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Techno-Economic Challenges of Fuel Cell Commercialization

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ABSTRACT

As resource scarcity, extreme climate change, and pollution levels increase, economic growth must rely on more environmentally friendly and efficient production processes. Fuel cells are an ideal alternative to internal combustion (IC) engines and boilers on the path to greener industries because of their high efficiency and environmentally friendly operation. However, as a new energy technology, significant market penetration of fuel cells has not yet been achieved. In this paper, we perform a techno-economic and environmental analysis of fuel cell systems using life cycle and value chain activities. First, we investigate the procedure of fuel cell development and identify what activities should be undertaken according to fuel cell life cycle activities, value chain activities, and end-user acceptance criteria. Next, we present a unified learning of the institutional barriers in fuel cell commercialization. The primary end-user acceptance criteria are function, cost, and reliability; a fuel cell should outperform these criteria compared with its competitors, such as IC engines and batteries, to achieve a competitive advantage. The repair and maintenance costs of fuel cells (due to low reliability) can lead to a substantial cost increase and decrease in availability, which are the major factors for end-user acceptance. The fuel cell industry must face the challenge of how to overcome this reliability barrier. This paper provides a deeper insight into our work over the years on the main barriers to fuel cell commercialization, and discusses the potential pivotal role of fuel cells in a future low-carbon green economy. It also identifies the needs and points out some directions for this future low-carbon economy. Green energy, supplied with fuel cells, is truly the business mode of the future. Striving for a more sustainable development of economic growth by adopting green public investments and implementing policy initiatives encourages environmentally responsible industrial investments.

1. Introduction

As the world population grows and fossil fuel energy supplies gradually decline, the world's energy supply may not meet the increasing demands or sustainable environmental targets. Therefore, there is an increasing need to ensure future energy security and a sustainable environment in many countries. Energy security is defined as "the uninterrupted availability of energy sources at an affordable price" by the International Energy Agency (IEA) [1]. Many countries have made efforts to develop a low-carbon economy and green industries as long-term objectives in order to ensure an energy supply that aligns with their economic development and sustainable environment goals [2,3]. There are two ways to achieve a low-carbon economy: One is to increase the share of green energy to meet increasing energy demands, and mitigate greenhouse gas (GHG) emissions by reducing fossil fuel dependency; the other is to save energy and reduce emissions by increasing the efficiency of existing energy systems.

The substantial development and integration of renewable energy can lead to a low-carbon green economy and to new business opportunities. A wide range of renewable resources have been developed such as wind energy, solar energy, bioenergy, and tidal energy [4–6]. While every type of renewable energy has its advantages and disadvantages, combining them with existing fossil fuel systems increases the complexity of managing energy systems and the difficulty for governments to direct policy and investment. Therefore, analysis of any single type of energy system alone is no longer sufficient in order to understand a country's energy security needs and future energy direction as a whole; rather, a systematic and rigorous understanding of a wider range of energy availability and diversity is required. In most countries, fossil

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fuel—including petroleum, natural gas, and coal—still dominates. For example, the US Energy Information Administration (EIA) reported that fossil fuels represented 79.78% of the total energy consumption in the United States in 2011 [7]. Therefore, there is a great deal of room for energy saving and reducing emissions, which can be achieved by improving the energy efficiency of existing energy systems. Because of their high thermal efficiency in converting energy, fuel cells can be an ideal alternative to the existing thermal energy systems, since their efficiency can be double that of traditional engines. Therefore, fuel cell technology can play an important role both in providing renewable energies and in saving energy and reducing emissions in traditional systems (Fig. 1).

As fuel cells scale up from their prototype phase to the product deployment phase, many considerations are required in order to ensure a sufficient capital return along with a net positive life cycle assessment. However, an adequate capital return has not been achieved without the benefit of government subsidies. In our series of publications, we analyzed and confronted these critical questions of fuel cell scaling-up [8]. We clarified the ambiguous, "chicken versus egg" problems of hydrogen fuel, a lack of hydrogen infrastructure, and fuel cell market penetration. Hydrogen infrastructure is not a key impediment to fuel cell technology. The hyperbole around fueling infrastructure is misleading for the fuel cell markets. On the other hand, the reliability of fuel cells might be more crucial than their durability for end-users' acceptance of the technology. However, it receives little attention [8]. We investigated issues of fuel cell scaling-up and introduced the criteria and theory for fuel cell scaling-up [9–12]. The goals and criteria of flow-field designs were recommended to improve fuel cell flow fields. We also suggested an integrated approach to address the issues of fuel cell scaling-up [13].

As a part of our series of studies on fuel cell scaling-up, the main objective of this paper is to analyze the techno-economic challenges of fuel cell commercialization through unified learning of the institutional barriers. We will examine life cycle and value chain activities of components, manufacturing, and assembly, and investigate end-use sectors. This will result in a better understanding of these challenges so that governments can make better-informed policies on how to develop low-carbon economies and technologies by encouraging more efficient use of resources and environmentally friendly energy. The secondary objective is to analyze a potential role for fuel cells in future low-carbon economies and discuss its potential to lead to a greener industrial sector.

