Professional MBA
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Economic viability of small-scale decentralized hydrogen fuel electrolysis in the Austrian market

A Master's Thesis submitted for the degree of
"Master of Business Administration"

supervised by
Prof. Dr. Christian Lüthje

Gabor Pongracz, MSc

00730786

Vienna, 30.06.2019

Affidavit

I, **GABOR PONGRACZ, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ECONOMIC VIABILITY OF SMALL-SCALE DECENTRALIZED HYDROGEN FUEL ELECTROLYSIS IN THE AUSTRIAN MARKET", 67 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

This thesis is aimed at assessing the basic economic viability of decentralized hydrogen fuel electrolysis in the Austrian market. As a first step, expert studies are investigated for establishing driving factors of the economic viability of such systems. Based on these studies, scenarios with specific projections for all major driving factors are derived, which are later used as input for the economic viability model of a single decentralized hydrogen fuel electrolysis system.

The second main part of the thesis suggests a techno-economic model for both the operational feasibility and investment viability of a decentralized hydrogen fuel electrolysis plant. After discussing the established model, different deployment options are exercised with the matching input values of the scenario projections from the first part of the thesis. Based on the results, the economic viability of each deployment option is studied.

Finally, a conclusion based on all results is presented, while also giving an outlook for additional studies to be carried out for further examining the topic at hand.

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1 Thesis introduction

> *"Just as coal gave way to oil, oil may now give way to hydrogen.*
>
> *'I sell here, Sir, what all the world desires to have. Power.' Matthew Boulton, the manufacturer who made James Watt's steam engine into an industrial tool, grasped the realities of the new industrial revolution from the beginning. For 100 years, the source of that power was coal. For almost another 100 it has been oil. But, as the revolution that Boulton helped to start enters its third century, it may be about to embrace a third fuel: hydrogen.* [3]

As stated in the above quote from *The Economist*, hydrogen is regarded as a resource, which might pave the way to a new industrial revolution, that instead of oil will be based on hydrogen as its main energy source. This statement will be used as a starting point for setting the context of this thesis, while also defining its outline and the structure in this introductory chapter.

1.1 Context of the thesis

Recent years have brought the topic of climate change, environmental protection and as a result the quest of reducing carbon-dioxide (CO_2) emissions increasingly in the focus of society and governments. As such, also the basis of the energy-hunger of the present world economy, namely fossil fuels and most prominently oil have been questioned and alternatives sought for. One of the possible alternatives in this context is hydrogen, a widely available gas, which could be used as a fuel in as a versatile way as fossil fuels currently are.

On the other hand, changing the basic resource of the worldwide energy supply raises fundamental questions, starting with an environmental-friendly production, distribution and utilization of hydrogen fuel in both broad and complex usecases. Which production technologies are mature enough to utilize? What is their environmental impact? How does a certain technology affect the cost structure of the overall supply chain? How can distribution be organized efficiently? How broad are the usecases a certain supply chain can satisfy? Are these usecases economically viable in the overall context to support the necessary investment? Obviously, the list of these questions is almost inexhaustible and the formulation of answers would clearly exceed the limits of this thesis. Due to this, the context will be limited both from the perspective of the hydrogen fuel production as well as the utilization to a very specific application in the Austrian market.

When thinking about carbon-dioxide emissions and air pollution in general, recent public awareness has been drawn to the transportation industry as one of the big industry segments currently relying on fossil fuels as an energy source. This focus has been created from two sides: at one hand due to scandals around emission regulations and on the other hand a technological advancement, namely that of electric propulsion of vehicles, relying on large batteries for storing electric energy. The latter development is having two distinct effects: first, the public mindset is now aware, that liveable alternatives for fossil fuel propulsion exist, second, it has drawn a light on the complexity of all such alternatives, in the form of questions raised in terms of the environmental sustainability of battery production for electric vehicles as well as the capacities of the electrical infrastructure to support a large-scale shift towards battery-electric propulsion. As such, the questions raised with regards to hydrogen as a fuel alternative for the transportation sector can be very well related to the questions raised towards battery-electric propulsion, when assessing them over the complete supply chain.

Consequently, the above relation will serve as a context for this thesis, with the purpose of studying hydrogen as a fuel alternative for transportation in the Austrian market. Due to the fact, that the demand side, specifically hydrogen fuel driven vehicles already exist and large-scale production of hydrogen for industries different from the transportation sector is available as well, the thesis will further focus on the possibility of decentralized, small-scale production of hydrogen fuel. Such decentralized production plants might be a viable option for bridging the challenge of the basic requirement of hydrogen fuel availability, both in terms of production as well as distribution, creating a well defined problem statement for this thesis.

1.2 Outline of the thesis

Based on the previous section, the problem statement for this thesis can be formulated as follows: are decentralized, small-scale production plants for hydrogen fuel a viable option for supplying at least certain segments of the transportation sector in Austria? This main problem statement can now further be split in smaller, more specific questions to be answered. First, the available technologies for hydrogen fuel production and the demand in the transportation sector need to be assessed. Here a generic overview will be given in Chapter 2, setting the context on the higher level of hydrogen economy.

Following the general introduction, the main problem statement regarding the viability of small-scale production plants for hydrogen fuel in Austria is broken down in Chapter 3 into smaller aspects and examined from different perspectives.

The goal is to find the main driving factors influencing the viability question, while also mapping out possible interconnecting effects. These factors will be assessed under the aspects of market demand, competition and cost structures while focusing on following questions: What is a main driver of a potential market demand of hydrogen fuel in general and how is this affected by competing technologies in the transportation segment? What effect can regulatory aspects have on this demand? How is the overall supporting infrastructure of the transportation industry affected by the aforementioned questions? How is the competitive setup for hydrogen fuel production in terms of technology and distribution? What is the cost structure both in terms of capital and operational expenditures for hydrogen fuel production systems suitable for decentralized production?

