate the determinants for this specific battle. The following questions are raised:

1 What determinants affect the outcome of this technology battle?
2 What is the relative importance of these determinants?
3 How do the competing technologies score on these determinants?

The focus lies on the fourth stage of the dominance process defined by Suarez (2004); the decisive battle, and the research includes both technical, economic, managerial and institutional variables.

Besides contributing to the literature on technology battles in the wind industry as described above, this paper also contributes to the ongoing research on determinants for technology success (Suarez, 2004; Schilling, 2002; Schilling, 1998; Shapiro and Varian, 1998), and more specifically it contributes to prior research that attempts to establish importance of determinants for technology success (van de Kaa et al., 2019; Van de Kaa et al., 2019; Van de Kaa et al., 2014; G. Van de Kaa et al., 2017) by providing empirical data for the case of technology battles for wind turbine drive trains.

2. Case description

The wind turbine is a promising sustainable energy technology that is being developed and diffused rapidly. The total power generation capacity of wind turbines in the European Union has increased eleven fold in 15 years, from 13 GW in 2005 to 153 GW in 2016 (European Wind Energy Association 2017). Overall, in 2017, 11.6% of the produced energy in the EU came from power generated by wind (European Wind Energy Association 2018). Therefore, the share of wind power is continuously increasing and is likely to keep increasing in the future. Generally, two types of wind turbine drive trains can be distinguished, namely the gearbox and the direct drive wind turbine (Li and Chen, 2009). The first gearbox wind turbines emerged in the 1970s (Gipe, 1995), whereas the first direct drive wind turbines were only developed in the early 1990s (Polinder et al., 2006). Currently, the two technologies are competing to become the dominant design.

The gearbox wind turbine has a gearbox between the rotor and the generator which increases the rotational motion produced by the rotor before it is fed into the generator. The first constant speed gearbox wind turbines became available in the 1970s (Kamp, 2007; Gipe, 1995) and were often equipped with a squirrel-cage generator and a multi-stage gearbox (Polinder et al., 2006). Since the 1990s, most wind turbines have switched to the variable speed wind turbine with a multi-stage gearbox (Polinder et al., 2006; Polinder et al., 2013). This gearbox is connected to a relatively standard doubly-fed induction generator.

Since 1991, wind turbine manufacturers have developed wind turbines without gearboxes. This type of wind turbine is known as the variable speed direct drive wind turbine and was introduced to eliminate gearbox failure and transmission losses. The rotor is directly connected to the generator, implying that the generator speed is equivalent to the rotor speed. Due to the relatively low rotational generator speed, the generator requires a larger number of magnetic poles to achieve a sufficiently high output frequency. The direct drive category contains two types; the permanent magnet direct drive and the electrically excited direct drive. In the 1990s, the electrically excited direct drive was often used since permanent magnets were expensive. Later, when the permanent magnet prices dropped, they became more popular (Polinder et al., 2013). However, in 2011 during the permanent magnet crisis, the interest in electrical excitation increased again. Currently, both categories are applied successfully and are therefore relevant under the general term direct drive wind turbine.

In 2011, about 83% of the wind turbines that were operational were gearbox wind turbines (Ragheb and Ragheb, 2011) while the share of direct drive turbines was about 17%. Several scholars (Polinder et al., 2013; McKenna et al., 2016) have described trends in wind turbine drive trains and concluded that it is uncertain to which of these generator technologies the developments will converge to.

3. Literature on technology battles

Technology management scholars proposed several determinants of technology success in industries that are affected by network effects. Network effects refers to a situation whereby the economic value of a technology increases exponentially with the number of people adopting that technology. Such effects are especially apparent in industries where products are physically interconnected such as (smart) phones.

Evolutionary economists argue that technological change is an evolutionary process: Innovations change incrementally until a breakthrough technology is introduced which ushers in a period of major changes to the existing technology. This changes the technological field considerably, which results in a new technological paradigm (Tushman and Anderson, 1986; Dosi, 1982). In that paradigm, various alternative designs are developed and, eventually, one 'dominant design' will emerge (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978). Various scholars have focused on strategies for the creation of these 'dominant designs' such as the point at which to enter the market (Christensen et al., 1998; Suarez et al., 2014) and learning from partners (Klepper and Simons, 2000).

Other scholars have studied standards-based markets. In these markets, a technology that accrues a significant installed base early on can achieve success by forces such as network effects (Farrell and Saloner, 1985; M.L. Katz and Shapiro, 1985). Because of the existence of such effects, the value of technologies will increase the more it is used. Therefore, the amount of people that adopt a technology (its installed base) is a crucial determinant for its market success (Shapiro and Varian, 1998).

