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Business Model Development for a High-Temperature (Co-)Electrolyser System

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Abstract: There are increasing international efforts to tackle climate change by reducing the emission of greenhouse gases. As such, the use of electrolytic hydrogen as an energy carrier in decentralised and centralised energy systems, and as a secondary energy carrier for a variety of applications, is projected to grow. Required green hydrogen can be obtained via water electrolysis using the surplus of renewable energy during low electricity demand periods. Electrolysis systems with alkaline and polymer electrolyte membrane (PEM) technology are commercially available in different performance classes. The less mature solid oxide electrolysis cell (SOEC) promises higher efficiencies, as well as co-electrolysis and reversibility functions. This work uses a bottom-up approach to develop a viable business model for a SOEC-based venture. The broader electrolysis market is analysed first, including conventional and emerging market segments. A further opportunity analysis ranks these segments in terms of business attractiveness. Subsequently, the current state and structure of the global electrolyser industry are reviewed, and a ten-year outlook is provided. Key industry players are identified and profiled, after which the major industry and competitor trends are summarised. Based on the outcomes of the previous assessments, a favourable business case is generated and used to develop the business model proposal. The main findings suggest that grid services are the most attractive business sector, followed by refineries and power-to-liquid processes. SOEC technology is particularly promising due to its co-electrolysis capabilities within the methanol production process. Consequently, an "engineering firm and operator" business model for a power-to-methanol plant is considered the most viable option.

Keywords: solid oxide electrolysis; power-to-X; market research; competitor analysis; business model development

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1. Introduction

The release of greenhouse gases is considered the main cause of global climate change. In recent decades, emissions of CO_2, the most common greenhouse gas in terms of quantity, have increased drastically, mainly due to the growing global demand for fossil fuels for transport and energy generation. Between 1990 and 2012, the global transport sector, driven by the automotive and shipping industries, has grown by more than 60% and currently accounts for a quarter of total CO_2 emissions [1]. Global energy demand is expected to double by 2050, with most models continuing to see strong dependence on fossil fuels and their petrochemical products in the coming years. New technologies, e.g., for the exploitation and production of natural gas from clay stones, lead to an increase in the availability of resources and, at the same time, allow keeping low prices [2,3]. Innovative and more sustainable energy systems are necessary to work against this trend and reduce emissions of environmentally harmful off-gases.

In recent years, significant progress has been made in technologies for utilising renewable energy sources, which have made it possible to build economically and technically efficient energy generation plants for wind power, hydroelectric power, or solar energy, for example. As a long-term goal, many countries are striving to make their energy supply more independent from the production or import of fossil fuels and, at the same time, fight climate change [4]. Moreover, at the 21st UN Climate Change Conference of the Parties (COP21) held in Paris in 2015, 194 countries decided to limit global warming to well below 2 °C compared to pre-industrial levels and are aiming for a target of 1.5 °C, including all major industrialised countries but the US. For example, the German Federal Government has already set the long-term goal of reducing greenhouse gas emissions by 40% by 2020 and by 80–95% by 2050 compared with 1990 levels [5]. This calls for a fundamental change in energy policy in which the existing industry for energy and petrochemical products needs to substitute carbon-intensive processes with increasingly carbon-neutral ones.

As an electrochemical process, water electrolysis allows electricity generation to be coupled with other branches of the energy economy (Power-to-X concept). Water electrolysis is the process of using electricity to decompose water into hydrogen and oxygen gas. Historically, hydrogen has been a valuable chemical feedstock, and may be a near-future energy vector. In addition, hydrogen or its derivatives produced via renewably-sourced electricity can be used as clean energy storage media [6] and as a secondary energy carrier in stationary and transport applications in various sectors. For that reason, increasing the use of green hydrogen as an energy vector can relieve our global dependence on fossil fuels and significantly contribute to decarbonising industrial processes and mobility.

Stimulated by the successful expansion of renewable energies over the past 15 years and increased public funding, various players have been able to gain a leading international position in the research, development, and demonstration of electrolysis technologies. Numerous power-to-gas (PtG) and, more recently, power-to-liquid (PtL) projects have been initiated. These include the H2FUTURE European flagship project, started in 2017 and with a duration of 4.5 years, which aims to produce green hydrogen from renewable electricity [6], as well as the P2X Kopernikus project, which explores Power-to-X routes as renewable energy storage solutions for mobility and heating sectors [7]. Moreover, the European Commission has set the strategy to reach 40 GW installed capacity in electrolysis systems by 2024 [8] with the support of the Green Deal programme [9], among other national programmes. Countries with a high renewable energy sources potential, such as Spain or Portugal, are playing an essential role in achieving these goals. For instance, Spain has committed to producing 10% of these 40 GW of green hydrogen.