After having mapped out the problem space and finding the most relevant driving factors in Chapter 3, Chapter 4 is focusing on deriving realistic scenarios and future projections with concrete numeric values for each of these variables. The basis for this assessment are third-party expert studies, complemented by own research and assumptions specific to the Austrian market where deemed necessary.

Core part of this thesis is Chapter 5, where numeric modelling of hydrogen fuel production plants is carried out for different plant configurations and target usecases. Modelling is split into stages, first defining a generic operational model and exercising it for finding operationally feasible configurations. After this, the generic model is extended towards a full investment viability model, whereas the previously found operationally feasible setups are further examined with regards to their overall economic viability. As a result, the net present value of the respective investment is presented and used for stating the economic viability of the given plant configuration.

Finally, Chapter 6 summarizes the findings of this thesis and provides an overall conclusion on the economic viability of decentralized hydrogen fuel production in the Austrian market. Additionally, an outlook on further topics to be studied in this field is given.

2 Introduction to the hydrogen economy

> *The idea of a 'hydrogen economy', in which that light, combustible gas would be the main source of energy, has been around for several decades. It was dreamed up by people who wondered what would happen when the oil ran out. In the way of predictions about the future, those peo-*

ple tended to extrapolate from the present. Hydrogen (probably made by splitting water using electricity from huge nuclear power stations) would be used in much the same way that petrol and its cousins are: burned in engines." [3]

The above quote from an article in *The Economist* from 1997 is a very good example how much potential is attributed to hydrogen as a global and flexible source and carrier of energy. A short account of how this potential has been built up throughout the years and its current implications will be introduced in the course of this section, while concluding with its relevance with regards to the topic of this thesis.

2.1 History of hydrogen and its applications

The discovery of the element hydrogen in 1766 by British scientist Lord Henry Cavendish and his realization that burning hydrogen (H_2) and oxygen (O) results in releasing heat and creating pure water without further emission of by-products first led to the scientific acknowledgement of the importance of hydrogen, leading to further research in this field. Further notable discoveries are firstly related to the production of hydrogen through electrolysis: in 1800 William Nicholson and Sir Anthony Carlisle have shown, that by applying electric current to water it can be split into hydrogen and oxygen. Secondly, 1839 Sir William Grove was able to reverse this process and induce an electric current by combining hydrogen and oxygen in a very simple and early version of the hydrogen fuel cell, allowing for the concept of a full hydrogen-based energy cycle where hydrogen can be produced using widely available electricity, stored in its gaseous or liquid form and utilized in versatile ways where electric energy is needed. In 1909, German scientist Fritz Haber discovered the procedure of synthesizing ammonia - used as fertilizer and base material for explosives - from hydrogen, earning him the Nobel prize in 1918. Apart from such industrial applications in chemical processes for agricultural and military needs, further significant application for hydrogen would have been lighting and heating, with some more extraordinary usecases like airships, abruptly ending with the demise of the Hindenburg in 1937, where hydrogen has been used as the filling gas for creating the necessary uplift of the airship. Although different applications of hydrogen have been established in the past, the boom of the oil industry catered for the resource needs in transportation and energy systems, leading to the restricted role of hydrogen to the chemical industry so far.[12]

Currently, more than 40 million tonnes of hydrogen are produced globally by various processes, while mostly relying on fossil resources as hydrogen production feedstock: 48 % natural gas, 30 % oil and by-product recovery of refinery and other chemical processes, 18 % coal, 4 % electrolysis. On the consumption side 40 % of the produced amount is used in refineries, 40 % for other non-refinery related chemical processes and the remaining 20 % for other uses.[11] This breakdown shows, that throughout the last century of oil-based economy both the production and consumption of hydrogen has been limited to very specific usecases, not related to energy and transportation systems.

2.2 Introduction to hydrogen production and distribution

As hydrogen can be produced by different processes while relying on various primary energy carriers as fossil fuels, electricity from nuclear or renewable sources and as the by-product of chemical processes, it creates versatile options for the application in energy and transportation systems. If we consider hydrogen harvesting as by-product from chemical processes as a non-scalable option for both large-scale and decentralized production, three major pathways for hydrogen production remain.[11]

Steam-methane reforming (SMR) Hydrogen is produced by reacting methane from natural gas (or biogas from biomass) with high-temperature water-steam on a nickel catalyst. As the process is based on methane, the output of the process will yield carbon-dioxide (CO_2), making this process non-CO_2 neutral in case the emitted CO_2 is not captured and stored by a technology called CO_2 capture and storage (CCS). During CCS, CO_2 produced in any chemical process is captured, pressurized and stored in underground chambers, usually in suitable geological structures of depleted natural gas wells, indefinitely. Currently, SMR is used in all major large-scale hydrogen production facilities, albeit without applying CCS.

Coal gasification (CG) Very similar technique to SMR, with the difference of using coal as an input resource for producing a hydrogen, methane and CO_2 gas mixture. As such, this technology can by used as a primary stage for SMR for producing methane, with the challenge of overall process efficiency and the separation of the resulting gases, resulting in a more expensive process than SMR. Again, the resulting CO_2 needs to be captured in order to achieve a carbon-neutral H_2 production.

Water electrolysis As discovered by 1800 William Nicholson and Sir Anthony Carlisle, water can be split in its elements oxygen and hydrogen by applying an electric current, creating a versatile option for hydrogen production due to the flexible availability of electricity and the possibility of a carbon-neutral production in case the electricity itself is generated by renewable technologies, making water electrolysis the most promising technology for decentralized hydrogen production. As the simple splitting of water on metallic electrodes results in an explosive gas mixture of hydrogen and oxygen, current electrolysis systems focus on technologies where the two gases are inherently separated during the process.