2. Potential role of fuel cells in a low-carbon economy

Fig. 1(a) shows a traditional business chain of fossil fuels. Fossil fuels, internal combustion (IC) engines and boilers, and end-users are the main components of this traditional economy. Fig. 1(b) shows a new economic mode with any type of green energy as an alternative energy source to existing fossil energy. As alternative energy sources, every type of renewable energy needs to provide the same functions and reliability as the current fossil fuel model. Therefore, Fig. 1 illustrates two approaches through which fuel cells could play a crucial role in the low-carbon technology and economy. First, fuel cells can be used as a new energy-storage technology in a renewable energy supply chain, as in Fig. 1(b). Second, fuel cells can be used as a highly efficient engine technology to replace the traditional IC engine, turbine, or boiler for energy conservation and emission reduction, as in Fig. 1(a). However, very few studies have been performed on the role of fuel cells and green energy sources in the low-carbon economy as a whole.

2.1. Fuel cells and rechargeable battery packs

Developing renewable energy is the key element in the creation of low-carbon technology for green industries. In general, wind, solar, and tidal energy is the primary generator of electricity in the renewable energy business chain (Fig. 1(b)). This electricity

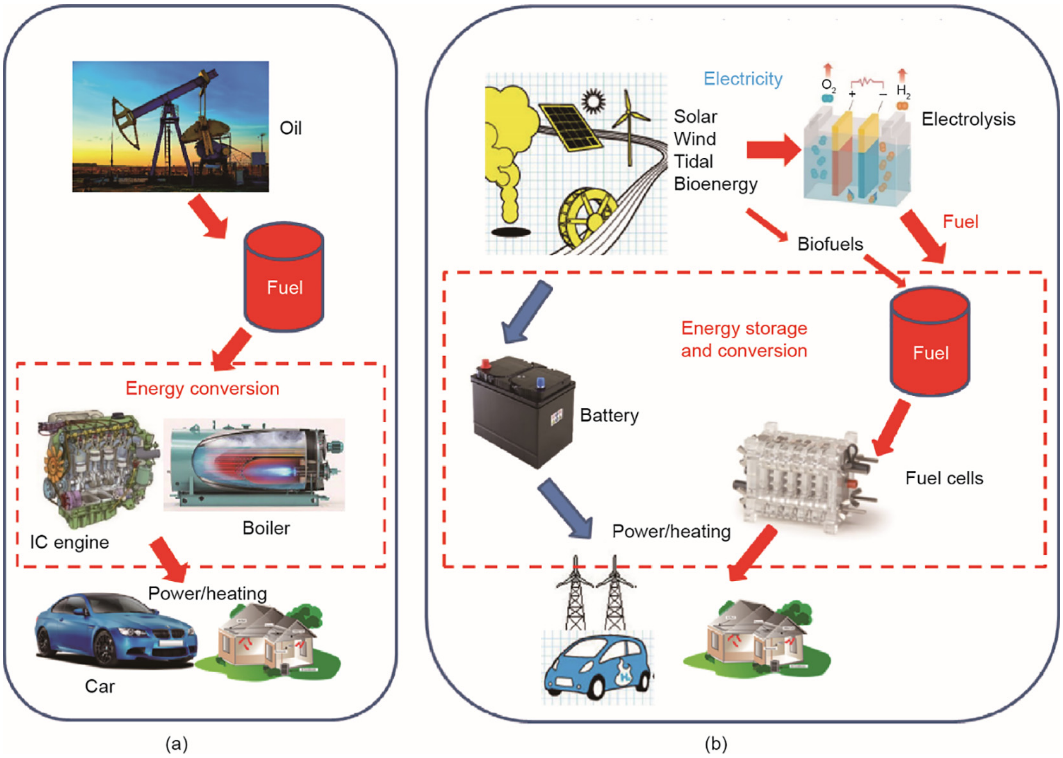

Fig. 1. The energy economy. (a) Fossil fuels energy economy; (b) renewable energy economy. IC: internal combustion.

can be used for power requirements that range from driving cars to heating houses. However, renewable energy is often dependent on the season, weather, or geological conditions, and its temporal and spatial distributions are very heterogeneous. The heterogeneity of renewable energy resources requires the storage of energy and smart networks for the distribution of the energy supply. However, the storage of electricity at large scales is a long-standing challenge [14]. Many technologies have been developed to address the issue of energy storage, such as pumped-storage hydroelectricity [15], phase-change materials [16], rechargeable batteries [17,18], and fuel cells [12,13]. Because electricity storage needs to be on a very large scale if renewable energy is to be viable as an alternative to fossil fuels, battery technology and fuels from electrolysis associated with fuel cells are two of the greatest potential approaches for large-scale energy storage (Fig. 1).

