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Towards sustainable energy technologies in the maritime industry: The dominance battle for hydrogen fuel cell technology

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ABSTRACT

This paper focuses on the determinants of establishing dominant hydrogen fuel cell technology designs in the maritime industry in Western Europe. By systematically studying the battle between the Solid Oxide Fuel Cell and the Proton Exchange Membrane Fuel Cell, utilizing the best-worst method it arrives at importance for factors for design dominance. It appears that 'fuel cell costs' is the most important factor: it received a global average weight of 0.18. This is the first time that factors for design dominance are studied in the maritime industry and the paper offers novel empirical material from a distinct sector. It also provides a first indication that the Solid Oxide Fuel Cell will have the highest chance to become the dominant design although the Proton Exchange Membrane Fuel cell is a close follower. The paper discusses contributions, implications, and future research recommendations for the literature on dominant designs.

1. Introduction

As natural disasters like the recent floodwaters in Valencia, Spain, or the extraordinary wildfires in Canada during the past summers have shown, global warming leading to climate change is undeniably one of the greatest challenges of the 21st century [1,2]. Over the last decade, the energy transition has gained worldwide momentum to address this existential threat [3]. As part of this sustainable transformation, many sectors are moving away from traditional fossil fuels like coal, natural gas, and oil. They are starting to focus on the use of green electricity. Consequently, the global demand for affordable and easily available energy is growing more rapidly every year [4]

One of the sustainable energy technologies undergoing rapid development that can pose a solution to this problem is the hydrogen fuel cell. Such a fuel cell is an electrochemical device that can transform the energy from hydrogen and oxygen into electrical power, with only water and heat as byproducts [5]. Hydrogen is considered the ideal substitute for oil and gas since the only product from its combustion with pure oxygen is the relatively harmless water vapor. Furthermore, hydrogen has an energy density of approximately 120 MJ/kg, which is significantly higher than that of natural gas (53,6 MJ/kg) and crude oil (44 MJ/kg) [6]. The higher the energy density of a substance, the less one needs it to acquire the same amount of energy. Fuel cells that use hydrogen as feedstock were studied from the 19th century onwards, but at that time they were not able to compete with fossil fuels [7]. More recently, interest in the technology resurfaced, and progress has been made in developing different types of hydrogen fuel cells with various operating conditions, efficiencies, and scaling-up potential [6].

It is not yet entirely clear what the future fuel cell will look like. There are currently two configurations available; based on low or high temperatures. However, it is still unclear which of these two design alternatives will be implemented in future products, and the decision for either design will determine, in part, the characteristics of the dominant design. This paper poses the question of what determines which of these two alternative configurations will be most successful, according to experts.

Many scholars have investigated factors that affect the chances that design choices are made and single dominant designs get established [8–10]. Some researchers state that dominant designs become established emergently, and that only afterward it can be explained why a design looks a certain way [11]. These scientists say that path dependencies can cause users to become locked into a technologically non-optimal design. Other scientists have studied various factors that lead to successful designs in terms of market acceptance [12–14]. They mainly focus on factors that positively affect the installed base [15]. Gallagher and Park [15] have studied several generations of battles between video gaming console designs and argue that when companies have enough resources (in terms of financial resources and reputation,

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for example) they can implement strategies that lead to a higher installed base [15]. This theme is also studied by standardization scientists and by scientists who try to better understand platform competition [16,17].

In this paper, we will utilize these insights and apply them to the case of the hydrogen fuel cell. This study will specifically investigate hydrogen fuel cell technologies in the maritime sector in Western Europe [18,19]. The research question that will be addressed in this study is: which factors determine the outcome of the battle for a dominant design for fuel cells for application in the maritime sector according to experts? To address this research question, primary and secondary data were collected to distill relevant factors for the geographical area, and the importance of these factors was determined by applying the best-worst method.

One of the factors that is often mentioned by both innovation management scholars that focus on dominant designs and standardization scholars concerns technological superiority [17], but only a few scholars attempt to zoom in on that factor. The case studied in this paper is still in an early stage and this factor often plays an important role in the early stages [8]. The focus will, therefore, mainly be on factors that determine the technological superiority of the design. This, e.g., relates to efficiency and lifetime. As a result, we will try to partially open the black box based on this research, which is one of its contributions. Although the factors and the technological comparison between technologies are available in the literature, the systematic comparison of the alternatives and the identification of weights for the factors is not, and this is where our contribution lies. More generally, we contribute to the literature on dominant designs by investigating factors for design dominance in an industry that has not been studied before: the maritime sector.