There are many examples of fierce technology competitions in the literature. Based on analysis of these battles, authors have proposed several determinants for technology success. For example, Cusumano (Cusumano et al., 1992) analysed the battle between VHS and Betamax and describes the importance of establishing connections with manufacturers of complementary goods, in this case video tapes. Gallagher (Gallagher and Park, 2002) concluded that availability of complementary goods in the form of video games increases installed base of gaming consoles and the other way around. Indeed, earlier, Schilling (Schilling, 1998) had already hypothesized this interrelation, and later this hypothesis was accepted (Schilling, 2002). Funk (Funk, 1998) studied technology battles in mobile telecommunications and points to the importance of early timing of entry. Khazam and Mowery (Khazam and Mowery, 1994) studied a technology battle in the computer workstation industry between reduced instruction set computers (RISC) and complex instruction set computers. Here, an open licensing policy was successfully applied, increasing the amount of complementary goods in the form of applications leading, in part, to the success of RISC.

Determinants for technology success have been incorporated in various frameworks such as the framework developed by Lee (Lee et al., 1995) and Suarez (Suarez, 2004). Suarez (Suarez, 2004) has also studied the relevance of factors in different stages of the dominance process. The first stage; R&D build-up starts when a firm conducts applied R&D. The second stage; technical feasibility, starts when a first prototype is ready. The third stage; creating the market, starts when a first commercial product is available. The fourth stage; the decisive battle, starts when a front runner appears in the market. Finally, the post-dominance stage starts when a dominant design has been established and it is in this stage that firms compete with their products that are based upon the dominant design. Suarez argued that in each stage, a specific set of factors for technology dominance are relevant.

While the Lee framework (Lee et al., 1995) (explicitly or implicitly) mentions 11 firm level determinants, the Suarez framework (Suarez, 2004) (explicitly or implicitly) mentions 15 firm level determinants. Van de Kaa et al. (Van de Kaa et al., 2011) offers the most complete framework, consisting of 23 firm level determinants. The 23 determinants are categorized into: characteristics of the technology, its supporters, their strategies, and other stakeholders.

The characteristics of the technology consist of:

- the quality of the technology
- (backwards) compatibility
- availability of complementary good
- flexibility (the extent to which the design can be adapted to changing user requirements).

The characteristics of the supporter of the technology include:

- financial strength (financial resources available),
- reputation and credibility
- operational supremacy (e.g. number of production facilities)
- learning orientation (the extent to which it can learn from earlier mistakes or from partners).

The strategies of the supporter of the technology include:

- timing of entry strategy
- the pricing strategy (lower prices of products that follow a certain design will entice users to adopt those technologies)
- appropriability strategy (the degree to which the design is protected)
- marketing communications (marketing campaigns can be used to increase demand for the design)
- pre-emption of scarce assets (by entering earlier, firms can gain access to scarce resources)
- distribution strategy
- commitment

Other stakeholders include

- installed base
- big fish (referring to a prominent stakeholder that has the influence to make technology an instant success)
- regulator (a stakeholder who can prescribe a technology)
- suppliers (e.g. of complementary goods)
- effectiveness of the formal standardization process (if any)
- characteristics of the network of stakeholders (such as its diversity in terms of industries that are represented)

This framework will be applied to the case of wind turbine technologies since it is the most complete framework to date.

4. Methodology

To answer the research questions posed in the introduction section, three methodological steps were applied. In research step one, the relevant determinants for technology dominance were selected for this case based on interviews with two experts and on literature that reports on the technologies (see Appendix A). The experts were selected based on their theoretical and fundamental knowledge about wind turbines and drive trains. A determinant is considered relevant if it is either (explicitly or implicitly) mentioned by at least one expert or in at least one of the papers. See Table 1 for background information of the experts.

In research step two, in order to determine the relative importance of the determinants in the model a multi criteria decision making study was performed, applying the Best-Worst Method (BWM). Using this methodology, the technology that had the highest chance of becoming dominant could also be determined. A BWM questionnaire was developed, which was completed by twelve interviewees from industry and academia. See Table 2 for background information of the interviewees.