Various types of rechargeable batteries have been developed, such as Li-ion and Ni-Mn batteries. One of the main advantages of rechargeable battery technologies is their convenience in storing energy. The electricity cost per kilowatt-hour from the grid can be low, while the energy can be generated in remote locations. As a result, battery technologies are widely used for various light-duty power sources such as uninterruptible power supply (UPS), mobile phones, and laptops. However, for heavy-duty or large-scale applications, there are many disadvantages with batteries, such as long recharge times, lower energy density than other fuels (e.g., methane or hydrogen), aging, environmental impacts, and higher manufacturing costs [19–21]. These disadvantages of the rechargeable battery may also be significant for vehicle applications.

Depending on how large the battery is, battery charging can take many hours at 240 V and varying amperage. A supercharger at 120 kW might require about 30 min to reach a similar level of charge [21,22]. In contrast, fuel cells using energy-dense fuels (e.g., hydrogen or methanol) have a clear advantage in bypassing the issue of recharging time and range. A fuel cell vehicle (FCV) could refill in 3–5 min with sufficient hydrogen fuel to drive 200–300 mi (1 mi = 1.61 km). The US DRIVE Fuel Cell Tech Team has identified a goal for an FCV: to be able to operate for around 8000 h or more (perhaps around 150 000 mi) [23]. A conventional lead-acid battery life has an average normal lifespan of four years under normal conditions, if it goes through full charge cycles without extreme temperatures. Therefore, batteries require replacement every few years, even if they are not used, due to leaching and aging. In contrast, the degradation of a fuel cell is based on operating hours. Also, the cost of a battery pack increases quickly as the battery pack capacity increases, and the battery cost is much higher than the cost of a similar-capacity fuel cell. Therefore, battery-powered vehicles are widely used for short distances and light-duty operation, such as forklifts and motor cycles, but are rather limited for long-distance travel or heavy-duty operation.

Many hybrid vehicles (HVs) have been developed [24–27]. An HV is based on the concept of using an engine and a battery as the powertrain system in one vehicle. This can be a hybrid powertrain of an IC engine with a battery pack, or a fuel cell with a battery pack. While the current purpose of an IC engine with a battery pack is to improve environmental impact of IC engine vehicles, the purpose of hybrid fuel cell electric vehicles (FCEVs) is to combine the features of an FCV and an electric vehicle (EV). Plug-in FCEVs drive using a fuel cell powertrain with a battery electric range of 30–50 mi. Such an HV facilitates a long range and a short refueling time using hybrid power [27,28]. Therefore, its driving range could be longer than those of other vehicles without facing the same limitations in range and refueling time as EVs. For example, Toyota reported that its HVs could have a driving range of up to 1035 km [24]. While the fuel cell breaks down, the battery can continue to drive, thus increasing the reliability of the HV. However, because there are two sets of power systems in one vehicle, the cost is higher than that of a single powertrain system. Furthermore, the control system of FCEVs is more complex due to the two sets of power systems.

It should be noted that both the battery and fuel cell costs need to be on a trajectory to make EVs and FCVs as affordable as IC engine cars in most countries by 2022, without government subsidies. The actual cost of fuel cells is subject to much debate and speculation, as most EV and FCV manufacturers avoid discussing this topic in detail. Recent studies have shown that EVs supported by government subsidies cannot sufficiently reduce GHG emissions in Canada [29] and in the United States [30]. Government subsidies toward the purchase of EVs have had little effect on GHG emissions and are much more expensive than other incentive measures. While it is obviously difficult to predict these future developments, fuel cell technology is an exciting and highly potential means to bridge the gap between the reduction of fossil fuel usage and the rise of renewable energy. This is because fuel cells have high converted efficiency and low emissions [8]. Thus, if the new economic mode with fuel cells can be successful as an alternative IC energy source, as shown in Fig. 1(b), it will lead to a low-carbon economy and environmentally friendly industries.

2.2. Alternatives to conventional engines

Most IC engines are extremely inefficient at energy conversion. In general, the thermal efficiency of an IC engine is around an average of 20%. Further improvement of IC engines or gas turbine technology is relatively difficult, even if raises efficiencies by 1% to 2%. A maximum thermal efficiency of around 38% is possible on occasion, but such a system is complex and the costs increase due to associated systems such as combined heat and power (CHP), which requires the application of a new technology. As a type of high-efficiency engine, fuel cells can reach over 50% efficiency. Since the efficiency of fuel cells can be as twice as high as that of the IC engines and boilers, emission reduction could be doubled if they were used in place of traditional engines. The usage of fuel cells translates to much lower operating costs at the same power generation capacity because of the higher efficiency of fuel cells. Furthermore, fuel cells are environmentally friendly. They are the ideal alternative to IC engines, turbines, and boilers with the objective of saving energy and reducing emissions. Furthermore, different types of fuel cells use different fuels. For example, solid oxide fuel cells (SOFCs) use natural gas, direct ethanol fuel cells (DEFCs) use ethanol, and proton exchange membrane fuel cells (PEMFCs) use hydrogen [8]. Therefore, no critical change is required to the current fuel-supply infrastructure.

