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.

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List of Abbreviations

Abbreviation	**Description**
COP21	21st UN Climate Change Conference of the Parties
PtX	Power-to-X
PtG	Power-to-gas
PtL	Power-to-liquid
RE	Renewable energy
PEM	Polymer electrolyte membrane
SOEC	Solid-oxide electrolysis
DC	Direct current
HHV	Higher heating value
LHV	Lower heating value
AE	Alkaline electrolysis
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
MEA	Membrane electrode assembly
YSZ	Yttrium-stabilized zirconia
PV	Photovoltaic
SMR	Steam-methane reforming
POX	Partial oxidation of hydrocarbons
IEA	International Energy Agency
OECD	Organization for Economic Co-operation and Development
CCS	Carbon capture and storage
IGCC	Integrated gasification combined cycle
EU	European Union
US	United States of America
CAGR	Compound annual growth rate
EIA	US Energy Information Agency
IMO	International Maritime Organization
NG	Natural gas
CNG	Compressed natural gas
MtG	Methanol-to-gasoline
FT	Fischer-Tropsch
TRL	Technological readiness level

PtM	Power-to-methanol
AAGR	Average annual growth rate
FCEV	Fuel-cell electric vehicle
HRS	Hydrogen refueling station
BEV	Battery-electric vehicle
FCR	Frequency Containment Reserve
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
RR	Replacement Reserve
ENTSO-E	European Network of Transmission System Operators for Electricity
DPM	Directional policy matrix
RE	Renewable Energy
TSO	Transmission Service Operator
APEJ	Asia Pacific excluding Japan
B2B	Business-to-Business
IP	Intellectual Property
UK	United Kingdom
R&D	Research and Development
MEA	Middle East and Africa
BM	Business Model
SWOT	Strengths, weaknesses, opportunities and threats

1 Introduction

The release of greenhouse gases is said to be 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. Since 1990, the global transport sector, driven by the automotive and shipping industries, has grown by more than 50 % 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 cause low prices [2, 3]. In order to work against this trend and to reduce emissions of environmentally harmful off-gases, the development of innovative and more sustainable energy systems is necessary.

In recent years, significant progress has been made in technologies for utilizing renewable energy (RE) 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 climate protection [4]. 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 [5]. 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 [6].

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.

2 Description of Technology

This chapter provides an overview of the technical background behind the electrolysis technology discussed within this work. Beginning with a summary of water electrolysis fundamentals, the working principles of alkaline, polymer electrolyte membrane and solid-oxide electrolyzers are described. Finally, the main characteristics are recapitulated of in terms of a technology comparison.

2.1 Fundamentals of Water Electrolysis

In general, water electrolysis is an electrochemical process in which a redox reaction takes place by applying a voltage high enough for the water to be separated into its components H_2 and O_2. Electrolysis takes place in a so-called electrolyzer. An electrolyzer, as shown in Figure 2-1 for example, 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 2.1:

$$2\mathrm{H_2O_{(liquid)}} \rightarrow 2\mathrm{H_{2(gaseous)}} + \mathrm{O_{2(gaseous)}} \qquad \text{Equation 2.1}$$

The reaction produces a product gas in a ratio of 2 (H_2) to 1 (O_2). In terms of gas volumes, the amount of H_2 produced is double of that of O_2. In terms of mass, the oxygen formed at the anode is eight times heavier than the hydrogen formed at the cathode [7].

In this reaction, the enthalpy of reaction of the liquid water corresponds to 286 kJ/mol, which in turn corresponds to the thermoneutral voltage of 1.48 V and the calorific value, also known as Higher Heating Value (HHV), of 3.54 kWh/m³. The reversible voltage U_0 is 1.23 V and corresponds to the lower heating value (LHV) of 3.00 kWh/m³ [8]. According to [9], the lower calorific value (LHV) of H_2 should be used for all efficiency calculations related to the entire H_2 process chain. However, if the hydrogen produced is subsequently chemically utilized, the calorific value (HHV) for H_2 must be used to calculate the efficiency, since water is supplied as a liquid starting material and the reaction enthalpy for the decomposition of liquid water to hydrogen is equal to the calorific value.

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 following sections. As shown in Table 2-1, these three electrolysis options differ in the temperature range, in the electrolyte, in the charge carrier and also in the cathode and anode reaction.

Table 2-1. Overview of the three main electrolysis technologies (with data from [9]).

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-}	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$

2.2 Alkaline Electrolysis

Alkaline electrolysis has been used commercially for over 100 years and is currently the most widely used.

In order to prevent mixing of hydrogen and oxygen during electrolysis, the electrolyzer is composed of two half cells as shown in Figure 2-1. The two half cells are separated by a diaphragm, for nickel oxide or plastic materials, e.g. polysulfone, are used. The electrodes are made out of perforated metal with porous surfaces and arranged closely to the separator [9]. The material of the electrodes consists mainly of nickel alloys [10]. Via vacuum plasma spraying, the Raney nickel alloys, for example, are applied onto the electrodes in specified layer thicknesses and porosities [11]. To avoid impurities in the electrolyzer, deionized water is used at the cathode side. To increase the electrical conductivity in the half cells, the alkaline electrolyte potassium hydroxide (KOH) is added in to the deionized water in concentrations between 25 and 39 % [10]. Although sodium hydroxide (NaOH) can also be used as an electrolyte, KOH has a higher conductivity than NaOH at the same concentration [12]. Alkaline electrolyzers are predominantly constructed in bipolar design in a filter press system. In the bipolar design, the individual cells are electrically connected in series and combined to form a stack (cell stack).

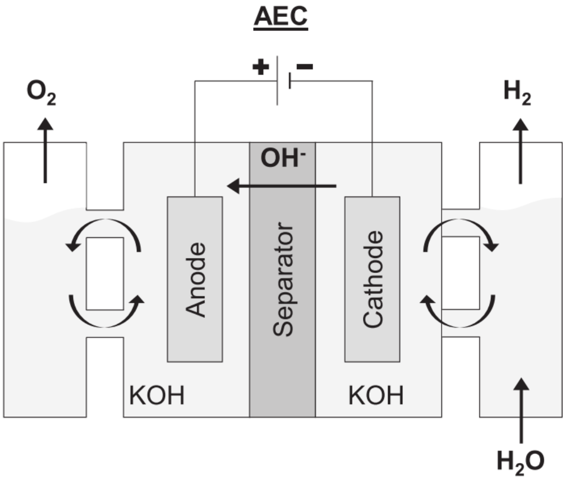

Figure 2-1. Basic structure of an alkaline electrolysis cell [13].

One of the electrodes is the anode, which forms the positive pole and attracts the OH^- anions, leading to the formation of oxygen though an oxidation process. The second electrode, the cathode, forms the negative pole. The water reduction takes place at the cathode and hydrogen is produced. On the half-cell side of the cathode, water is supplied and negatively charged hydroxide ions are formed in addition to the hydrogen. The hydroxide ions pass through the ion conducting membrane of the diaphragm and are converted to oxygen and water on the anode side [14].

The production of 1 kg H_2 requires around 52 kWh of direct current and 28 liters of deionized water. Because 1 kg H_2 corresponds to 33.33 kWh of energy, the electrolyzer's efficiency is around 62 %. The cell voltage and the efficiency of electrolyzers depend on the current density. For this reason, the efficiency of an electrolyzer increases in the partial load range [14]. This property is particularly advantageous when operating the electrolyzer with electricity from renewable energy sources, such as wind power and photovoltaic plants [11].

AE can be distinguished between atmospheric electrolysis and pressurized electrolysis. The working temperature of electrolyzers is between 40 °C and 90 °C for atmospheric electrolyzers and between 90 °C and 100 °C for pressurized electrolyzers. The advantages and disadvantages of atmospheric and high-pressure electrolysis are summarized in Table 2-2. The atmospheric AE operates at slightly more than the ambient pressure and the working pressure of the pressurized AE is between 30 and 60 bar.

Table 2-2. Comparison of atmospheric and pressurized electrolyzers (with data from [15]).

Pressurized Electrolysis	**Atmospheric Electrolysis**
Advantages	**Advantages**
• More compact design due to smaller pipe cross-sections and plant components • Greater development potential through improving the ratio between stack capacity and number of cells through higher current densities • Direct connection to industrial applications that work with process pressures of ~ 30 bar	• Simple and solid system design • Low demand for operating personnel • Larger load ranges from 20 to 100 % • No explosion protection certification required • Lower investment costs of 20 to 30 % compared to pressure electrolyzers • Reliable, many years of operating experience
Disadvantages	**Disadvantages**
• Higher investment costs • More complicated measurement, control and regulation technology • Higher safety-related expenditures • At higher pressures (>10 bar) the usable load is can reduce from 100 % to 30 % • Higher maintenance efforts	• Larger footprint • More complex gas drying • Higher costs due to additional compressor stage • Stack capacity limited by maximum current density during atmospheric operation

Recent developments in alkaline electrolysis are more frequently characterized by a compact design, integrated in standard containers. Current developments are less aimed at cell size, operating pressure or temperature, but rather at increasing current density from currently about 0.2 to 0.4 A/cm² to values of up to about 1 A/cm² in order to reduce specific investment costs. This is to be achieved primarily by using electrochemically more active electrodes, optimizing the bipolar plate-electrode network and improving electrolyte flow. One challenge here is to achieve an operating lifetime similar to that of conventional alkaline electrolysis, despite more complex catalyst systems and a higher current density [6].

2.3 Polymer Electrolyte Membrane Electrolysis

Electrolysis technology with a proton-conducting membrane is a much more recent technology than alkaline electrolysis technology and therefore also less commercially available. In contrast to alkaline electrolysis, charge transport in PEM electrolysis takes place not via hydroxide ions, but via protons. In addition, PEM electrolysis does not have a liquid electrolyte, but a solid proton exchange membrane, which consists of Nafion in most cases [10]. The membrane is characterized by a high ionic conductivity. The schematic structure of a PEM electrolysis cell is illustrated in Figure 2-2.

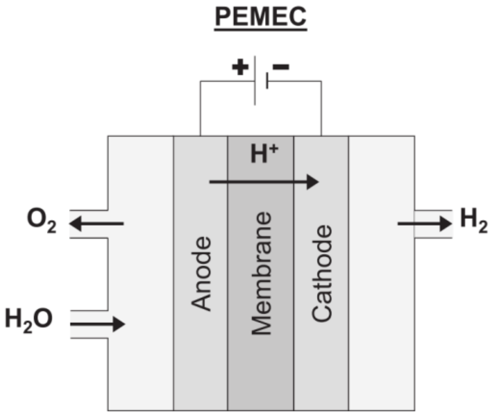

Figure 2-2. Conceptional set-up of PEM electrolysis [13].

In PEM electrolysis, the electrodes are usually applied directly to the membrane, creating a zero-distance configuration that helps reducing the voltage surge. This combination of membrane and electrodes is called the membrane electrode assembly (MEA). The electrodes are usually composed of carbon-supported noble metals. The electrodes are contacted with a porous current transmitter over the entire surface. As with alkaline electrolyzers, the cells of a PEM stack are arranged bipolarly. The bipolar plates have flow channels (flow field) for the supplied water and the resulting gases. The high-purity water required for electrolysis is supplied to the cell on the anode side. Decomposition of the water takes place at the anode and, according to the reaction from Table 2-1, oxygen and protons are formed. The protons migrate through the membrane to the cathode and form hydrogen gas molecules, with the help of the electrons (cathode reaction in Table 2-1).

This arrangement enables the production of high-purity hydrogen, since there is no liquid electrolyte that would allow oxygen to enter the anode side in comparison to AE. In addition, this offers the advantage that PEM electrolysis can also be operated in very low load ranges. Even at partial load operation close to 0 %, there are no critical impurity gas concentrations [38]. In addition to the possibility of rapid load changes in a large range, PEM electrolysis has the advantage over alkaline electrolysis that there is no need to handle a highly concentrated alkaline solution. Also, PEM electrolysis has significantly higher current densities and a very simple and compact system structure. However, high investment costs of the technology are to be mentioned as a disadvantage. Besides, PEM is a young technology compared to alkaline electrolysis and for this reason is not yet technically mature to the same extent [9, 10, 16].

Over the past 20 years, PEM electrolysis has established itself primarily in industrial or niche applications with small production capacities and high operating pressure (operating temperature of approx. 60 °C). Due to their suitability for coupling with renewable energies (fast start and stop behavior, partial load and overload capability at stack level, high compressive strength in compact design, etc.), intensive development efforts have been initiated in almost all countries in the last ten years, both on the industrial side and in research facilities. Above all, the scale-up of the cell areas and the increase in stack performance was and is the focus of current development work. While cell areas of up to 200 cm^2 were common in the niche applications mentioned above, cells with an active area of 600 to 1,500 cm^2 are currently used in the modules for the small megawatt class. However, there is no clear trend towards higher operating pressures and temperatures. Although stack prototypes with an operating pressure of up to 100 bar have been repeatedly presented in recent years, an operating pressure of 30 to 50 bar seems to be established from the end-user's point of view and also for cost reasons. Current density, on the other hand, has high upward potential. Today's cells typically operate at current densities of 1 to 2 A/cm^2. Current densities of up to 4 A/cm^2 are implemented in the current prototypes, while membrane electrode assemblies for current densities above 10 A/cm^2 are also being investigated in research laboratories. This is to be achieved mostly by improved and thinner membranes. In addition, more active electrocatalysts need to be used. Technically, these cell concepts can be implemented, but the question remains as to whether they can also increase the service life at the same time [6].

2.4 Solid Oxide Electrolysis

First research in the field of high-temperature electrolysis with solid-oxide electrolysis cells date back to General Electric (GE, 1968) and the Brookhaven National Laboratory (1970). Since 1990, however, research has focused more on high-temperature fuel cells, the so-called solid-oxide fuel cells (SOFCs), although SOEC has also profited from this development [9].

The structure of the high-temperature electrolysis cell is shown graphically in Figure 2-3. The electrolysis cell contains a cathode, an anode and a membrane through which the oxygen ions pass. The membrane consists of yttrium-stabilized zirconia (YSZ) and represents the solid electrolyte. The YSZ blocks the electrons but allows the oxygen ions to travel through. Oxide 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.

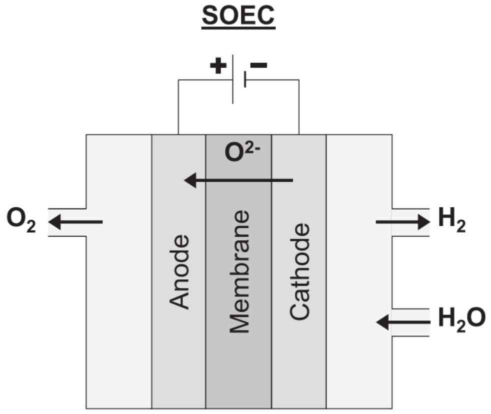

Figure 2-3. Scheme of a solid-oxide electrolysis cell [13].

Efficiencies of over 85 % can be achieved in high-temperature electrolysis. If an external waste heat source of 200 - 300 °C is available, the electrical energy requirement for SOEC is about 25% lower. 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 % [12]. Apart from the high electrical efficiencies and the option to operate in reverse 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 2.2) [13].

$$\mathrm{H_2O + CO_2 \rightarrow H_2 + CO + O_2} \qquad \text{Equation 2.2}$$

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 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 [9, 12]. 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 oxygen electrode and improving the porous properties of the cathode. 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. The pressure resistance up to about 10 bar is usually made possible by an additional external pressure compartment. Due to the use of ceramic materials, the cell area of SOEC is significantly smaller than that of PEMEL or AEL. Larger performance classes can therefore only be achieved by increasing the number of stacks/modules used (numbering-up) [6].

2.5 Technology Comparison

To conclude, the main system characteristics of alkaline, PEM and solid-oxide electrolyzers are summarized in Table 2-3 below, based on data from a 2017 elicitation study [13].

Table 2-3. Main characteristics of alkaline, PEM and solid-oxide electrolyzer systems, as of 2017 [13].

	AE	**PEM**	**SOEC**
Electrolyte	Potassium hydroxide (20-40 wt% KOH)	Polymer membrane (e.g. Nafion)	Yttria stabilized Zirconia (YSZ)
Cathode	Ni, Ni-Mo alloys	Pt, Pt-Pd	Ni/YSZ
Anode	Ni, Ni-Co alloys	RuO_2, IrO_2	LSM[a]/YSZ
Current density (A/cm²)	0.2 - 0.4	0.6 - 2.0	0.3 - 2.0
Cell voltage (V)	1.8 - 2.4	1.8 - 2.2	0.7 - 1.5
Voltage efficiency ($\%_{HHV}$)	62 - 82	67 - 82	<110
Cell area (m²)	<4	<0.3	<0.01
Operating Temp. (°C)	60 - 80	50 - 80	650 - 1000
Operating Pressure (bar)	<30	<200	<25
Production rate[b] (m^3_{H2}/h)	<760	<40	<40
Product gas purity (%)	>99.5	99.99	99.9
Lower partial load range[c] (%)	10 - 40	0 - 10	>30
System response	Seconds	Milliseconds	Seconds
Cold-start time (min)	<60	<20	<60
Stack Lifetime (h)	60,000 - 90,000	20,000 - 60,000	<10,000
Technology maturity	Mature	Commercial	Demonstration
Capital cost (€/kW_{el})	1000 - 1200	1860 - 2320	>2000

[a] Perovskite-type lanthanum strontium manganese ($La_{0.8}Sr_{0.2}MnO_3$).
[b] Refers to norm cubic meter of hydrogen (at standard conditions).
[c] Minimum operable hydrogen production rate relative to maximum specified production rate.

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

- **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.

As can be seen from Table 2-3, PEM electrolyzers seem to be most suitable to meet the above stated requirements with lifetime potentially increasing from intermittent power supply. Alkaline and solid-oxide electrolysis are said to be more appropriate in the future, as their technical components are currently engineered to better operate with intermittent electricity sources [13].

3 Market Analysis

The following chapter provides an overview of the current state of the hydrogen market. First, the main commercial methods of large-scale hydrogen production are described. The present state of global production shares and capacities is presented as well as economic parameters of the processes involved.

Secondly, the main conventional and emerging segments of the hydrogen market are introduced and described based on application and end use. After identifying and discussing future trends, prospects and restraints, the potential of electrolysis technology is analyzed for each segment.