2. Hydrogen based fuel cells

The year 1839 marks the discovery of the fuel cell principle by Sir William Grove. This demonstrated the generation of electricity through the combination of hydrogen and oxygen. The discovery started a period of research and development in the late 19th and early 20th centuries, leading to breakthroughs like the Alkaline Fuel Cell (AFC) in 1939, that was, e.g., used by NASA on its Apollo missions, and the Proton Exchange Membrane Fuel Cell (PEMFC) in 1955 [20]. Fuel cells gained recognition in space exploration during the 1960s, providing reliable power and drinking water for astronauts. After that, during the 1980s and 1990s, fuel cell technology was applied to stationary and mobile power generation [20]. In the late 20th century and early 21st century, the need arose for a hydrogen refueling infrastructure that could support the emergence of hydrogen fuel cell vehicles introduced by major automakers like Toyota and Honda.

Various other sectors are expected to apply fuel cell technology in the future, further enhancing their efficiency and cost-effectiveness [21]. One of these sectors is the maritime industry. Since the maritime industry can be considered a conservative industry, adopting fuel cell technology is expected to be slower than in less conservative sectors such as the space industry. Still, the integration of hydrogen fuel cells in the maritime industry has witnessed some milestones. This started with research and development in cleaner propulsion systems [20], leading to the first demonstration of hydrogen fuel cell-powered boats, which can potentially reduce emissions and enhance efficiency in maritime transportation. However, a highly developed infrastructure is needed to successfully deploy these boats. Norway is a great example of a country where the expansion of hydrogen maritime infrastructure led to significant developments that showcase boats that use alternative fuels, like the MF Hydra and MF Tycho Brahe.

Currently, two configurations of fuel cells exist: a low-temperature hydrogen fuel cell, proton exchange membrane fuel cell (PEMFC), and a high-temperature hydrogen fuel cell, Solid Oxide Fuel Cell (SOFC) [22–24]. These two technologies will be discussed in more detail in the following paragraphs. The two fuel cell types are similar in some respects. For example, the efficiency of both hydrogen fuel cell designs lies in the same range [25]. Furthermore, both fuel cells operate using an electronically insulating electrolyte to separate fuel and air. The disadvantage of using this electrolyte is that a high activation energy is necessary and that it requires high operating temperatures. On the other hand, both fuel cells differ considerably regarding their respective operating conditions. A more detailed description of both fuel cells is given in Table 1.

2.1. PEMFC

PEMFCs are currently most frequently used in maritime transportation applications [22]. According to Lu et al. [26], PEMFCs are highly efficient as they are not limited by the Carnot cycle. This means PEMFCs do not rely on emerging temperature differences, and therefore, even at relatively low operating temperatures, it is possible to achieve a high efficiency. Especially with the emergence of sustainable alternatives and their high power density, zero CO_2 emissions, and high-efficiency PEMFCs have become a promising strategy.

Nonetheless, one hindrance has to be considered in using fuel cells based upon PEMFC, as the chemical element platinum which is used as one of the main resources for the fuel cell catalysts, is costly and rather scarce. This forms a nuisance to scale up the wide use of PEMFCs as a commonly used commodity in the maritime sector [27]. According to Nagar et al. [28], more research and development is required to scale up this technology, particularly in financial viability. Finally, a technological aspect that plays in favor of PEMFC is that it has a high power density [29].

2.2. SOFC

SOFCs make use of electrochemical conversion by oxidizing a fuel. A solid oxide or ceramic electrolyte is used. One of the main advantages of SOFC is that it operates at high temperatures, which causes a great electrical efficiency of 50%–60% [30], resulting in a longer lifetime. Due to the wide range of power, from milliwatts to megawatts [31], the scalability of SOFCs is significant. However, at the same time, the high operating temperatures and high output can be a downside due to thermal gradients across the fuel cell stack, which causes thermal stresses on the cell components, which affects its stability [32].