Electrolysis technologies can be classified as low-temperature electrolysis (LTE) and high-temperature electrolysis (HTE). The alkaline electrolysis (AEL) is the most mature technology within LTE, mainly in MW-scale industrial applications. The second most mature LTE technology is the proton-exchange membrane (PEM) electrolysis, which has already reached the MW scale and a predominant position within the renewable energy sector due to its dynamic response to intermittent electricity sources [10]. On the other hand, and within HTE, the solid oxide electrolysis cell (SOEC) is regarded as a highly efficient and promising technology. The SOEC presents clear advantages in green hydrogen production efficiency due to the higher operating temperature, which gives thermodynamic and kinetic advantages to the water reduction process [11]. As an example, the current density attained during green hydrogen production by AEL is 0.5 A cm^{-2} at 1.4 V. This current density can be almost doubled in PEM electrolysers (1 A cm^{-2} at 1.6 V) and tripled in SOEC systems (1.5 A cm^{-2} at 1.3 V) [12]. The huge potential of HTE systems is raising high interest, being the driving force of new ambitious public projects from the European Commission and private investments. The typical scale of SOEC systems has been accomplished up to hundreds of kW [13], supplied mainly by German manufacturer Sunfire [14]. Thus, an immediate scale-up of SOEC installations through some flagship projects is expected, such as (i) the GrInHy2.0 project, which announced installing a 1 MW SOEC electrolyser in 2021 [15], (ii) the MultiPLHY project, which intends to install a 2.5 MW SOEC electrolyser by 2023, to produce green hydrogen on a large scale and decarbonise a biorefinery in Rotterdam (The Netherlands) [16], and (iii) an industrial project to produce jet fuel using the Fischer–Tropsch process with a 20 MW electrolyser in Herøya (Norway) [13], being an unprecedented scale-up development for HTE technologies.

Besides the superior efficiency of HTE, which gives an unfair advantage compared with the other commercial technologies, SOEC presents other benefits, such as fuel flexibility. Thus, a SOEC can also reduce mixtures of steam and carbon dioxide (CO_2) in parallel (co-electrolysis), generating a mixture of carbon monoxide (CO) and H_2, called synthetic gas or syngas, which is vastly used for chemicals production [17]. The obtained renewable syngas can be used as a feedstock for the generation of a wide range of synthetic fuels (e.g., synthetic methane, methanol, diesel, DME) by the well-known catalytic process of Fischer-Tropsch [18]. These synthetic fuels will be crucial for the transition to a more sustainable energy scenario in the coming years and, as well, the solution for specific industrial applications and heavy transport vehicles (e.g., ferries, planes). This co-electrolysis technology is under development, with examples of commercial-scale systems [19], and is expected to be demonstrated at a large scale in 2022–2025 [20]. Therefore, studies regarding SOEC are considered hot topics. Substantial efforts are being made toward high-performance and durable materials. In addition, relevant works on operation and durability improvement of the SOEC are getting high impact [20]. With the deployment of the SOEC approaching, understanding the business model towards the commercialisation of co-electrolysers is relevant, as well as for new PtL routes.

Thus, this study proposes a sustainable business model for a potential venture specialising in SOEC products. The business model development is firstly based on an extensive hydrogen market analysis, after which the business prospects of the most promising market segments for electrolysers are assessed. Furthermore, the current state and future developments of the electrolyser industry are studied, along with a review of the competitive environment. Building on these assessments, a viable business case and business model is proposed and discussed. The contribution of the present work is to, first, analyse the state-of-the-art of the SOEC different applications and its potential as the adopted technology for the generation of green hydrogen in industrial sectors, and to point out some of the viable routes for this industrial application.

2. Description of the Technology

2.1. Fundamentals of Water Electrolysis

Water electrolysis is an electrochemical process in which the redox reaction occurs by applying a voltage high enough for water to split into its basic components, H_2 and O_2. This process takes place on the water electrolyser and is catalytically assisted by the electrode/electrocatalytic materials, varying with the selected technology. An electrolyser consists of two spatially separated electrodes (anode and cathode) separated by an ion conductor called the electrolyte. H_2 and O_2 gases are formed during electrochemical reactions at the cathode and anode surfaces. The redox reaction for water electrolysis under standard conditions is described by Equation (1).

$$2H_2O_{(liquid)} \rightarrow 2H_{2(gaseous)} + O_{2(gaseous)} \quad (1)$$

Different methods for the production of hydrogen via electrolysis exist today. Table 1 presents an overview of alkaline electrolysis (AEL), proton-exchange membrane (PEM) electrolysis, and high-temperature electrolysis, specifically SOEC, including its co-electrolysis capability. These three electrolysis options differ in the temperature range, electrolyte, charge carrier, and cathode and anode reactions. Table 1 also compares the CAPEX and power consumption of the three leading technologies reported on the multi-annual work plans of the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) [21]. To date, the cost of SOEC systems is in the range of 2000 EUR kW^{-1}. This cost is projected to decrease to 1000 EUR kW^{-1} by 2030 and 530 EUR kW^{-1} by 2050 [22].

Table 1. Overview of the three leading electrolysis technologies (adapted from [23]).