Finally, an opportunity analysis is intended to conclude the outcomes and main findings of the market analysis by evaluating and ranking the business attractiveness of solid oxide electrolyzer technology within the previously discussed market segments.

3.1 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 reforming of natural gas (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 [17, 18].

Global production volumes and shares

The market survey by Ball et al. (as found in [18]) in 2009 about the real production volume of hydrogen found that the global production has seen annual growth up until 600 to 720 billion m³ (54-65 Mt) per year. In the European Union, it was estimated that an annual amount of 80 billion m³ is produced, with Germany as the largest producer (22 billion m³) followed by the Netherlands (10 billion m³). The production in the United States is projected to be about 84 billion m³. 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 3-1) [17].

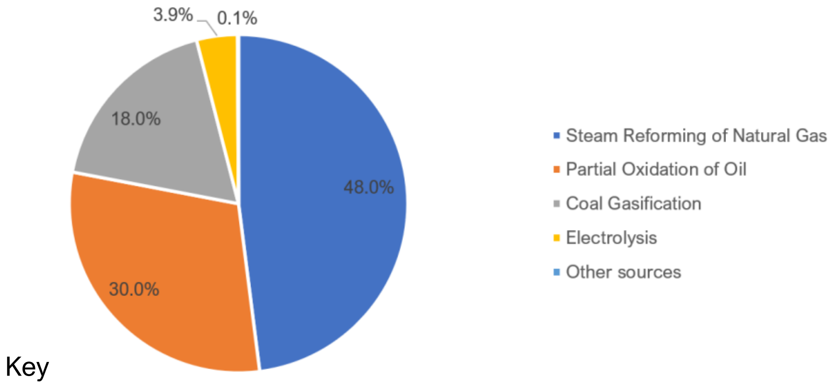

Figure 3-1. Share of global hydrogen production by technology as of 2018 (with data from [17]).

Hydrogen from Steam Reforming

Steam reforming of natural gas is the most common industrial pathway for producing hydrogen on a large scale. The process typically consists of two main steps where purified methane from a natural gas feedstock is converted at up to 750-800 °C into syngas and ultimately into CO_2 and H_2. Even though the process involves the emission of large quantities of environmentally harmful CO_2, it is currently the most economical and widely used method for hydrogen production. Its efficiency of 65 % to 75 % is among the highest of the commercially available production processes [19, 20].

SMR plants are mostly realized as large industrial plants for centralized hydrogen production, for direct use in surrounding petrochemical industries, ensuring minimum levels of emissions and costs. In areas with a lower concentration of hydrogen demanding industries, decentralized SMR plants are potentially more economical than large-scale centralized production, by avoiding expensive hydrogen transportation and distribution infrastructures. Still, smaller reforming facilities are about five to then percentage points less efficient and significantly more expensive than centralized plants (on an investment cost per installed capacity basis). In an extensive technology analysis by the IEA and OECD from 2005 [21], the economies of scale[1] for SMR units were analyzed. As can be seen in Figure 3-2, reformer cost per unit of capacity declines with increasing capacity installed. Decentralized plants are estimated to be up to four times more expensive to build than their large-scale counterparts. The resulting cost of production for centralized plants is therefore 3-5 USD/GJ H_2 and more than 50 USD/GJ for hydrogen from decentralized facilities.

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[1] Economies of scale refer to reduced costs per unit that arise from increased amount of production [85].

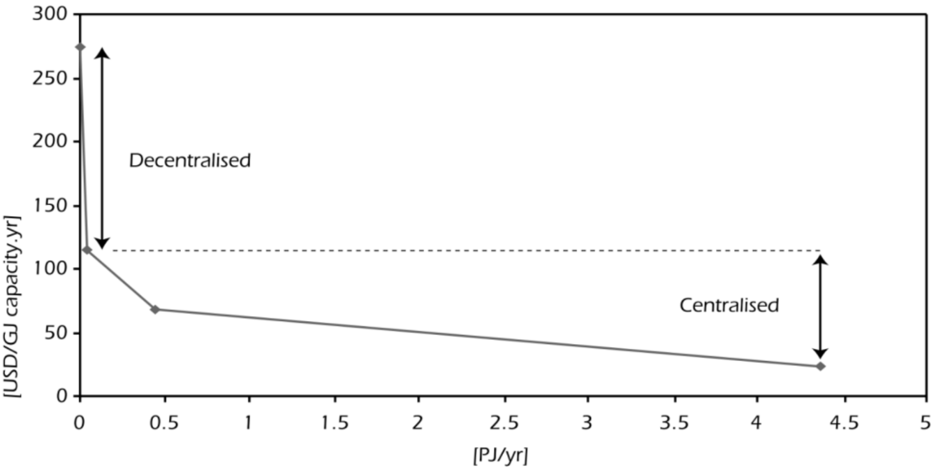

Figure 3-2. Investment costs for steam reforming units vs. capacity [21].

Hydrogen from Coal Gasification

Hydrogen production from coal through endothermic gasification produces a gas mixture of hydrogen, carbon monoxide, carbon dioxide, methane and other components. Through a series of separation processes, pure hydrogen can be obtained with CO_2 being the predominant by-product. Although being a more complex process, coal gasification is a mature and cost-effective technology for producing hydrogen and can compete with SMR. Due to significant economy of scale effects and the complexity of implementing CO_2 capture and storage (CCS) systems, small-scale coal gasification is not yet economically feasible. In general, producing hydrogen from centralized plants without CCS costs between 6 and 7 USD/GJ H_2 the while the addition of CCS technology increases the cost up to 8-10 USD/GJ. New technology concepts with integrated gasification combined cycle (IGCC) plants and cogeneration are projected to decrease future hydrogen production costs from coal (for more, see [21]).Other production processed from fossil fuels, biomass or directly from renewable sources are currently significantly more expensive and therefore not further described in this work (additional information, see [22]). The following Figure 3-3 summarizes the current cost of production from centralized and decentralized SMR as well as from coal gasification. As previously mentioned, hydrogen production from small-scale reformers is exceedingly expensive and therefore subjected to competition from alternative hydrogen production technologies [21].

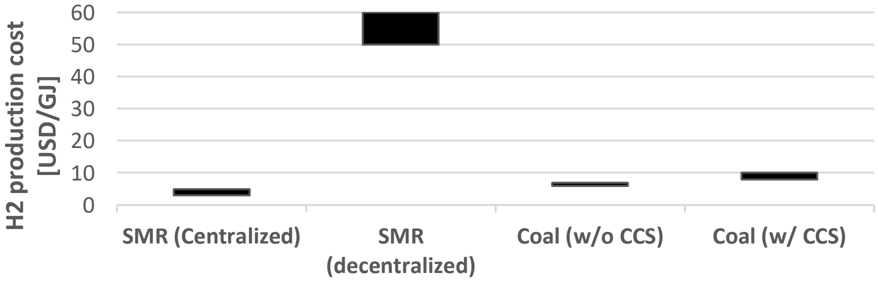

Figure 3-3. Current costs of hydrogen production from natural gas and coal (with data form [21]).

Hydrogen Distribution

Only a small fraction of the globally produced hydrogen is available as merchant hydrogen in the free market. Today, the main distribution and transportation options include delivery by trailers (gaseous or liquid) and via pipelines. In the EU, the biggest pipeline infrastructure with 810 km built by Air Liquide connects industrial sites in the Netherlands, Belgium and France. Linde and Air Liquide have realized two other hydrogen pipeline projects in Germany with 100 and 240 km, respectively. With 95 %, most hydrogen is directly used on-site of the production. Generally, a typical industrial setting with high hydrogen demand (e.g. in refineries or ammonia plants, see chapter 3.2.1) incorporate small to medium scale SMR plants for independent, on-site production [18, 23].

3.2 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 [17, 24, 25].

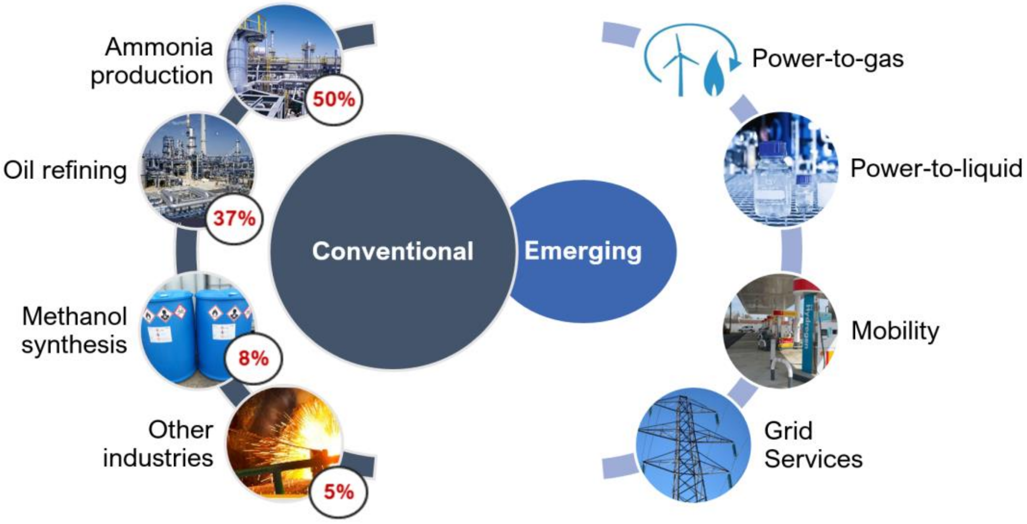

Figure 3-4. Overview of conventional and emerging hydrogen market segments, including the market share from 2017 (with data from [17, 24]).

As can be seen in the right part of Figure 3-4, 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 [23]. Although numerous other potential applications exist, this work has identified the use of renewable hydrogen for grid injection or further methanation (power-to-gas), the production of carbon-neutral liquid fuels and direct use in the mobility sector as the most promising emerging markets. Additionally, grid balancing services make up another potential market segment especially suitable for the implementation of electrolyzer systems.

3.2.1 Conventional Hydrogen Markets

Hydrogen has been an important resource material in the chemical and petrochemical industry for centuries. The conventional markets for hydrogen are thriving and have been seeing a steady annual growth rate (CAGR[2]) of 5 % since 2003, where the global consumption increased from 41 to 73 million tons in 2016. Ammonia production and refineries are still leading the worldwide hydrogen demand with 87 % in 2011 (see Figure 3-5) [26, 27]. For this reason, these industries should be considered as promising market entry segments fields for alternative hydrogen generating systems like electrolyzers.

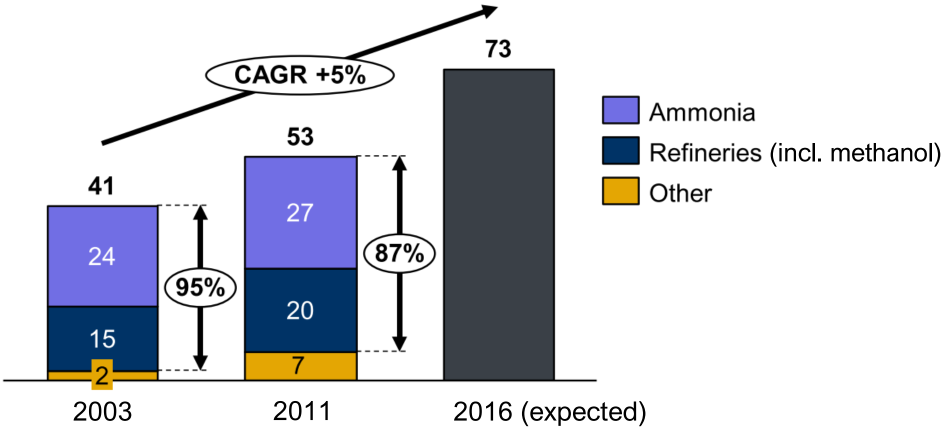

Figure 3-5. Global hydrogen consumption (2003, 2011 and 2016) in million tons [26].

It has to be noted that the market for hydrogen is these segments is mostly captive, meaning that hydrogen is mainly directly consumed on-site by the producer. In 2003, the share of merchant hydrogen from the free market was only 6 % but is expected to increase to 16 % in 2016 [18, 26]. The next subsections will describe the main conventional markets for hydrogen, followed by summarizing each

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[2] The compound annual growth rate (CAGR) is the annualized average rate of value growth between two given years, assuming growth takes place at an exponentially compounded rate [86].

current market situation as well as key drivers and restraints. Finally, the potential of implementing clean hydrogen from electrolysis will be assessed.

3.2.1.1 Ammonia Production

Ammonia (NH_3) is one of the world's most extensively produced chemicals and mainly used as a raw material for the manufacturing of approx. 500 million tons of nitrogen fertilizer annually. Known as the Haber-Bosch process, the main ammonia synthesis route combines nitrogen and hydrogen gas at elevated pressure and temperature (150 – 250 bar; >350 °C) in the presence of an iron catalyst (see Equation 3.1).

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad \text{Equation 3.1}$$

In 2017, a total of 150 million tons of ammonia were produced globally, a 20 % increase from 2007 (125 Mt). The global production capacity is expected to increase by 8% during the next four years [28]. About 88 % of the produced ammonia is directly further processed on-site, since its handling and transportation requires high technological and cost-intensive efforts. As can be seen in Figure 3-6, China is by far the biggest producer, followed by countries that have access to cheap feedstock material for hydrogen production (natural gas, coal). France (blue in Figure 3-6) is the only European country in the list and also Europe's largest producer of ammonia. Notable production companies include Yara (Norway), CF Industries and Koch (both US), Potash Corp and Agrium (both Canada), TogliattiAzot and Eurochem (both Russia), Sinopec (China) and IFFCO (India) [26, 28].

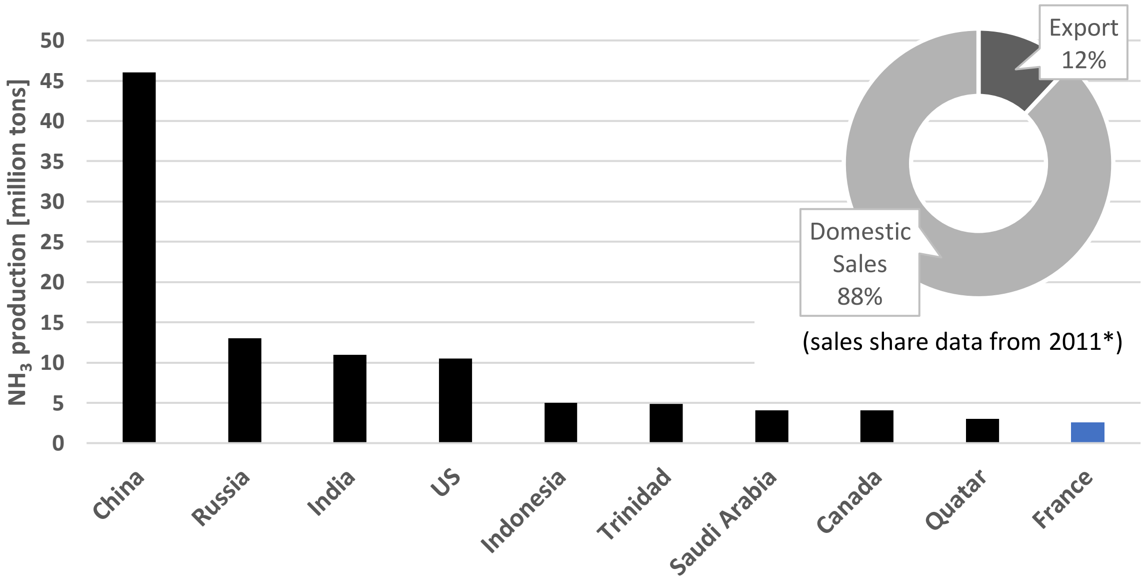

Figure 3-6. Top 10 ammonia producing countries in 2017 (with data from [28] and [26]*).

Role of hydrogen production cost

The value of ammonia lies in its nitrogen content, a molecule that is readily available in the earth's atmosphere. The other essential compound, besides water and external energy, hydrogen, needs to be produced separately. Ammonia production facilities are typically coupled with on-site hydrogen generation in large integrated plants to cover all hydrogen demand and to maximize process efficiencies. Steam reformers make up 77 %, particularly in areas with low natural gas prices (e.g. US, Saudi Arabia). 14 % of ammonia plants use coal gasifiers, mainly in China and for small and medium sized sites. Other countries, such as India, use light hydrocarbons from diversified feedstocks in their ammonia plants.

The cost of ammonia manufacturing is largely influenced by the cost of producing hydrogen. In case of an SMR-based ammonia plant, the purchasing cost of natural gas contributes approximately 70 - 85 % to the overall production cost. Even though coal feedstock is cheaper than natural gas, SMR-integrated plants are 1.5 - 2.5 times less capital cost intensive require a comparably lower energy intake. As a result, newly built ammonia plants predominantly rely on steam reforming integration [26, 27].

Potential of electrolytic hydrogen using excess renewable energy

Since the market for hydrogen in the ammonia fertilizer industry is almost entirely captive, existing plants are very unlikely to make use of surplus renewable energy for on-site electrolyzers in the medium-term future. However, it is more likely that small-scale ammonia production in some remote locations would make economic sense when coupled with distributed electrolytic hydrogen generation sites in the short-to-medium term. The economic feasibility is mainly dependent on the following two criteria.

- **Transportation**: As a hazardous material, ammonia needs to be shipped in special containers, which significantly adds up to the final cost. In the US, the increase in price due to transportation can vary between 25-75 %, especially when transported to isolated farm lands.
- **Gas and power infrastructure**: Since conventional hydrogen production is highly reliant on natural gas and electricity, remote locations with a poor infrastructure would potentially benefit from the use of electrolytic hydrogen from renewable sources.

Especially in the US, numerous small-scale ammonia plants with electrolytic hydrogen generation from renewables were commissioned in the late 2000s. Most initiatives come to a hold when the discovery of shale gas lead to a drastic cut in domestic gas prices. Nevertheless, projects in very remote farm lands and islands with difficult access to the fertilizer market are still potentially feasible [26, 29].

3.2.1.2 Petroleum Refineries

Petroleum refineries require large amounts of hydrogen for the processing of crude oil into higher quality fuels. The following points are the two main hydrogen demanding operating steps:

- **Hydro-treating**: The process for desulphurization of crude oil, especially for producing low-sulphur diesel fuel. Hydrotreaters are the most common process units in modern refineries [30].
- **Hydrocracking**: This catalytic process converts long-chained, high-boiling hydrocarbons of petroleum into shorter, low-boiling products (e.g. gasoline, kerosene) by injecting hydrogen [31].