As hydrogen is a highly volatile gas, its storage and distribution poses significant challenges compared to liquid fossil fuels or even natural gas. Storage is possible either in the gaseous form at 350 - 700 bar, compared to 200 - 250 bar of compressed natural gas or in liquid form at a temperature of -253°C. This results in further considerable costs during hydrogen production, both in terms of the required fixed costs for a complex storage system as well as the variable costs of the additional energy feedstock for achieving the required compression or cooling.[11]

In case of centrally produced hydrogen, the transportation can either happen by transporting the gaseous or liquid storage tank by truck or train to the required location, or by pipeline. Although different options are available, the challenge of hydrogen distribution is obvious from the following OECD finding:

> *"In comparison with natural gas, hydrogen pipelines are twice as expensive in terms of investment cost and require five times more energy."* [11]

Based on the above, the utilization of hydrogen with up to 10 % concentration in the existing distribution pipelines for natural gas also seems a feasible option. As such, production of pure hydrogen would not necessarily be a requirement, while having a de-carbonizing effect in the energy supply for homes and industry sites, yet again opening up wider adoption and production as a global, primary energy carrier.[9]

2.3 Hydrogen in the transportation industry

Currently, the transportation industry is dominated by propulsion technologies relying on fossil fuels as gasoline, diesel and natural gas. These are burned in internal combustion engines (ICE), converting the chemical energy of the fuel to mechanical propulsion and emitting the end-products of the combustion process, mainly water steam, carbon dioxide and some noxious gases. Due to these local emissions, policy makers and society have pushed for technologies with firstly lower local emissions of harmful materials and secondly a general reduction of CO_2 emission of the transportation industry for fighting global climate change. Due to this, two new propulsion technologies are gaining popularity in later years:

Plug-In Hybrid Vehicle (PHEV) being a hybrid, such a plug-in hybrid vehicle utilizes both an internal combustion engine and an electric drive for vehicle propulsion. The rationale behind the setup is the following: as most of the vehicles do not travel more than 60 km a day, a moderately powerful electric drive with a comparably small traction battery is able to cater for a high percentage of daily drives. As the traction battery can be charged externally, locally emission-free mobility can be achieved under the design limitation of maximal daily mileage and reduced propulsion power. Flexibility of operation is ensured by the internal combustion engine, as longer trips or driving situations with a higher propulsion power need are supported based on fossil fuel combustion on demand.

Battery-Electric Vehicle (BEV) opposed to a PHEV, a battery-electric vehicle is only equipped with an electric drive, which is powerful enough to handle all driving situations. In addition, the traction battery is able to store substantially more electric energy compared to a PHEV, providing driving ranges between 120 - 450 km for currently available models. Uptake of this technology is currently restrained by the limited availability of charging infrastructure and the duration of the charging process, as well as the costs of the large battery, while also raising increasing concerns about the environmental friendliness of the production and recycling process of the latter.

Clearly, both of the above technologies have distinct advantages and disadvantages in terms of local and global emissions, flexibility of technology, duration of refuelling or recharging and the overall environmental footprint. Under these circumstances, hydrogen fuel-cells are increasingly investigated for the propulsion of vehicles, leading to the fourth vehicle category based on propulsion technology: the fuel-cell electric vehicle (FCEV). From the standpoint of the drivetrain, a FCEV utilizes a fully electric drive, but instead of drawing the necessary electric energy from an on-board battery, the electricity is generated by a hydrogen fuel-cell. The fuel-cell itself is then supplied by the on-board hydrogen tank, which provides the advantage of being able to be refilled as fast as a conventional gasoline or diesel vehicle, while having the same properties in terms of local emissions as a BEV. On the other hand, the availability and accessibility of hydrogen refuelling infrastructure is lacking, thus limiting both the development and the uptake of FCEV-s.[2]

Based on the above, addressing the challenge of hydrogen refuelling availability and accessibility is a key question not only from the perspective of the adoption of FCEV-s, but also as a determining factor for establishing a hydrogen economy not limited to certain industries, with hydrogen being the next generation fuel after coal and oil globally. As the application of hydrogen as a fuel is imminent in the transportation industry – where it would pose as an important additional pillar of hydrogen economy – with a well-defined problem statement, namely the availability of hydrogen fuelling and the applicable solution options, namely central production and distribution of hydrogen fuel or decentralized production, this thesis will focus on determining the feasibility of decentralized water electrolysis systems when considering conditions specific to the Austrian market. For this purpose, this thesis is structured as follows: first the influencing factors and parameters for decentralized electrolysis systems need to be defined, while also establishing the priority of the same in the given complex problem set. As a next step, reasonable projections are necessary for creating modelable scenarios in order to be able to perform techno-economic calculations on the feasibility for different decentralized hydrogen production plants.

2.4 Status quo of hydrogen as a fuel in Austria

Being an emerging field of application, data on hydrogen fuel production specifically for Austria is scarce. Thus, establishing the status quo can only be based on the current market demand perspective, which is firmly assessable through the vehicle statistics of the governmental statistics office, Statistics Austria as shown in Table 1[1]. Overall, 3 different FCEV passenger car models are available in Austria, while all of them are exceeding the average Austrian capital expenditure on their respective vehicle segment.

	2014	2015	2016	2017	2018	Q1 2019
Absolute number of FCEV-s	3	6	13	19	24	31
Year-on-year growth	-	50 %	54 %	32 %	21 %	23 %
Absolute number of BEV-s	3386	5032	9073	14618	20831	23958
Year-on-year growth	63 %	33 %	45 %	38 %	30 %	38 %

Table 1: Historic numbers and growth rates of FCEV-s and BEV-s in Austria

Comparing both the absolute numbers and the growth rates to those of battery-electric vehicles, it becomes obvious that the market of FCEV-s in Austria is still in its initial pioneering stage. On the other hand, due to the assumed similarities with the market development of BEV-s, a considerable growth for FCEV-s can be

[1]Data retrieved from `http://www.statistik.at` on 16.06.2019

expected in case the the current cost and infrastructure barriers are breached. In addition, this assessment affects all projections to the future, as those can not be based on firm historic developments and thus are even more prone to extensive uncertainties than usual.