It was ensured that every expert had comprehensive knowledge on the topic of the study. Both gearbox and direct drive wind turbine manufacturers were interviewed to even out a potential bias. For this same reason, also experts that were not related to either of the two wind turbine technologies were interviewed. Experts were selected in such a way to ensure a dataset that is representative for the wind turbine industry from multiple perspectives. In earlier research (van de Kaa et al., 2019; Van de Kaa et al., 2019; G. Van de Kaa et al., 2017), a similar approach was successfully applied to various other cases. In research step three, the final results of our study were presented to the experts and they were asked to examine the results and to provide a possible explanation for them, based on their expertise. A visualization of the procedures followed to obtain the output of the analysis is shown in appendix B.

In the remainder of this methodology section the focus is on explaining the BWM in detail. This method was chosen because it has a higher consistency and fewer comparisons, compared to other multi-criteria decision models (MCDMs), and uses only integers in the questionnaire. The BWM as used in this study can be shortly described as follows (Rezaei, 2015; Rezaei, 2016):

***Step 1*:** Determine a set of decision criteria $\{c_1, c_2, \ldots, c_n\}$

Relevant determinants for technology dominance (decision criteria) for the particular case under investigation were determined by conducting a literature review and conducting expert interviews (first round of interviews).

Step 2: *Determine the best and worst criterion from the main set of criteria* $\{c_1, c_2, \ldots, c_n\}$

A set of 12 experts were asked to select the most and least important determinant for technology dominance (second round of interviews).

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

The interviewees were asked to assign a number from one to nine to specify the importance of the most important determinant over the remaining determinants. This results in the best-to-others vector,

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

where

a_{Bj} indicates the preference of the best determinant B over determinant j.

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

The interviewees were asked to assign a number from one to nine to specify the importance of the other determinants over the worst determinant resulting in the others-to-worst vector,

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

Where

a_{jW} indicates the preference of determinant j over the worst determinant W.

Step 5: *Calculate the optimal weights* $(w_1^*, w_2^*, \ldots, w_n^*)$

Table 1
Background of respondents in first round of interviews.

Background	Job	Expertise (besides wind turbine technologies)
Academia	Researcher, Delft University of Technology	Electrical engineering, Electrical machines, Analytical modelling, Efficient FEM usage, Multi-objective optimization
Academia	Associate Professor, Delft University of Technology	Electrical machines and drives, Generator systems for renewable energy

Table 2
Background of respondents in second round of interviews.

Background	Job	Expertise
Academic	Researcher	Professor conducting research in wind energy.
Academic	Researcher	Researcher working in electrical engineering. Focus on study of network robustness for e.g., metro networks and power grids.
Academic	Researcher	Researcher working in electrical engineering. Focus on wind turbine generators.
Industry	Engineer	Reliability engineer working at a wind asset operations management company in north-western Europe. Focus on assisting wind farm owners, fund managers and wind project companies to maximize the revenues of their wind assets.
Industry	Consultant	Consultant in the wind energy sector. Focus on design review, training and operations & maintenance for wind developers, utilities and manufacturers.
Academic	Researcher	Researcher in electrical engineering.
Industry	Manager	Team leader in technical & operational support including for gearbox, generator repairs / replacement, and improvement projects to optimise production.
Industry	Manager	Manager responsible for wind resource assessment and other related topics for company projects.
Industry	Business controller	Senior business controller working at a power company.
Industry	Department manager	Head of offshore business development of a large power company.
Industry	Department manager	Head of primary structure design, offshore support structures at the wind power division of a large engineering multinational.
Industry	Chief technology officer	CTO at a company that specializes in wind turbines. The company's wind turbines are leading in the 250kW-1MW range.

Solving the following linear programming problem, the optimal solution is found:

$$\min \xi^L$$

s.t.

$$|w_B - a_{Bj}w_j| \le \xi^L, \text{for all } j$$
$$|w_j - a_{jw}w_W| \le \xi^L, \text{for all } j$$
$$\sum_j w_j = 1$$

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

Solving this model for the determinants for technology dominance per expert provided a set of weights, $(w_1^*, w_2^*, ..., w_n^*)$ for the determinants. The same process was applied to rank the two wind turbine drive train technologies. Final scores for both technologies were obtained by utilizing the following function (Keeney and Raiffa, 1976).

$$V_i = \sum_{j=1}^{n} w_j p_{ij}$$

5. Results

In research step 1, eight determinants for technology dominance were identified as relevant for the technology battle between wind turbine gearbox and direct drive, based on literature and expert interviews. *Brand reputation and credibility;* technological characteristics in terms of *total energy yield, cost of energy*, and *reliability; pricing strategy* (initial purchase price and the price of the subsequent service contracts); *pre-emption of scarce assets* (the scarce asset in this case is rare earth magnets that are used for permanent magnet direct drive generators); *commitment* of the wind turbines manufacturers; and the number of *suppliers* for wind turbine components (Polinder et al., 2006; Polinder et al., 2013).