Refineries also produce significant amounts of hydrogen as a by-product during catalytic reforming (process of upgrading naphtha molecules to more valuable high-octane products), that typically is recovered. On average, approximately 30 % of the total hydrogen demand can be covered through that, depending on crude oil type and quality. The amount that needs to be supplied by external sources is characterized by the refinery-specific hydrogen balance (Equation 3.2) [26, 32]:

$$\text{External Hydrogen} = \text{Consumption} - \text{Production} + \text{Losses} \qquad \text{Equation 3.2}$$

Increase in merchant hydrogen utilization

Similar to ammonia plants, the additional hydrogen demand is almost entirely met by on-site steam reforming units. A smaller fraction is supplied by by-product hydrogen obtained from other processes of nearby chemical facilities (e.g. chlor-alkali industry) or merchant hydrogen [32].

In the US, the share of merchant hydrogen in refineries has risen significantly in the recent decade. Data from the US Energy Information Administration (EIA) in Figure 3-7 show that the amount of natural gas used as feedstock for on-site hydrogen production only increased by 1.6 % from 2008 to 2017, whereas the net input of hydrogen more than doubled during the same timeframe. This shows that while the installed capacity of SMR units stagnated, the additional hydrogen was provided by industrial suppliers and merchants [32]. Reliable information about the situation in European refineries varies greatly depending on the source and was therefore not considered in this study.

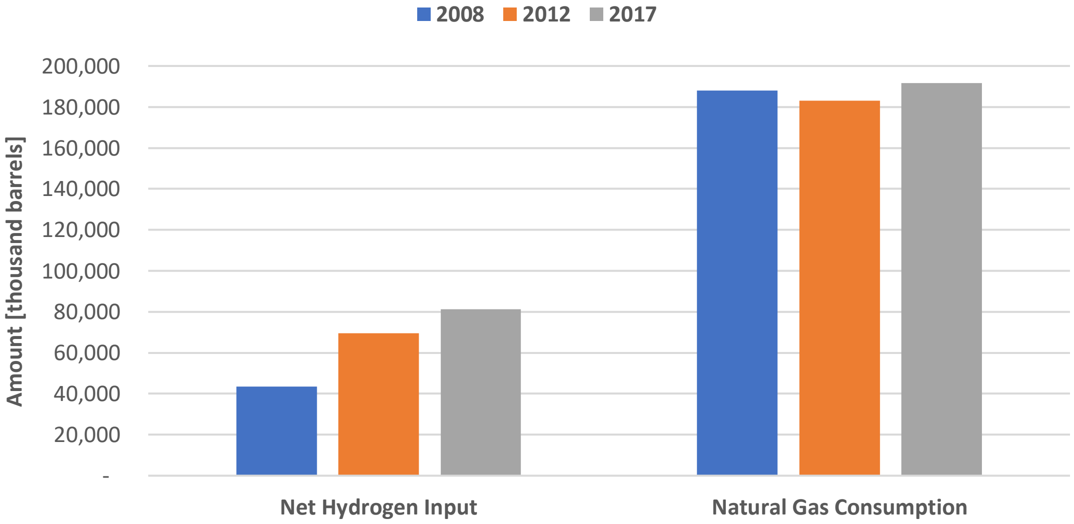

Figure 3-7. Net refinery hydrogen input (left series) in and natural gas used as feedstock for hydrogen production in US refineries from 2008, 2012 and 2017 (with data from [33, 34]).

Impact of crude oil quality on the hydrogen demand in refineries

As has been mentioned previously, the crude oil quality has great impact on the demand of hydrogen in refineries. Especially the Sulphur content of crude oil and environmental legislation on Sulphur limits in processed fuels are the main driver of hydrogen demand for hydro-treating in refineries. Recent regulatory efforts in North America, Europe, parts of Asia and Australia have been implemented to curb harmful sulfur dioxide (SO_2) emissions in the transport and power plant sector. The last main consumer of high-sulfuric fuel is the marine industry, but new legislation set by the International Maritime Organization (IMO) lowers the global sulfur limit for ship fuels from 3.5 % to 0.5 % by 2020. Consequently, refineries are forecasted to increase their production of low-sulfuric products accordingly [23, 26, 36].

Furthermore, most crude oil variants on the global markets are becoming heavier, meaning that they contain a relatively low share of light fractions that can be processed directly into valuable products (e.g. gasoline, diesel). At the same time, demand for heavy fuels is rapidly decreasing due to carbon-emissions regulations and more cost-competitive alternatives like gas or coal [26]. Figure 3-8 shows the distribution of oil fractions from different sources next to the expected evolution of the demand from 2005 to 2030. The need for light fractions will almost double, which is going to increase the necessity for hydrocracking treatment of less valuable heavy fractions and residues and ultimately affect the hydrogen balance of refineries negatively.

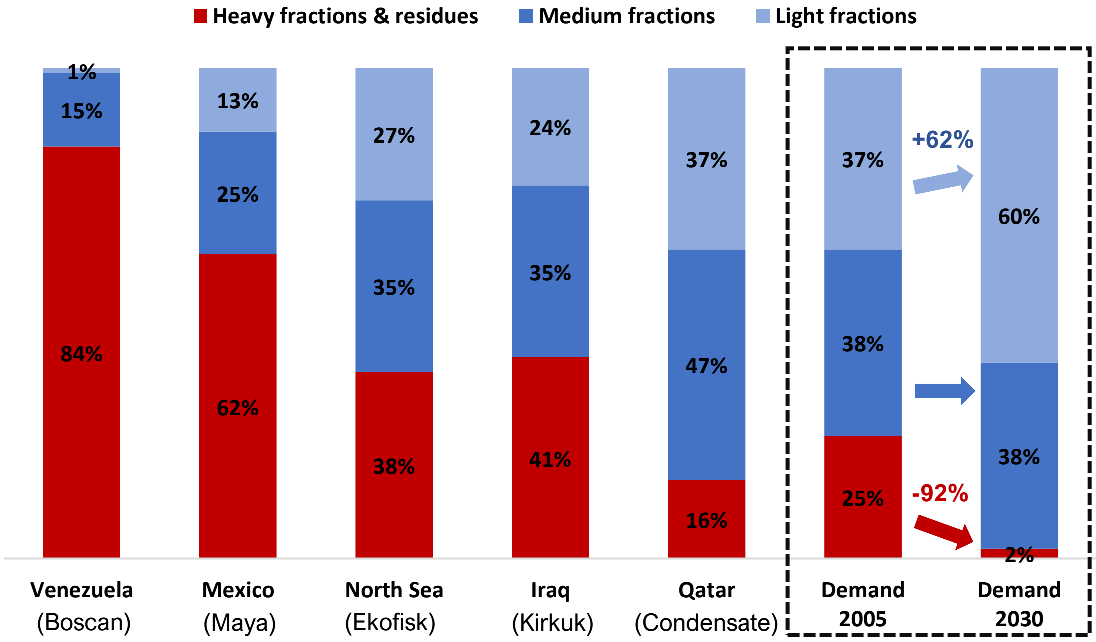

Figure 3-8. Distribution of crude oil fractions from different geographic zones compared to the demand in 2005 and 2030 (with data from [26] and [37]).

Adding electrolysis as hydrogen source in refineries

Refineries can be classified based on their actual hydrogen balance into three categories [26]:

1. **Refineries with positive hydrogen balance**: Production of hydrogen in excess, virtually no demand constraints, possibilities to generate added revenues through H_2-resale.
2. **Refineries close to equilibrium:** Generally optimized hydrogen balance, periods of H_2-shortages probable, which represents a restraint on operation flexibility and profitability.
3. **Refineries with negative hydrogen balance:** Hydrogen consumption is higher than refinery's own production, typically with incorporated SMR units or connected to hydrogen networks.

Electrolytic hydrogen cannot compete economically with steam reforming for a continuous and dedicated hydrogen supply that is needed for type-3 refineries. However, when hydrogen shortages are a reoccurring problem, operators of type-2 refineries need to consider either investing in an external hydrogen generator (e.g. additional SMR-units) or buying merchant hydrogen on the spot market. Due to the high market prices (6-10 $/kg or 152-254 $/MWh) and the fact that the demand fluctuates significantly depending on the crude oil quality, small-scale electrolyzers can be a suitable alternative source of hydrogen in those cases [26].

3.2.2 Emerging Hydrogen Markets

The following section introduces the concepts of the main emerging hydrogen market segments, while pointing the benefits and disadvantages as well as their future outlook. This includes the predominant power-to-X routes (with X standing for either gas, liquid or mobility) and grid services.

3.2.2.1 Power-to-Gas

In general, power-to-gas (PtG) is the process of converting excess electricity from renewable sources into hydrogen gas, typically followed by the injection into an existing natural gas grid. The main benefits of this technique for industrialized countries are the following [26, 38]:

- **Energy storage capabilities** for the electricity grid, when combined with re-electrifying systems like fuel cells or gas turbines.
- **Relieving of electricity-grid infrastructure**, by using the vast storage capacity of a NG-grid.
- Reduced demand for NG imports and partial decarbonization of the NG value chain.

As of 2014, about 2.4 MW of capacity were installed and ~9.1 MW planned, mainly close to windfarms in Germany and Denmark around the North Sea area. PtG, therefore, is the main technology used for electrolytic hydrogen projects [39]. Today, two forms of the power-to-gas concept exist: Direct injection of hydrogen into the gas grid and (also known as "H2-Blending") or after converting hydrogen into synthetic methane (methanation) [40].

Direct Injection vs. Methanation

Direct Injection is a relatively simple and early stage solution for creating new value streams from excess renewable electricity, especially in countries with highly developed natural gas infrastructures. Table 3-1 summarizes the main benefits and drawbacks of that from of PtG.

Table 3-1. Pros and cons of H2-Blending [26].

H_2 - Blending	
Advantages	**Disadvantages**
• Minimal investment costs (in case of existing infrastructure). Grid connection cost is estimated at €250 /kW_{ch} plus €1.5 /MWh_{ch} of operational feed-in costs [41] • No dedicated hydrogen storage necessary • Minimal energy/material losses • Extensive energy and storage capacity • Reduced carbon content of sold NG	• H_2/NG gas ratio is technically limited to 17-25 vol.% in parts of the distribution grid and ca. 5 vol.% in the transportation grid • Limitations by grid integrity, safety and specifications of end-use applications • Recovery of blended H_2 from NG-grid not economical feasible • Difficulties to comply with blending & pipeline requirements, due to fluctuating H_2-production • Few legislations on blending-limits • Seasonal injection limits (low NG demand in summer)

The biggest advantage of H_2-Blending is the low additional cost of injection facilities without the need for capital-intense pressure tanks. The main drawback currently seems to be the difficulty of NG-grid operators to precisely assess the maximum tolerable H_2/NG blending ratio for preexisting, unmodified gas infrastructure. The sensitive of end-use appliances to H_2/NG blends also very greatly, as can be seen in greater detail in Figure 8-1 (Annex). Consequently, many countries have no or very limited legislation on authorized blending limits [26, 42]. The legal restriction on hydrogen injection of selected countries is shown in Figure 3-9.

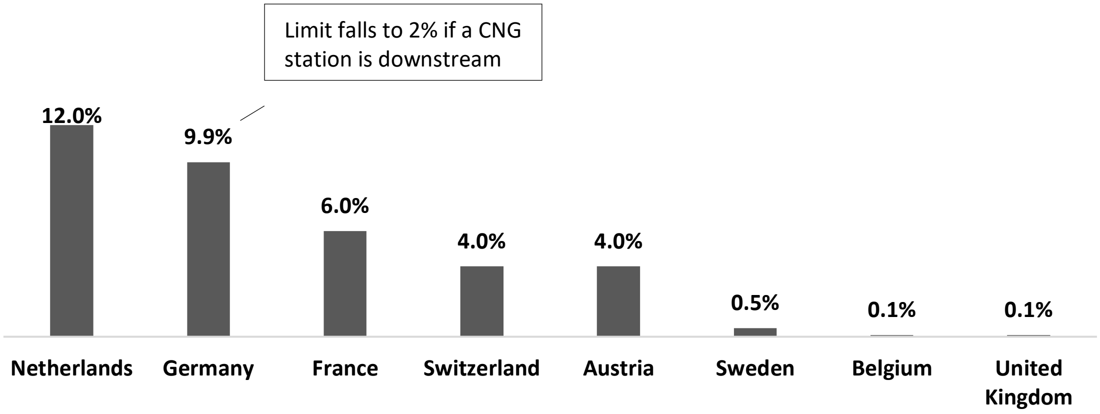

Figure 3-9. Hydrogen injection limit in national gas networks (with data from [43]).

In the other main PtG-process, electrolytic hydrogen is further processed, typically with CO_2, to obtain methane that can be directly injected into any natural gas grid. Even though methanation is a well-established technology, full-scale PtG systems continue to be in demonstration and pilot-plant stages [44]. Table 3-2 shows the most important pros and cons of this concept in comparison to direct injection.

Table 3-2. Benefits and drawbacks of methanation [26, 44].

Methanation	
Advantages	**Disadvantages**
• No blending limit for gas grid injection • Methane is easier to handle than hydrogen • Recycling of CO_2 emissions from industries	• Additional process step in already long PtG value chain • Extra investment costs, due to methanation plant and add. Infrastructure (> €2,000 /kW of capacity, falling to ~€700 /kW in 2020) • Lower energy efficiency (~60 %, 80 % if heat is monetized) • Location limitation: CO_2-source and NG-grid

For economic reasons, PtG systems relying on methanation need to be geographically close to a CO_2-source. Most current pilot plants have found raw biogas from biomethane plants to be most suitable because no additional energy is needed for carbon capture technologies (energy penalty), but also off-gases from gasification plants and other industries can be used. In addition to tackling the high cost of such systems, studies suggest to further investigate new carbon sources with a low energy penalty, to enable more suitable locations [44].

Economics of Power-to-gas projects

Without policy support, stand-alone PtG projects based on direct injection are not profitable business ventures in the short-to-medium term. Economic feasibility of methanation PtG systems are expected to be achieved in some cases, largely dependent on the methanation and electrolyzer technology used as well as location an existing infrastructure. In any case, investors are facing the complications of heavy initial investment costs, long payback periods and varying amortization. Currently, two policy instruments are envisioned to enhance the bankability of PtG business cases [42]:

1) **Feed-in tariffs**: An injection tariff for green hydrogen, similar to what already exist in some countries for biomethane (see Table 8-1 in the Annex). There is currently no regulatory framework for green or low-carbon hydrogen in EU.
2) **Carbon price**: A price or “carbon tax” that would apply on conventional natural gas could significantly improve the competitiveness of methane produced via PtG routes.

3.2.2.2 Power-to-Liquid

The concept of power-to-liquid (PtL) is the production of synthetic, hydrocarbonaceous liquids (also known as “synfuels”) from surplus renewable electricity, water and usually CO_2. Depending on the process routes used, the market for electrolyzers can be significantly extended with products that can vary from formic acid, dimethyl ether, methanol and methane to longer-chained hydrocarbons like gasoline, kerosene and diesel. The demand in the transportation sector for liquid fuels is still enormous, mainly due to their unparalleled volumetric energy density (see Figure 3-10). Another advantage of synfuels is that they are so called “drop-in fuels”, meaning that existing technologies can directly use them, without prior adaptation. In comparison with PtG, the location of synfuel plants is only limited by the access to a carbon source and not primarily by infrastructure [26, 45].

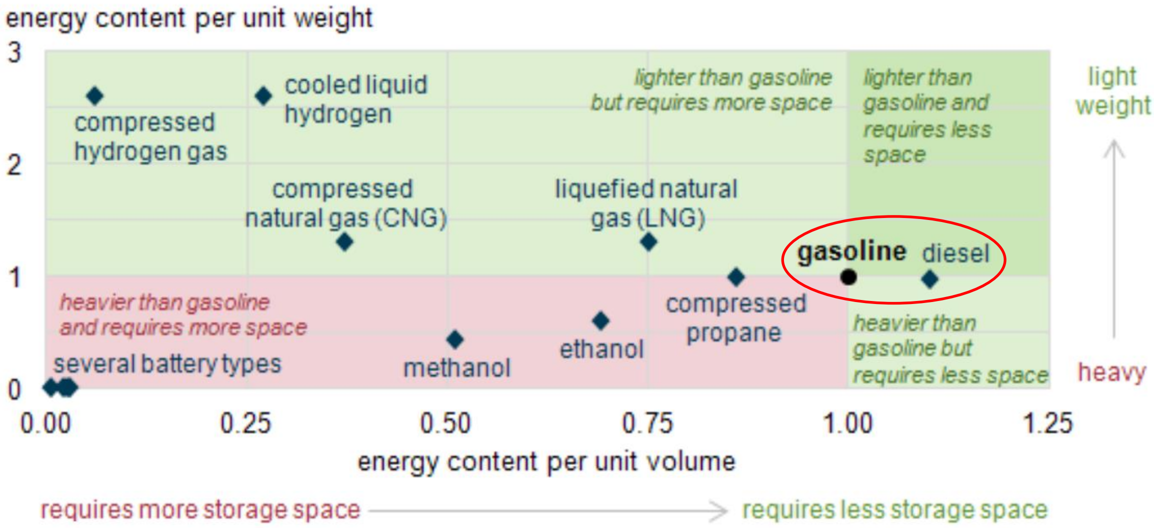

Figure 3-10. Energy density comparison of several transportation fuels (indexed to gasoline = 1.00) [46].

Technological Readiness of PtL

Two main industrial processes have been developed [45], [47]:

- **Methanol-to-gasoline** (MtG), first methanol synthesis followed by chemical upgrading
- **Fischer-Tropsch (FT) synthesis**, with syngas[3] or CO_2 as carbon source

Both pathways make use of well-established industrial processes, that are widely available today with technological readiness levels between 8 and 9 (TRL, see

Table 8-2 in Annex for details). Some large-scale and fully integrated PtL-systems have already been deployed and, mainly using the Fischer-Tropsch process. The first demonstration plant was operated by Audi in cooperation with the German hydrogen-technology company Sunfire from 2014 - 2016. The

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[3] Syngas, or synthesis gas, is a gas mixture of hydrogen and carbon monoxide (CO), which is generally described by the H/C-ratio [47]

project incorporated SOEC electrolyzers (TRL 5) that directly produced syngas for the FT-reaction, significantly increasing the process efficiency. In late 2017, the company and its partners Ineratec and Energiedienst Holding announced the construction of another pilot project for e-diesel in Switzerland. The plant with a capacity of 400,000 l/a is supposed to bring the TRL up to 6. A similar project is currently underway in Norway: The cleantech company Nordic Blue Crude plans to produce 8,000 t/a of synthetic oil substitutes in the Heroya Industrial Park from 2020 with an electrical output of 20 MW [45, 48].

