Business Model Development for a High-Temperature Co-Electrolyzer System

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ABSTRACT

With increasing international efforts to combat climate change by reducing the emission of greenhouse gases, the use of electrolytic hydrogen as energy carrier in decentralized and centralized energy systems and as a secondary energy carrier for a variety of applications is projected to grow. Currently, electrolysis system with alkaline and polymer electrolyte membrane (PEM) technology are commercially available in different performance classes. The less developed solid-oxide electrolysis cell (SOEC) promises higher efficiencies, co-electrolysis and reversibility functions, but is still in an introductory market stage. This work uses a bottom-up approach in order to develop a viable business model for a SOEC-based venture. In the first stage, the broader market for electrolyzers is analyzed, including conventional and emerging market segments. An opportunity analysis further ranks these segments in terms of business attractiveness. Subsequently, the current state and structure of the global electrolyzer industry is reviewed and a ten-year outlook is provided. Key players of the industry are identified and profiled, after which the major industry and competitor trends are summarized. Based on the outcomes of the previous assessments, a promising business case is generated and used for the development of two possible business model proposals. The main findings are that grid services are the most attractive business sector, followed by refineries and power-to-liquid. SOEC technology was found to be particularly promising due to its co-electrolysis capabilities within the methanol production process. Consequentially, a "Engineering Firm & Operator" business model for a power-to-methanol plant was proposed to be most viable.

Keywords: Solid-oxide electrolysis; Power-to-x; Market research; Competitor analysis; Business model development.

I. INTRODUCTION

In recent years, significant progress has been made in technologies for utilizing renewable energy sources, which made it possible to build economically and technically efficient energy generation plants from 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 contribute to actions against climate change [1]. This has enabled the construction of economically and technically efficient energy generation plants, for example from wind power, hydroelectric power or solar energy. At the 21st UN Climate Change Conference of the Parties (COP21) 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 industrialized countries but the US. In its 2010 Energy Concept, the German Federal Government already set itself the long-term goal of reducing greenhouse gas emissions by 40 % by 2020 and by 80 - 95 % by 2050 compared with 1990 levels [2]. This calls for a fundamental change in energy policy in which the existing industry for energy and petrochemical products need 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). Hydrogen or its derivatives that were produced via renewably-sourced electricity can be used as clean energy storage media. They are used not only as raw materials for chemical processes, but also as secondary energy carriers in stationary and transport applications in various sectors. For that reason, an increasing use of electrolytic hydrogen can have a meaningful contribution to the efforts of decarbonizing industrial processes. 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 [3].

As will be reviewed within the following sections, the main water-splitting technologies used nowadays are the technologically mature alkaline electrolysis and, to a lesser extent, polymer electrolyte membrane (PEM) electrolyzers. High-temperature electrolysis based on solid-oxide electrolyzer cell (SOEC), although regarded as a highly promising technology, is essentially still in the research and development stage with only few examples of commercialization. Therefore, the aim of this work is to propose a sustainable business model for a potential venture, specialized 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 electrolyzers are assessed. Furthermore, the current state and future developments of the electrolyzer 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.

II. Description of Technology

A. Fundamentals of Water Electrolysis

Water electrolysis is an electrochemical process in which a redox reaction takes place by applying a voltage high enough for water to be separated into its components H_2 and O_2. Electrolysis takes place in a so-called electrolyzer. An electrolyzer consists of two spatially separated half-cells which are separated by a diaphragm or by a salt bridge. In each half-cell there is one electrode. At the electrodes, which are called cathode and anode, the gases H_2 and O_2 are formed, respectively, during the electrochemical reaction and can be collected pneumatically. The redox reaction for water electrolysis that takes place under standard conditions is described by Equation 1 [4].

$$2H_2O_{liquid} \rightarrow 2H_{2(gaseous)} + O_{2(gaseous)} \qquad \text{Eq. 1}$$

Different methods for the production of hydrogen via electrolysis exist today. Therefore, the processes of alkaline electrolysis (AE), polymer electrolyte membrane (PEM) electrolysis and high-temperature electrolysis, based on solid-oxides, (SOEC) are explained in the work. As shown in the Table 1, these three electrolysis options differ in the temperature range, in the electrolyte, in the charge carrier and also in the cathode and anode reaction.