In terms of production capacities of hydrogen fuel in Austria, no firm number could be retrieved on the overall Austrian industry. Based on information from the Austrian Mineral Oil Administration (OMV), their refinery in Schwechat is producing 50 000 tones of hydrogen annually. This amount is mainly attributed to general oil refinery processes, where hydrogen is released as a by-product of chemical reactions. A smaller portion is produced by steam-methane reforming of natural gas, while also having established a research plant with the nominal power of 100 kW for producing hydrogen by electrolysis powered by solar electricity. As such, this research plant can be recognized as the only Austrian industrial plant with the nominal power in the range applicable to decentralized, small-scale hydrogen production plants based on water electrolysis.[1]

Distribution of the hydrogen fuel produced in the OMV Schwechat refinery is handled by gaseous truck transports to hydrogen fuelling stations. OMV is maintaining 5 hydrogen fuelling stations in Austria, namely in Vienna, Wiener Neudorf, Graz, Asten by Linz and Innsbruck, thus having one station in the vicinity of almost all major Austrian cities with the hydrogen storage capacity sufficient to refill 60 FCEV-s each. In order to relate this, according to the ÖAMTC, 186 fuelling stations in Austria are providing natural gas as vehicle fuel for the roughly 25 000 natural gas driven vehicles in the country, leading to the conclusion that the Austrian hydrogen fuelling infrastructure would not be able to sustain a large increase of FCEV-s in its current state. The German subsidiary of OMV is participating in the H2 Mobility initiative and maintaining 6 hydrogen fuelling stations across Germany, whereas no data could be found about the source of the German hydrogen supplies.[1]

3 Driving factors of decentralized H_2 electrolysis systems

This chapter defines the driving factors of small-scale decentralized H_2 electrolysis systems on following dimensions: market demand factors, competition and market share factors and factors influencing operational and capital expenses. In order to give a comprehensive view along these dimensions, all factors will be discussed in detail, also showing wider effect chains and possible cross-effects between the above factors. An overall aim on the other hand is to only define the critical core factors for further evaluation, thus resulting in a manageable number of driving parameters in the feasibility calculations to come. This will also be achieved by discussing the above-mentioned effect chains and pinpointing the central element in the chain.

3.1 Market demand factors

Obviously, the need of H_2 electrolysis systems only arises, if there is a substantial need for H_2 on the market. Assuming an individual feasibility of a single decentralized H_2 electrolysis system, the overall deployable number of such systems - the market demand - will determine if these will be developed as a product. Currently, this substantial need may emerge with the spread of Fuel-Cell Electric Vehicles (FCEV) which would need a tightly knot net of H_2 fuelling stations similar to those supplying fossil fuels. Disregarding any other possible future systems consuming H_2, we can already conclude that the number of FCEV-s and H_2 fuelling stations at any given year are considerable driving factors for the market demand for decentralized H_2 electrolysis systems on a macro-level. An additional effect by which the number of FCEV-s will have a considerable impact on the the feasibility of small-scale hydrogen electrolysis systems is the cost of H_2 fuel. As the number of such vehicles rises, the demand for hydrogen fuel will rise, thus in turn making investments in large-scale production of hydrogen viable, decreasing the price of H_2 fuel due to economies of scale. This leads to the fact, that the change in number of FCEV-s can have both supporting and hindering effects on decentralized H_2 electrolysis systems.

In order to be able to project the spread of FCEV-s in the market, we first need match the capabilities and advantages against other propulsion technologies. As of today, these competing technologies are the following: conventional Internal Combustion Engine (ICE) vehicles, Plug-In Hybrid-Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV). As all of these technologies have certain implicit advantages and disadvantages, it is useful to distinguish depending on the particular usage of the vehicle and a balanced mix of car segments. For instance, it can be easily assumed, that the segment of small cars and any users mainly using their car in the city could be well served by BEV-s only. On the other hand, the larger the vehicle and the longer the driving range to be achieved, the more advantages arise from utilizing either a conventional ICE vehicle, a FCEV or a PHEV.[14]

The uptake of the new propulsion technologies - both electric and hydrogen-based - is largely depending on the infrastructure needed to sustain a widespread amount of vehicles with these technologies. Although electricity is commonly available throughout Europe, the electricity infrastructure is very much on the edge of its capacity, requiring substantial investments to sustain a large-scale electric mobility.