The potential of power-to-methanol

Even though MtG (or power-to-methanol, PtM) is the less common power-to-liquid pathway, studies found methanol to be one of the most promising electrolytic synfuel. Its synthesis process is much easier than that of liquid hydrocarbons via Fischer-Tropsch, specifically decentralized and in smaller scales.

Methanol has a wide field of applications as a precursor material for dimethyl ether, acetic acid, formaldehyde it is also used in the biodiesel production and can be blended directly into gasoline. About 36 % of the global methanol demand ends up as fuel. As can be seen in Table 3-3, methanol is the fastest growing market for syngas and is expected to see unprecedented growth between 2015 and 2025. The growth is mainly pushed by China's efforts to substitute oil imports, increasing the focus on fuel applications and methanol to olefins technology [49, 50].

Table 3-3. Syngas market sizes [49].

End Use	**Global Market size, 2016**	**AAGR[4], 2011 - 2016**
Ammonia	180 million t/a	2.0 %
Methanol	85 million t/a	9.3 %
Hydrogen	40 million t/a	5.0 %
Fischer-Tropsch liquids	21 million t/a	4.3 %
Syngas to power (IGCC)	~25 million t/a	n/a
Synthetic natural gas	~8 million t/a	n/a

Especially interesting for renewable electrolytic-methanol production is the utilization of SOECs. If the necessary electricity is sourced from surplus renewables, systems with high-temperature electrolysis offer highest energetic efficiencies with a flexible and completely scalable process. Other systems that directly produce synfuel methanol in SOECs have been proposed but remain in early research phase (TRL <5) [26].

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[4] The Average Annual Growth Rate (AAGR) measures the average rate of return or growth over a series of equally spaced time periods [87].

Opportunities of other synthetic hydrocarbons

Other studies suggest that PtL's economic feasibility can be greatly improved when the production is focused on synthetic hydrocarbons of higher value such as waxes for the cosmetics and other industries. In Germany and as of 2018, revenues for waxes are assumed to be ~2 €/kg and much higher than for fuel with 0.45 €/l. The proposed technical realization consists of SOEC stacks coupled with a Fischer-Tropsch reactor [51].

The global wax market is a mature but huge market with yearly revenues of currently about 8.5 billion dollars and is anticipated to grow gradually with a CAGR of 2.9 % during 2017 and 2026. Demand for paraffin wax, usually derived from petroleum, is currently declining in favor of eco-friendly and renewable substitute products, especially in the Asia-Pacific region [52].

Economics and Scalability

The biggest challenge for the deployment of power-to-liquid plants in the short-term is the high production costs of synfuel in comparison to conventional fuels. Costs can be reduced through declining electricity costs from renewable energies, increasing PtL process efficiencies through enhanced technologies, e.g. SOEC, CO_2 sourcing and separation, as well as by number through economies of scale effects.

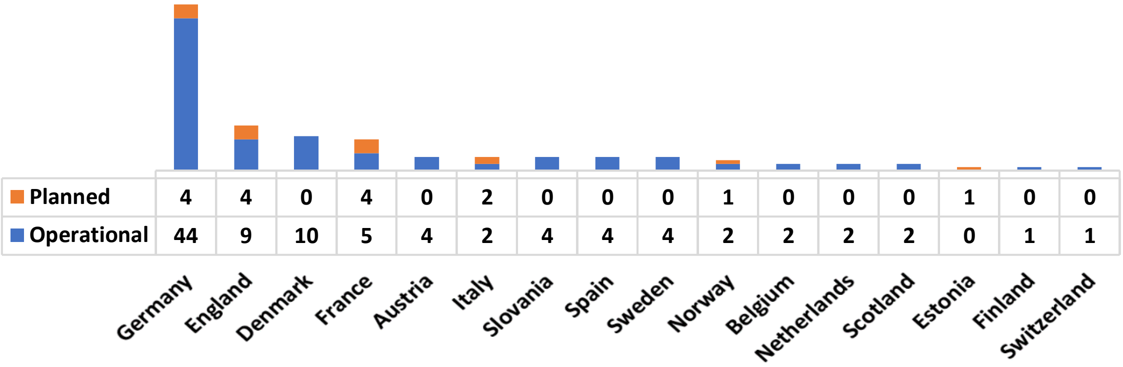
The main advantage of PtL lays in the tremendous potential of wind and solar parks, exceeding the local energy demand. Therefore, PtL projects are able to increase energy security and add value locally while offering new sustainable business opportunities for regions with excess renewable electricity in the near-to-medium term future [45].

3.2.2.3 Power-to-Mobility

The application of hydrogen for road transportation is an emerging market that has been declared as an environmentally friendly alternative to fossil fuels since the 1970s. Since then, the concept has been facing several economic and technological issues, that are especially connected to the development of fuel-cell electric vehicles (FCEVs).

Main drawbacks

Even though significant progress has been made during the past decade, one of the main problem continues to be the so-called "chicken-and-egg dilemma": the absence of an hydrogen infrastructure and refueling stations hamper the development of FCEVs and the other way round. As can be seen in Figure 3-11, only 93 hydrogen refueling stations (HRS) exist in Europe today, that are available to the public, primarily located in Germany. The majority of those HRS is using either hydrogen from central SMR-plants or using grid-electricity to power nearby electrolyzers [26, 53].



	Germany	England	Denmark	France	Austria	Italy	Slovania	Spain	Sweden	Norway	Belgium	Netherlands	Scotland	Estonia	Finland	Switzerland
🟧 Planned	4	4	0	4	0	2	0	0	0	1	0	0	0	1	0	0
🟦 Operational	44	9	10	5	4	2	4	4	4	2	2	2	2	0	1	1

Figure 3-11. Hydrogen refueling stations in Europe, open to the public, as of June 2018 (data from [53]).

As a possible solution, decentralized electrolyzers powered by renewables have been proposed, that produce hydrogen on-site of the refueling station. By that, the problems of having to rely on an expensive H_2-distribution infrastructure and the electric grid can be avoided. So far, only a limited number of these stations have been realized, mainly for demonstration purposes [53].

Another drawback of using hydrogen in mobility is competition with battery-electric vehicles (BEV). The overall energy efficiency of FCEV is negatively influenced through energy losses that occur during electrolysis, gas compression and fuel-cell operation. BEV are only affected by the charger and lithium-ion battery efficiency. Therefore, the so-called wheel-to-wheel efficiency is lower and the lifecycle CO_2 emissions are higher for FCEVs, as it is illustrated in Figure 3-12.

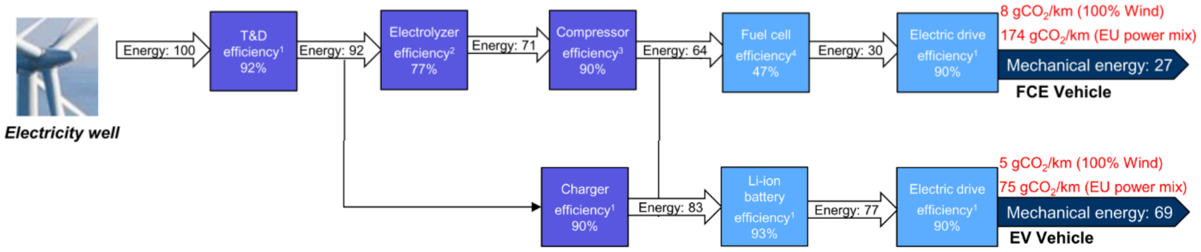


Figure 3-12. Wheel-to-wheel efficiency and lifecycle CO_2 emissions of FCEV and BEV [26].

Key drivers and market outlook

Nevertheless, considerable research and development efforts are being made, mostly by industrialized, westernized countries (USA, Japan, Germany, France, etc.) to realize the commercialization of hydrogen as a transport fuel. The main motivation are reasons of geopolitical economics, to stabilize trade imbalances and energy security when countries aim to reduce their national fossil-fuel consumption either to increase energy-export revenues or to cut energy imports. Also, international agreements to combat climate change, e.g. the Paris Agreement of 2015, and efforts to reduce local emission and noise pollution in densely populated areas are key drivers for social and political commitment to hydrogen in mobility. Predictions about commercialization with bankable business cases remain extremely uncertain, that are mainly depending on the cost of technology and the price that consumers would be willing to pay for electrolytic hydrogen fuel. For that, identifying possible market entry scenarios are still hypothetical. It seems that undertakings with hydrogen-powered bus fleets, forklifts, trucks and trains might be early adopters of this technology [26].

3.2.2.4 Grid Services

To maintain reliable system operation, electricity grid operators must ensure a constant power grid frequency (50 Hz in Europe). Grid services like control reserve and grid congestion management are measures that ensure frequency stability in the event of grid disturbances (e.g. rapid voltage changes, flicker phenomena, voltage phase unbalances, etc.) [54].

Control reserve, a.k.a. load-frequency control, is a key grid service and a potential revue stream for electrolyzers both in transmission and distribution grids. Typically, it is supplied by qualified and grid-connected plants that provide positive and negative reserve by in- or decreasing their electricity generation or consumption when needed (an exemplary electrolysis operation is shown in Figure 3-13). Regulatory and technical requirements for auxiliary services, e.g. from electrolyzers, vary greatly within European countries, so possible participation and integration need to be assessed individually [42, 54].

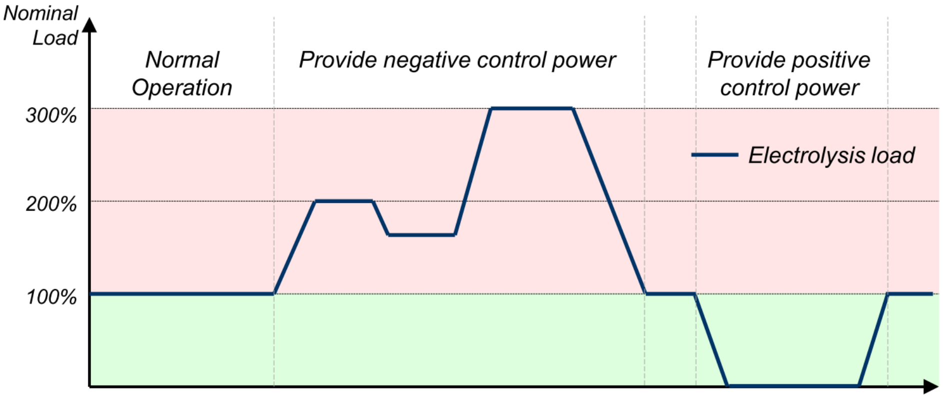


Figure 3-13. Illustration of electrolysis operation as control reserve capacity [26].

In case of a disturbance, the *Frequency Containment Reserve (FCR)* is activated to restore the frequency within the first seconds. It is followed by the *automatic Frequency Restoration Reserve (aFRR),* to provide balance automatically for a short-term. The *manual Frequency Restoration Reserve (mFRR)* is activated manually afterwards, in case the disturbance continues. Some countries implement an additional *Replacement Reserve (RR),* which follows the mFRR and replaces capacities if power outages last for a longer period [42, 54]. The consecutive activation sequence of load-frequency services is depicted in Figure 3-14.

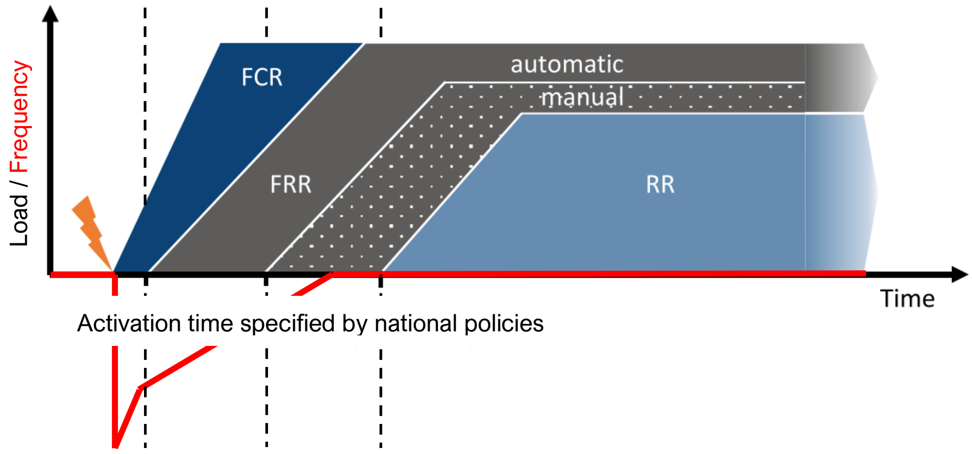


Figure 3-14. Activation order of load-frequency services [54].

Technical Requirements for Control Services

The activation times for each reserve are individually specified by national grid policies. For example in Germany, it is 30 seconds for FCR, 5 minutes for aFRR and 15 minutes for mFRR; ~1 hour for RR. The demand response participation and activation times for other EU member states can be found in Table 8-3 in the Annex. Since Even though FCR is the highest-value service, it requires very fast reaction times, typically <30 s, and suitable technologies must be chosen that are able to supply this service. Additionally, successful tenders usually require a minimum system bid size of ≤1 MW. Currently only certain PEM-electrolyzers can fully activate within that timeframe (check Table 2-3 in chapter 2.5). The suitability of electrolyzers for aFRR is also connected with their ramping-up ability and the fact that this service is controlled automatically, leading to cost-intensive requirements for instrumentation and control. Manual FRR, on the other hand, requires lower ramping abilities from electrolyzers, due to a longer activation time of ~15 min. This makes manual Frequency Restoration Reserve the most interesting grid service for the potential participation of electrolyzers [42, 54].

Regulatory constraints

National demand response policies define if a country's control reserve market is opened to end-user participation, which is crucial for electrolyzer integration. The European Commission and the European Network of Transmission System Operators for Electricity (ENTSO-E) promote the support of demand management within their regulatory frameworks, but certain countries are still hesitant to the idea of end-user partaking in the national control reserve market. Table 3-4 shows the current policy situation for European countries, with more complete information in Annex (Table 8-3). Notably, electrolyzer participation in control markets are not accepted in Spain, Italy, Ireland and Poland [54].

Table 3-4. Openness to demand response participation of electrolyzers in European countries (data from [54]).

Fully accepted	Accepted for designated control reserve types	Not accepted
• Austria • Denmark • Finland • France • Germany • Great Britain	• Belgium • Netherlands • Norway • Slovenia	• Spain • Italy • Ireland • Poland

Market size and future trends

The market size of frequency control services depends on the total power sector size of a country. The available reserve capacity in Germany for control services are about 5 GW_{el}, representing 6 % of its peak demand. FCR, as the service with the highest value, covers roughly 1 % (800 MW), FRR and RR are available with about 2.5 % (2000 MW) each [42].

The market for control reserve services has undergone significant changes during the past decade. Developments within the EU are progressing on different levels, as country-specific policies are still a critical aspect. However, especially the ENTSO-E is advancing its efforts to establish cross-border balancing markets through sharing available grid control resources. This market harmonization is based on the already existing joint trading platform between Germany, Belgium, Netherlands, Switzerland and Austria (France and Denmark projected to join at some point [55]). These EU-wide harmonization efforts, in combination with the tendencies for shortened tenders, would widen the possible market participation for electrolyzers, but rarely any definite timeframes have been defined yet [54].

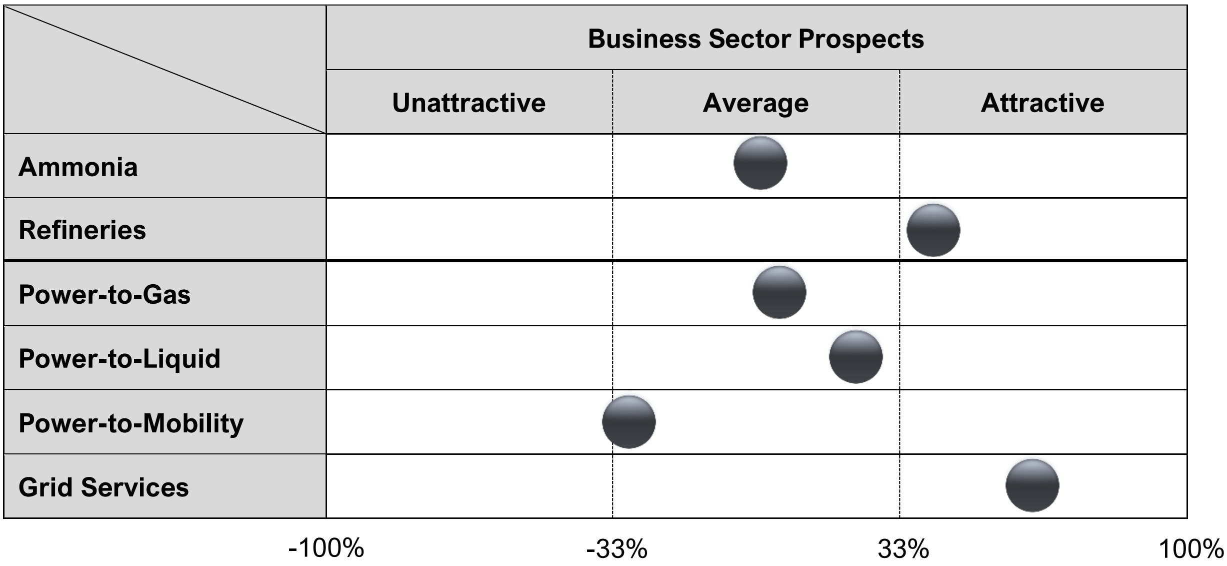
3.3 Opportunity Analysis

Conventional and emerging market segments for electrolyzers were introduced and discussed in the previous section 3.2. Now, 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 (or segment) and the business position of the venture itself [56]. The latter is out of the scope of this work and was therefore neglected. 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 (see Figure 8-2 in the Annex).