In research step two, during the second round of interviews, our interviewees provided weights for the relevant determinants. The importance of the determinants and corresponding weights can be found in Table 3. The average weights based on the twelve experts that were interviewed are reported in the far right-hand column. All of the individual expert results proved to be consistent (after applying the steps to test for consistency as proposed by Rezaei (Rezaei, 2016)).

Table 3 shows that the consistency ratios (ξ^{L*}) of all experts are close to zero (max = 0.112), which means that the comparisons are highly consistent with the final weights and that the results are highly reliable. The results show that the most important determinant appears to be *cost of energy,* closely followed by *reliability*.

In research step three, these results were explained by the experts as follows. *Cost of energy* refers to two aspects. First, wind turbine manufacturers must compete with firms that offer other (renewable and non-renewable) energy technologies. They must ensure that wind energy is attractive in terms of price. The cost of wind energy should therefore be lower than that of other energy sources, for example, energy from gas-fired power plants and solar energy from PV panels. Secondly, firms must compete with other wind turbine manufacturers and consortia. One of our interviewees stated that the tender process for wind farms is mainly driven by the cost of energy. In these types of tenders, the consortium is responsible for delivering electricity at a fixed price for a prescribed period. Therefore, in the long term, the technology with the lowest cost of energy is likely to have an advantage over its competitors, and the lowest electricity cost is crucial for winning the tender.

Reliability is the second most important determinant. Wind turbines are positioned in a wide variety of landscapes varying from locations that are easily accessible to remote locations in mountainous areas or offshore. A wind turbine should be able to operate consistently in these specific locations. Breakdowns in major wind turbine components will shut down the turbine. Repairing major components can be a time-consuming and costly event, especially if the wind turbine is positioned in a remote location. Several experts explained that performing routine scheduled maintenance is not necessarily expensive but that unpredicted maintenance and unscheduled repairs as a result of poor reliability time-consuming and extremely costly (Polinder et al., 2013; McKenna et al., 2016). Implementing technologies like smart monitoring will increase overall reliability (McKenna et al., 2016).

The twelve experts also compared the two technologies for each separate criterion using a number between 1 and 9 (following the steps of BWM) divided by the sum of those two assigned numbers resulting in performance scores. Table 4 shows the average results obtained from 12 experts. The weighted score is obtained by multiplying the average global weight (Table 3) and the average performance score. Based on

Table 3
Weights assigned to the eight determinants by each interviewed expert.

Determinants	1	2	3	4	5	Experts 6	7	8	9	10	11	12	Average global weight
Brand reputation and credibility	0.048	0.027	0.058	0.077	0.083	0.069	0.180	0.082	0.051	0.036	0.033	0.083	0.069
Total energy yield	0.123	0.168	0.146	0.087	0.087	0.142	0.120	0.069	0.038	0.067	0.065	0.117	0.103
Cost of energy	0.281	0.288	0.365	0.334	0.341	0.318	0.271	0.295	0.407	0.292	0.377	0.259	0.319
Reliability	0.281	0.168	0.219	0.218	0.217	0.142	0.090	0.172	0.169	0.101	0.152	0.175	0.175
Pricing strategy	0.092	0.067	0.063	0.062	0.072	0.107	0.180	0.172	0.102	0.317	0.065	0.175	0.123
Pre-emption of scarce assets	0.027	0.084	0.063	0.026	0.087	0.085	0.072	0.027	0.064	0.081	0.065	0.088	0.064
Commitment	0.074	0.084	0.055	0.087	0.028	0.030	0.060	0.114	0.085	0.081	0.152	0.033	0.074
Suppliers	0.074	0.112	0.032	0.109	0.087	0.107	0.026	0.069	0.085	0.026	0.091	0.070	0.074
ξ^{L*}	0.089	0.049	0.073	0.103	0.093	0.109	0.090	0.048	0.102	0.112	0.079	0.092	0.087

Table 4
Ranking of alternatives during the technology battle.