B. Solid Oxide Electrolysis

The structure of the high-temperature electrolysis cell is shown graphically in Figure 1. The electrolysis cell contains a cathode, an anode and a membrane through which the oxygen ions pass. The membrane consists of yttrium-stabilized zirconium oxide (YSZ) and represents the solid electrolyte. The YSZ blocks the electrons but allows the oxygen ions to travel through. Ceramic materials such as nickel-zirconium oxide for the cathode and lanthanum-manganese (III) oxide for the anode are used for the electrodes. As soon as water vapor enters the cell, hydrogen is formed at the cathode and oxygen at the anode. When the electrochemical process is reversed, the cell can be used as a high-temperature fuel cell. In terms of construction design, planar is typically preferred to tubular cell design [5].

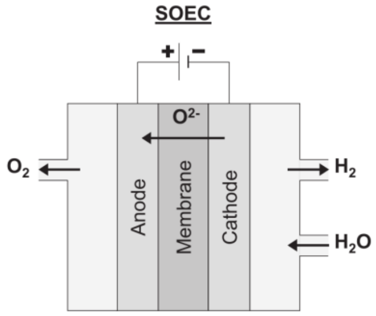


Figure 1. Scheme of a solid-oxide electrolysis cell [6].

The high working temperatures of 700 - 1000 °C reduce the cathodic and anodic overvoltage through the activation of thermal and electrochemical processes. As a result, higher current density (0.3 A/cm^2) can be achieved at a relatively low cell voltage and with a very thin solid electrolyte layer. As soon as the cell voltages are close to the thermoneutral voltage of 1.5 V, efficiencies can be close to 100 % [7]. Apart from the high electrical efficiencies and the option to operate in reverse mode as a fuel cell, other potential advantages exist. These include low material cost and the possibility to produce syngas ($CO + H_2$) from water vapor and carbon dioxide, in the so-called co-electrolysis mode (Equation 2) [6].

$$H_2O + CO_2 \rightarrow H_2 + CO + O_2 \qquad \text{Eq. 2}$$

Although the SOEC cell responds quickly to different load requirements in full and partial load operation, the systems can only be ramped up and down relatively slowly. Mechanical and chemical material problems arise as a result of the temperature-induced tensions during start-up and shut-down, which drastically reduce the service life of the cells. Lifetimes of up to 10,000 hours (slightly more than one year) have been achieved so far, which is a clear difference to the lifetimes of alkaline electrolysis and PEM electrolysis, which are in the range of several years [7]. For that reason, recent R&D efforts focus on the material level, including reducing the internal resistance of the anode, increasing the service life of the cathode and improving its porous properties. In principle, lowering the operating temperature is desirable in order to increase the service life, but this is often ignored in favor of better kinetics. Due to the use of ceramic materials, the cell area of SOEC is significantly smaller than that of PEM or AE. Larger performance classes can therefore only be achieved by increasing the number of stacks/modules used (numbering-up) [3].

Table 1. Overview of the three main electrolysis technologies (with data from [5]).

Technology	Temperature range	Electrolyte	Charge carrier	Cathode reaction	Anode reaction
AE	40 - 90 °C	Aqueous alkaline	OH^-	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$
PEM	20 - 100 °C	Solid polymer	H^+	$2H^+ + 2e^- \rightarrow H_2$	$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$
SOEC	700 - 1000 °C	Solid oxide (ZrO_2/Y_2O_3)	O^{2-}	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

C. Integration with Renewable Energies

For the purpose of operating electrolyzers with intermittent power sources (e.g. solar PV, wind plants), the technical requirements are generally the following:

- Fast response of system components enabling dynamic operation.
- Operation at lower partial load without negative impact on product gas quality.
- Short cold-start times or energy efficient stand-by operation.

PEM electrolyzers are currently most suitable to meet the above stated requirements with lifetime potentially increasing from intermittent power supply, while AE and SOEC are said to be more appropriate in the future as their technical components are currently further developed [6].