The complete description of building the DPM as well as the included factors, values and detailed outcomes can be found in Table 8-4 in the Annex. The results of the market segments' attractiveness assessment are summarized in Table 3-5 and discussed in the following. The scale of the table ranges from -100% to +100%; -100% indicates the worst possible business-sector prospect and +100% the best.

Table 3-5. Prospects of market segments for solid-oxide electrolyzer businesses cases in the short-term future.



Discussion of the outcomes of the Directional Policy Matrix evaluation

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-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.

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.

Power-to-gas 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.

The **power-to-liquid** 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 RE-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.

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 from electrolysis would greatly impact the willingness-to-pay for hydrogen as a transportation fuel and can therefore not be considered a viable business scenario.

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.

Concluding remarks

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 PtX segments. The outcomes of the market and opportunity analysis will be used in the following to develop viable business models for SOEC-based systems.

4 Industry & Competitor Analysis

In this chapter, the current state of the global electrolyzer industry is portrayed including a ten-year outlook. The analysis contains information on different regions, product types and sizes. Subsequently, the competitive landscape is analyzed. Throughout the competitor assessment, the main players of the industry are identified and profiled. Further, the key trends of the industry are reviewed.

4.1 Electrolyzer Industry Overview

The data for the following industry analysis were extracted from the 2017 edition of Future Market Insight's extensive Global Hydrogen Electrolyzer Industry Analysis [57].

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).

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).

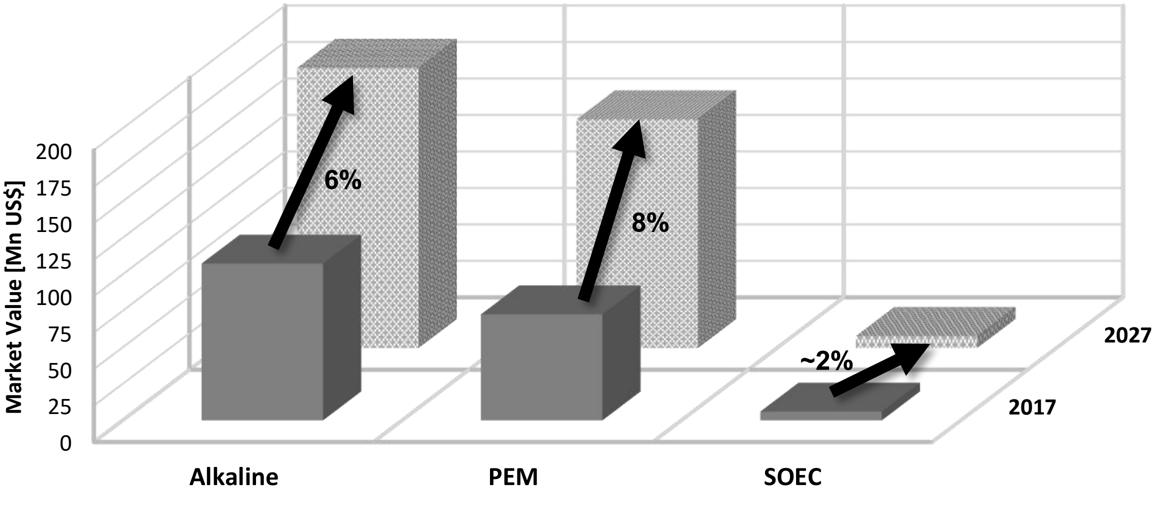


Figure 4-1. Global Hydrogen Electrolyzer Market Value 2017 – 2027, incl. estimated CAGR (with data from [57]).

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. The global electrolyzer market values are illustrated in Figure 4-1.

A clear **industry trend** is that PEM electrolyzers are increasingly preferred to the well-established alkaline electrolyzers, due to their technological advantages. This is the main driver of the higher market growth rate of PEM. Companies are also extensively investing in the research and development of advanced electrolyte materials. The industry trends are further elaborated in section 4.4.

4.2 Structure of Industry

As a basis for the formulation of a competitive strategy, understanding the structure of the electrolyzer industry is necessary. The Structural analysis of an industry is typically done using the analytical framework of Michael Porter’s five forces. It describes an industry as an open system, that competitors exit and enter, and where suppliers and buyers have major effects on the prospects and profitability of the industry. The Porter’s five forces model has been generated for the current state of the global electrolyzer industry and is depicted in Figure 4-2. Necessary information was obtained during several interviews with industry experts, from market & industry research reports [57, 58, 59] and from following the events of the 2017 and 2018 editions of Europe’s largest hydrogen and fuel cell exhibition, the Group Exhibit Hydrogen + Fuel Cells + Batteries at Hannover Messe [60, 61].

Forces driving the electrolyzer industry

The intensity of **rivalry among existing firms** has significant impact on the ability of generating profitable margins. The electrolyzer industry is, independent of the product type, still relatively small and fragmented; meaning that only a small number of small competing businesses exist, and no major companies drive the direction of the industry. Electrolyzer manufacturers are usually not vertically integrated businesses, and therefore depended on other companies during their production process. Most competing firms do not differ much in their product portfolio, but mainly in the way they develop their business model (e.g. B2B sales of electrolyzer cells/stacks, complete-system sales, Manufacturing, project management & installation). For those reasons, it can be said that the intensity of competition is currently relatively low, as companies are still striving to reach viable and profitable business operations.

New entrants to an industry add capacity that can reduce profitability in cases where there is lower growth in demand. With the market for electrolyzers still being in an embryonic stage, new companies need high initial capital to start operation without much possibilities of economies of scale effects. Other entry barriers are big influence of country-specific government policies (favorable or unfavorable), largely patented intellectual property and the fact of not having an established brand identity. Many times, new ventures of the electrolyzer business are spin-offs of large conglomerates (e.g. Siemens, Areva, General Electric) in addition to more specializing or experimental start-ups. Due to the high entry barriers, the threat of new industry entrants in the electrolyzer business is generally low.

Substitutes are products that perform the same function or satisfy the same need the competing product. In case of electrolyzers, this includes hydrogen generation from Steam-Reforming or battery-systems for energy storage applications. At present, the main threat is that those substituting products are generally cheaper and more cost effective than electrolyzers. A common strategy for companies facing that problem is to start making or supplying also the substitute. For most electrolyzer businesses, this is not a viable option as it requires completely new logistics, retailing and branding. It is also financially easy for potential buyers to switch to a substituting product, which is the main reason of the currently strong propensity of buyers to substitute electrolyzers with cheaper technology. In general, the threat of substitutes is particularly high in the electrolyzer business.

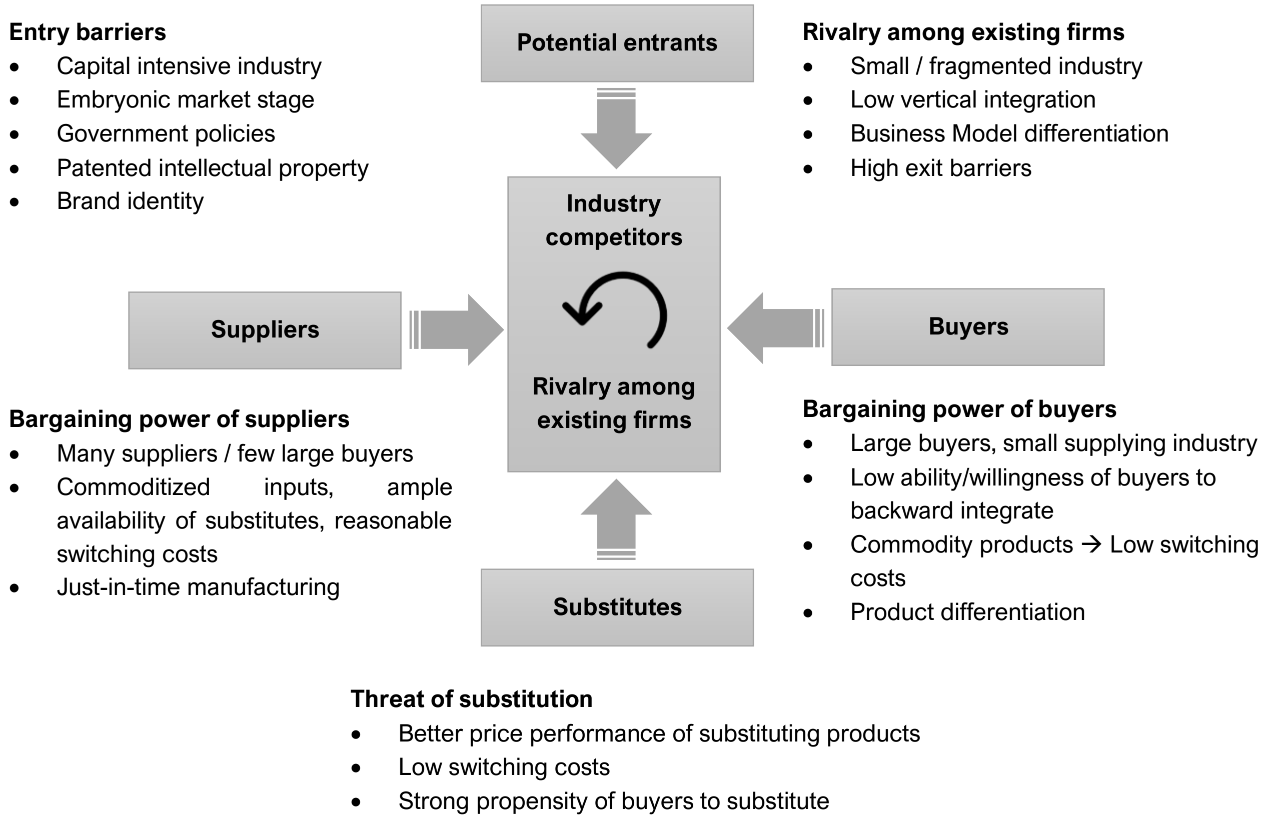


Figure 4-2. Forces driving the electrolyzer industry competition (Porter's five forces).

The **bargaining power** of suppliers to the supplied industry is mostly depending on the stage of industry. The manufacturing process of electrolyzer companies requires a large number of suppliers, especially for commodities and mass-produced, basic materials and equipment. These are amply available and are mostly not associated with any switching costs for the company, which leads to a limited ability of suppliers to bargain prices. On the other hand, most electrolyzer business only produce in small series, holding low stocks or on request with single-unit production ("just-in-time manufacturing"), increasing their dependency on suppliers. To reduce the bargaining power of suppliers, strategies are to maintain a diversified base of suppliers.

The prices that businesses can obtain is one of the biggest impacts on their profitability. Therefore, the **bargaining power of buyers** needs to be identified. As stated before, electrolyzers face heavy competition through substituting products / technology. The associated switching costs are almost nonexistent for buyers, giving them a strong price bargaining standpoint. Product differentiation is therefore essential. In general, buyers of electrolyzer systems are much larger than the supplying industry (Petrochemical companies, state agencies, utility firms, etc.), which further increases their bargaining power. On the other hand, buyers are usually not able, or willing, to backward integrate the production of electrolyzers (producing their own electrolyzers in-house), which is mainly because of previously discussed entry barriers (capital intensity, IP, etc.).

4.3 Competitor Profiling

The relatively small electrolyzer industry industrial consists of several companies that are mainly located in Europe, the United States and China. The predominant players are as follows:

- NEL Hydrogen AS (Norway)
- McPhy Energy (France)
- Hydrogenic Corporation (Canada)
- Giner ELX (US)
- ITM Power Plc (UK)
- Tianjin Mainland Hydrogen Equipment (China)
- Sunfire (Germany)

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 [57].

Nel Hydrogen

Nel Hydrogen is a global, dedicated renewable hydrogen company based in Oslo, Norway. Its customers include industries as well as energy and gas companies. With currently 86 employees, Nel generated around 12.0 M€ in 2016, which increased to 31.2 M€ in the following year mainly due to the acquisition of the US American company Proton Onsite [62]. Its global market share was expected to be around 45 % in 2017. Since its foundation in 1927, Nel Hydrogen has been developing plant-sized alkaline electrolyzer technology but expanded its product portfolio with the advanced, large-scale PEM electrolyzers of Proton Onsite. Nel is now covering the entire hydrogen value chain, including hydrogen generation, manufacturing of hydrogen reveling stations as well as distribution and monitoring services [62, 63].

McPhy Energy

McPhy Energy is amongst the leading developers for hydrogen-based solutions in industry, mobility and energy markets. The company is based in La Motte-Fanjas, France, and owns three production and engineering sites in France, Germany and Italy as well as a R&D laboratory in France and three sales subsidiaries in North America, Asia Pacific and Eastern Europe. It is currently collaborating on R&D with the Italian electrolyzer company De Nora from Milan and has a signed industrial and commercial partnership with EDF from France [64, 65]. Their specialized alkaline electrolyzer, storage and refueling stations resulted in 7.5 M€ of total revenues in 2016, increasing to 10.1M€ in 2017 [64]. Founded in 2008, McPhy now has 66 employees and accounts for 12 % of the global electrolyzer market.

Hydrogenics Corporation

Hydrogenics is a globally operating, leading company for design, development and manufacturing of hydrogen generation, storage and fuel cell products, based both on alkaline and PEM technology. It was founded in 1995 in Mississauga, Canada, where now its corporate headquarters are located. Other operations offices are currently in Belgium and Germany, satellite offices are maintained in the United States and branch offices in Russia and Indonesia [66]. Currently, 145 people are employed in their offices globally. Hydrogenics revenues totaled 24.7 M€ in 2016 and enlarged to 40.9 M€ in the following year, with an electrolyzer market share of about 10 % [67].

Giner ELX

Giner ELX is a spin-off of Giner, Inc., a worldwide leader in electrochemistry. The company was founded in 1973 and has been selling PEM electrolyzer stacks and systems mostly to military and commercial customers, including the US Navy, Lockheed Martin, General Motors, NASA, Areva, Abengoa, Parker-Hannifan, Boeing and General Electric. Their markets cover hydrogen for energy storage, mobility, industries, aerospace and life support [68]. Giner ELX has its headquarters in the United States in Newston, Massachusetts and employs around 50 people together with Giner, Inc. Its electrolyzer business has an estimated global market share of 2 % but no official financial statements could be obtained during the time of this study.

ITM Power Plc

ITM Power Plc is a manufacturer of integrated PEM electrolyzer and fuel cell solutions for grid balancing, energy storage, mobility and chemistry. Its main customers are National Grid, RWE, Engie, BOC Linde, Toyota, Honda, Hyundai and Anglo American. The company has entered a collaboration with Royal Dutch Shell for hydrogen refueling stations in late 2015 [69]. ITM Power is listed on the AIM market of the London Stock Exchange since 2004 and employs about 159 people in its main office in Sheffield, Great Britain. The business generated around 2.15 M€ in total revenues in 2016 and 2.70 M€ in 2017 [70], with an electrolyzer market share of approximately 10 %.

Tianjin Mainland Hydrogen Equipment

The Chinese company Tianjin Mainland Hydrogen Equipment designs and manufactures large-scale, high pressure alkaline electrolyzers (containerized, complete systems and plants). End-user applications include large-scale hydrogen production, energy storage, power-to-liquid concepts and others. The company has entered a strategic partnership with HydrogenPro of Norway, which is responsible for the business activities in Europe and the US [71]. Tianjin Mainland Hydrogen Equipment was founded in 1994 in Tianjin, China, and is expected to account for 12 % of the global electrolyzer business. Financial reports were not publicly available and no information about the number of employees was found.

Sunfire GmbH

Sunfire is a young company focused on the development of solid-oxide electrolyzers and fuel cell. Its electrolyzer sector is aiming to enter the power-to-X markets (specifically for synfuel) but the business operations are still mostly in pilot-plant and demonstration stages. Its only commercial plant for synfuel-production is currently engineered in cooperation with Nordic Blue Crude AS, Climeworks, EDL Anlagenbau and additional partners and projected to begin operation in 2020, with an electric capacity of 20 MW [72, 72]. Their 20 employees are located in the German city of Dresden since its foundation in 2010. Due to their early stage, no reliable information on revenues or market shares could be found.

Electrolyzer competition dashboard

The most important information of the key players of the electrolyzer industry are summarized in Table 4-1 on the following page.

Table 4-1. Electrolyzer competition dashboard.

Key Players	**Nel Hydrogen***	**McPhy Energy**	**Hydrogenics Corporation**	**Giner ELX**	**ITM Power Plc**	**Tianjin Mainland Hydrogen Equipment**	**Sunfire**
Headquarters [57]	Oslo, Norway	La Motte-Fanjas, France	Mississauga, Canada	Newton, MA, US	Sheffield, UK	Tianjin, China	Dresden, Germany
Total revenue* (2016)	12.0 M€ [62]	7.5 M€ [64]	24.7 M€ [67]	N/A	2.15 M€ [70]	N/A	N/A
Total revenue* (2017)	31.2 M€** [62]	10.1 M€ [64]	40.9 M€ [67]	N/A	2.70 M€ [70]	N/A	N/A
Estimated Market Share (2017) [57]	45 %	12 %	10 %	2 %	10 %	12 %	< 1 %
Prominent regions [57]	• 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 [57]	• 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

4.4 Industry & Competitor Trends

The company landscape within the electrolyzer industry has undergone considerable change during the last years. There are three major trend categories that have been identified, firstly, by following the events of the Group Exhibit Hydrogen, Fuel Cells and Batteries at Hannover Messe from 2016 [74], 2017 [61] and 2018 [60] as well as through interviews with managers of associated businesses.

General industry snapshot & trends

The electrolyzer industry has experienced growing demand from industries that had rather little importance about a decade ago. These synergetic effects are specifically noticeable with the growing manufacturing industry for solar photovoltaic (PV) panels, were hydrogen is used as a reducing agent thought the production process. Large orders for electrolyzers have been placed from companies based in China, Taiwan and the rest of Asia-Pacific and Central Asia, which account for almost 85 % of the global PV module production [75].

With no relevant changes during the last years, contract negotiations continue to be lengthy procedures. Due to its capital-intensive nature, orders typically require in-depth feasibility studies, techno-economic assessments and due diligence audits. Two to four years are the typical time frames from order inquiry to contract conclusions. In general, crucial factors that influence purchase decisions of potential buyers turned out to be mostly a project's capital cost, since that is what companies usually budget for, the total cost of ownership and equipment lifetime.