Unlike PEMFC, SOFCs do have attractive applications in the maritime industry as it has a high efficiency and the ability to use hydrocarbon fuels [33]. Furthermore, as of now, any SOFC can run efficiently on any hydrogen source due to its lack of contaminants and ease of

Table 1
Details of alternative technologies.

Aspect	PEMFC	SOFC
Electrolyte used	Platinum (scarce)	Solid oxide or ceramic (abundantly available)
Application area	Transportation sector	Domestic/industrial sector
Electrical efficiency	50%–60%	50–65%
Stability	Stable	Not stable
Cost-effectiveness	1700 to 2800 $/kW	800 to 1900 $/kW
Operating temperature	60 °C to 200 °C	600 °C to 1200 °C
Maintenance	Lower maintenance due to lower operating temperatures	Higher maintenance due to higher operating temperatures
Compatible fuels	Pure hydrogen (99.99% purity)	Hydrogen, methane, natural gas, and other types of (hydrocarbon) fuels
Manufacturing costs	Low	High
Power density	High (between 400 and 2000 kW/m^3)	Low (between 8 and 10 kW/m^3)

oxidation [32]. A disadvantage of the high fuel compatibility of the SOFC, is that when carbon-containing fuels are used to power the fuel cell, it is inevitable that CO_2 is formed and emitted. Therefore, when not operating solely on hydrogen, the SOFC does have a negative impact on the environment. If regulations regarding carbon emissions in the maritime industry become stricter, this high fuel compatibility may prove to be an advantage however, since this allows for the usage of low-carbon fuels as well and hence carbon emissions can be phased-out gradually. The carbon emissions related to these low-carbon fuels are significantly lower than those contributed to diesel used in combustion engines in the maritime sector [34].

2.3. On-board hydrogen storage

Next to a hydrogen fuel cell, a sufficient amount of hydrogen needs to be stored on-board to ensure a continuous operation. Three main techniques for on-board hydrogen storage are commonly identified [35,36]: compressed hydrogen, liquefied hydrogen and metal hydride materials. Compressed hydrogen, in which gaseous hydrogen is pressurized in a range of up to 70 MPa, is seen as the most mature and feasible way to store hydrogen on-board [34,36,37]. Due to the spatial limitations on a ship and the relatively low storage density of compressed hydrogen, an approach of liquefied hydrogen storage may result in a higher power density. Liquefied hydrogen can be obtained by cooling gaseous hydrogen to below minus 253 °C [38]. The storage tanks on-board of the vessel need to be kept below this temperature constantly, which can be considered as a power intensive process. A more convenient way to store liquefied hydrogen is hydrogen in the form of a carrier, like ammonia (NH_3), methanol (CH_3OH) or via a Liquid Organic Hydrogen Carrier (LOHC). At room temperature and atmospheric pressures, both ammonia and methanol are a liquid and hence both can be easily stored in tanks on-board of a ship, without the necessity of pressurizing or cooling [34]. The same is true for most LOHC's, although this specific technology is quite novel and not well developed. On the other hand, ammonia is already a widely available commodity in the fertilizer industry, while methanol is an important compound in many industrial chemical processes. Unlike methanol, the current state-of-the-art hydrogen fuel cells do not support a feed-in of ammonia, although NH_3 can be considered as a promising future sustainable fuel source [35]. On-board hydrogen can also be stored in the form of a metal hydride. This form of hydrogen storage is reversible and exhibits a good storage density, while the costs of the metals that are being used are usually high and the system is susceptible to impurities in the hydrogen gas. Due to the maturity of the technology, it is assumed that the on-board hydrogen is compressed in storage tanks for both PEMFC and SOFC technologies.

2.4. Safety & regulations

Regarding the use of hydrogen on-board a maritime vessel, several safety concerns may arise. Hydrogen, when used in gaseous form, is colorless and odorless, which makes it difficult to detect leakages in pipelines or around valves [36]. Furthermore, hydrogen gas has a high flammability and a lower minimal ignition energy than methane and propane. In principle however, hydrogen only becomes reactive or explosive when a reactant agent is present [36]. When hydrogen gas is exposed to an open atmosphere, it rapidly diffuses on account of its buoyancy and therefore the threshold concentration for flammability will not be reached.