The use of such a highly efficient and environmentally friendly system could greatly enhance the market for power-generating engines and create a new business mode, if fuel cells were used to replace conventional energy systems in the backup power, material handling, batteries, and CHP markets. Thus, a new clean energy revolution could result if a technical breakthrough in fuel cell scaling-up is achieved.

3. Fuel cell life cycle and value chain

As a new energy technology, fuel cells have not yet significantly penetrated the energy market. Cost, durability, and reliability are the main challenges in the commercialization of fuel cells. Here, we analyze the life cycle and value chain of fuel cell development and identify what activities should be undertaken to overcome its barriers, according to its value chain activities and end-user acceptance criteria. Many factors must be considered, such as the feasibility of manufacturing processes, proper materials, product quality and cost, supply chain resilience, and end-user acceptance.

3.1. Manufacturing cost modeling

A new product initially achieves its economic and technical targets in the laboratory, and is then scaled up to an industrial scale with designed metrics within the complete system. The manufacturing life cycle and value chain represent the production procedure and cost, as shown in Fig. 2. The techno-economic life cycle of a fuel cell stack can be categorized into two main stages: manufacturing and end-user stages.

The manufacturing cost includes the design, materials, component fabrication and assembly, labor, and equipment capital, which is required in the overall assembly of custom fabricated and commercially produced fuel cells. Ahluwalia et al. [31] presented an 80 kW_{net} Argonne proton exchange membrane (PEM) fuel cell system configuration (Fig. 3). Yang [32] analyzed the costs of this 80 kW_{net} Argonne fuel cell stack system, and determined the total stack cost to be about 30 $USD{\cdot}kW^{-1}$. The electrodes, including a cathode, anode, and catalyst, represented 51% of the entire stack cost. The stack assembly and conditioning made up about 7% of the total cost. Therefore, the three remaining components—the electrodes, bipolar plates, and seals—were the most costly parts of the stack (Fig. 4(a)).

The 80 kW_{net} PEM fuel cell stack system cost 59 $USD{\cdot}kW^{-1}$ at mass production volume. Its stack represented 50% of the whole system cost (Fig. 4(b)). The stack, air management, fuel management, and thermal management were the most expensive parts of the system. The stack system assembly and balance made up 14% of the total cost.

In fact, fuel cell manufacturing technology and materials for PEM fuel cells have advanced considerably. Some of the material cost has also been considerably reduced. For example, platinum loading on anodes and cathodes was based at 0.1/0.15 $mg{\cdot}cm^{-2}$ with a variation of 0.12–0.3 $mg{\cdot}cm^{-2}$. The whole system cost analysis was based on a platinum price of 2000 $USD{\cdot}t\ oz^{-1}$ (1 t oz = 31.10348 g) [32], which was close to being the highest platinum price in its history (Fig. 5). However, the price of platinum varies by ±40%, thus ranging from about 800 to over 2000 $USD{\cdot}t\ oz^{-1}$ [33]. At present, the price of platinum is less than 1000 $USD{\cdot}t\ oz^{-1}$, which is less than half of the earlier maximum cost. Therefore, platinum loading is not a major factor in the overall system cost, and the fuel cell stack cost should be reduced now that its main material of platinum is at less than its maximum price. Thus, the stack cost may be less than 50% of the overall system cost.

3.2. Manufacturing cost comparison between fuel cells and IC engines

Elnozahy et al. [34] compared the costs of FCVs, IC engine vehicles, and HVs (Table 1). The cost of an FCV was around 24 355 USD, the cost of an IC engine vehicle around 15 805 USD, and the cost of

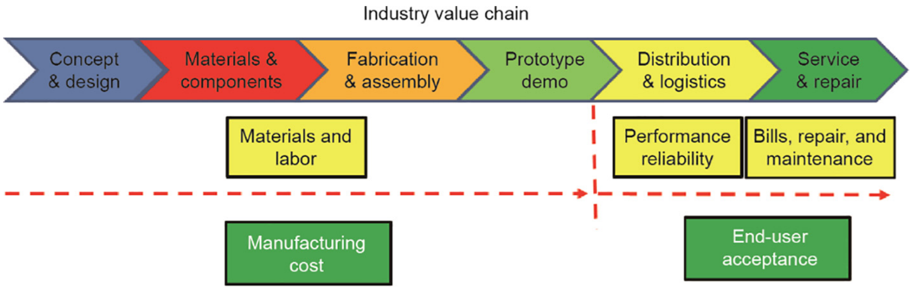

Fig. 2. The fuel cell life cycle and value chain.