Parameters	AEL	PEM	SOEC/(CoSOEC)
Temperature range	40–90 °C	20–100 °C	700–1000 °C
Electrolyte	Aqueous alkaline	Solid polymer	Solid oxide (ZrO_2/Y_2O_3)
Charge carrier	OH^-	H^+	O^{2-}
Cathode reaction	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$ ($2CO_2 + 4e^- \rightarrow 2CO + 2O^{2-}$)
Anode reaction	$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$	$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$
System efficiency (LHV)	51–60%	46–60%	76–81%
Degradation rate	0.03–0.17%/1000 h	0.06–0.3%/1000 h	0.6%/1000 h

2.2. Solid Oxide Electrolysis

The electrolysis cell contains two electrodes, the cathode or fuel electrode (the negative electrode) and the anode or oxygen electrode (the positive electrode), separated by an electrolyte through which the oxygen ions are conducted (Figure 1). The typical state-of-the-art solid electrolyte consists of yttria-stabilised zirconia (YSZ). However, other stabilising elements for the zirconium oxide can reduce the cell's operating temperature [24]. The solid electrolyte blocks electrons but keeps a high ionic conductivity (in this case of oxygen ions, O^{2-}) at high working temperatures. Besides that, catalytically active materials (e.g., nickel) are used for the fuel electrode (cathode under electrolysis mode), usually a NiO-YSZ composite that is reduced to the active form Ni-YSZ on the first steps of operation. Perovskites, such as lanthanum strontium manganite (LSM) or lanthanum strontium cobalt manganite (LSCM), are typically used for the oxygen electrode (anode under electrolysis mode). The water (steam electrolysis) or water and carbon dioxide reduction (co-electrolysis) takes place on the so-called triple-phase boundaries of the fuel electrode, where the H_2O molecule is split into H_2 and O^{2-} ions, with the latter being transported through the electrolyte.

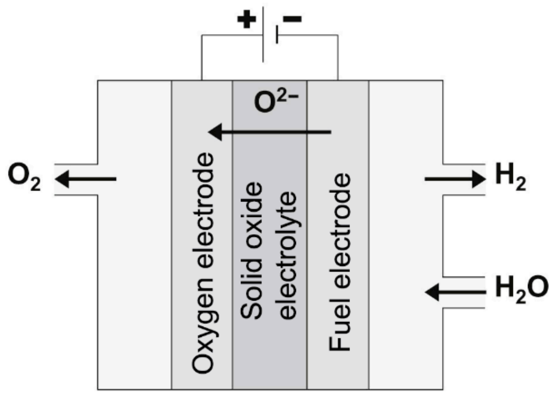

Figure 1. Scheme of a solid oxide electrolysis cell (adapted from [25]).

Once the O^{2-} ions arrive at the oxygen electrode, their oxidation through the oxygen evolution reaction (OER) takes place, releasing O_2. When the electrochemical process is reversed, the cell can be used as a high-temperature fuel cell, generating power through the oxidation of H_2. In terms of construction design, the planar design is typically preferred over the tubular cell design [23].

The high working temperatures of 700–900 °C reduce the cathodic and anodic overvoltage by activating the thermal and electrochemical processes. As a result, higher current densities can be achieved at a relatively low cell voltage. The maximum output current densities, directly related to hydrogen production, are remarkably higher for SOEC. As reported, SOEC systems can attain current densities (1.5 A cm^{-2} at 1.3 V) significantly higher than AEL (0.5 A cm^{-2} at 1.4 V) and PEM electrolysers (1 A cm^{-2} at 1.6 V) [12].

When the cell voltages are close to the thermoneutral voltage of 1.29 V for steam electrolysis, efficiencies can be close to 100% [26]. Apart from the high electrical efficiencies and the option to operate in reverse mode, as a fuel cell, other potential advantages exist in using high-temperature SOECs. These include low material cost and the possibility of producing syngas ($CO + H_2$) from water vapour and carbon dioxide in the so-called co-electrolysis mode, as described by Equation (2) [25].

$$H_2O + CO_2 \rightarrow H_2 + CO + O_2 \quad (2)$$

Although the SOEC responds quickly to different load requirements in full and partial load operation, one of the main drawbacks could be the mechanical and chemical material requirements resulting from the temperature-induced tensions during start-up and shut-down, which can drastically reduce the service life of the cells. However, lifetimes of more than 30,000 operating hours have been proven to date by Sunfire systems [19]. Recent R&D efforts focus on the material level, including reducing the anode's internal resistance, increasing the cathode's service life, and improving its porous properties. In principle, lowering the operating temperature is desirable to increase the service life, but this is often ignored in favour of better kinetics.

3. Market Analysis

3.1. Hydrogen Production Overview

There are numerous industrial methods for producing hydrogen that are mostly location-dependent in terms of the production demand and the availability of raw materials or other resources. Hydrogen can be produced directly (as a gas or a liquid) from primary or secondary resources. Large-scale industrial processes are primarily based on fossil raw materials. They include steam methane reforming (SMR), partial oxidation of hydrocarbons (POX), and the gasification of carbonaceous material such as coal or biomass. Commercial production from other sources is virtually limited to water electrolysis using electricity. While other technologies that involve biological processes or nuclear energy exist, they have not yet been completely advanced to a commercial level and still require substantial research and development [11,12]. Global hydrogen production is mostly sourced from fossil fuels (49% from steam reforming of natural gas, 29% from the partial oxidation of oil or naphtha, 18% from coal gasification), with only 4% coming from water electrolysis (Figure 2).

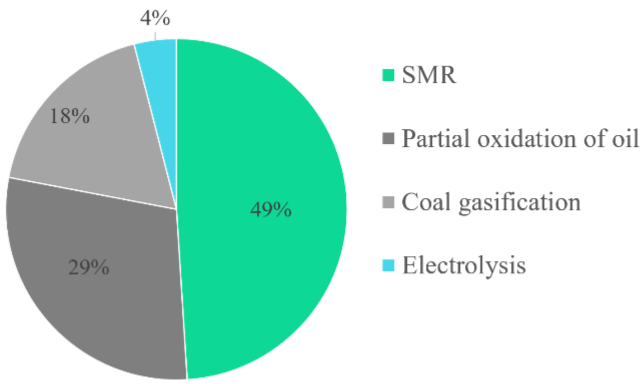

Figure 2. Share of global hydrogen production by technology [27]. Reprinted with permission by John Wiley and Sons.