The aforementioned intrinsic properties of hydrogen lead to several safety concerns when stored on-board of a maritime vessel. Generally, three main safety concerns can be identified [35,36]: hydrogen embrittlement, hydrogen permeation and composite material failure. Hydrogen embrittlement is the phenomenon in which the mechanical properties of metallic tanks or pipes decrease due to enduring hydrogen exposure. Hydrogen permeation occurs on account of the small size of the hydrogen molecules and concerns the leakage of hydrogen through the walls of the tank or via microcracks in the materials. Lastly, exposure to hydrogen also leads to the failure of composite fiber materials of which the storage tanks are comprised. Although a lot of research has already been conducted to improve the storage tank materials and minimize safety concerns, this is, however, an ongoing process.

Due to the safety concerns regarding hydrogen gas, it is to no surprise that specific regulation around this topic already exists, while new legislation is being prepared. Already in 2015, the International Maritime Organization (IMO) adopted the *"International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels Including Hydrogen"* [34]. Furthermore, the Norwegian and German DNV-GL have come up with a comprehensive list of requirements for the usage of fuel cells onboard a ship [34]. Next to the legislation regarding hydrogen powered maritime vessels, there already have been several successful and safe pilots with both SOFC and PEMFC, like Nemo H2 in Amsterdam or the Viking Lady in Norway [34,35,39]. Furthermore, studies into hydrogen fuel cell risk scenarios as conducted by Aarskog et al. [40] show that the risk of sustaining casualties on-board of a hydrogen powered vessel are well below the acceptable risk tolerance levels.

3. Method

To address our research question, we gathered both secondary and primary data. Secondary data consisted of key academic papers that examined factors influencing the success of standards for SOFC and PEMFC technologies while primary data was collected through expert interviews (details of the experts are provided in Table 2).

The secondary data search focused on the keywords "SOFC" and "PEMFC,". Papers that studied these technologies in the maritime environment were analyzed. However, due to the novelty of this technology in the maritime sector, papers discussing broader factors related to fuel cells were also considered, provided they were relevant. Factors were regarded as significant if explicitly or implicitly mentioned in the literature.

The selection of experts for this study was guided by three key criteria to ensure their relevance and expertise: expertise, certification, and social acclamation [41]. With respect to expertise, all experts have at least seven years of professional experience in areas directly related to the study, such as the maritime industry and hydrogen fuel cell technologies. Regarding certification, all selected experts possess a minimum of a master's degree. Lastly, social acclamation was established through peer recommendations, with experts being suggested by other professionals in the field.

Finally, the process yielded 21 papers, from which initially 9 key factors were identified and are presented in Table 3. A detailed overview of the factors that match the sources from the literature review, is presented in Appendix A. During the expert interviews, these factors were reviewed and adjusted. Notably, the 9th factor, performance, was

Table 2
Details of interviewees.

Expert	Expertise	Background	Years of experience since graduation
1	Alternative propulsion technologies for ships, focusing on fuel cells, focusing on SOFC and PEMFC	Academic	10
2	Performance and scalability of electrochemical technologies; fuel cells, transport, and energy systems	Academic	12
3	Aero-engine technology, combustion engines, hydrogen combustion aircraft	Academic	23
4	Sustainable shipping	Industry	7
5	Hydrogen racing, hydrogen fuel cell systems	Industry	8

Table 3
Factors and definitions.