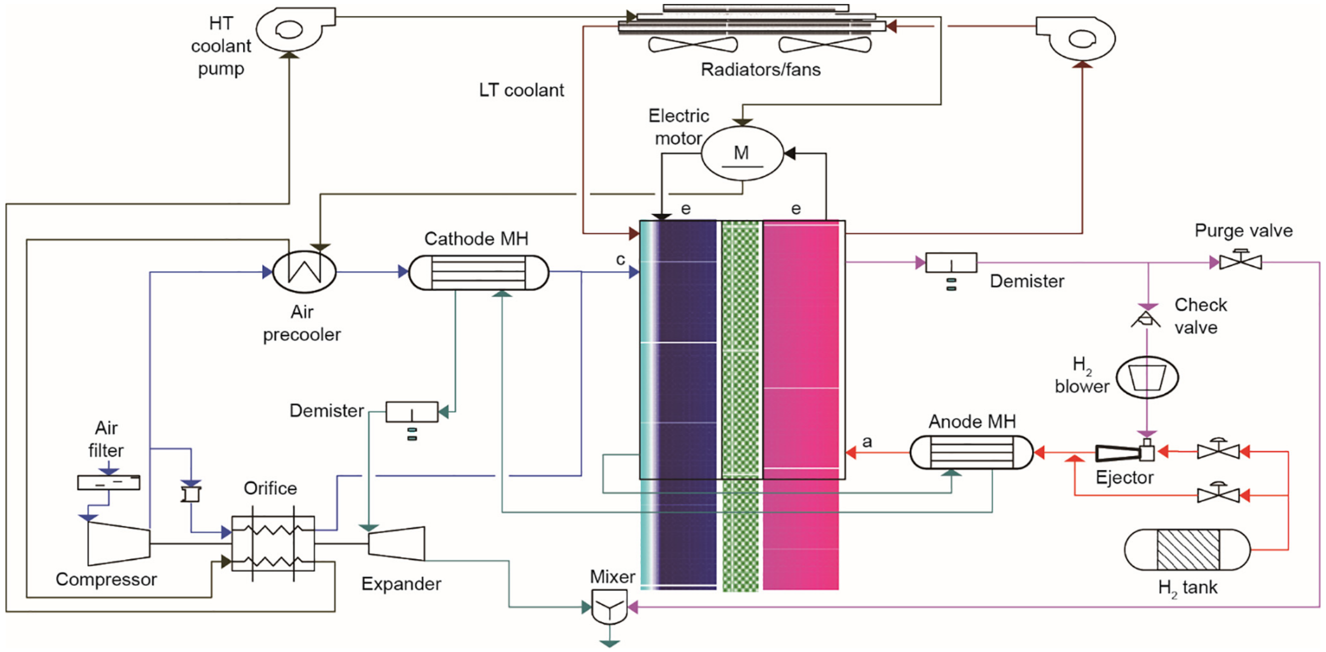

Fig. 3. The Argonne 2009 PEM fuel cell system configuration [31]. HT: high temperature; LT: low temperature; MH: membrane humidifier.

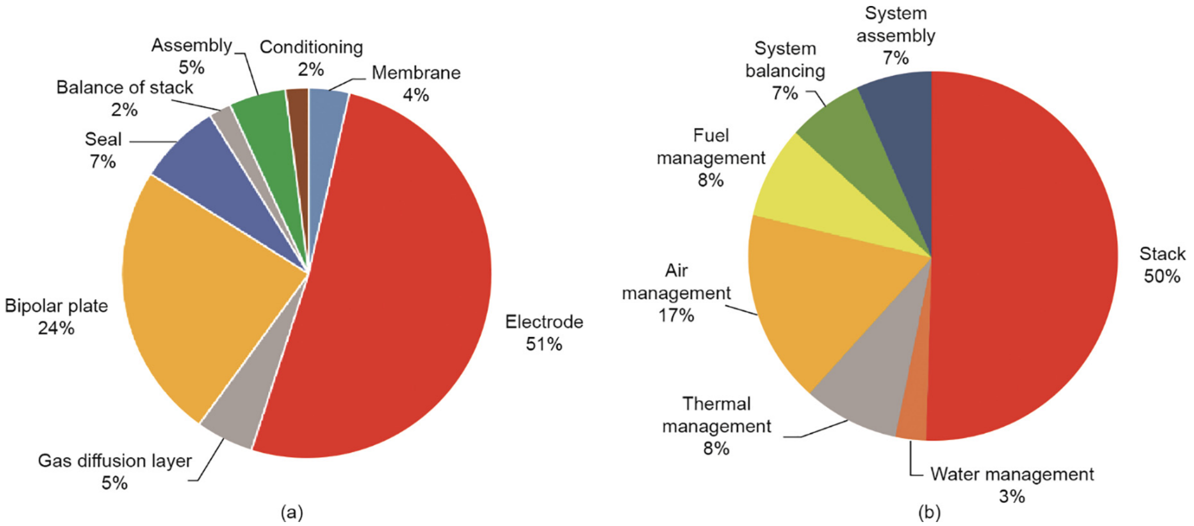

Fig. 4. Costs of an 80 kW_{net} PEM fuel cell stack system [32]. (a) Stack costs; (b) stack system costs.