III. Market Analysis

A. Hydrogen Production Overview

There are numerous industrial methods for producing hydrogen that mainly depend on location-dependent aspects such as the production demand and the availability of raw materials or other resources. As a gas or liquid, hydrogen can be produced directly from primary resources or from secondary sources. Large-scale industrial processes are primarily based on fossil raw materials and 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 by electricity. While more technologies that involve other application forms of renewable sources, biological processes or nuclear energy exist, they have not yet been advanced to a commercial level and still require substantial research and development [8, 9]. Currently, almost the entire global production of hydrogen is based on fossil fuels, with 48 % from steam reforming of natural gas, 30 % from partial oxidation of oil or naphtha, 18 % from coal gasification, 3.9 % from water electrolysis and a negligible amount from other sources (see Figure 2) [8].

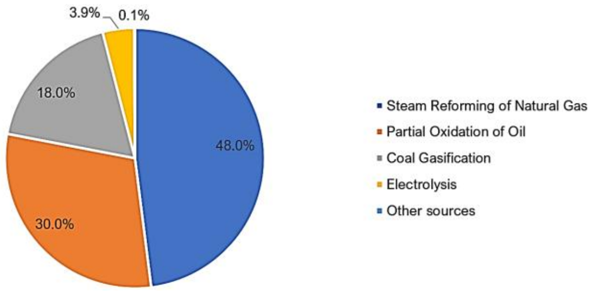


Figure 2. Share of global hydrogen production by technology as of 2018 (data adopted from [8]).

B. Market Segmentation

The market for hydrogen includes various forms of applications. It is predominantly used as a key resource material in the petrochemical and fertilizer industry. As of today, nearly half of the globally produced hydrogen is used for the synthesis of ammonia in the fertilizer industry. About 37 % are used during the processing of crude oil in refineries, which makes it the second most significant application field. The manufacturing of other important chemicals also demand hydrogen as a raw material in large quantities, especially during the production of methanol (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 [8, 10, 11].

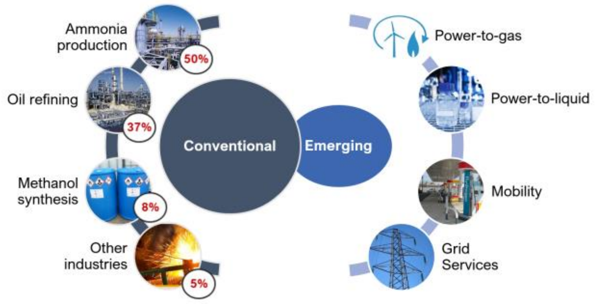


Figure 3. Overview of conventional and emerging hydrogen market segments, including the market share from 2017 (data adopted from [8, 10]).

As can be seen in the right side of Figure 3, new market segments have emerged during the past few years. As a consequence of recent efforts in environmental and energy policies to decarbonize entire electric energy systems, the concept of "renewable hydrogen" has come to special attention. In general, the term describes hydrogen produced carbon-neutrally via electrolysis powered by renewable energies [12].