Trends in product requirements

The product requirements for being successful in the emerging electrolyzer market have been influenced by changing and redefined factors. The US Department of Energy has concluded in 2018 that electrolytic hydrogen needs to reach prices of about 4 $/kg in North America and about 5 €/kg in Europe in order to be competitive for wide-scale deployment. In order to be more cost-effective, companies are now increasingly offering complete systems (incl. electrolyzer, storage, compressors, balance-of-plant, etc.), instead of individual components. A large trend can be observed towards more modular and scalable systems, so that products can be used and adapted for a maximized number of applications.

In terms of underlying technology, alkaline electrolyzers are more and more promoted for large-scale installations (> 1 MW) in energy storage and industries. This is mainly due to their unparalleled price/performance ratio, low operational costs and long component lifetime. PEM electrolyzers are mostly found in products for small- and medium scale applications, e.g. residential buildings, universities, hospitals and HRS for small fleets in off grid or backup scenarios. Another point is the higher power density of PEM over alkaline, so it can be designed for cases with stringent space-requirements. With

Sunfire being the only major player that uses solid-oxide technology, their first SOEC product focuses on pure hydrogen production for industrial customers with a maximum capacity of 300 kW. Since 2016 they are commercializing their second stage product, a 10 kW co-electrolyzer system for synfuel production purposes [76].

Trends in Business Models

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 [77]. On the other hand, it encouraged companies to develop more innovative ways of making business. With the help of government-funded studies and research (e.g. [42] and [26]), 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 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 [60].

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 [78]. 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 [79]. 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 [80].

5 Business Model Development

The business opportunities of conventional and emerging market segments have been assessed and the electrolyzer industry as well as its competitive environment were examined. Based on the outcomes of these analyses, a viable business models (BMs) for new ventures with SOEC-based products is developed in this chapter.

In the first part, a business case involving solid-oxide electrolyzers is generated that shows the highest business prospects, based on findings from the previously conducted market and industry analysis.

Subsequently, two different business model including unique value propositions will be proposed with which a potential company could address the selected business case. The business models will be evaluated in terms of strengths, weaknesses, opportunities, and threats. Potential risks to the proposed model will be determined and assessed in the last part.

5.1 Generation of Business Case

5.1.1 Difficulties of generating electrolyzer-based business cases

Independent of the technology used, the challenges of electrolytic hydrogen projects are economic instead of technical. Reducing the cost of production is one main part of achieving larger-scale commercialization. Those costs need to be balanced by sufficient revenues, in order to reach profitability and bankability. Especially when it comes to projects within the emerging market segments, the market size is currently virtually zero. These uncertainties over potential cost reductions as well as the market development are the complex difficulties when it comes to creating electrolyzer-based business cases.

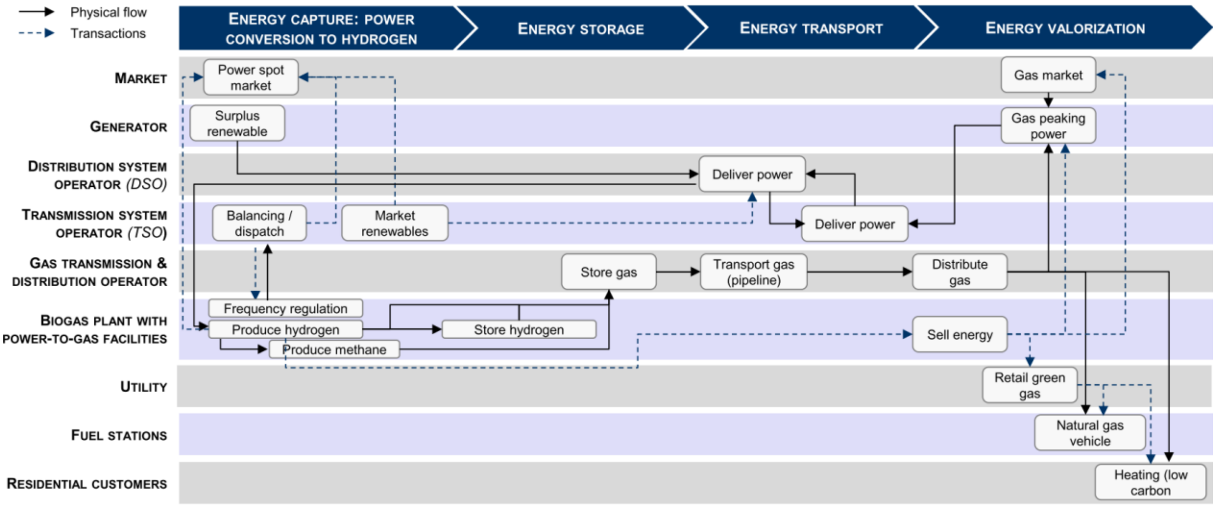


Figure 5-1. Simplified stakeholder interactions in power-to-gas pathways [26].

The fact that hydrogen conversion solutions typically involve a **large number of stakeholders** adds a project's complexity. As can be seen in the following Figure 5-1, for an exemplary power-to-gas project, it can be seen how various players from legal, political, and market backgrounds interact. This fact can discourage smaller stakeholders from investing [26].

Conventional energy systems are usually based on a simple model where one input source in transformed into another, based on demand requirements. These layouts apply for conventional power plants or hydrogen production though SMR (single-source / single-product). The new business concepts of electrolytic hydrogen increasingly involve more than just one raw material and also generate more products, as illustrated in Figure 5-2. This is especially the case for power-to-gas and -liquid systems, where electricity, water and carbon sources are used to generate not just valuable products like methane, other gases or liquids but also heat while contributing to the frequency control market. In order to optimize the financial but also the technical side, new multi-dimensional optimization tools need to be developed [81].

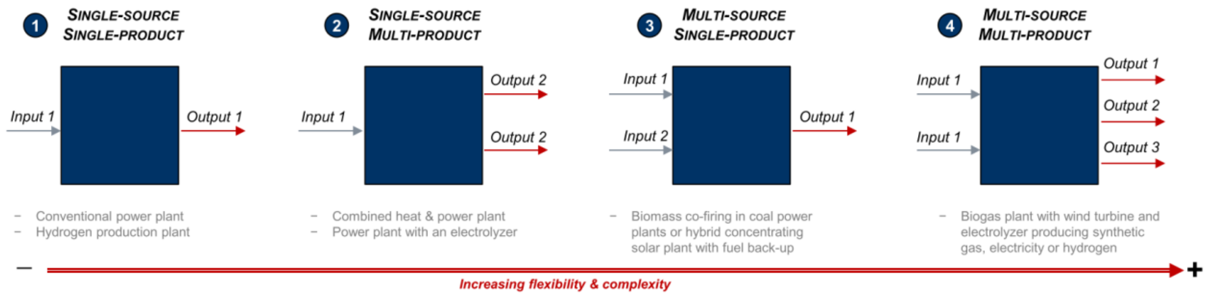


Figure 5-2. Illustration of energy system layout from single-source single-product to multiple-source multiple-product [26].

Lastly, I can be said that the economics of commercial electrolyzer projects are fundamentally system- and application specific. Therefore, the elaboration of thorough techno-economic assessments is always mandatory for evaluating the feasibility and profitability of any business case. As such, an assessment is out of the scope of this work, the following business case can only be seen as a first proposal based on the outcomes of the analyses that have been conducted within this study.

5.1.2 Business Case Selection

In chapter 3.3, the short-term business prospects of potential electrolyzer market segments have been assessed. It was found that the most attractive end-market are grid services, followed by refineries and the emerging field of power-to-liquid. 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:

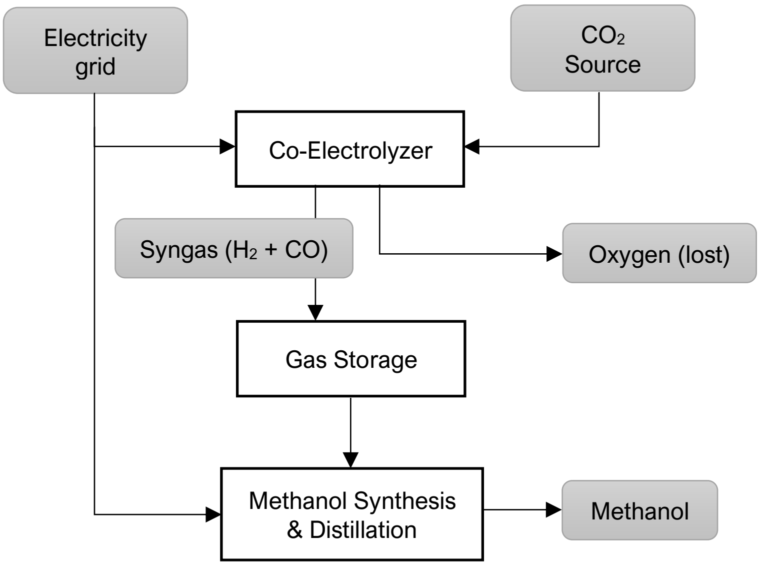
- Larger capital cost and considerably lower stack lifetime (see Table 2-3), leading to additional costs for stack-replacement
- Industry trend towards using alkaline electrolysis for large-scale hydrogen production projects (see chapter 4.4)
- Industry investment decision factors: Capital cost; Total cost of ownership; Equipment lifetime (as discussed in chapter 4.4)
- Focus on hydrogen production: Revenue diversification difficult / not possible

This leads to the conclusion that solid-oxide electrolysis is likely 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 power-to-liquid. 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 that was introduced in section 3.2.2.2. SOEC is the only electrolyzer technology capable of performing co-electrolysis, which gives it a technological advantage over alkaline and PEM. Here, the actual economic benefit should be validated by an in-depth, comparative financial analysis, which is not part of this study. A guide with key parameters on how to determine the economics of a power-to-x project is provided in Figure 8-3 in the Annex.

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. The main characteristics and a simplified project layout are shown in Table 5-1.

Table 5-1. Business Case: Grid-connected power-to-methanol plant, selling methanol to the wholesale market.

Project type	Large-scale power-to-liquid plant for electrolytic methanol
Location	Denmark
Electrolyzer size	1 MW_{el} solid-oxide electrolyzer (co-electrolysis mode)
Electrolyzer parameters	• co-electrolysis mode (syngas production) • minimum load 25% of installed power[a] • maximum load 100% of installed power[a] • ramping 10 mins from minimum to maximum load[a]
Feedstock	• Electricity: base-case electricity (price: 40 €/MWh_e) • Carbon source: Carbon capture OR biomass gasification (approx. cost: 15 €/tCO_2) [82]
Revenue model	• **Primary** revenue streams: ○ Methanol to commercial wholesale market ○ By-product oxygen: none • **Secondary** revenue streams: ○ (manual) Frequency Restauration Reserve service
Simplified project layout	

[a] based on [82]

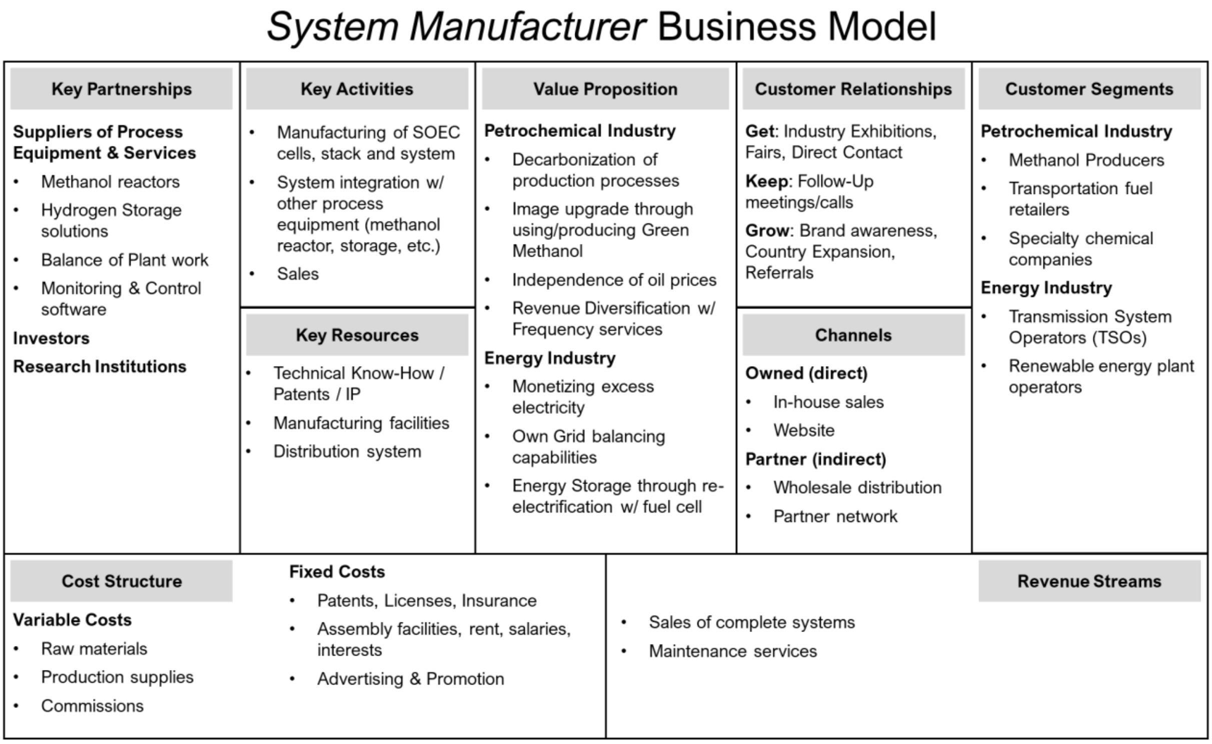
5.2 Business Model Proposals

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.

5.2.1 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 called ***System Manufacturer***.

Table 5-2. Canvas of the "System Manufacturer" business model.



System Manufacturer Business Model

Key Partnerships

Suppliers of Process Equipment & Services
- Methanol reactors
- Hydrogen Storage solutions
- Balance of Plant work
- Monitoring & Control software

Investors

Research Institutions

Key Activities
- Manufacturing of SOEC cells, stack and system
- System integration w/ other process equipment (methanol reactor, storage, etc.)
- Sales

Key Resources
- Technical Know-How / Patents / IP
- Manufacturing facilities
- Distribution system

Value Proposition

Petrochemical Industry
- Decarbonization of production processes
- Image upgrade through using/producing Green Methanol
- Independence of oil prices
- Revenue Diversification w/ Frequency services

Energy Industry
- Monetizing excess electricity
- Own Grid balancing capabilities
- Energy Storage through re-electrification w/ fuel cell

Customer Relationships

Get: Industry Exhibitions, Fairs, Direct Contact

Keep: Follow-Up meetings/calls

Grow: Brand awareness, Country Expansion, Referrals

Channels

Owned (direct)
- In-house sales
- Website

Partner (indirect)
- Wholesale distribution
- Partner network

Customer Segments

Petrochemical Industry
- Methanol Producers
- Transportation fuel retailers
- Specialty chemical companies

Energy Industry
- Transmission System Operators (TSOs)
- Renewable energy plant operators

Cost Structure

Variable Costs
- Raw materials
- Production supplies
- Commissions

Fixed Costs
- Patents, Licenses, Insurance
- Assembly facilities, rent, salaries, interests
- Advertising & Promotion

Revenue Streams
- Sales of complete systems
- Maintenance services

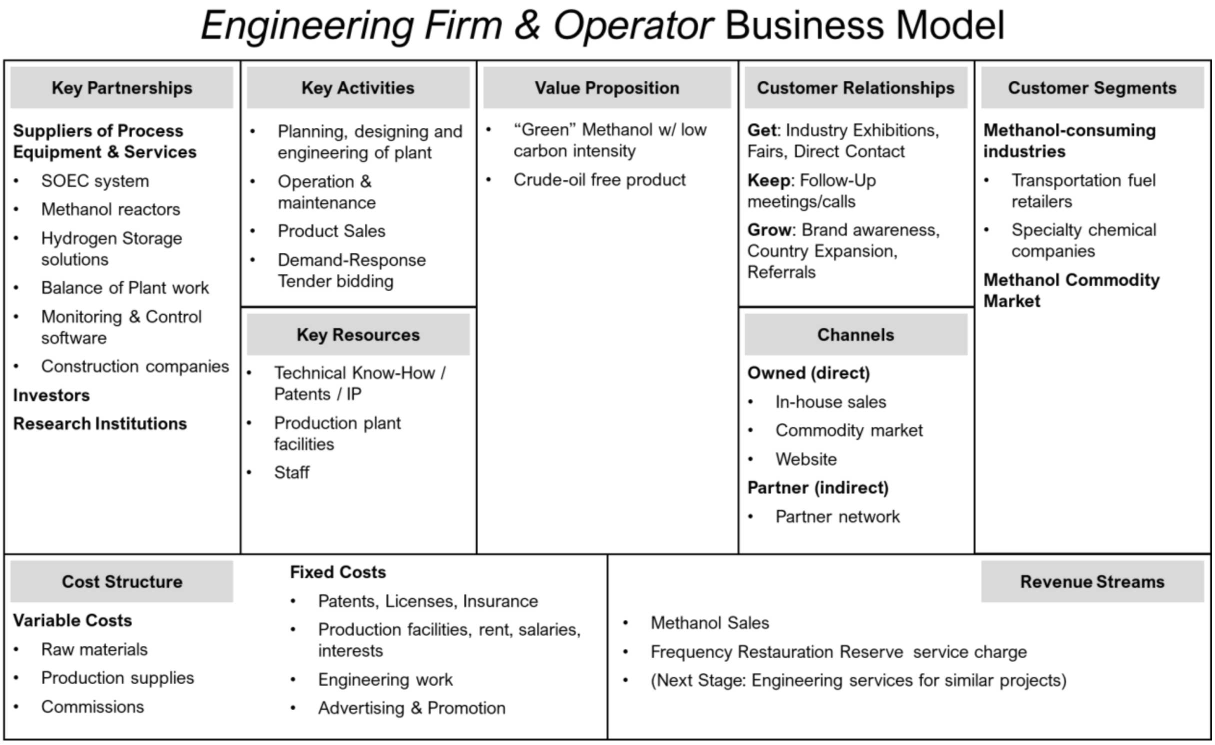
As can be seen in the business model canvas (Table 5-2)), the company would be able to **address two customer segments**. The first segment are petrochemical industries that either produce methanol themselves, use it for blending transportation fuel or other specialty chemical companies. The offered **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. The other parts of the business model canvas are self-explanatory and will not be discussed any further.