3.2. Market Segmentation

The market for hydrogen includes various forms of applications. It is predominantly a key resource material in the petrochemical and fertiliser industry. Today, nearly half of the globally produced hydrogen is used to synthesise ammonia in the fertiliser industry. About 37% is used during the processing of crude oil in refineries, which makes it the second most significant application field. Other essential chemicals also demand hydrogen as a raw material in large quantities, especially during methanol production (approx. 8%). Minor amounts are needed in other industries, e.g., as a compound in reducing atmospheres for the heat treatment of steel; in electronics as an oxygen-eliminating carrier gas in high-temperature semiconductor manufacturing; and in the food and beverage industry, where it is used to hydrogenate unsaturated vegetable oils to obtain solid fats [27–30].

As shown on the right side of Figure 3, new market segments have emerged during the past few years, such as mobility, PtG, or PtL routes. The main constraint of these arising markets is still the high price of hydrogen compared to the current price of fossil fuels. However, grid services can drastically reduce the cost of H_2 production via electrolysis.

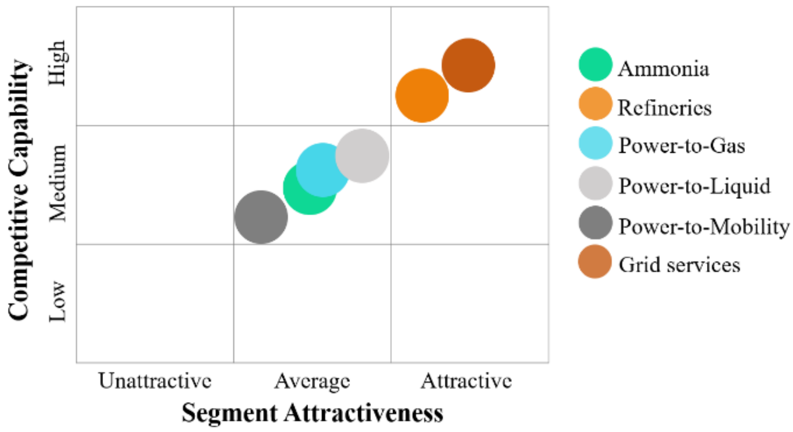

Figure 3. Short-term prospects of market segments for solid oxide electrolysis businesses cases.

As a consequence of recent environmental and energy policies efforts to decarbonise electric energy systems, the concept of "green hydrogen" has generated a growing interest. The term describes carbon-neutral hydrogen production via electrolysis and powered by renewable energies [31]. This scheme and European public strategies pushing towards the 40 GW electrolysis capacity in the next 10 years represent an excellent opportunity for the deployment of SOEC technology as the one that produces the highest amount of green hydrogen for each renewable kWh. SOECs are, by far, the most efficient electrolysis systems (>80% LHV) and, more importantly, and often disregarded, are the ones with higher production yields (<4 kWh Nm^{-3} of H_2), with electrical energy consumptions remarkably below the competing technologies (>5 kWh Nm^{-3} for alkaline and >6 kWh Nm^{-3} for PEM) [32,33].

3.3. Opportunity Analysis

A preliminary opportunity analysis was conducted to assess the business attractiveness of these segments, specifically for new ventures that involve solid oxide electrolysis technology in the near future (approx. five-year time period). To do so, a simplified directional policy matrix (DPM) was carried out. This tool is an analytical approach that investors typically use for making strategic investment decisions.

Based on factors that describe the market, technology, policies, and economics, the tool evaluates the prospects of a business sector [34]. The numerical valuation of these factors has been done based on previously conducted market analysis. To further increase objectivity, the values were discussed with experts from science and industry during interviews, mostly carried out during the Hannover Messe industrial fair of 2018 [35]. The results of the attractiveness assessment for the market segments are summarised in Figure 4.

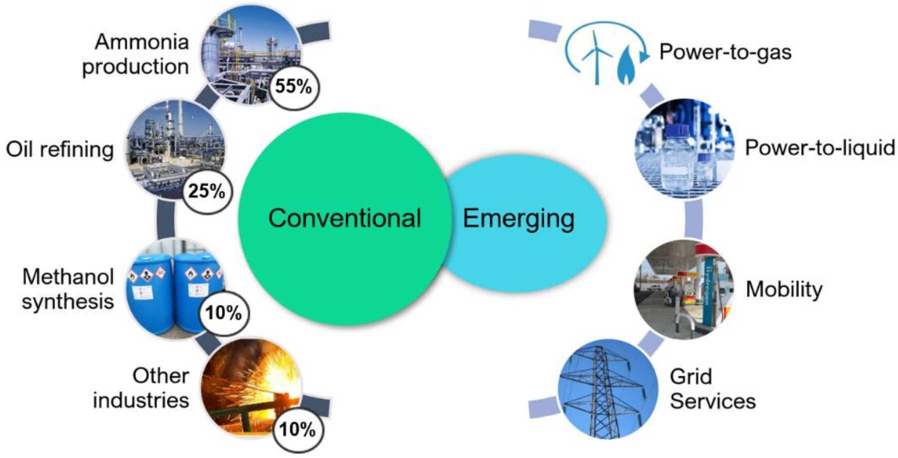

Figure 4. Overview of conventional and emerging hydrogen market segments, including the market share (adapted from [27,29] with permission by John Wiley and Sons).