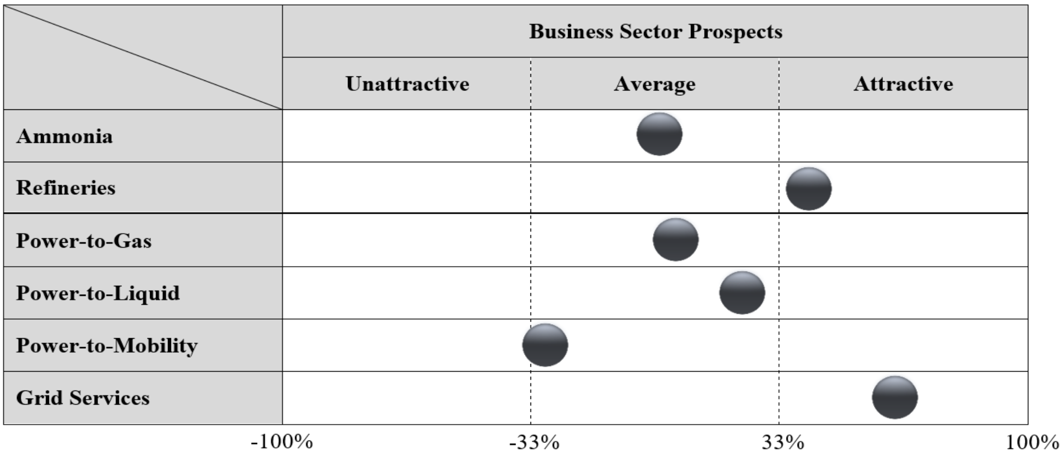
C. Opportunity Analysis

A rudimentary opportunity analysis was conducted to assess the business attractiveness of these segments, specifically for new ventures that involve solid-oxide electrolyzer technology in the near future (approx. five-year time period). To do so, a simplified directional policy matrix (DPM) has been carried out. This tool is an analytical approach that is typically used by investors for making strategic investment decisions. Based on factors that describe the market, technology, policies and economics, it evaluates the prospects of a business sector [13]. The numerical valuation of these factors was done judgmentally, on basis of the previously conducted market analysis. To further decrease the level of subjectivity, the values were discussed with experts from science and industry during interviews. The results of the market segments' attractiveness assessment are summarized in Table 2.

1) Ammonia production

Even though ammonia production is highly dependent on the plant's access to natural gas, substituting SMR-units with electrolyzers for on-site hydrogen generation does currently not make economic sense for existing plants. The use of electrolytic hydrogen could potentially be feasible for new small-

Table 2. Prospects of market segments for solid-oxide electrolyzer businesses cases in the short-term future.



scale, decentralized fertilizer plants in remote locations. Consequently, this greatly limits the possible target market size and it is not expected to grow significantly in the near-to-medium term. In case electrolyzers are considered, the most reliable, longest living and cheapest technology is generally preferred, independent of its efficiency. Especially since the ammonia price is highly affected by cost of hydrogen production, SOEC systems are in a weak competitive position within this market segment.

2) Refineries

Refineries are a more promising, non-energy related, market segment for the electrolyzer business. With the demand for low-sulfur fuels currently rising and the trend of increasingly lower-quality crude oil, merchant hydrogen utilization is growing considerably at the moment. Supportive hydrogen supply by nearby electrolyzer units has been identified to be a technologically and economically achievable solution, that could be realized in many refinery locations around the globe. As for ammonia plants, SOEC-based businesses are facing the internal competition from AE and PEM electrolyzers, due to their cost and lifetime advantages. Partly due to ongoing technological improvements, petroleum refineries could nevertheless be an attractive business sector for ventures relying on SOEC in the short-term future.

3) Power-to-gas

Power-to-gas (PtG) is an innovative concept of combining electrolyzer technology with renewable energy production, with the prospect of monetizing otherwise curtailed surplus electricity in form gaseous products. Yet its attractiveness as a market segment from an economic standpoint is only average, due to a number of restraints. Apart from grid integrity issues, technically feasible PtG facilities are limited to certain locations (CO_2-source, RE-plants, NG-grid), which confines the potential market size. Projects usually involve various stakeholders (technology suppliers, grid & RE-plant operators, TSOs, etc.) which adds to their technical, logistical and organizational complexity as well as financing risks. Profitability is also relying on favorable policy support schemes, which yet have to be passed and approved on 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 in and install PtG systems that go beyond demonstration purposes.

4) Power-to-liquid

The power-to-liquid (PtL) sector is facing similar difficulties as PtG, that include location limitation (market size), project complexity and the dependence of supportive policies. As of now, synthetic fuels cannot compete economically with conventional fuels, but technological advancements and decreasing renewable energy costs are auspicious trends. The main benefit of PtL over PtG is the fact that more valuable products (e.g. methanol and waxes) can be produced, which do not require existing infrastructure or modified appliances. Large global markets for these products already exist with promising growth rates. PtL can take direct advantage of SOEC's co-electrolysis capability in order to simplify the process steps, increase the overall power efficiency and effectively reduce operational costs. Higher possible revenues and beneficial technical suitability are the main reasons why power-to-liquid has above-average business sector prospects for SOEC-based undertakings.

5) Power-to-mobility

The utilization of hydrogen as a transport fuel in power-to-mobility has shown to be virtually unattractive as a potential market segment for new SOEC businesses. This is mainly because of direct interrelation between the negligible amount of hydrogen refueling stations that are available and the low sales of fuel-cell electric vehicles ("chicken-egg-dilemma"). Even though research and development are continuing to improve the underlying technologies, competition through battery-electric vehicles is out of reach at least in the short-to-medium term future (competitive advantage: simpler & more widespread charging infrastructure, higher wheel-to-wheel energy efficiency). Currently, the high costs of producing hydrogen through electrolysis would negatively impact the willingness-to-pay for hydrogen as a transportation fuel and can therefore not be considered as a viable business scenario.