Determinants	Gearbox wind turbine		Direct drive wind turbine	
	performance score	weighted score	performance score	weighted score
Brand reputation and credibility	0.414	0.029	0.586	0.040
Total energy yield	0.383	0.039	0.617	0.063
Cost of energy	0.665	0.212	0.335	0.107
Reliability	0.296	0.052	0.704	0.123
Pricing strategy	0.584	0.072	0.416	0.051
Pre-emption of scarce assets	0.633	0.041	0.367	0.023
Commitment	0.491	0.036	0.509	0.037
Suppliers	0.649	0.048	0.351	0.026
Total		0.528		0.472

the expert opinions, it can be observed that both technologies score about evenly. This can mean two things. Either the battle is not yet over, and both technologies have an equal chance of achieving market success or there is not one winner and the two wind turbine types co-exist in the market. In the discussion section below, these options will be elaborated upon and future scenarios will be discussed.

6. Discussion and conclusion

The realization of large-scale implementation of wind power can in part solve some of the grand challenges that our society faces today. For example, it can help reaching the sustainability goals defined by the United Nations. Therefore, many firms are developing and/or investing in different types of wind turbines to realize the large-scale implementation of wind power. To reduce the risk of investing in the 'wrong type' of wind turbine and thereby having to pay extra 'switching costs', an important question is which of these different options will turn out to become the dominant design. In this study two types of wind turbines are studied; the gearbox wind turbine and the direct drive wind turbine. The paper has not only analysed which technology will have the highest chances of achieving success but it has also analysed which factors affect the success of the alternative technologies. It turns out that the cost of energy and reliability were the most important determinants for technology success and that both technologies still have an equal chance of achieving success.

6.1. Main findings

A contribution is made to the literature on dominant designs (Suarez, 2004; Schilling, 2002; Schilling, 1998; Shapiro and Varian, 1998), and, in particular, to the literature that aims to understand determinants that affect technology dominance, specifically in the wind turbine industry, in three ways.

First, a contribution is made to the literature that focuses on technology dominance in relation to the wind turbine industry. That literature is descriptive in nature and mostly focuses on emergence of wind energy as a source of renewable energy in general or the technology competition in the first stages of the dominance process as defined by Suarez (Suarez, 2004). Furthermore, it does not identify the specific determinants that can explain the outcome of this competition and their relative importance. The current research focuses on battles for design dominance in the fourth stage of the technology dominance process and it applies a multi-criteria decision making method in order to identify the factors that determine the outcome of this technology battle and their relative importance.

Second, two factors were found that determine the technological characteristics: cost of energy and reliability are found to be the most important factors for technology success thus providing a first indication of which elements of competing technologies may affect their quality. Thus, a first contribution is made to opening up the black box of the factor technological characteristics in the literature on technology dominance.

Third, by studying the battle between direct drive and gearbox drive wind turbines further empirical proof of the notion that it is possible to explain and predict technology success was provided by identifying relevant determinants for technology dominance, determining their weights, and applying them to technologies that are vying for market success. Given the fact that network effects are low, it is expected that a single dominant technology will not emerge per se as these markets are not necessarily characterized by winner-take-all situations. In these markets, designs can co-exist. In the wind turbine market this appears to be indeed the case. Table 4 shows that the gearbox wind turbine has an overall score of 0.528 and the direct drive turbine has an overall score of 0.472. These results are in line with the current installed base of gearbox and direct drive wind turbines (Ragheb and Ragheb, 2011). According to some experts that participated in our study, each technology has its own technical advantages that might be more suitable in specific niche markets depending on accessibility of the site, turbine weight, etc. However, other experts indicated that the direct drive technology will eventually become the dominant technology. They come up with three arguments. First, the costs for the offshore support structure for direct drive wind turbines is lower than for gearbox wind turbines due to overall lower weight. Second, direct drive has more potential for further improvement. According to these experts, the gearbox wind turbine is approaching its maximum efficiency point, whereas direct drive turbines still have more possibilities for improvement. Third, for future wind turbines with higher power ratings than the current rating, the direct drive is more efficient since gearbox wind turbines require extra stages of gears, which leads to more gearbox losses.

There are more possible outcomes with regard to technology dominance though. If the technologies continue to co-exist, a new technology with superior performance might also enter the market and gain dominance. Although, to our knowledge, this has not yet occurred in the wind turbine market, it is a viable future scenario. Another possibility is that a hybrid design will emerge combining design elements of the gearbox and direct drive designs. Some of our interviewees commented that a design may be developed whereby the number of stages in the gearbox is limited to 1 (as opposed to several), combined with a generator type that is used in the direct drive turbine. This may put an end to the battle and create more certainty in the market.