Factor/subfactor	Definition
Fuel compatibility	Considers the types of fuels that can be used with each fuel cell technology. Some fuel cells are designed to work with specific fuels, while others are more versatile. The higher the number of fuels with which the fuel cell technology is compatible, the more attractive the fuel cell technology becomes, increasing its chances of becoming dominant.
Efficiency	Assesses how efficiently the fuel cell converts the energy from the fuel into electricity. Higher efficiency is generally desirable as it minimizes fuel consumption and emissions, hence the higher the efficiency of the fuel cell, the higher the chances that it will become dominant.
Operating temperature	Different fuel cell technologies operate at different temperature ranges. This criterion considers the temperature requirements and how they align with the maritime environment. Fuel cells operating temperatures need to be kept low in order to maintain lifetime and efficiency in place, and therefore, a design that has a higher operating temperature will have a lower chance of becoming dominant.
Lifetime	Evaluates the expected lifespan of the fuel cells. Longer lifetimes can lead to lower maintenance costs and better overall value, so a fuel cell that has a longer average lifetime will have a higher chance of becoming the dominant design.
Power density	This factor refers to the amount of power a fuel cell can produce per unit of volume or weight. Higher power density can be important in applications with limited space or weight constraints as it means a longer vessel range can be accomplished. Also, power density can influence efficiency. So, when a fuel cell guarantees a higher power density, the chances will increase that it will achieve dominance.
Fuel cell costs	Assesses the initial and ongoing costs associated with each type of fuel, including manufacturing, installation, and maintenance costs. The higher the costs, the lower the chances that the fuel cell will achieve dominance.
Scalability	Considers how easily the fuel cell technology can be scaled up to meet different power requirements within the maritime sector. A higher scalability will positively influence the chances that the design will achieve dominance. SOFCs are typically more rigid and bulkier, making them more suitable for larger vessels with more fuel purposes. PEMFCs are more compact and suited for smaller vessels but have limitations in terms of scalability and power output, making them more ideal for smaller vessels.
Safety	Evaluates the safety features and risks associated with each type of fuel cell. Safety is especially critical in maritime applications, where there are inherent risks or environmental concerns. The safer a fuel cell design is, the higher the chances that it will achieve dominance.
Performance	Concerns the design's reliability, availability and maintenance (these three aspects are 'subfactors' and explained in Table 4).

further elaborated and divided into three sub-factors (detailed in Table 4), resulting in a total of 9 factors, under which 3 sub-factors.

Subsequently, we performed a best-worst method (BWM) investigation to assess the importance of each relevant factor. The BWM was chosen because it results in more reliable and consistent results and requires fewer comparisons than other MCDM methods (Rezaei 2015). Finally, expert 1 assigned performance scores to each factor for the two alternatives (see section 2), which were multiplied by the corresponding factor weights to find out which alternative would have the best chances of achieving success in Fig. 1, the methodological steps are illustrated.

Table 4
Subfactors and definitions.

Performance – reliability	Concerns the system's ability to perform its required functions, and not causing breakage.
Performance – availability	Considers to what degree all components of the system are available when needed.
Performance – maintenance	Concerns the actions that are taken to maintain the system's functionality and the ability to repair it to operational status.

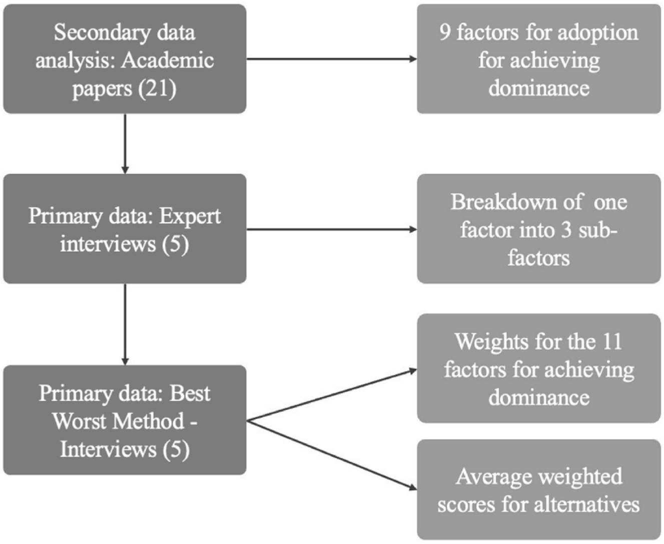

Fig. 1. Research flow diagram.

To determine the weight of the factors, we applied the linear version of the best-worst method. The 9 factors are compared with each other. For one of the factors, performance, we zoom in and compare the 3 subfactors using the same method. The steps are indicated in the following section.

Step 1 involves drawing up a list of relevant factors for the case. By reading relevant literature and interviewing several people, we arrive at a list of relevant factors. In step 2 we ask the expert to indicate what they think is the most important and least important factor. In step 3 we ask the expert to compare the most important factor with all the other factors. The preference of factors over other factors is determined by assigning a number ranging from 1 to 9. When an expert chooses to assign a 1, this means that the most important factor is equally important to the factor under consideration, while when a 9 is assigned, this means that the expert finds the most important factor to be extremely more important as compared to the factor under consideration. This exercise results in the best-to-others vector: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})\, w$. In this vector, a_{Bj} is the preference of most important factor (best factor) B over the other factor ***j***.