6) Grid Services

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

7) Outcomes of the Opportunity Analysis

In summary, the refineries were identified to be an attractive non-energy market segment for businesses built on SOEC technology, while fertilizer plants are much less appealing from an economic perspective. While still an emerging market, grid services, or control reserve services, are potentially the most attractive business sector for electrolyzer ventures. Even though less attractive than the refinery sector, power-to-liquid shows above-average business prospects in the short-term future and has higher profit possibilities than the other power-to-x segments.

IV. Industry & Competitor Analysis

A. *Electrolyzer Industry Overview*

The global sales of hydrogen electrolyzers are estimated to account for US$ 181.6 million by the end of 2017 and is likely to reach a market value of about US$ 357.0 million by 2027, at a robust CAGR of 7.0 % during that period. 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 are to be the fastest growing market (7.5 % CAGR) [14].

In terms of capacity, electrolyzers having an electrolysis capacity greater than 1 MW have become the segment with the highest market value share in 2017 and will register a CAGR of 7.4 % in the forecast period, followed by medium (150 kW - 1 MW) and low capacity units (≤ 150 kW) [14].

On the basis of technology type, alkaline electrolyzers dominated the market in 2017 with US$ 107.4 million in revenues globally. This dominating trend is estimated to continue within the next ten years, reaching up to US$ 190 million at a CAGR of about 6 %. At the moment, most sales are taking place in Europe (with up to US$ 50 million in 2027), followed by Asia Pacific excluding Japan (APEJ), Latin America and finally North America; no major changes are projected until 2027. With 8 %, PEM electrolyzers are estimated to witness a higher growth rate than competing technologies, with an increase in global sales from US$ 72.6 million (2017) to US$ 157 million (2027). Significant growth is especially expected to take place in western Europe, were the PEM market value could reach more than US$ 35 million, followed by the Middle East, Africa and APEJ. Solid-oxide electrolyzers generated approximately US$ 6 million in 2017, which is projected to have a comparatively low market value of US$ 8.25 million at the end of the following decade, resulting in a rather stagnating CAGR of ca. 2 %. Currently, Europe leads the global SOEC market by far, followed by APEJ, Latin and North America [14]. The global electrolyzer market values are illustrated in Figure 4.

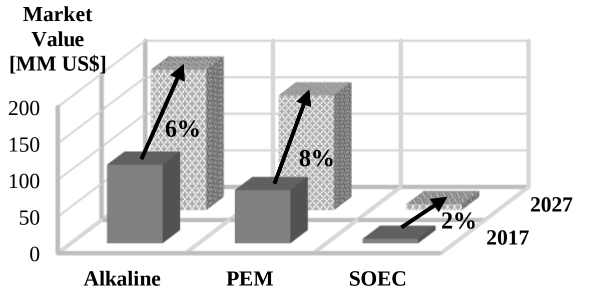


Figure 4. Global Hydrogen Electrolyzer Market Value 2017 – 2027, incl. estimated CAGR (data adopted from [14])

B. *Competitor Profiling*

The relatively small electrolyzer industry industrial consists of several companies that are mainly located in Europe, the United States and China. In the following, those key players are shortly described and profiled in terms of revenues, market share and company size (in case the financial statements were available for to the public). The companies' headquarters and numbers of employees were extracted from LinkedIn; the estimated market share from the FMI market research 2017 [14]. The most important information of the key players of the electrolyzer industry are summarized in Table 3.

C. *Business Trends*

The previously described price target for hydrogen has put high pressure on companies, in terms of cost-effectiveness, and even led to bankruptcies, with the most prominent example being the failure of Heliocentris and Odasco in 2017 and 2018 [15]. On the other hand, it encouraged companies to develop more innovative ways of making business. With the help of government-funded studies and research [16, 17], companies have elaborated more suitable business models to be able to address conventional market segments as well as to enter the emerging markets.

To be profitable and bankable in the early-stage market segments, it was realized that projects need to have secondary value streams. This can be achieved when facilities with electrolyzer systems combine sales of primary products like hydrogen, oxygen and/or heat

Table 3. Dashboard of key players within the global electrolyzer industry.