6.2. Practical implications, limitations, and areas for future research

A practical implication for both policymakers and firms that follows from this study is that they now better understand which factors determine success for their technology and how they score on those determinants. Because some of the determinants can be directly influenced by firms or policymakers, they can use the results of this study to their advantage by influencing those determinants and thus increasing the likelihood that the technology that they are in favour of will be successful. For example, one factor that appeared to be relevant is the price of products that follow a certain design as this may entice users to adopt those products. Governments may influence that factor by subsidizing the product thereby decreasing its price. If governments would subsidize the adoption of the gearbox that would increase the weighted score of that factor in Table 4 increasing the overall total weighted score of the gearbox wind turbine (increasing its chances of achieving dominance).

A drawback of the used research methodology is that it is static. Experts were asked for their opinion on the relative importance of determinants and they were asked which technology will win the battle at one point in time. However, the relative importance of determinants could change over time, which might lead to other outcomes regarding which technology will win the battle. Therefore, an interesting avenue for further research would be a longitudinal research which follows one technology for a period of time and then investigates whether the relative importance of determinants changes over time and throughout the technology dominance process.

Author statement

Geerten van de Kaa, Martijn van Ek, Linda Kamp and Jafar Rezaei contributed equally to the article and were responsible for conceptualization, investigation, writing the original draft and writing, reviewing and editing subsequent versions.

Appendix A: Overview of the papers that were used as secondary data to identify the relevant determinants for technology dominance

1 Duan, Y., & Harley, R. G. (2009). Present and Future Trends in Wind Turbine Generator Design. *IEEE Power Electronics and Machines Wind Applications*, 1–6.
2 Cheng, M., & Zhu, Y. (2014). The state of the art of wind energy conversion systems and technologies: A review. *Energy Conversion and Management, 88*, 332–347.
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Appendix B: a visualization of the procedures followed to obtain the output of the analysis

Step	Procedure	Outcome
1: finding relevant determinants of technology dominance for the wind turbine drive trains case	Two experts were interviewed and the literature reporting on the wind turbine drive trains was reviewed. A determinant is considered relevant if it is mentioned by an expert or in one of the papers.	Relevant determinants of technology dominance for wind turbine drive trains (the eight determinants as mentioned in paragraph 1 of Section 5).
2. establishing the weights of the relevant determinants of technology dominance for the wind turbine drive trains case	Establishing weights for the determinants by comparing them utilizing steps 2 to 5 of the best-worst method as described in the methodology section (Section 4)	Weights of the relevant determinants of technology dominance for wind turbine drive trains (average global weights: last column of table 3)
3. establishing a ranking of the two wind turbine drive train technologies	Comparing the two technologies for each separate determinant using a number between 1 and 9 (following steps 2–5 of the best-worst method) and multiplying these with the average global weight of the determinant obtained in step 2 resulting in weighted scores per determinant. Adding up the weighted scores per technology.	Total weighted scores per technology (last row of table 4).

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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 international journal of standardization research and he teaches courses in strategic management, technology and strategy and standards battles.

Martijn van Ek is a technical trainee at TBI. He holds an M.*Sc.* from Delft University of Technology. He is currently involved in a two-year program consisting of three assignments at different companies within TBI Holdings B.V. In one project 1: he was responsible for the feasibility study to assess the automated insulation of prefab concrete walls in a semi-automatic production process at Voorbij Prefab. In project 2 he was responsible for the development of a business plan where solar panels, energy storage, and electric vehicle chargers are integrated into a local smart grid. This smart grid can be exploited via an as a service model for a wide variety of customers of Croonwolter&Dros | Smart Energy. Currently he is working in project 3 as a project engineer at the company Mobilis for the project Theemswegtracé. Additionally, he is involved in the stakeholder management of a large stakeholder in the area.

Linda Kamp is assistant professor in Energy & Industry. Within the MSc Sustainable Energy Technology (SET) she coordinates the Economics and Society profile. Within this MSc, she is member of the Board of Examiners. For three years, she was Chairperson of the Board of Studies of the MSc SET. She graduated in Technology and Policy (Utrecht University, 1996), where she completed a Master thesis on the system-dynamic modelling of sustainable land use. After that, she completed a PhD thesis on the development of wind energy in the Netherlands and Denmark (Utrecht University, 2002).

Jafar Rezaei is an associate professor and Head of Section Transport and Logistics. He did his Ph.D. at the faculty of Technology, Policy and Management (TPM), Delft University of Technology (TU Delft). He has a background in Operations Research, and has published in several peer-reviewed journals. He is the Editor-in-Chief of Journal of Supply Chain Management Science. In 2015, he developed the Best Worst Method (BWM).