3.3.1. Refineries

Refineries are a more promising, non-energy related market segment for the electrolyser business. With the increasing demand for low-sulphur fuels and the trend of lower-quality crude oil, merchant hydrogen utilisation is growing, and it is expected to grow at a compound annual growth rate (CAGR) of 6.25% through 2026 [36]. Supportive hydrogen supply by nearby electrolyser units has been identified as a technologically and economically feasible solution that could be undertaken in many refinery locations around the globe. As for ammonia plants, SOEC-based businesses face increasing competition from AEL and PEM electrolysers due to their lower cost, despite lower efficiency. Due to ongoing technological improvements, petroleum refineries could nevertheless be an attractive business sector for ventures relying on SOEC in the short-term.

3.3.2. Power-to-Gas

PtG is an innovative concept of combining electrolyser technology with renewable energy production and the possibility of monetising otherwise curtailed surplus renewable electricity in the form of gaseous fuel products. Battery storage has been the predominant renewable energy storage medium in the last decade. However, due to their limited lifespan of around 8.5 years and the environmental waste generation, hydrogen is becoming competitive as an energy storage medium with increased efficiency and longer life cycles than batteries [37]. Its attractiveness as a market segment from an economic standpoint is important, notwithstanding the technical issues associated with grid integrity and the regulatory framework that have yet to be defined. PtG facilities are limited to specific locations (CO_2-source, RE-plants, NG-grid), constraining the potential market size. Nowadays, PtG projects usually involve various stakeholders (e.g., technology suppliers, grid and RE-plant operators, TSOs) to ensure the control and balance of the complete value chain, since the grid balance and the diversification of developed fuel applications are key for economic viability. Profitability also relies on favourable policy support schemes, which have yet to be passed and approved at a European level. Further, interviews with European grid operators revealed that curtailment of renewable electricity is currently not associated with a significant loss of revenues, which negatively impacts the willingness to invest and build PtG systems that go beyond demonstration purposes. However, the increasing deployment of renewable energy technologies to supply the necessary energy for a zero-emission scenario in 2050 will require the installation of higher energy storage capacities in the near future, where the PtG routes can have a vital role in decarbonising the industry and the mobility sectors.

3.3.3. Power-to-Mobility

The use of hydrogen as a transport fuel in the power-to-mobility sector is the most attractive solution nowadays in the heavy-duty transport market segment [38]. Along with urban freight transport, which adopted battery electric vehicles (BEVs) as the preferred solution, freight transport with heavy vehicles requires larger autonomies and shorter refuelling times. Currently, it accounts for 25% of the energy consumption in the transport sector [39]. Furthermore, considering a near-future deployment of hydrogen as fuel in mobility for long-distance transportation, where BEVs' autonomy remains out of reach, it is estimated that by 2030 fuel cell trucks will reach >1% of annual sales within this niche market [40]. Nevertheless, this will be achievable by the cost reduction in hydrogen production and refuelling infrastructure, which is intrinsically linked to the future scale-up of fuel cell electric vehicles (FCEVs) and a decrease in hydrogen production costs through the use of more efficient fuel production systems.

3.3.4. Power-to-Liquid

The main benefit of PtL over PtG is that more valuable products (e.g., ammonia and methanol) can be produced using the existing production and distribution infrastructure. Globally, about 72% of the ammonia produced and 60% of methanol comes from natural gas via SMR [41,42]. For example, the green ammonia market (when ammonia is produced using renewable electricity via electrolytic hydrogen) is projected to reach USD 852 million by 2030 with a CAGR of 54.9%, where the SOEC technology segment is expected to make the largest contribution to the green ammonia market during the forecast period [43]. However, the PtL sector faces similar difficulties as PtG, including location limitation (market size), project complexity, and dependence on supportive policies. Currently, synthetic fuels cannot compete economically with conventional fuels, but technological advancements and decreasing renewable energy costs are auspicious trends. Nevertheless, PtL can take direct advantage of SOEC co-electrolysis capability to simplify the process steps, increase the overall power efficiency, and effectively reduce operational costs. Technical suitability and higher potential revenues are the main reasons PtL has above-average business sector prospects for SOEC-based undertakings.

3.3.5. Grid Services

Grid services, in the form of frequency control services, were found to be an attractive market segment for any kind of electrolyser venture. With only a few exceptions, most EU member states allow at least some form of end-user participation within their control reserve markets. Currently, European efforts are pushing towards even greater grid harmonisation and openness towards demand response participation. Country-based assessments are still needed beforehand, since technical requirements and regulations can differ significantly. The grid control market directly correlates with the national electricity grid size and offers untapped business opportunities. SOEC-based systems are technologically limited to the medium-response Frequency Restoration Reserve (FRS) service that generates a steady flow of income for electrolyser businesses. Even though projects cannot reach profitability solely based on control services, they can essentially provide secondary revenue streams and increase economic feasibility with minimal technical effort [44].