Key Players	Nel Hydrogen*	McPhy Energy	Hydrogenics Corporation	Giner ELX	ITM Power Plc	Tianjin Mainland Hydrogen Equipment	Sunfire
Headquarters [14]	Oslo, Norway	La Motte-Fanjas, France	Mississauga, Canada	Newton, MA, US	Sheffield, UK	Tianjin, China	Dresden, Germany
Total revenue* (2016)	12.0 M€ [28]	7.5 M€ [29]	24.7 M€ [30]	N/A	2.15 M€ [31]	N/A	N/A
Total revenue* (2017)	31.2 M€** [28]	10.1 M€ [29]	40.9 M€ [30]	N/A	2.70 M€ [31]	N/A	N/A
Estimated Market Share (2017) [14]	45 %	12 %	10 %	2 %	10 %	12 %	< 1 %
Prominent regions [14]	- Europe - MEA	- Western Europe - Asia Pacific - MEA	- Europe - North America - Asia	- North America	- Europe - North America	- China - Europe (as "Hydrogen Pro")	- Europe
Electrolyzer Product type	- PEM (Proton Onsite) - Alkaline (Nel)	- Alkaline	- PEM - Alkaline	- PEM	- PEM	- Alkaline	- SOEC
Business Strategy [14]	- Mergers & Acquisitions - Product Launch - Collaborations	- Collaborations - Expansion	- Product Launch - Collaborations	- Product Launch - Collaborations	- Product Launch - Collaborations	- Collaborations	- Product Launch - Expansion - Collaborations

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

or other gases with secondary business opportunities, such as grid control services, providing HRS 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 of 2018 [18]. Other companies are increasingly shifting towards the extension of the product range by covering large parts of the total value & supply chain of electrolyzer-integrated projects. For instance, McPhy Energy and Hydrogenics, operate their own manufacturing plants, logistic services, sales and maintenance offices, to lower their dependence on suppliers or third-party distributors. In addition to their electrolyzer portfolio, Nel Hydrogen also provides storage solutions, data-surveillance and monitoring software, distribution services and hydrogen dispensers for refueling stations.

Collaborations with other companies or institutions have become more important for two main reasons. First, corporate-research agreements with local universities or research institutes can contribute directly to the costly and non-revenue-generating R&D activities of companies. An example is the strategic partnership between Hydrogenics and the Chinese developer SinoHytec for conducting product tests [19]. Secondly, cooperation agreements with end-user businesses (B2B agreements) can boost the brand awareness, increase the market share of an electrolyzer 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 is developing and providing the associated refueling equipment and infrastructure [20]. Another example is the strategic partnership agreement between ITM Power and Sumitomo, one of the largest automotive, electronics and infrastructure companies in Japan, where ITM is guaranteed to be the sole supplier of electrolyzer and fuel cell equipment.

Further trends have been identified in the formulation of the value proposition of electrolyzer firms. Especially with the growing competition through battery technology, lithium-ion in particular, in the energy storage sector, the longer-term energy storage capabilities of hydrogen have been promoted more forcefully. Business risks through competing technologies have also been tackled by mergers and acquisitions, for instance, when Nel acquired Proton Onsite from the US in order to add advanced PEM technology to their products, which has previously only consisted of alkaline-based electrolyzers [21].

V. Business Model Development

A. Business Case Selection

It was found that the most attractive end-market are grid services, followed by refineries and the emerging field of PtL. All three application fields require relatively large-scale electrolyzer systems within the MW-scale. In contrast with the other stated applications, electrolyzers in Refineries are primarily used for their hydrogen production function. This makes it rather difficult for SOEC-based systems to compete with alkaline and PEM electrolyzers, due to the following reasons:

- Larger capital cost and considerably lower stack lifetime leading to additional costs for stack-replacement
- Industry trend towards using alkaline electrolysis for large-scale hydrogen production projects
- Industry investment decision factors: Capital cost; Total cost of ownership; Equipment lifetime
- Focus on hydrogen production: Revenue diversification difficult / not possible

This suggests that solid-oxide electrolysis is not the most favorable and competitive electrolyzer technology for the application in refineries, from an investor's standpoint.