In step 4 we ask the same expert to compare the least important factor with the other factors resulting in the others-to-worst vector: $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$. In this vector, a_{jW} is the preference of factor *j* to the least important factor (Worst factor) W. This is the information we need to calculate the optimal weights using the linear programming problem as presented in Rezaei [42]:

$$\xi$$

s.t.

$$\left|w_B - a_{Bj}w_j\right| \le \xi, \text{for all j}$$

$$\left|w_j - a_{jW}w_W\right| \le \xi, \text{for all j}$$

$$\sum_j w_j = 1$$

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

4. Results and discussion

Relevant factors that were the result of our primary and secondary data analysis are listed and defined in Table 3. In Table 4 the performance factor is subdivided into 3 ‘subfactors’ with accordingly their definitions.

Table 5 presents the outcome of the best-worst method. It can be observed that fuel cell costs is the most important factor (0.18) followed closely by efficiency (0.15) and power density (0.13). All consistency levels were acceptable. Table 6 presents the assigning of performance scores to each alternative. SOFC receives a total score of 5.45 while PEMFC receives a score of 5.15.

5. Discussion

5.1. Interpretation of the results

From Table 5, we can conclude that the most important factor for design dominance is fuel cell costs. The importance of this factor is also discussed in the literature thoroughly, where it is stated that costs are an important factor and that for the coming years, fuel cell systems will likely remain expensive [18]. Alaswad et al. [43] stressed that the electricity produced by hydrogen fuel cells is too expensive as compared to a conventional combustion engine. Other research suggests that PEMFC will be the more expensive type of fuel cell since it needs to be supplied with high-quality hydrogen [22]. Since the compatibility of a SOFC is high, it can be supplied with lower-grade fuels, which lowers its operating costs [18,25,43].

From Table 6, we can conclude that SOFC scores lower (and thus less favorable) on this factor, according to the experts. SOFCs tend to be more expensive than PEMFCs due to their complex ceramic construction and higher operating temperatures. Therefore, upfront costs are significantly higher for SOFCs, which translates into a lower score for costs for SOFCs. Expert 3 addresses that PEMFCs are mostly cost-effective for smaller maritime applications because of their space and weight constraints. Furthermore, expert 1 indicated that SOFC is less mature than PEMFC, and therefore installation is more expensive at the moment. The expert also pointed to the fact that both fuel cells depend on expensive hydrogen, but SOFC can also use alternative fuels (LNG, methanol) and that has a positive influence on its compatibility and costs. From an energy transition perspective, according to expert 3, “this transition is emerging very slowly due to scarcity in resources. Compatibility, therefore, makes it important for a fuel cell to win the battle for dominance.”

As already derived from the literature (see the supplemental file), efficiency scores highest in SOFC. All experts agree with this and have addressed the fact that SOFC could be very useful in ocean-going vessels once it crosses the implementation barrier. On the other hand, the more mature PEMFC could be used in short sea vessels. Only expert 3 shows himself more sceptical toward PEMFC, as “PEMFC efficiency will not be high enough for usage in the maritime sector, SOFC for that case is more efficient.” The addressed difference between ocean-going vessels and short-sea vessels may be substantiated by power density. The importance of range, and thus power density, lies within the application of the hydrogen fuel cell. For close distances and short-coast applications in the maritime sector, lower power density is needed than off-coast, longer distances. In the initial phase, hydrogen fuel cells will be mostly important for low, short coast distances applications, and thus, a lower power density (lower costs) is the most obvious choice.

5.2. Theoretical contributions and practical implications

This paper makes a theoretical contribution to the literature on dominant designs and de-facto standards in various ways. First, in line with previous research, it finds additional empirical evidence that the outcome of battles for design dominance can be influenced by determinants [44,45]. In other words, the paper replicates earlier findings and provides empirical proof that the fuzzy processes occurring between technological discontinuities and dominant designs are possible to explain and even predict. Furthermore, although the technologies have previously been compared regarding their economic viability, energy efficiency, and contribution to sustainability [38,46,47], this paper takes the research further by focusing on criteria that determine design dominance. It also is the first time that hydrogen fuel cell technologies are compared in a systematic way utilizing the BWM method in the context of the maritime industry in Western Europe. Furthermore, the paper opens up the black box of the factor of technological superiority by zooming into its constituents.