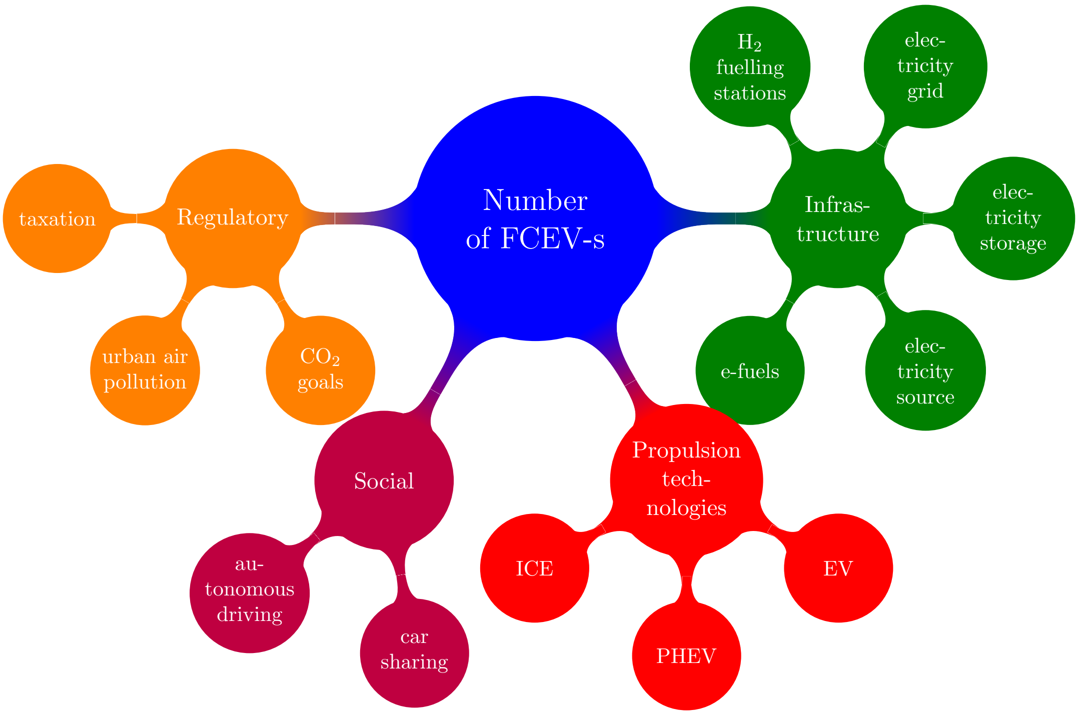

Figure 1: Map of market demand factors

Additionally, there is no efficient method for substantially storing electric energy, especially when it comes to the utilization of volatile renewable energy as solar- and wind power. Storing renewable electric energy would on the other hand be possible by hydrogen electrolysis and in the second step by methanization of hydrogen to fossil fuel substitutes, also known as synthetic fuels or e-fuels.[2] Such a development would both promote FCEV-s as well as benefit conventional ICE vehicles and PHEV-s to remain on the market against BEV-s, as the first stage of the process would provide pure hydrogen fuel, while the second stage would convert the hydrogen fuel to a fossil fuel substitute, allowing for flexible balancing between the fuel demands of FCEV-s and vehicles with combustion engines.

Besides the technological and infrastructure related driving factors social and regulatory drivers can play an important role in the market demand of different mobility technologies. Both expert reports from the FCH JU[14] and the ÖAMTC[2] assume an unchanged mobility behaviour of the society, although there are clear drivers of change in this regards due to the spread of car-sharing services, especially in the urban environment and the very likely deployment of autonomous driving technologies in the following decades. Both car sharing and autonomous driving technologies would support a change from individual vehicle ownership towards mobility as a service, leading to a reduction in the overall number of vehicles and the consolidation of the supporting infrastructure.[4] Regulatory wise, different aspects of environmental protection goals, especially the reduction of CO_2 emissions and local air pollution in cities, can drive the uptake of alternative propulsion technologies against ICE vehicles. On the other hand it is also to be considered, how a potential decline of tax revenues currently realized by the heavy taxation of fossil fuels for ICE vehicles would affect government's budgets, what alternative revenue streams could be introduced instead and how these would affect both the number of vehicles in use and the mobility behaviour.[2]

When focusing on the market demand for small-scale decentralized H_2 electrolysis systems for producing hydrogen fuel for FCEV-s, Figure 1 shows the various factors which can come in to consideration. Ultimately, the number of FCEV-s can be defined as a common ground for all other elements, as this parameter is the one affected by each of the branches individually. Thus, the number of FCEV-s will be taken as the parameter representing the market demand in the following sections.

3.2 Competition and market share factors

On a broad scale, competition for small-scale decentralized H_2 electrolysis systems are all other energy and fuel types which can be used to propel vehicles. As the fuel type is usually a defining attribute of a vehicle and the different types of propulsion systems have already been discussed in section 3.1, this section will only focus on competitive systems utilizing H_2 as an energy storage medium. Based on the assessment of FCH JU[14], there are 3 major pathways for H_2 production: steam methane reforming (SMR), water electrolysis and coal gasification. Additionally, hydrogen is the basis for the production of synthetic fuels, thus the deployment of synthetic fuels for the continued powering of ICE vehicles and PHEV-s would also pose as a direct competition to pure hydrogen fuel.

From the above technologies for hydrogen production, SMR and coal gasification are regarded as being only feasible for large-scale H_2 production, based on the scalability, overhead system costs and infrastructure for an efficient operation. Water electrolysis on the other hand is easier to scale, requires only water and electricity as an input and depending on the utilized electrolyzer stack technology can output the produced hydrogen gas at pressures which are more suitable for direct usage in a pressurized H_2 storage tank.[5] This makes water electrolyzer systems the only technology suitable for both large-scale centralized and small-scale decentralized operation. Based on this, the main competition factor will be the cost of large-scale hydrogen when delivered to H_2 fuelling stations versus the cost of small-scale, decentralized H_2 production based on water electrolysis, deployed either at H_2 fuelling stations or even on a smaller scale at company sites or households. When consider-