The second next most attractive market segment is PtL. This field, on the other hand, is not primarily focused on the production of hydrogen. One main benefit of SOEC is its co-electrolysis mode, where syngas is directly produced from water and carbon dioxide. This function is particularity beneficial in the production process of methanol, a possible PtL-route. SOEC is the only electrolyzer technology capable of performing co-electrolysis which gives it a technological advantage over alkaline and PEM. For this reason, the business case proposal will be built around a conceptual power-to-methanol system. The system is grid-connected which is, together with the 1 MW capacity requirement, mandatory for the participation in the frequency control market. The carbon source can either be a biomass gasifier or an unspecified carbon-capture plant. The produced methanol is supposed to be sold on the commercial wholesale market as a commodity.

B. *Business Model Proposals*

For a company to enter the market of large-scale power-to-methanol, it needs to elaborate a viable business model. This work has come up with two possible business forms that are built around that business case.

1) *System Manufacturer Business Model*

The first business model proposal describes a potential solid-oxide electrolyzer company that acts as a manufacturer of complete, containerized power-to-methanol systems. This BM is subsequently named *System Manufacturer*.

In summary, the company would be able to address two customer segments. The first segment are petrochemical industries that either produce methanol themselves, use it for blending transportation fuel or other specialty chemical companies. The offered value proposition for this segment is that the proposed PtM system allows these customers to decarbonize their production, through the ability of using renewable carbon sources. This enables new marketing capabilities by offering or utilizing "green methanol" and decreases their depending on oil prices - the raw material needed for conventional methanol production. Ultimately, added value can be generated through the diversification of revenues with participating in the frequency reserve market. Customers of the energy industry include Transmission System Operators and renewable energy plant operators. The companies can benefit from monetizing otherwise curtailed electricity by transforming it into valuable methanol and its sales, which also adds to their own grid balancing capabilities. Re-electrification can be achieved by installing also a methanol-based fuel cell.

The main activities of the business basically include manufacturing the SOEC cells, stacks and systems as well as integration of all the other process equipment (methanol reactor, storage solutions) as well as the sales procedures. For these business activities, several partnerships are necessary. These comprise mainly of collaboration with suppliers of process equipment and software. Further, cooperation with research facilities are necessary for continuous R&D activities. Partnerships with investors are required for covering initial investments and costs. Revenues are to be generated by selling the complete, containerized power-to-methanol system and by providing maintenance services.

2) *Engineering Firm & Operator Business Model*

Instead of manufacturing the solid-oxide system, integrating it with the other process units and selling the final system, the *Engineering Firm & Operator* Business Model instead describes a company that first designs and engineers a single PtM plant and then acts as its operator. Its business model canvas is depicted in Table 4.

This business model addresses two different customers segments. First, the methanol produced in the company-owned PtM can be sold directly to any kind of methanol-consuming industries, e.g. transportation fuel retailers and chemical companies. Secondly, methanol is an easily transportable and widely used commodity that can also be sold on the commercial wholesale market. In both cases, the value proposition to these customer segments is sustainable "green methanol" that has been produced with a low carbon intensity - free from using crude oil.

In the first stage, the company's key activities consist solely of planning, designing and engineering of the plant. After completion, it will operate and maintain the methanol production facilities while being responsible for all sales activities. Simultaneously, activities include tender bidding for participating in the demand-response market of frequency control services. Especially for the first stage, the company has to rely on several key partnerships; especially suppliers of all

Table 4. Canvas of the "Engineering Firm & Operator" business model.

Engineering Firm & Operator Business Model

Key Partnerships	Key Activities	Value Proposition	Customer Relationships	Customer Segments
Suppliers of Process Equipment & Services • SOEC system • Methanol reactors • Hydrogen Storage solutions • Balance of Plant work • Monitoring & Control software • Construction companies **Investors** **Research Institutions**	• Planning, designing and engineering of plant • Operation & maintenance • Product Sales • Demand-Response Tender bidding **Key Resources** • Technical Know-How / Patents / IP • Production plant facilities • Staff	• "Green" Methanol w/ low carbon intensity • Crude-oil free product	**Get**: Industry Exhibitions, Fairs, Direct Contact **Keep**: Follow-Up meetings/calls **Grow**: Brand awareness, Country Expansion, Referrals **Channels** **Owned (direct)** • In-house sales • Commodity market • Website **Partner (indirect)** • Partner network	**Methanol-consuming industries** • Transportation fuel retailers • Specialty chemical companies **Methanol Commodity Market**