The framework of Suarez [8], proposes an integrative framework for understanding the process of achieving dominance when battles arise between different technological designs. The battle for a dominant design for fuel cell applications in the maritime sector is still in its infancy. Applying the integrative framework of Suarez to our case, it can be concluded that the battle between PEMFCs and SOFCs within the maritime transportation sector is located in phase 3 as the first commercial product (MF Hydra) is available. Strategic maneuvering is intuitively seen as the most important factor [8]. Our research confirms this intuition for the case of the maritime industry as one aspect of strategic maneuvering concerns the pricing strategy, which is related to the factor of cost-effectiveness.

It appears that the experts indicate that SOFC has a higher chance of achieving dominance. Our results can be used to investigate how the alternative PEMFC can reach dominance. This could be accomplished by attempting to change the values of factors. For example, PEMFCs efficiency might be improved. It is currently rated at 5.33 while SOFC efficiency is 7. As indicated by expert 1, in theory, PEMFC can be as efficient as SOFC, but the reactions are slower at low temperatures. PEMFC is often used at lower temperatures than SOFC, and therefore, its efficiency is lower. Therefore, SOFCs achieve around 65% efficiency while PEMFCs reaches roughly 50–60%.

We have found that cost effectiveness is the most important factor and SOFC scores lower on this aspect. Earlier research has also showed the importance of energy costs which is related to cost effectiveness. Van de Kaa et al. [48] mentioned in their research on wind turbine technology battles the *cost of energy*. It mentioned two aspects of the cost of

Table 5
Final results.

Categories/factors	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Local average weight	Global average weight
Fuel compatibility	0,04852	0,10229	0,1190	0,09576	0,170999	0,11	0,09
Efficiency	0,16983	0,20458	0,1785	0,04788	0,191518	0,16	0,15
Operating temperature	0,02426	0,05845	0,0714	0,02736	0,047880	0,05	0,05
Lifetime	0,16983	0,06819	0,08925	0,07661	0,095759	0,10	0,10
Power density	0,08492	0,02923	0,29324	0,12768	0,184679	0,14	0,13
Fuel cell costs	0,27901	0,08183	0,04462	0,31464	0,111719	0,17	0,18
Scalability	0,11322	0,06819	0,1190	0,05472	0,051984	0,08	0,09
Safety	0,04246	0,05114	0,0595	0,19152	0,05928	0,08	0,09
Performance	0,06793	0,33609	0,0255	0,06384	0,086183	0,12	
Reliability	0,72619	0,54167	0,54167	0,54167	0,541667	0,59	0,07
Availability	0,07143	0,16667	0,29167	0,16667	0,291667	0,17	0,02
Maintenance	0,20238	0,29167	0,16667	0,29167	0,166667	0,24	0,03

Table 6
Performance scores.

	Performance scores	SOFC					Average weighted score	Performance score	PEMFC					**Average weighted score**
	expert 1	expert 2	expert 3	expert 4	expert 5	average Performance score		expert 1	expert 2	expert 3	expert 4	Expert 5	**Average performance score**	
Fuel compatibility	3	3	6	7	9	5,6	0,60	7	1	3	2	1	2,8	0,19
Efficiency rowhead	6	9	7	8	9	7,8	1,26	5	7	4	7	7	6	0,94
Operating temperature	1	3	7	1	8	4	0,23	1	3	4	1	6	3	0,16
Lifetime	7	7	4	8	8	6,8	0,69	8	7	6	4	7	6,4	0,68
Power density	6	4	4	5	3	4,4	0,62	3	4	6	4	8	5	0,85
Fuel cell costs	9	5	4	2	2	4,4	0,79	9	5	6	4	7	6,2	1,05
Scalability	8	4	4	7	4	5,4	0,46	5	6	4	7	8	6	0,46
Safety rowhead	2	4	6	6	7	5	0,45	2	5	6	7	7	5,4	0,50
Reliability	4	6	5	8	6	5,8	0,38	4	7	7	5	8	6,2	0,42
Availability	4	9	6	2	3	4,8	0,13	4	6	4	8	8	6	0,13
Maintenance	4	8	5	5	7	5,8	0,21	4	8	7	5	7	6,2	0,21
							5,82							**5,60**