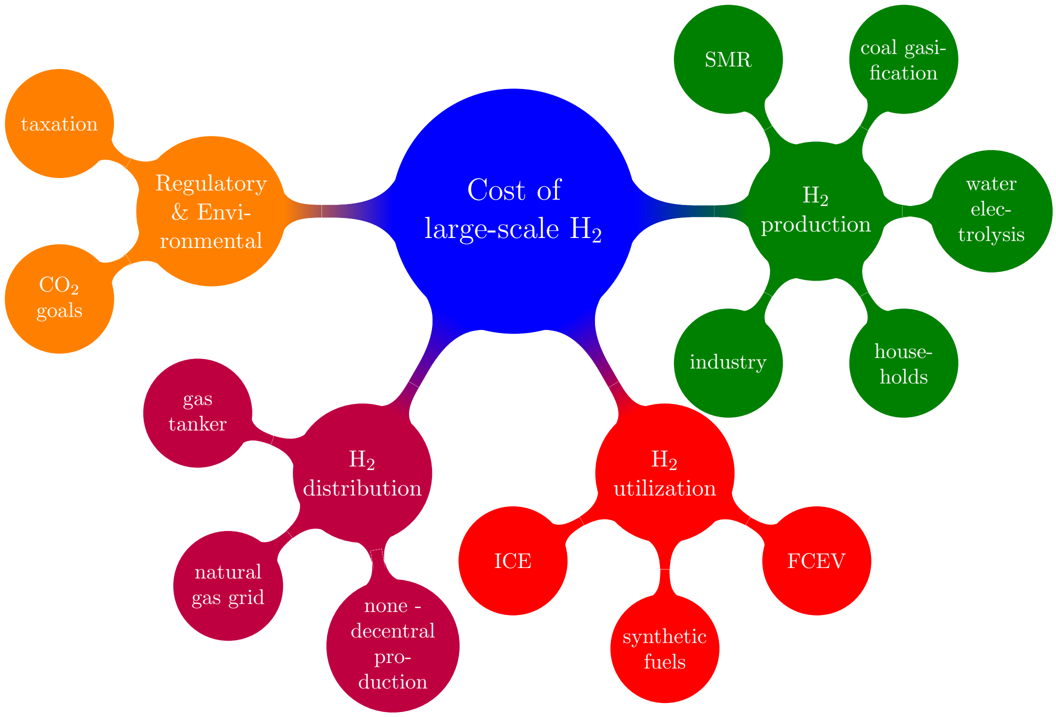

Figure 2: Map of competition and market share factors

ing a central production versus a decentralized production based on the same core technology, the main difference in terms of economic feasibility will be the transportation and infrastructure overheads compared to the efficiency gains in terms of economies of scale. In case the cost of transportation and infrastructure (e.g. storage and pipelines for hydrogen fuel) outweigh or at least level out the effects of scale in central production, decentralized systems can gain advantage on the long-term.

As centrally produced hydrogen needs to be transported to the consumers, both the technologies and the costs for H_2 transport needs to be considered, when assessing the competitiveness of decentralized production. For the case of hydrogen fuelling stations, this would most commonly be achieved with gas tanker trucks, similarly to the distribution of conventional fuels, with the difference being the density of the transported medium: hydrogen in gaseous or liquid form compared to fossil fuels. When assuming the same transportable volume per truck, this difference in the density of the transported medium can render individual truck-based transport inefficient, leading to the demand for a hydrogen pipeline infrastructure for efficient distribution, with considerable further investment requirements for the large-scale hydrogen production industry. This makes the transportation and infrastructure costs for H_2 fuel distribution an especially important factor, when thinking about the alternative of introducing hydrogen gas in the already widely available natural gas networks for the utilization in households and the industry for heating purposes instead of dispensing at hydrogen fuelling stations.[9]

When considering the above technologies, it is also worth to mention their attributes regarding CO_2 emissions. Although SMR is regarded as the most cost-efficient technology for large-scale hydrogen production, both SMR and coal gasification takes fossil or otherwise carbonated energy sources as an input, thus can not serve the goal of producing CO_2-neutral hydrogen fuels. This would also be the case for the production of e-fuels based on these technologies. As there are regulatory aims to drive the energy industry towards the reduction of CO_2 emissions, environmental policy making and taxation of CO_2-emitting technologies can play a major role in the competitiveness of water electrolysis systems compared to other technologies.

All the above factors regarding competitive technologies and utilizations, as well as the possible market shares of the these, directly effect the cost of large-scale H_2 when delivered at hydrogen fuelling stations. Thus, this parameter will be taken as an aggregated factor of competition and market share effects when considering feasibility scenarios for small-scale, decentralized production of hydrogen.

3.3 Factors influencing capital expenditure

The capital expenditure for setting up a small-scale water electrolyzer for producing hydrogen is considered as a key factor for the economic feasibility of such a systems. Being a technology on the way to gather widespread traction, effects of economies of scale and learning curves needs to be additionally assessed to the fixed costs of certain key components making up the bill of materials (BoM) of the system at any given point in time.

One of the key components of any water electrolyzer system is the electrolyzer cell stack, comprised of numerous single cells, where one cell is the atomic component responsible for splitting water into hydrogen and oxygen. This property allows for a flexible scaling of the electrolyzer system size, as the number of cells in the cell stack correspond to the overall hydrogen production capacity and the required input power of the system. Three different technologies can be utilized as a cell stack: alkaline electrolysis cells (AEC), proton exchange membrane electrolysis cells (PEMEC) and solid oxide electrolysis cells (SOEC). All of these technologies have a similar working principle, where the electrodes of the cell are surrounded by an electrolyte and divided by a membrane leading to a separation of the product gases hydrogen and oxygen. The difference lies in the combination and type of electrolyte and membrane materials, consequently affecting overall system properties. Maturity, efficiency, scalability, lifetime and as well as operational costs of these technologies