Fig. 5. Historical platinum prices (in USD·t oz^{-1}) since 1996. The price of platinum was 923.95 USD·t oz^{-1} on June 22, 2017 [33].

Table 1
Cost comparison between FCVs, IC engine vehicles, and HVs. (Adapted from Ref. [34])

Vehicle type	Engine type	Power (hp)	Efficiency (%)	Fuel cost (USD·kg^{-1})	Driving range (mi)	Cost (USD)					
						Propulsion system	Chassis and body	Transmission	Fuel tank	Others	Total
Proposed FCV	Fuel cell systems	112	60–70	2–3	300.0	13 964.0	7902.5	316.1	750.00	1422.45	24 355.05[a]
Honda Civic Sedan	IC engine	140	10–16	0.98–1.05	475.0	4741.5	7902.5	1580.5	158.05	1422.45	15 805.00
Honda Civic Hybrid	Hybrid	110	10–16	0.98–1.05	580.8	7215.0	12 025.0	2405.0	240.50	2164.50	24 050.00

1 hp = 0.7457 kW; 1 mi = 1.61 km.

[a] The original number from Ref. [34] is 24 363.1.

an HV around 24 050 USD. This comparison shows that the cost of fuel cell systems is comparable to that of HVs but higher than that of the IC engine vehicle, if we consider the materials, manufacturing, and fuel. However, it can be seen in Table 1 that the efficiency of the fuel cell was 60%–70%, which is much higher than that of the IC engine. Therefore, the fuel bill of the fuel cell will be significantly reduced because of a higher thermal efficiency, and the total cost of the fuel cell should be comparable to that of the IC engine over a long period of operation. It should be noted that the current fuel cell operations are at 40%–60% thermal efficiency reported by the

US Department of Energy (DOE) [35], which is lower than that in Table 1. However, when configured for CHP, fuel cell efficiency can be greater than 90%.

In the section above, we analyzed fuel cell cost issues. Although the cost of fuel cells is still higher than that of conventional IC engines (Table 1), the gross spread is comparable with IC engines because of the higher efficiency of fuel cells. Therefore, the cost of fuel cells should not be the main factor in end-user acceptance. It is clear that most studies on existing fuel cell costs are based only on stack manufacturing costs, without consideration of repair and maintenance costs. However, the cost of repair and maintenance is necessary for stack service and end-user acceptance. Because there are few reports on what percentage the repair and maintenance costs are of the whole life cycle cost, it is only possible to identify current service activities where there appears to be a competitive disadvantage in end-user acceptance. Using fuel cells to power a business is directly linked to achieving a competitive service advantage.

Because fuel cell scaling-up uses repeat cells (so-called "scale-up by number-up"), the failure of a component such as a membrane or gas diffusion layer (GDL) could lead to cell failure and, further, to failure of the whole stack. In particular, a component failure usually requires the disassembly of the stack to replace it [8,13]. Thus, every small failure of a component adds 100% of the cost of the assembly, conditioning, and balancing of the stack and system. As analyzed in the section above, stack system assembly and balancing make up 14% of the whole system cost (Fig. 4(b)). The balance of stack, assembly, conditioning, and seal make up 16% of the stack (Fig. 4(a)), and they should be halved because of 50% of the system cost (i.e., 8%). Thus, the assembly, balance of stack, and conditioning with its system can represent about 22% of the whole stack system cost. For each repair or maintenance, the cost of 22% is included since the assembly, balance of stack, and conditioning are necessary. Therefore, a single component failure might significantly increase the cost of the whole stack.

If repairs are required twice in the duration of a fuel cell stack, the cost of the assembly, conditioning, and balancing will be about 44%. It is necessary to consider the transport cost and failure component cost too. The repair and maintenance cost of a stack system can exceed 60% of the overall system cost [36], depending on the times of repair and maintenance. Thus, it is clear that reliability and durability are important factors in substantially reducing the whole system cost and increasing the end-user acceptance of the system. Therefore, if a business that is supplied by fuel cells hopes to outperform its competitors, which may use IC engines or boilers, its value chain activities must be better than those of its opposition by being differentiated through higher quality and reliability. A strategy based on seeking quality and cost leadership is necessary to improve fuel cell reliability and to reduce repair and maintenance activities.

4. Fuel cell technical challenges: Durability and reliability

Reliability and durability can significantly affect the availability of fuel cells. This is a critical factor for end-user acceptance [8,13]. The fuel cell market will require reliable technology to advance and improve operation tolerance for end-user acceptance. However, there is a substantial gap between the existing fuel cell development and the end-user requirements [13].

4.1. Reliability for end-user acceptance

End-user acceptance factors include functionality, cost, performance (i.e., efficiency and reliability), and environmental impacts. The functions of a fuel cell with a motor are identical to those of an IC engine. Fuel cells are environmentally friendly with low noise; the primary concern regarding fuel cells is performance, including efficiency and reliability. The former is not an issue, as the efficiency of fuel cells is usually much higher than that of IC engines. Therefore, it is reliability that is the greatest potential technical barrier to end-user acceptance, in addition to extra costs due to unexpected repair and maintenance.