energy that could also be applied in the case of hydrogen fuel cells. First, hydrogen fuel cell manufacturers must compete with firms that offer other (non-renewable and renewable) energy. Therefore, in terms of price, hydrogen fuel cell manufacturers should provide adequate and accurate pricing on their products. Secondly, hydrogen fuel cell manufacturers must compete with other hydrogen fuel cell manufacturers. In the longer term, the technology with the lowest cost of energy is likely to have an advantage over its competitors [48].

However, although the initial investment costs of SOFCs are higher, with a longer lifetime, these costs could be balanced out. The supplemental file already states the higher maintenance for SOFCs due to their higher operating temperature. Putting a focus on improving the lifetime of SOFCs might decrease the overall costs and will contribute to the increase of SOFCs' chances of achieving dominance even further. Interestingly, PEMFC scores higher then SOFC on the most important factor while it still has a lower chance of achieving dominance.

6. Conclusion and future research directions

This paper has focused on factors that affect the establishment of dominant hydrogen fuel cell technology designs in the maritime industry in Western Europe. In this area there are ample possibilities for future research. For example, in the maritime sector, a distinction can be made between short and long-distance shipping. Vessel sizes depend on application and short or long-distance navigation. Various experts foresee that it is more likely that PEMFC will prevail over SOFC for shorter distances. For example, they expect that PEMFC technology will have a higher chance of achieving adoption for applications related to inland shipping due to its lower operating temperature and the fact that it is an already proven technology. Furthermore, expert 1 indicated that smaller and inland shipping will be operated best with PEMFC, as hydrogen is easier to supply near the coast. On the other hand, it is believed that SOFC will probably come out as the dominant technology for longer-distance shipping on account of its larger fuel compatibility, which makes it a more flexible design. Future research could, therefore, investigate to what extent factor relevance and importance differ depending on vessel size and type. Additionally, this research focused on Western Europe. Future research could study other regions and determine whether the importance of the factors differs depending on the region.

Future research can also focus on relations between factors for design dominance. For example, in our case, lifetime is related to efficiency and operating temperature. A high efficiency in combination with a low operating temperature in the fuel cell results in a longer lifetime. In that respect, PEMFCs are highly efficient; they have more maintenance and are more sensitive to impurities and operating conditions and, therefore, have a shorter operational lifetime when compared to SOFCs. Furthermore, expert 4 indicated that performance, power density, efficiency, and compatibility/scalability could be directly related to the factor of cost-effectiveness. For example, he indicated that the better the performance or the higher the power density, the lower the costs of the fuel cell will be. Furthermore, expert 1 indicated that PEMFC is much more mature which results in lower transition costs and makes integration of the system easier. This influences scalability in a positive way for PEMFCs. Furthermore, expert 2 indicates there might be a strong link between reliability and material availability and costs: "high-temperature systems (SOFC) have risks of breaking when there are large temperature swings." Finally, expert 4 argued that power density influences the efficiency and costs in terms of both CAPEX and OPEX.

Additionally, when sustainable technologies such as SOFCs become dominant, this can negatively impact the environment due to the variety of fuels that can be used. It can also be observed for, e.g., electric cars as CO_2 emissions during the manufacturing of batteries are high. Future research can study the (negative) consequences of design dominance of sustainable technologies relating to, e.g., the environmental impact.

Finally, future research can investigate the role of the regulator. With the right regulations, hydrogen fuel cells have sufficient playgrounds to develop and enter a greater market. The Paris Agreement of 2015 played an important role in decision-making and regulation-making in hydrogen-innovative countries, enabling sustainable technologies to develop and receive more subsidies.

CRediT authorship contribution statement

K.T. De Graaf: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **I.H.E. Hus:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **H.J. Van Leeuwen:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **G. Van de Kaa:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.12.162.

Sensitivity: general.

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