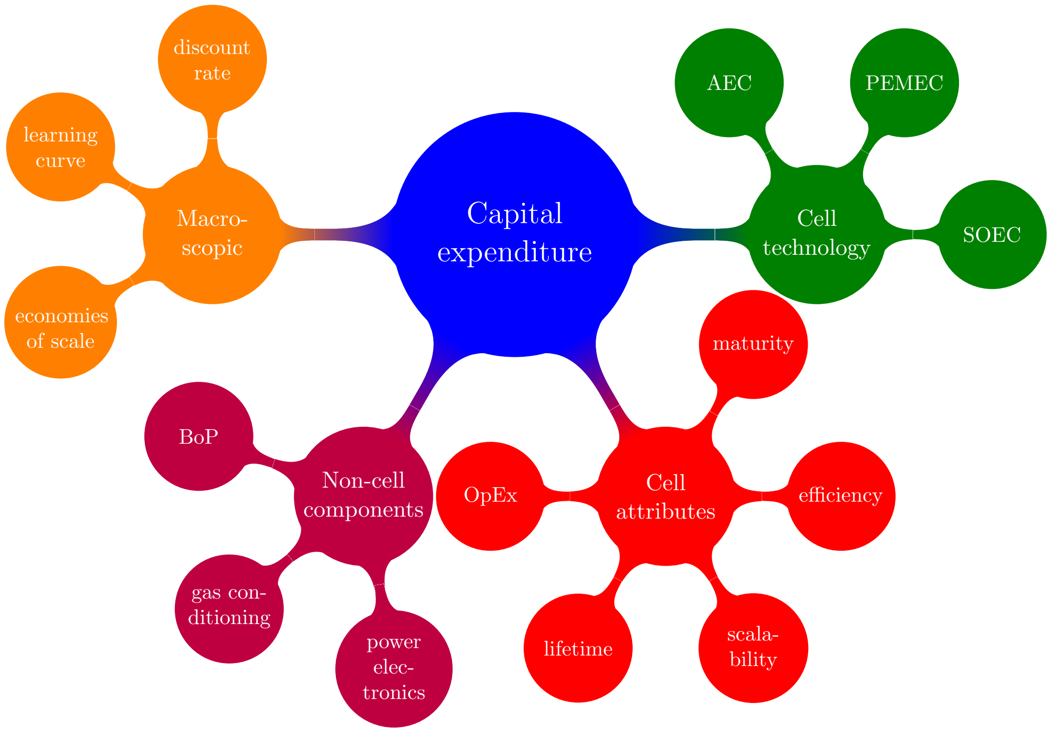

Figure 3: Map of CapEx factors

are different, resulting in different capital expenditure when applied in a small-scale electrolysis system. Although the cell stack makes up the greatest part of the overall capital cost of the electrolysis system, the cost of power electronics, gas conditioning components as driers, purifiers and compressors, as well as the balance of plant (BoP), consisting of supporting components like pipes, tanks, fittings and supporting parts need to be considered.[16, 8, 5]

Based on the above, the assessment of the capital expenditure needs to take into account the suitability of an electrolysis stack technology for small-scale operation, assess the cost proportion of cell stack and non-cell stack components of the BoM for the chosen system size and assess effects of learning curves and economies of scales during the addressed scenario periods.

3.4 Factors influencing operational expenditure

Operational expenditure for an electrolysis system consists of the cost of electricity, water and any maintenance and warranty costs, whereas the latter can be correlated to the maturity of the underlying cell stack technology and its robustness. The water costs are usually fixed on the installed location of the system.

When considering the price of the electricity used, the flexibility of pricing is a key issue for the operation of an electrolysis system. In Austria, households can only

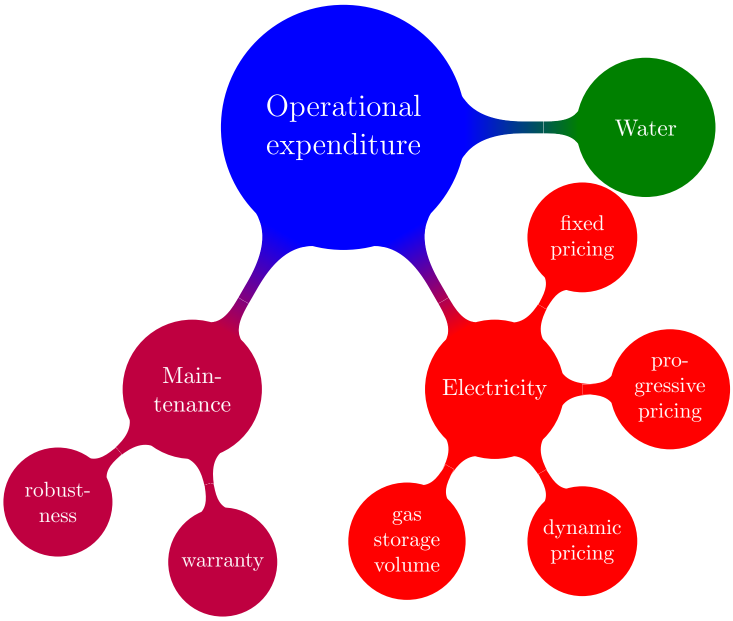

Figure 4: Map of OpEx factors

obtain electricity for a fixed price per kWh, which does not allow for operational optimization of any electric load to times of low electricity prices. Progressive pricing models, where the costs per kWh rise when breaching certain annual consumption thresholds do not allow for dynamic operation either, while additionally limiting the efficient operational range, as an extensive usage is penalized. Different time-variable or dynamic pricing models of electricity on the other hand can effectively enhance the feasibility of a water electrolysis system, by shifting its operation to times with low electricity costs. This capability is only limited by the maximum hydrogen gas storage volume of the system and the rate of hydrogen usage.

3.5 Summary of key driving factors

Based on the above, we can conclude the factors detailed below can be considered as the key drivers for the viability of decentralized hydrogen fuel production plants. In addition, main cross-effects between these factors also have been mapped out in the previous sections, thus these main factors and their correlation is additionally represented in Figure 5.

Market demand of hydrogen fuel in the transportation industry in a macroscopic perspective can be derived from the number of deployed FCEV-s. As such, this factor drives both the demand for hydrogen fuel, thus its price, as well as the potential demand for decentralized H_2 plants.

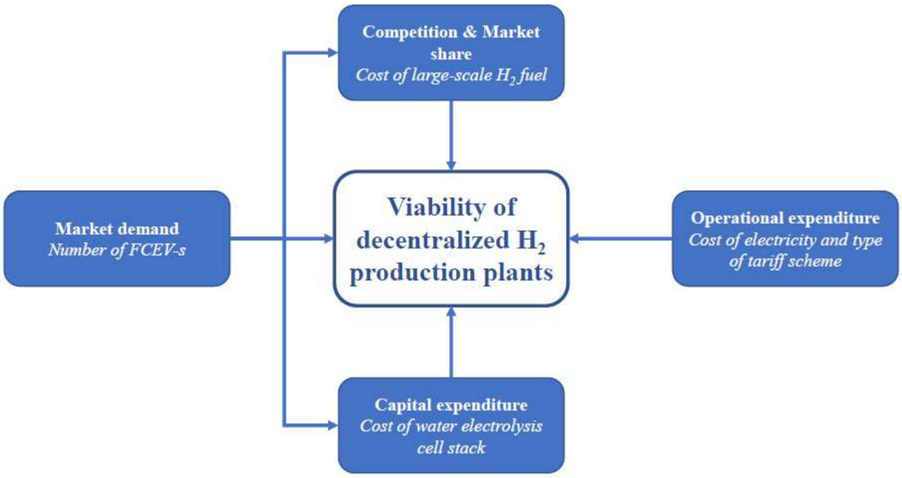

Figure 5: Map of main driving factors and their correlation for decentralized H_2 production

Competition and market share for decentralized hydrogen fuel plants is obviously large-scale production, more specifically in terms of cost and availability, which on the other hand are driven by the market demand. Competitive advantage of decentralized production can be realized through benefits in terms of cost and efficiency of distribution and possible regulatory effects in case subsidized environmental friendly technologies can be better utilized for the decentralized systems.