4.2. Technology readiness levels

A disciplined process that facilitates repeatability, consistency, and regularity must be achieved using repeatable steps and criteria to perform the assessment. Technology readiness levels (TRLs) are widely used as a measurement of the maturity level of a particular technology [37,38]. Therefore, the TRL of fuel cell development is an assessment of the readiness of fuel cells to achieve the scaling-up goals of durability and reliability. This assessment provides a common understanding of the technology status in the whole innovation chain. TRLs can be categorized into ten levels, where TRL 0 is the lowest and TRL 9 is the highest (Fig. 6) [37]. TRLs 1 and 2 are for future and emerging technologies, TRLs 3–8 are for industrial development projects, and TRL 9 is for commercialization.

Evaluating the TRL of fuel cells is as intricate as evaluating a complex chemical processing facility. Unlike other products, fuel cells have no clear TRL. Fuel cell products exist at all TRLs, from TRL 1 (fundamental research), to TRL 8 (present in commercial systems), to the peak at TRL 9 (fuel commercial deployment). Although a great deal of fundamental research has been performed on postulated principles such as the catalyst and the multiphase flow in a channel [39–41], the deployment of fuel cell systems has been reported frequently [42,43].

End-user acceptance may be the "golden criterion" for TRL 9, which references fuel cell cost, functions, and performance (e.g. efficiency and reliability). As discussed in Section 4.1, because a fuel cell system is a repeat unit, a single component failure could lead to failure of the whole stack. Thus, a cost of 10% composite component failure might drive a fuel cell system cost up by 60% [13]. As such, an assessment of fuel cell reliability is critical in the integrated processing system and the technology maturation process [8]. Therefore, it is necessary to form a credible judgment of fuel cell reliability based on the technology's maturity and validation, as this is the main factor for high costs and low availability.

4.3. Technical barriers to reliability

As described above, the cost impact of maintenance and repairs due to unexpected defects could be high [13,36]. The channels in a cell and the cells in a stack system need to be operationalized under the same conditions. The framework and scaling-up approach need to be examined carefully with respect to the operation and risks associated with the fuel cells and systems used in the scaling-up, which are important in assessing the deployment of the fuel cell technologies. Solving the reliability issues is essential in order to address the high cost and low availability of fuel cells.

It is very difficult to keep all channels and cells working at the same levels. The theory of scaling-up has shown that an absolutely uniform flow distribution is still a challenge [12,44–47]. A small, uneven flow distribution can lead to an operational misalignment of cells and stacks, introducing high levels of uncertainty and decreased efficiency. As a result, the high cost of fuel cells can be affected by frequent repair and maintenance downtime, leading to an impression of low reliability [8]. Powell [44] indicated similar issues with microreactor scaling-up, which uses a similar modularity. There are uncertainties in the implementation of

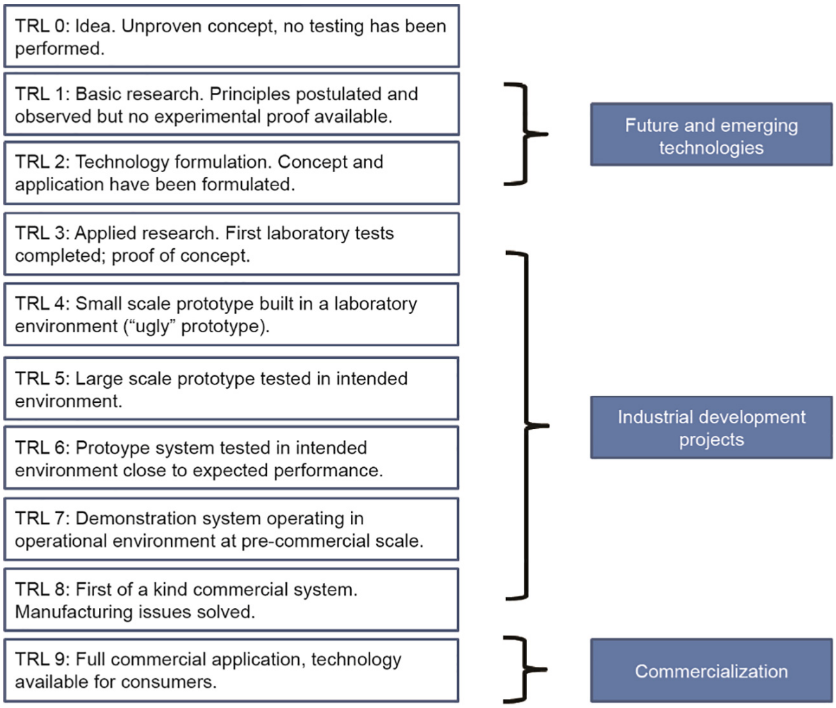

Fig. 6. Technology readiness levels. (Adapted from Ref. [37])

"scale-up by number-up" as an engineering way in the chemical industry. This is, it is not clear what is resulting from an inefficient flow distribution design in the design and the modeling and operation of the pilot [48]. However, if we can carefully design the flow field, based on the theory of low distribution, it is possible to control the non-uniformity of a fuel cell stack in a small range or within manufacturing tolerances [13].