4. Industry and Competitor Analysis

4.1. Electrolyser Industry Overview

The global hydrogen electrolyser market is estimated to account for USD 193 million by the end of 2020. It is expected to reach a market value of more than USD 270.4 million by 2026, at a robust CAGR of 5.8% during 2021–2026 [45]. The region of western Europe is projected to dominate the global market in terms of revenues generated, independent of the product type, while the United States is projected to be the fastest-growing market (7.5% CAGR) [46].

In terms of capacity, having an electrolysis capacity greater than 1 MW has become the segment with the highest market value share in 2017 and will register a CAGR of 7.4% in the forecasted period, followed by medium (150 kW–1 MW) and low capacity units (≤150 kW) [46].

Based on technology type, alkaline electrolysers dominated the market in 2017, with USD 107.4 million in market value globally. This dominating trend is estimated to continue within the next ten years, reaching up to USD 190 million at a CAGR of about 6%. At present, most sales are taking place in Europe (with up to USD 50 million expected by 2027), followed by the Asia Pacific excluding Japan (APEJ), Latin America, and finally North America; no major changes are projected until 2027. Furthermore, PEM electrolysers are expected to witness a higher growth rate than competing technologies at a CAGR of about 8%, with an increase in the market value of USD 72.6 million in 2017 to USD 157 million by 2027. Significant growth is especially expected to take place in western Europe, where the PEM market value could reach more than USD 35 million, followed by the Middle East, Africa, and APEJ [46]. On the other hand, the solid oxide fuel cell market generated approximately USD 410 million in 2019, which is projected to have a market value of USD 840 million in 2024, resulting in a CAGR of about 12.9%. Currently, Europe leads the global SOEC market by far, followed by APEJ, Latin and North America [47].

4.2. Competitor Profiling

The electrolyser industry depicted in consists of several companies mainly located in Europe, the United States, and China. Those key players are shortly described and profiled in terms of revenues, market share, and company size, for those whose financial statements were available to the public (Table 2). The estimated market share has been obtained from the FMI market research report [46].

Table 2. Key players within the global electrolyser industry [46].

Key Players	**Nel Hydrogen**	**McPhy Energy**	**Hydrogenics Corporation**	**Giner ELX**	**ITM Power Plc**	**Tianjin Mainland Hydrogen Equipment**	**Sunfire**
Headquarters	Oslo, Norway	La Motte-Fanjas, France	Mississauga, Canada	Newton, MA, US	Sheffield, UK	Tianjin, China	Dresden, Germany
Total revenue * (2016)	EUR 12.0 M [48]	EUR 7.5 M [49]	EUR 24.7 M [50]	N/A	EUR 2.15 M [51]	N/A	N/A
Total revenue * (2017)	EUR 31.2 M ** [48]	EUR 10.1 M [49]	EUR 40.9 M [50]	N/A	EUR 2.70 M [51]	N/A	N/A
Estimated Market Share (2017)	45%	12%	10%	2%	10%	12%	<1%
Prominent regions	Europe; MEA	Western Europe; Asia Pacific; MEA	Europe; North America; Asia	North America	Europe; North America	China; Europe (as "Hydrogen Pro")	Europe
Electrolyser Product type	PEM (Proton Onsite); Alkaline (Nel Hydrogen)	Alkaline	PEM; Alkaline	PEM	PEM	Alkaline	SOEC
Business Strategy	Mergers and Acquisitions; Product Launch; Collaborations	Collaborations; Expansion	Product Launch; Collaborations	Product Launch; Collaborations	Product Launch; Collaborations	Collaborations	Product Launch; Expansion; Collaborations

* Total revenue may include income from other business sectors than electrolysers. ** Also contains the revenue share of Proton OnSite, due to the acquisition of the latter.

4.3. Business Trends

To be profitable and bankable in the early-stage market segments, projects need to have secondary value streams. This can be achieved when facilities with electrolyser systems combine sales of primary products such as hydrogen, oxygen, and/or heat or other gases with secondary business opportunities, such as grid control services, hydrogen-refuelling stations, or the integration of subsequent power-to-X concepts. This diversification of revenues was specifically promoted by the French company AREVA H2Gen at the Hannover Messe industrial trade fair of 2018 [52]. Other companies are increasingly shifting towards extending the product range by covering large parts of the total value and supply chain of electrolyser-integrated projects. For instance, McPhy Energy and Hydrogenics operate their manufacturing plants, logistic services, sales, and maintenance offices to lower their dependence on suppliers or third-party distributors. In addition to its electrolyser portfolio, Nel Hydrogen also provides storage solutions, data surveillance and monitoring software, distribution services, and hydrogen dispensers for refuelling stations.

Collaborations with other companies or institutions have become critical for two main reasons. Firstly, corporate-research agreements with local universities or research institutes can contribute directly to costly R&D activities that are not profitable for companies. For example, there is a strategic partnership between Hydrogenics and the Chinese developer SinoHytec to conduct product tests [53]. Secondly, cooperation agreements with end-user businesses (B2B agreements) can boost brand awareness, increase the market share of an electrolyser company and ultimately affect the general market pull of the technology. Prominent examples are the collaborations between Nel Hydrogen and Nikola, a Tesla-competitor producing hydrogen-electric trucks, in which Nel Hydrogen is developing and providing the associated refuelling equipment and infrastructure [54]. Another example is the strategic partnership agreement between ITM Power and Sumitomo, one of Japan's largest automotive, electronics, and infrastructure companies. ITM is guaranteed to be the sole supplier of the electrolyser and fuel cell equipment. Other trends have been identified in the formulation of the value proposition of electrolyser firms. With the growing competition from battery technology in the energy storage sector, lithium-ion in particular, hydrogen's longer-term energy storage capabilities have been promoted more forcefully. Mergers and acquisitions have also tackled business risks through competing technologies. For instance, Nel acquired Proton Onsite from the US to add advanced PEM technology to their products, which previously consisted only of alkaline-based electrolysers [55].