5.2.2 Engineering Firm & Operator Business Model

The second business model proposal approaches the power-to-methanol business case from a different angle. 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 5-3.

Table 5-3. Canvas of the "Engineering Firm & Operator" business model.



Engineering Firm & Operator Business Model

Key Partnerships

Suppliers of Process Equipment & Services
- SOEC system
- Methanol reactors
- Hydrogen Storage solutions
- Balance of Plant work
- Monitoring & Control software
- Construction companies

Investors

Research Institutions

Key Activities
- 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

Value Proposition
- "Green" Methanol w/ low carbon intensity
- Crude-oil free product

Customer Relationships

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

Customer Segments

Methanol-consuming industries
- Transportation fuel retailers
- Specialty chemical companies

Methanol Commodity Market

Cost Structure

Variable Costs
- Raw materials
- Production supplies
- Commissions

Fixed Costs
- Patents, Licenses, Insurance
- Production facilities, rent, salaries, interests
- Engineering work
- Advertising & Promotion

Revenue Streams
- Methanol Sales
- Frequency Restauration Reserve service charge
- (Next Stage: Engineering services for similar projects)

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 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 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.

5.2.3 SWOT Analysis

Both business models have unique internal strengths and weaknesses in the context of external opportunities and threats (SWOT). A SWOT analysis is a strategic reviewing tool for achieving the optimum match of a firm's resources with the business environment in order to gain a sustainable competitive advantage though the following points [56]:

- Building on a company's strengths
- Reducing weaknesses or adopting a strategy that avoids weaknesses
- Exploiting opportunities, particularly using the company's strengths
- Reducing exposure to or countering threats

When it comes to business planning, the SWOT analysis gives a snapshot of a business's position and provides an input into the generation of strategic options. It gives on outline of the major issues affecting the industry and the business as well as it identifies the basis for developing strategies.

For the *System Manufacturer* and *Engineering Firm & Operator* business model, the outcomes of the SWOT analysis have been summarized in Table 5-4 and Table 5-5, respectively.

Table 5-4. SWOT Analysis of the System Manufacturer business model.

Internal	
Strengths	**Weaknesses**
• First-mover advantage (possibility of gaining technology-leadership) • Economies of scale • Innovative technology • Strong product position within PtX-segment • Extensive, unique value proposition	• High cost base, depending of buyer's willingness-to-pay • Low TRL of SEOC manufacturing process • Ongoing Research & Development • Tight financial resources • No brand reputation / No market dominance
External	
Opportunities	**Threats**
• PtM: New market opportunity, but… • Changing customer demands (decarbonization, green image, etc.) • (Currently) favorable political support • Potential demand from various industries	• … Embryonic market size, difficult to enter • Market growth difficult to forecast • Highly dependent on regulation and legislation

Table 5-5. SWOT Analysis of the Engineering Firm & Operator business model.

Internal	
Strengths	**Weaknesses**
• Differentiated, "green" product • Mostly well-proven technology • High energetic efficiency • Economies of scale • Revenue diversification possible • Access to commodity market	• Low technological readiness level of SOEC system • Capital intensive initial investment • Large supplier network • Few core competencies (risk of imitation)
External	
Opportunities	**Threats**
• Innovative Technology, new markets • New demand through eco-conscious customers • Positive market growth • Increasingly favorable political support (EU) • Access to funding (Horizon 2020, FCH JU) • Market liberalization	• Methanol prices linked to oil prices → risk of fluctuation • Threat from cheaper produced products • Strong competition through huge industry

5.3 Evaluation and Discussion

Both the *System Manufacturer* and the *Engineering Firm & Operator* business model describe very different companies. Nevertheless, both potential businesses have similar relationships with their customer segments. The sales channels are also comparable as they both need to rely on owned, direct channels, like in-house sales, as well as on their partner network. Furthermore, similarities can be observed within their cost structures, where the occurring variable and fixed costs are from the same nature but, in reality, will vary greatly in the specific numbers.

When comparing both business models with each other, unique advantages and drawbacks can be identified on a qualitative level. They are summarized in the following Table 5-6.

Table 5-6. 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.

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 assumption can only be confirmed by generating a complete economic valuation for each business model and comparing the financial results.

6 Conclusions

This work began with providing introductory technical background of water electrolysis in general and summarized the underlying concepts of the three main technologies: Alkaline, PEM and solid-oxide electrolysis. 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. Special focus was given to hydrogen production by steam-methane reforming and coal gasification. The market was further analyzed in terms of possible end-user applications for electrolyzers. Ammonia production and refineries were assessed as conventional, or pre-existing, 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. A Porter's five forces model was generated to understand the current structure of the industry. 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. The first model describes a manufacturing business of power-to-methanol systems, whereas the second business model assumes a company to be designer and operator of a PtM plant.

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 valuation of both business models.

7 Bibliography

[1] International Energy Agency, "CO2 Emissions From Fuel Combustion”, International Energy Agency , Paris, 2014.

[2] International Energy Agency, "World Energy Outlook 2012”, International Energy Agency , Paris, 2012.

[3] C. Growitsch, Interviewee, *Das neue Gaszeitalter.* [Interview]. January 2014.

[4] Intergovernmental Panel on Climate Change, "Climate Change 2014 Mitigation of Climate Change”, Cambridge University Press, New York City, 2014.

[5] German Ministry of the Environment, Nature Conservation and Nuclear Safety, Referat KI I 1 , "Klimaschutzplan 2050”, The German Ministry of the Environment, Nature Conservation and Nuclear Safety, Berlin, 2016.

[6] T. Smolinka, "H2-Erzeugung durch Wasserelektrolyse: Entwicklungstrends und Herstellerübersicht”, *HZwei,* April 2017.

[7] F.W. Bolle, K. Genzowsky, S. Gredigk-Hoffmann and M. Reinders, "Einsatz der Wasserstofftechnologie in der Abwasserbeseitigung”, Forschungsinstitut für Wasser- und Abfallwirtschaft - RWTH Aachen, Aachen, 2012.

[8] B. Höhnlein, M.F. Kock, T. Kattenstein, A. Feige, J. Mergel and A. Schadowski, "Wasserstoff - Schlüssel zur Energiewende”, EnergieAgentur Nordrhein-Westfalen, Düsseldorf , 2013.

[9] T. Smolinka, "Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien”, Fraunhofer-Institut für Solare Energiesysteme (ISE), Freiburg, 2011.

[10] V. M. Schmidt, Elektrochemische Verfahrenstechnik: Grundlagen, Reaktionstechnik, Prozess-optimierung, Weinheim: Wiley-VCH, 2003.

[11] W. Schurnberger, H. Janssen and U. Wittstadt, "Methoden der Wasserstofferzeugung „Wasserspaltung mit Strom und Wärme““, in *Jahrestagung des Forschungsverbunds Sonnenenergie*, Berlin, 2004.

[12] H. Wendt and G. Vogel, "Die Bedeutung der Wasserelektrolyse in Zeiten der Energiewende”, *Chemical Engineering Today,* vol. 86, no. 1-2, pp. 144-148, 2014.

[13] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study”, *International Journal of Hydrogen Energy,* vol. 42, pp. 30470-30492, 2017.

[14] F. Bolle, K. Genzowsky, S. Gredigk-Hoffmann, M. Reinders and H. Riße, "„Einsatz der Wasserstofftechnologie in der Abwasserbeseitigung“ - Phase I, Band I: Kompendium Wasserstoff”, Forschungsinstitut für Wasserund Abfallwirtschaft an der RWTH Aachen, Aachen, 2012.

[15] M. Wenske, "Wasserstoff - Herstellung durch Elektrolyse”, in *15. Symposium Nutzung Regenerativer Energiequellen und Wasserstofftechnik*, Stralsund, 2008.

[16] M. Wenske, "Stand un neue Entwicklungen bei der Elektrolyse”, in *DBI-Fachforum für Energiespeicherkonzepte und Wasserstoff*, Berlin, 2011.

[17] K. Santhanam and R. J. Press, Introduction to Hydrogen Technology. Second edition., Hoboken, NJ: Wiley, 2017.

[18] M. Ball and M. Wietschel, The Hydrogen Economy - Opportunity and Challanges, Cambridge: Cambridge University Press, 2009.

[19] New York State Energy Research and Development Authority, Hydrogen Production - Steam Methane Reforming (SMR), Albany, 2005.

[20] Union of Concerned Scientists, "Fulfilling the potential of fuel cell electric vehicles”, Cambridge, MA, 2015.

[21] International Energy Agency (IEA); Organisation for Economic Co-Operation and Development (OECD), "Prospects for Hydrogen and Fuel Cells”, OECD/IEA, Paris, 2005.

[22] C. M. Kalamaras and A. M. Efstathiou, "Hydrogen Production Technologies: Current State and Future Developments”, *Conference Papers in Energy,* vol. 2013, pp. 1- 9, 2013.

[23] D. Thomas, *Renewable Hydrogen Solutions,* Brussels: Hydrogenics , 2017.

[24] B. Frois, "Balancing the Grid with hydrogen technologies”, in *13th European SOFC & SOE Forum*, Lucerne, 2018.

[25] Centre for Industry Education Collaboration, "The Essential Chemical Industry - online - Hydrogen”, Department of Chemistry, University of York, UK, July 2016. [Online]. Available: http://www.essentialchemicalindustry.org/chemicals/hydrogen.html. [Accessed 8 July 2018].

[26] B. Decourt, B. Lajoie, R. Debarre and O. Soupa, "The hydrogen-based energy conversion FactBook”, The SBC Energy Institute, Paris, 2014.

[27] International Energy Agency, "World Energy Outlook 2012”, IEA, Paris, 2012.

[28] L. E. Apodaca, "Mineral Commodity Summaries - Nitrogen (Fixed) Ammonia", U.S. Geological Survey, Washington, 2018.

[29] W.-y. Huang, "Impact of Rising Natural Gas Prices on U.S. Ammonia Supply", United States Department of Agriculture (USDA), Washington , 2007.

[30] P. Robinson, "Hydrotreating and Hydrocracking: Fundamentals", in *Practical Advances in Petroleum Processing*, New York, Springer, 2006, pp. 177-218.

[31] U.S. Energy Information Administration, "Hydrocracking is an important source of diesel and jet fuel", 18 January 2013. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=9650. [Accessed 20 July 2018].

[32] S. Hicks and P. Gross, "Hydrogen for refineries is increasingly provided by industrial suppliers", *Today in Energy,* 20 January 2016.

[33] Energy Information Administration, "Form EIA-810, "Monthly Refinery Report"", Washington , 2018.

[34] Energy Information Administration, "Form EIA-820, "Annual Refinery Report"", Washington, 2018.

[35] TransportPolicy, "EU: Fuels: Diesel and Gasoline", International Council on Clean Transportation, 2018. [Online]. Available: https://www.transportpolicy.net/standard/eu-fuels-diesel-and-gasoline/. [Accessed 23 July 2018].

[36] Exhaust Gas Cleaning Systems Association, "2020 - Damatic reduction in high sulphur fuel oil price predicted", *Commentary, Emissions Regulations,* 21 December 2017.

[37] E. Freund and P. Lucchese, L'Hydrogène, carburant de l'après-pétrole?, Paris: Editions Technip, 2012.

[38] D. Thomas, D. Mertens, M. Meeus, W. Van der Laak and I. Francois, "Power To Gas - Roadmap for Flanders", WaterstofNet vzw, Turnhout, 2016.

[39] L. Grond, P. Schulze and J. Holstein, "Systems analyses Power to Gas: A technology review", DNV KEMA Energy & Sustainability, Groningen, 2013.

[40] Hydrogenics, "Renewable Hydrogen Solutions Brochure 09/2017", 2017.

[41] W. Urban, H. Lohmann and K. Girod, BMBF-Verbundprojekt Biogaseinspeisung- Band 4, Fraunhofer Institute, 2009.

[42] C. Chardonnet, L. D. Vos, F. Bart and T. D. Lacroix, "Study on early Business Cases for H2 in Energy Storage and more broady Power to H2 Applications", Tractebel Engineering S.A., Hinicio, Brussels, 2017.

[43] ITM Power PLC, "Power-to-gas: A UK feasibility study", Sheffield, 2013.

[44] M. Bailera, P. Lisbona, L. M. Romeo and S. Espatolero, "Power to Gas projects review: Lab, pilot and demo plants for storingrenewable energy and CO2", *Renew. Susta. Energy Rev.,* vol. 69, pp. 292-312, 2017.

[45] P. Schmidt, W. Weindorf, A. Roth and V. Batteiger, "Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel", German Environment Agency, Dessau-Roßlau, 2016.

[46] "Few transportation fuels surpass the energy densities of gasoline and diesel", U.S. Energy Information Administration, 3 January 2014. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=14451. [Accessed 05 September 2018].

[47] D. Wilhelm, D. Simback and A.D, "Syngas production for gas-to-liquids applications: technologies, issues and outlook", *Fuel Processing Technology,* vol. 71, no. 1-3, pp. 139-148, 2001.

[48] J. Göbelbecker, "Kraftstoffe aus Power-to-Liquid-Verfahren", *Chemie Technik,* 17 April 2018.

[49] R. Hands, "Market drivers for the snygas industry", BCInsight Ltd., Colorado Springs, 2017.

[50] C. Conthran and A. Singh, "Global Trends in Syngas", Stratas Advisors, Houston, 2016.

[51] G. Herz, E. Reichelt and M. Jahn, "Techno-economic analysis of a co-electrolysis-based synthesis process for the production of hydrocarbons", *Applied Energy,* vol. 215, pp. 309-320, 2018.

[52] Persistence Market Research (PMR), "Global Wax Market for the Forecast Period 2017 - 2026", New York City, 2017.

[53] U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), "Hydrogen Analysis Resource Center: International Hydrogen Stations", H2 Tools, 30 June 2018. [Online]. Available: https://h2tools.org/sites/default/files/data/International%20Hydrogen%20Fueling%20Stations.xlsx.

[54] K. Münch, P. Larscheid, L. Lück, R. Canalejas, J. Simon, A. Arnedo and V. Gil, "Elyntegration - D2.1 Assessment of th regulatory framework and end-use/customer", Swiss State Secretariat for Education, Research and Innovation, 2016.

[55] Elia, "International Frequency Containment Reserve (FCR) Cooperation: Belgium joining the coupled German, Dutch, Swiss & Austrian markets", Elia, 2 August 2016. [Online].

[56] G. Friend and S. Zehle, Guide to Business Planning, London: The Economist , 2004.

[57] H. Tiwari, "Hydrogen Electrolyzer Market: Global Industry Analysis 2012–2016 and Opportunity Assessment, 2017–2027", Future Market Insights (FMI), London, 2017.

[58] Persistence Market Research, "Hydrogen Electrolyzer Market: Global Industry Analysis and Forecast, 2016-2026”, New York City, 2018.

[59] K.-A. Adamson and C. Longman, "The Fuel Cell and Hydrogen Annual Review”, 4th Energy Wave, Edinburgh, 2017.

[60] Hannover Messe, "Group Exhibit Hydrogen + Fuel Cells + Batteries at HANNOVER MESSE 2018”, 23-27 April 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/index.html.

[61] Hannover Messe, "Group Exhibit Hydrogen + Fuel Cells + Batteries at HANNOVER MESSE 2017”, 24-28 April 2017. [Online]. Available: https://www.h2fc-fair.com/hm17/index.html.

[62] Nel ASA, "Annual Report 2017”, Oslo, 2018.

[63] Hannover Messe, "Nel Hydrogen: Company Profile”, Group Exhibit Hydrogen, Fuel Cells and Batteries, 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/nel-hydrogen.html.

[64] McPhy Energy, "Press Release - Strong revenue increase in 2017 for McPhy: +34%”, La Motte-Fanjas, 2018.

[65] Hannover Messe, "McPhy Energy SA: Company Profile”, Group Exhibit Hydrogen, Fuel Cells and Batteries, 2017. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/mcphy.html.

[66] Hannover Messe, "Hydrogenics Corporation: Company Profile”, Group Exhibit Hydrogen + Fuel Cells + Batteries, 2017. [Online]. Available: https://www.h2fc-fair.com/hm17/exhibitors/hydrogenics.html.

[67] Hydrogenics Corporation, "2017 Annual Report”, Mississauga, 2018.

[68] Hannover Messe, "Giner ELX: Company Profile”, Group Exhibit Hydrogen, Fuel Cells and Batteries , 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/giner.html.

[69] Hannover Messe, "ITM Power Plc: Company Profile”, Group Exhibit Hydrogen, Fuel Cells and Batteries, 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/itm.html.

[70] ITM Power, "2017 Annual Report and Financial Statements”, Sheffield, 2018.

[71] Hannover Messe, "HydrogenPro: Company profile”, Group Exhibit Hydrogen, Fuel Cells and Batteries, 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/h2pro.html.

[72] Sunfire, "First commercial plant for the production of blue crude planned in Norway”, 10 July 2017. [Online]. Available: https://www.sunfire.de/en/company/press/detail/first-commercial-plant-for-the-production-of-blue-crude-planned-in-norway.

[73] Hannover Messe, "Sunfire GmbH: Company profile", Group Exhibit Hydrogen, Fuel Cells and Batteries, 2018. [Online]. Available: https://www.h2fc-fair.com/hm18/exhibitors/sunfire.html.

[74] Hannover Messe, "Group Exhibit Hydrogen, Fuel Cells and Battaries 2016", 25-29 April 2016. [Online]. Available: https://www.h2fc-fair.com/hm16/index.html.

[75] Fraunhofer Institute for Solar Energy Systems, "Photovoltaics Report", Freiburg, 2018.

[76] Sunfire GmbH, "Products & Technology", [Online]. Available: https://www.sunfire.de/en/products-and-technology.

[77] Hydrogeit, "Heliocentris again files for bankruptcy", *H2-international,* 12 January 2018.

[78] B. Motz, "Hydrogenics Signs Development Agreement with Chinese Partner", Hydrogenics Corporation, 8 June 2016. [Online]. Available: https://www.hydrogenics.com/2016/06/08/20160608hydrogenics-signs-development-agreement-with-chinese-partner/.

[79] R. Gilroy, "Nikola Awards Nel Hydrogen Contract to Support 30 Fueling Stations", Transport Topics, 29 June 2018. [Online]. Available: https://www.ttnews.com/articles/nikola-awards-nel-hydrogen-contract-support-30-fueling-stations.