5. A strategy for fuel cell commercialization

Many fuel cell installations have been reported by the DOE and others. For example, a notable increase of fuel cell backup system deployment in the United States was reported since 2009 [42]. Over 7000 fuel cell systems totaling 16.3 MW have been installed through 2013. There are over 2000 backup power systems used for telecommunications systems. The DOE reported a 400 kW fuel cell installation at CTtransit in Connecticut [30]. This system supplied power to the transit agency's maintenance and storage facility. A 2.8 MW fuel cell system was installed for a wastewater treatment plant in Ontario, California. However, all the installed fuel cells benefited from government subsidies. Behling [43] indicated that the deployment of all fuel cells is almost entirely based on government subsidies to build commercial markets for fuel cell deployment. The influence of materials and catalyst performance on the durability of fuel cells has been studied extensively [39,40]. These studies stressed that scaling-up issues are mainly issues with materials and catalyst performance that have led to higher costs. However, these materials and catalyst issues are scientific issues, so the problem is not only scale dependent. Thus, the fuel cell scaling-up issue has not been adequately realized due to the substantial uncertainty [49], and TRLs of fuel cell products and systems are not as high as people have estimated. Wang [13] performed a series of studies on fuel cell scaling-up. The inability to directly scale a pilot plant up to deployment due to reliability issues is a key barrier to investment into this new energy-conversion technology. A systematic integration has been recommended in order to address the reliability issue. However, knowledge gaps exist among the stages of components, individual cells, and stacks [13]. Wang [13] stressed the importance of reliability in fuel cell commercialization. He proposed three operating windows to connect components, flow-field design, individual cells, stack and program design of the process, and system control in order to address durability and reliability issues. In this study, we recommend building criteria and stages of critical scaling-up technologies for fuel cell commercialization using TRL and life cycle analysis. All parties related to the scaling-up and reliability should work together, including scientists, modelers, engineers, and designers with key knowledge, skills, and experience, as well as governments and investors. Governments, investors, and funding agencies should support the technology integration. The technology must perform at higher levels through high reproduction and consistency with larger scale demonstration units, in order to justify the investment risk.

6. Concluding remarks

Many countries have made efforts to develop low-carbon economies and green industries as long-term targets in order to ensure a sustainable energy supply that aligns with their economic development and sustainable environmental objectives. There are two ways to develop a low-carbon green economy: first, to increase the share of new and renewable energy in order to meet increasing energy demands, mitigate GHG emissions, and reduce fossil fuel dependency; and second, to conserve energy and reduce emissions by increasing the efficiency of existing energy systems. Fuel cells can play a pivotal role in both ways. As a highly efficient energy-conversion and environmentally friendly technology, fuel cells can improve thermal efficiency by 5%–40% if they are used as a substitute for IC engines and boilers. The results of this analysis indicate that fuel cells could be the most effective alternative to IC engines and boilers; fuel cells can thus contribute to a low-carbon green economy, and even to a green industrial revolution.

However, significant market penetration of fuel cells has not yet been achieved. In this paper, we performed a techno-economic and environmental analysis of fuel cell systems using a life cycle analysis and value chain. We analyzed the life cycle and value chain activities of fuel cells and end-user acceptance criteria, resulting in a holistic and unified learning of the institutional barriers to fuel cell commercialization. It was found that although the current fuel cell manufacturing cost is still higher than the cost of IC engines, its operating costs can be much lower than those of its competitors (e.g., IC engines or boilers) because of a higher thermal efficiency. In addition, the manufacturing cost is not a major factor for end-user acceptance and fuel cell commercialization. However, the unexpected repair and maintenance costs of fuel cells due to their low reliability can result in a substantial cost increase of up to 60%, and can reduce fuel cell availability. Therefore, the additional costs of maintenance and repairs and reduced availability are the greatest barriers to end-user acceptance and fuel cell commercialization. The fuel cell industry must face the challenge of how to overcome the technical barriers of reliability and durability.

Although this paper questions whether fuel cell targets will be achieved, given the current pace of development, it provides the readers with an insightful overview of this energy field. A change of priority is necessary, with the use of system integration to significantly improve reliability and durability issues and to reduce the service cost of fuel cell systems after installation. Over several years, we have studied the main technical barriers in fuel cell R&D and considered how best to address the fuel cell scaling-up challenges [13]. Scaling-up continues to rely on the effective piloting of repeat units. The theory of flow-field design and practice can be fundamental for scaling-up repeat units [12,13]. Green energy through fuel cells is very likely to be the future business mode in the search for a more sustainable pathway to economic growth.

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Compliance with ethics guidelines

Junye Wang, Hualin Wang, and Yi Fan declare that they have no conflict of interest or financial conflicts to disclose.

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