Cost Structure		Revenue Streams
Variable Costs • Raw materials • Production supplies • Commissions	**Fixed Costs** • Patents, Licenses, Insurance • Production facilities, rent, salaries, interests • Engineering work • Advertising & Promotion	• Methanol Sales • Frequency Restauration Reserve service charge • (Next Stage: Engineering services for similar projects)

relevant process equipment, including the SOEC system, methanol reactors, balance of plant work and construction companies. As before, all engineering work and initial investment costs need to be funded accordingly and R&D activities need collaborations with research institutions. As soon as the plant is fully operational, the main source of incoming revenue is due to the sales of methanol. Secondary revenue streams are

Table 5. Advantages and Disadvantages of the System Manufacturer and Engineering Firm & Operator business.

System Manufacturer Business Model	
Advantages	**Drawbacks**
- Wider potential customer range, addressing two big industrial areas - More added value is proposed (Low-carbon intensive methanol production, Participation in frequency reserve market, image boost) - Value proposition customized to each end-user segment	- More capital intensive due to development and operation of own SOEC manufacturing facility - Own patents and intellectual properties necessary for SOEC technology - Difficult sales approach, lengthy negotiations expected - Lack of long-term experience with performance, lifetime, reliability of product (power-to-methanol system) → intense testing phase needed prior to initial sales to lower business risks - High expenses during testing phase → Prolonged period of negative cash flow before product launch
Engineering Firm & Operator Business Model	
Advantages	**Drawbacks**
- Little risk of finding buyer for methanol on commodity market at market prices - Partnership with SOEC system supplier - No own patents/IP or manufacturing facilities needed - Participation in frequency control market is the company's secondary revenue stream (instead of being a value proposition) - Possibility of future company expansion though offering engineering services	- Higher operational risk due to strong dependency on network of suppliers for process equipment, construction, etc. - In case of economic necessity to sell methanol above market price, sales dependent on buyer's willingness-to-pay - Location of production plant limited by: Availability carbon sources, market regulations for frequency control services, favorable political support and options of access to methanol commodity market.

from providing frequency restauration reserve services. In an advanced stage, the company can offer its engineering service and know-how to similar projects, expanding its business opportunities.

3) Evaluation & Discussion

When comparing both business models with each other, unique advantages and drawbacks can be identified on a qualitative level. They are summarized in Table 5.

At this stage of the business model development it is difficult to weigh the actual business opportunities of both proposals. From a qualitative standpoint and after comparing both advantages and drawbacks, the subjective impression is that the *Engineering Firm & Operator* business model might be more attractive for a new SOEC-based venture. Nevertheless, this initial claim can only be confirmed by generating a complete economic valuation for each business model and comparing the financial results.

VI. SUMMARY AND CONCLUSION

In order to propose a viable business model for solid-oxide electrolyzer, a top-down approach was chosen. As the first part of an extensive market analysis, the state-of-the-art in hydrogen production was examined on a global scale. The market was further analyzed in terms of possible end-user applications for electrolyzers. Ammonia production and refineries were assessed as conventional market segments. Additionally, several emerging market segments for electrolyzers have been identified and described, including power-to-X applications and grid services. Building up on that, the business attractiveness of these segments has been evaluated within on opportunity analysis. It was found that in the short-to-medium term future, participating in frequency control reserves services are have the highest business prospects for electrolyzers, followed by refineries and power-to-liquid plants.

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

The main findings of the market and industry analysis were then used for elaborating suitable business models for a potential, new SOEC-based company. It was found that commercial deployment of solid-oxide electrolysis systems is affected by their low technological readiness and high cost, in comparison with competing alkaline and PEM technologies, especially for applications focused on pure hydrogen generation. Although, SOEC technology was found to have a competitive advantage through its co-electrolysis operation mode, a feature that is particularly useful in the emerging power-to-liquid sector. For that reason, a business case involving a power-to-methanol (PtM) system was recommended. On this basis, two inherently different business models were proposed that can enable a company's market approach.

While qualitative assessments indicate that the *Engineering Firm & Operator* business model is more attractive, more research work needs to be devoted to validating this claim. In particular, a comprehensive business & marketing plan needs to be elaborated for both business models, 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. The results of the economic assessment will allow a quantitative evaluation of both business models.

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