[80] R. Healy, "Nel acquires Proton OnSite to create world's largest electrolyser company", gasworld Magazine, 28 February 2017. [Online]. Available: https://www.gasworld.com/nel-acquires-proton-onsite/2012338.article.

[81] C. He and X. Feng, "Evaluation indicators for energy –chemical systems with multi-feed and multi-product", *Energy,* vol. 43, pp. 344-354, 2012.

[82] L. R. Claussen, N. Houbak and B. Elmegaard, "Technoeconomic analysis of a methanol plant based on gasification of biomass and electrolysis of water", *Energy,* vol. 35, pp. 2338-2347., 2010.

[83] T. Brümmer, "“DVGW-Forschungsprojekt Energiespeichkonzepte", presentation at the European Commission workshop H2 in the economy", Deutscher Verein des Gas-und Wasserfaches, 2013.

[84] U.S. Department of Defense, "Technology Readiness Assessment (TRA) Guidance", U.S. Department of Defense, Virginia, 2001.

[85] Investopedia, "Economies of Scale", [Online]. Available: https://www.investopedia.com/terms/e/economiesofscale.asp. [Accessed 6 July 2018].

[86] Gartner, Inc., "Compound Annual Growth Rate (CAGR)", [Online]. Available: https://www.gartner.com/it-glossary/cagr-compound-annual-growth-rate. [Accessed 19 July 2018].

[87] Investopedia, "Average Annual Growth Rate (AAGR)”, [Online]. Available: https://www.investopedia.com/terms/a/aagr.asp. [Accessed 10 September 2018].

[88] W. Zittel, "Die Zukunft der europäischen Energieversorgung”, *Biogas Journal,* no. 6, pp. 108-113, 2014.

8 Annex

8.1 Supporting Information for the Market Analysis

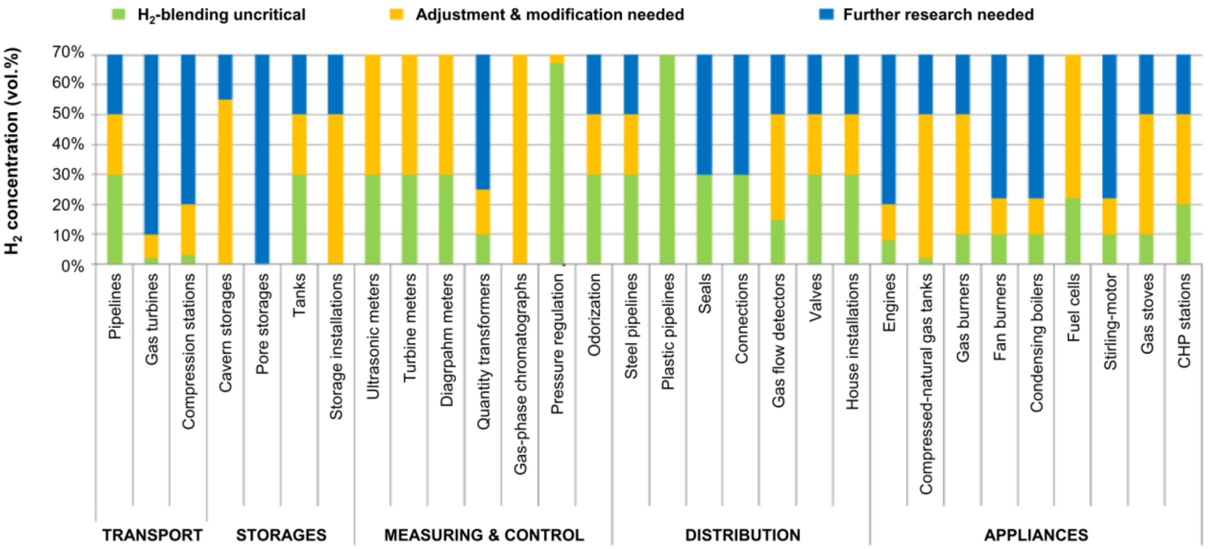


Figure 8-1. Limit of H2 blending along the natural gas infrastructure [83].

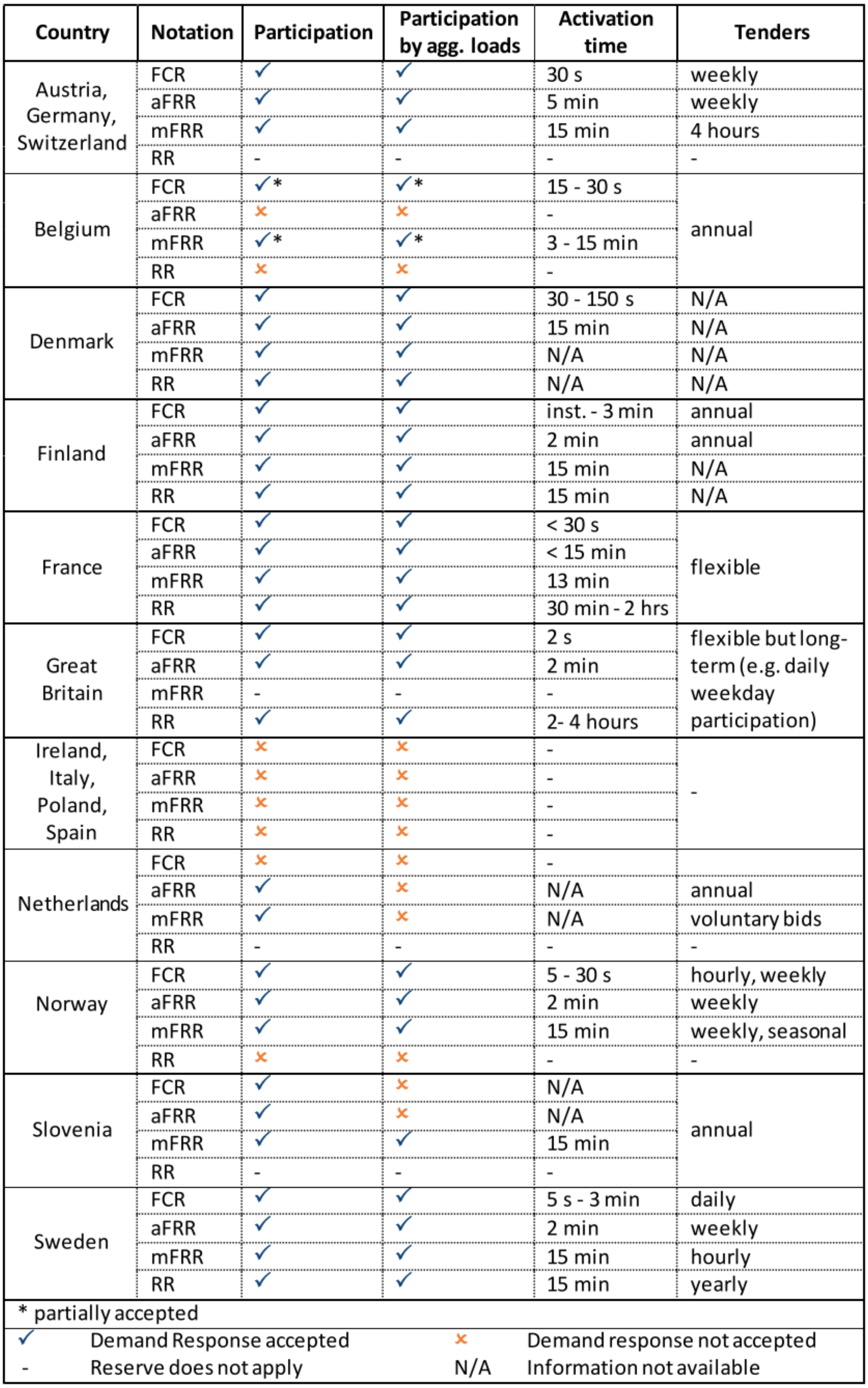
Table 8-1. Biomethane injection tariff and hydrogen equivalence for selected European countries [42].

	Germany	France	United Kingdom	Denmark
Biomethane injection tariff	32.3 €/MWh	45-140 €/MWh (2015)	50.5 €/MWh	67.5 €/MWh
Hydrogen equivalence	1.3 €/kg	1.8-5.5 €/kg	2.0 €/kg	2.6 €/kg

Table 8-2. Definition of technological readiness levels [84].

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations

Table 8-3. Demand response and activation time for control reserve in European countries [54].



Country	Notation	Participation	Participation by agg. loads	Activation time	Tenders
Austria, Germany, Switzerland	FCR	✓	✓	30 s	weekly
	aFRR	✓	✓	5 min	weekly
	mFRR	✓	✓	15 min	4 hours
	RR	-	-	-	-
Belgium	FCR	✓*	✓*	15 - 30 s	annual
	aFRR	×	×	-	
	mFRR	✓*	✓*	3 - 15 min	
	RR	×	×	-	
Denmark	FCR	✓	✓	30 - 150 s	N/A
	aFRR	✓	✓	15 min	N/A
	mFRR	✓	✓	N/A	N/A
	RR	✓	✓	N/A	N/A
Finland	FCR	✓	✓	inst. - 3 min	annual
	aFRR	✓	✓	2 min	annual
	mFRR	✓	✓	15 min	N/A
	RR	✓	✓	15 min	N/A
France	FCR	✓	✓	< 30 s	flexible
	aFRR	✓	✓	< 15 min	
	mFRR	✓	✓	13 min	
	RR	✓	✓	30 min - 2 hrs	
Great Britain	FCR	✓	✓	2 s	flexible but long-term (e.g. daily weekday participation)
	aFRR	✓	✓	2 min	
	mFRR	-	-	-	
	RR	✓	✓	2- 4 hours	
Ireland, Italy, Poland, Spain	FCR	×	×	-	-
	aFRR	×	×	-	
	mFRR	×	×	-	
	RR	×	×	-	
Netherlands	FCR	×	×	-	
	aFRR	✓	×	N/A	annual
	mFRR	✓	×	N/A	voluntary bids
	RR	-	-	-	-
Norway	FCR	✓	✓	5 - 30 s	hourly, weekly
	aFRR	✓	✓	2 min	weekly
	mFRR	✓	✓	15 min	weekly, seasonal
	RR	×	×	-	-
Slovenia	FCR	✓	×	N/A	annual
	aFRR	✓	×	N/A	
	mFRR	✓	✓	15 min	
	RR	-	-	-	
Sweden	FCR	✓	✓	5 s - 3 min	daily
	aFRR	✓	✓	2 min	weekly
	mFRR	✓	✓	15 min	hourly
	RR	✓	✓	15 min	yearly

* partially accepted

✓ Demand Response accepted × Demand response not accepted

- Reserve does not apply N/A Information not available

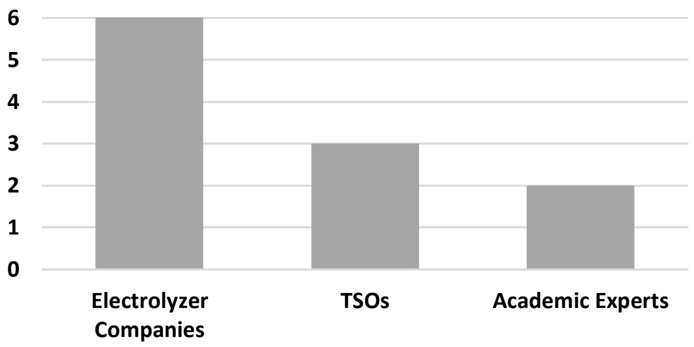


Figure 8-2. Experts and Managers interviewed during this work.

The general interaction procedure with the experts or company managers can be described by the following:

1. Initial contact (via email or LinkedIn): Personal introduction of and providing a description of the scope of the study
2. Arrangement of interview date and format (Phone, Skype or email questionnaire)
3. Conducting the interview
4. Sending follow-up emails or messages

During this study, 78 companies, managers and academic experts were contacted from which 11 were open to having an interview or answering an email questionnaire. The interviewees asked to not disclose any names or associated positions within the associated company or institute.

8.2 Directional Policy Matrix

According to [56], the method used to quantify the business-sector prospects in the **directional policy matrix** is as follows:

1. An importance score is assigned to each factor. The importance scale ranges from 0 to 5. A factor with a zero-importance score could be omitted for the purposes of the calculation, but it is still valuable to record the fact that a particular factor is of no importance and has not just been missed.
2. A score is assigned to indicate the strength of the influence of the factor on your business. The scale ranges from –5 to +5. A negative number indicates a negative influence.
3. The two scores for each factor are multiplied to produce a total score for business-sector prospects for your firm’s product.
4. The score achieved by your firm’s product is expressed as a percentage of the maximum score (all scores set to +5 and totaled).

Table 8-4. Directional policy matrix for electrolyzer market segments.

		Ammonia		**Refineries**		**Power-to-Gas**		**Power-to-Liquid**		**Power-to-Mobility**		**Grid Services**	
Factor	**Importance**	**Strength**	**Score**	**Strength**	**Score**	**Strength**	**Score**	**Strength**	**Score**	**Strength**	**Score**	**Strength**	**Score**
Market Factors													
Potential market size	5	-4	-20	5	25	2	10	4	20	-5	-25	5	25
Barriers to entry	4	-4	-16	2	8	-1	-4	-1	-4	-4	-16	4	16
Market growth	5	-4	-20	5	25	3	15	3	15	-4	-20	1	5
Cyclical risk	3	1	3	2	6	1	3	1	3	-1	-3	4	12
Price elasticity of demand	3	-3	-9	-1	-3	-3	-9	-1	-3	-2	-6	0	0
Technology Factors													
Scope for innovation	2	2	3	2	4	4	8	4	8	4	8	2	4
Speed of development	4	2	8	2	8	3	12	3	12	-1	-4	1	4
Technological readiness	4	2	8	2	8	-1	-4	2	8	1	4	3	12
Complexity	5	3	15	3	15	-2	-10	-2	-10	-4	-20	3	15
Differentiation	2	0	0	0	0	2	4	2	4	1	2	2	4
Flexible operating	4	1	4	2	8	2	8	1	4	1	4	4	16
Capacity utilization	3	3	9	2	6	0	0	2	6	1	3	2	6
Financial and Economic Factors													
Margins	3	2	6	2	6	-1	-3	-1	-3	-3	-9	1	3
Capital intensity	5	-1	-5	-1	-5	-3	-15	-3	-15	-3	-15	3	15
Cost of capital	4	1	4	1	4	0	0	0	0	-1	-4	2	8
Political Factors													
Social trends	2	0	0	1	2	4	8	4	8	2	4	0	0
Subsidies	4	3	12	3	12	3	12	3	12	1	4	1	4
Regulation and legislation	3	3	9	3	9	-2	-6	1	3	2	6	3	9
Pressure groups	3	-3	-9	-1	-3	0	0	0	0	-2	-6	1	3
Total score			2		135		29		68		-93		161
Maximum possible score			340		340		340		340		340		340
Percentage score			**1%**		**40%**		**9%**		**20%**		**-27%**		**47%**

8.3 Other Supporting Data

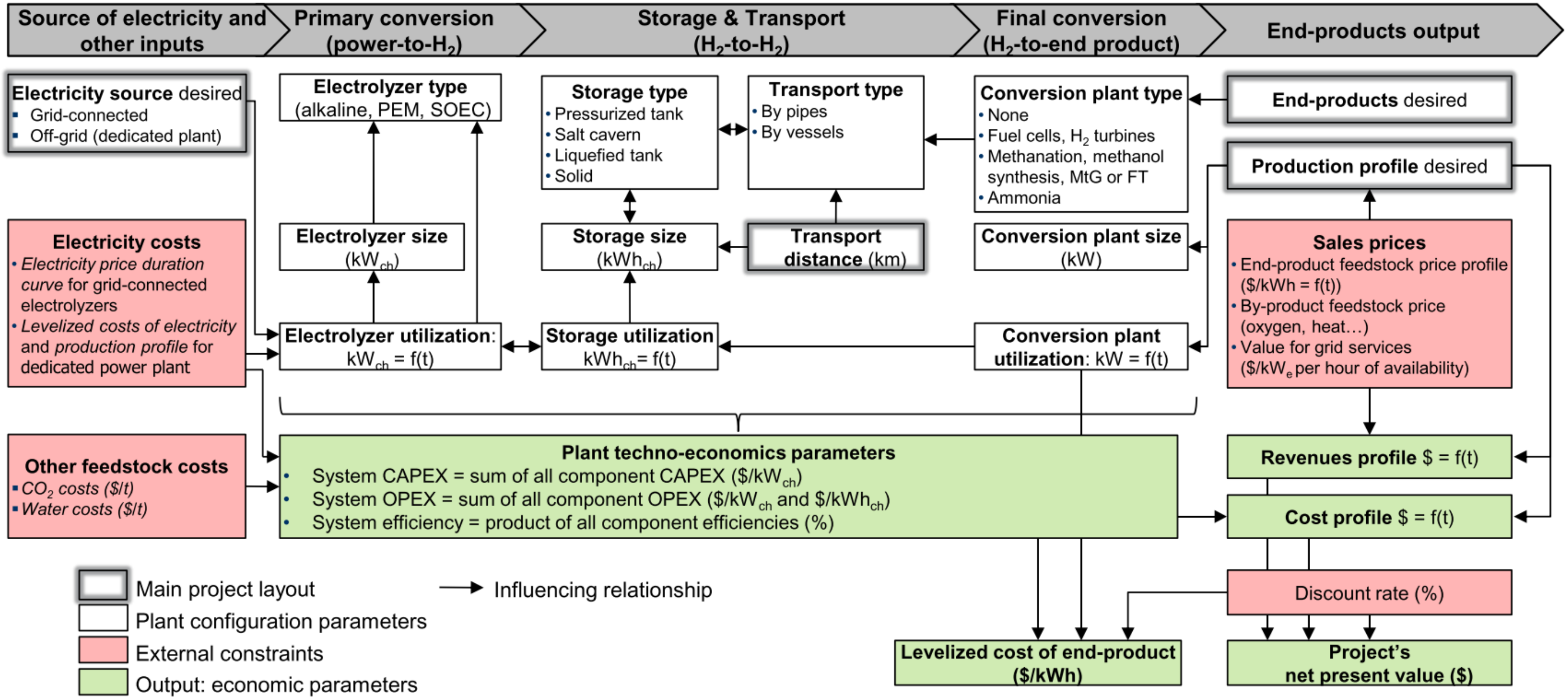


Figure 8-3. Key parameters influencing choice of plant configuration and determining project economics [26].