5. Business Model Development

Based on the outcomes of the previous analysis, a viable business model for new ventures with SOEC-based products is assessed in this section.

5.1. Challenges for Electrolyser-Based Businesses

Independently of the technology used, the challenges of electrolytic hydrogen production projects are economic instead of technical. The costs need to be balanced by sufficient revenues to reach profitability and bankability. Besides, the fact that hydrogen generation solutions typically involve a large number of stakeholders, from legal, political, and market perspective, adds additional complexity to projects.

Conventional energy generation systems are usually based on a simple model where one input source is transformed into another, based on demand requirements. These layouts apply to traditional power plants or hydrogen production through SMR (single-source/single-product). The new business concepts of electrolytic hydrogen generation increasingly involve more than just one raw material and generate more products [56]. This is especially the case for PtG and PtL systems, where electricity, water, and carbon sources are used to generate not just valuable products such as methane, other gases, or liquids, but also heat, while contributing to the frequency control market. To optimise the financial and technical side, new multi-dimensional optimisation tools need to be developed [57].

5.2. Opportunities for Electrolyser-Based Business

Hydrogen is the most promising and viable approach to storing large quantities of electricity with ranges from 1 GWh to 1 TWh, compared to other systems such as batteries and pumped hydro, which generally range from 10 kWh to 10 MWh and 10 MWh to 10 GWh, respectively [58]. For example, in the United States, the Tri-State Generation and Transmission Association is considering the production of ammonia using electricity from the grid to produce fertilisers. The project will use a reversible SOEC to produce hydrogen when electricity costs drop below USD 25 per MWh [59].

Furthermore, the electrolytic generation of hydrogen and its role in producing synthetic renewable gases enables the coupling between the two main energy infrastructures, the electric and gas networks, via smart and flexible schemes facilitating the path to reach complete decarbonisation of the economy.

Energy-intensive industries (EIIs) represent one of the main opportunities for a hydrogen-based business, in addition to the power generation and the transport sector. Among them, ammonia, refinery, and steel manufacturing industries are presented as the most feasible since they currently use grey hydrogen produced by fossil fuel reforming. These sectors can adopt electrolysis technologies to substitute grey hydrogen for green hydrogen, free of GHG emissions. Some examples of projects in the topic are the REFHYNE (10MW-PEM) for refinery applications and the H2FUTURE (6MW-PEM) for the steel manufacturing sector [21].

5.3. Business Case Selection

It has been determined that the most attractive end-market segments are grid services, followed by refineries and the emerging field of PtL. Nevertheless, all three application fields require large-scale electrolyser systems within the MW scale.

The PtL market is not primarily focused on the production of hydrogen. One main benefit of SOEC is its co-electrolysis capability, where syngas is directly produced from water and carbon dioxide. This functionality is particularly beneficial in the production process of ammonia and methanol, a high-potential PtL route. In this context, SOEC is the only electrolyser technology capable of performing co-electrolysis, providing a technological advantage over alkaline and PEM technologies. Moreover, the reversible operation implies a significant economic edge over the competition as hydrogen re-electrification can be carried out by the same system [60]. For this reason, the business case proposal will be built around a conceptual power-to-ammonia/methanol system. The system will be grid-connected, which is, together with the 1 MW capacity requirement, mandatory for participation in the frequency control market. The carbon source can either be a biomass gasifier or an unspecified carbon-capture plant. The produced fuel is conceived to be sold on the commercial wholesale market as a commodity.

In contrast with the other stated applications, electrolysers in refineries are primarily used for their hydrogen demand in the plant. This has been historically covered by alkaline and PEM electrolysers due to the lower CAPEX and larger capacities. However, recent projects such as the MultiplHy propose using large-scale SOEC (2.6 MW) for green hydrogen generation in refinery applications.

5.4. Business Model Proposal

For the reasons given above, PtL was selected as the most promising application sector for an electrolyser-based business. A viable engineering firm and operator business model was described for a company entering into a large-scale PtL market with a SOEC-based system.

Manufacturing a solid oxide system requires intensive capital and intellectual property ownership, along with an intensive testing phase before the commercialisation of the final system. This entails high expenses during the testing phase and a prolonged period of negative cash flow preceding the SOEC system commercialisation. Thus, the engineering firm and operator business model incorporates an engineering company that firstly designs a single PtL plant and subsequently acts as its operator. The business model canvas for this venture is depicted in Table 3.

Table 3. Canvas of the engineering firm and operator business model.

Key Partnerships	Key Activities	Value Propositions	Customer Relationships	Customer Segments
Suppliers of process equipment and services · SOEC system · Ammonia/methanol reactors · Hydrogen storage solutions · Balance of Plant work · Monitoring and control software · Construction companies · Investors Research institutions	· Planning, designing and engineering of plant · Operation and maintenance · Product sales · Demand-response tender bidding	· Ammonia/methanol with low carbon intensity · Crude-oil free product	Get: Industry exhibitions, fairs, direct contact Keep: Follow-up meetings/calls Grow: Brand awareness, country expansion, referrals	Ammonia/methanol-consuming industries · Transportation fuel retailers · Specialty chemical companies Ammonia/methanol commodity market
	Key Resources		Channels	
	· Technical know-how/Patents/IP · Production plant facilities · Staff		Owned (direct) · In-house sales · Commodity market · Website Partner (indirect) · Partner network	
Cost Streams			**Revenue Streams**	
Variable costs · Raw materials · Production supplies · Commissions	Fixed costs · Patents, licenses, insurance · Production facilities, rent, salaries, interests · Engineering work · Advertising and promotion		· Ammonia/methanol sales · Frequency restoration reserve service charge · Engineering services for similar projects	

This business model addresses two different customer segments. Firstly, the fuel produced in the PtL plant sells directly to consuming industries, e.g., fuel retailers and chemical companies. Secondly, ammonia and methanol are easily transportable and widely used commodities traded on the commercial wholesale market. In both cases, the value proposition to these customer segments is sustainable as "green ammonia or methanol" and can be produced with low carbon intensity, free from crude oil.

In the first stage, the company's key activities consist solely of planning, designing, and engineering the production plant. After completion, the operation maintains the ammonia/methanol production facilities while responsible for all sales activities. Simultaneously, other activities include tender bidding for participating in the demand-response market of frequency control services. Especially for the first stage, the company relies on several key partnerships. These include suppliers of all relevant process equipment (e.g., the SOEC system), ammonia/methanol reactors, the balance of plant (BoP) work, and construction companies. Furthermore, all engineering work and initial investment costs must be funded accordingly, and R&D activities need collaborations with research institutions. Once the plant is fully operational, the main source of incoming revenue is sourced from the sales of ammonia/methanol and secondary revenue stream sources from providing frequency restoration reserve (FRR) services, where the market size for load-frequency services is dependent on the power requirements of a country [44]. Moreover, in an advanced stage of the enterprise, the company can offer its engineering services and know-how to similar projects and ventures, expanding its business opportunities.

6. Summary and Conclusions

SOEC technology currently presents two main limitations. On one side, there is the need for a CAPEX reduction, which will come with the industrialisation of SOEC systems' production. This will increase the fabrication of ceramic cells, metallic interconnects, and the optimisation of the BoP, from prototyping to industrial and commercial systems. The second limitation, which is the goal of future research, is the need to increase the durability of the cells working at high production rates. This has been improved during the last few years but is still one of the main research topics in the field.

In this work, a top-down approach was chosen to propose a viable business model for SOECs. As the first part of the market analysis, state-of-the-art hydrogen production was examined globally. The market was further analysed in terms of possible end-user applications for electrolysers. Ammonia production and refineries were assessed as conventional market segments. Several emerging market segments for electrolysers have been identified and described, including power-to-X applications and grid services. Building upon that, the business attractiveness of these segments has been evaluated within an opportunity analysis. It was found that in the near to medium term, participating in frequency control reserve services has the highest business prospects for electrolysers, followed by refineries and PtL plants.

In the second part, the current state of the global electrolyser industry was reviewed, and an outlook for developments within the next decade was provided. Subsequently, the seven most prominent electrolyser companies were identified and profiled in the context of a competitor analysis approach. Finally, the main industry and competitor trends observed throughout the study were summarised.

The main findings of the market and industry analysis were used for describing a suitable business model for a potential new SOEC-based company. It was found that commercial deployment of SOEC systems was affected by their low technological readiness and high cost compared to competing alkaline and PEM technologies, especially for applications focused on pure hydrogen generation. However, these trends are already changing with new large-scale projects, such as GrInHy2.0 and MULTIPLHY, which propose installing different MW-scale systems for the steel industry, refineries, and jet-fuel production industries. Moreover, SOEC technology was found to have a competitive advantage through its co-electrolysis operation capability, which is particularly useful in the emerging PtL sector. For that reason, a business case involving a PtL system was recommended. On this basis, an engineering firm and operator business model was considered to enable the company's market approach.

While qualitative assessments indicate that the engineering firm and operator business model is the most attractive, more research work is needed to validate this claim. In particular, a comprehensive business and marketing plan needs to be described for the business model to better understand the economics and drivers of the proposed company structures. This includes in-depth financial planning that captures all relevant revenues, operating costs, capital expenditures, and cash flow forecasts. In addition, the economic assessment results will allow a quantitative evaluation of the business model.

It should be emphasised that despite the simplistic appearance of the developed model, it is instructive and demonstrates the high potential of SOEC technology for generating green hydrogen more efficiently than alternative electrolysis technologies. In fact, the energy required for green hydrogen production using SOEC technology can be less than 4kWh/Nm^3 of H_2, significantly lower than that of competing technologies (>5 kWh/Nm^3 for alkaline electrolysis and >6 kWh/Nm^3 for PEM) [33,61]. Of course, one has to account for the current challenges, which must be tackled, including powering SOECs with real fluctuating renewable energy sources [62]. Along with the overview and analysis of the SOEC technology, the present study points out some of the main industrial routes that could be easily adopted during the next few years to help decarbonise industry, with a special interest in the highly intensive energy industries.

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