Capital expenditure of H_2 production in decentralized plants is driven by the cost of the chosen electrolysis cell stack. A reduction of the required capital expenditure based on economies of scale and learning curves is achievable based on the market demand for such systems, enforcing the importance of that factor.

Operational expenditure during water electrolysis for hydrogen production is mainly affected by the cost of electricity and the electricity tariff scheme (fixed, staged, based on market spot-price).

In the next chapter, more detailed projections and scenarios will be derived around these key driving factors in order to allow subsequent quantitative modelling.

4 Scenario projections of economic driving factors

Based on the economic driving factors defined in Chapter 3, different realistic scenario projections are created in which the feasibility of small-scale decentralized H_2 electrolysis systems will be studied in Chapter 5. For all scenario cases, both the data as well as the justification of the scenario itself will be reflected on projections from relevant third-party studies. As the variety of the economic driving factors with all of their sub-elements would create a far too complex system for feasibility modelling and some of these elements are not even quantifiable as a single independent variable, a prudent simplification is needed in order to create a meaningful scenario set with a reasonable combination of different variables. By using the mind-map figures (Figures 1-4) as a guidance, a set of the most representative scenarios can be condensed covering a realistic projection set based on different resources and a wide array of economic driving factors. The aim is to create one variable for each of the 4 identified main driving factors, which can be quantified based on data from third-party studies, while the remaining sub-factors are considered as influencing variables of these main variables as part of the formulation of scenario justification in a non-numerical way. As a result, the scenarios are expected to define realistic limits for the feasibility model, whereas it is worthy to note that the underlying feasibility model could be also used to find future feasible scenarios outside of these limits.

4.1 Scenarios for FCEV deployment

For the market demand factor of small-scale decentralized H_2 electrolysis systems the number of deployed FCEV-s is the variable where ample data is available, creating a good basis for scenario building, as this variable directly correlates with the market need in terms of number of deployable decentralized hydrogen fuel production plants as well as the driving variable for the cost of centrally produced H_2 fuel when dispensed at fuelling stations. Both expert reports from the FCH JU[14] and the ÖAMTC[2] propose projections on the composition of newly deployed passenger vehicles, while assuming a relatively unchanged mobility behaviour on the social dimension of the driving factor.

4.1.1 EU-scale FCEV scenario based on FCH JU study

Figure 6 shows the projected FCEV deployment scenario by 2050 on an EU-wide scale by FCH JU. Although the projected base number of 100 000 FCEV-s by end of 2015 has not been confirmed as of end-2017 by the IEA[13], the prognoses as per newly registered vehicle percentages can still give representative projections as follows:

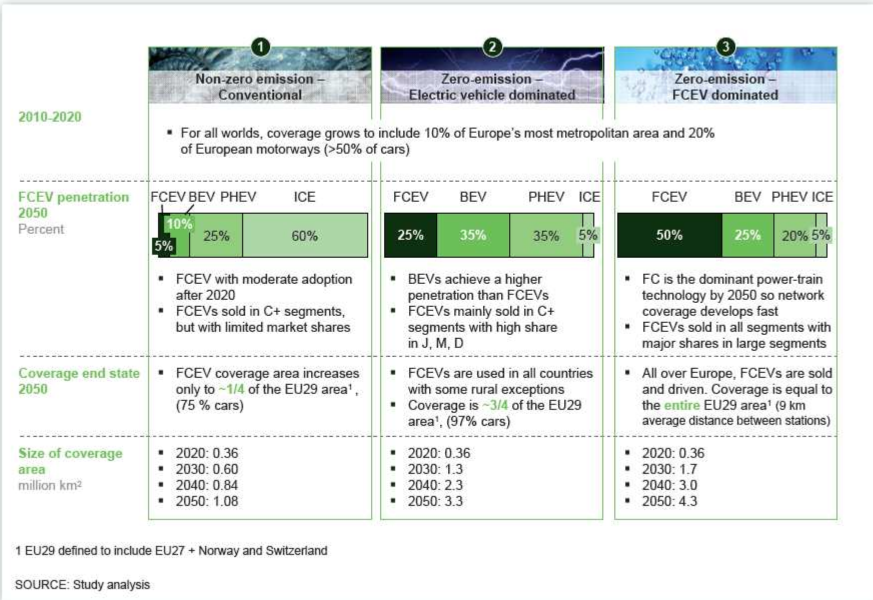

Figure 6: EU-scale FCEV scenarios, source: FCH JU[14]

Prognosis 1 Conventional propulsion engines still have dominant market share (60 % ICE and 25 % PHEV) due to low prices of conventional fuels (or alternatives) with no regulatory incentives for alternative propulsion technologies. Consequently, the infrastructure coverage for large-scale hydrogen production and H_2 fuelling station remains low and FCEV-s are only competitive in the large passenger car and transportation segments, albeit with a penetration rate of only 5 %.

Prognosis 2 A realistically balanced prognosis, with high BEV penetration especially for the urban and small vehicle segment (overall 35 %), while the medium and especially large vehicle segments experience an uptake of FCEV-s up to 25 % and the remaining vehicles mainly consist of PHEV-s (overall 35 %) and a marginal pure combustion engine segment. In this prognosis a fairly wide adoption of hydrogen fuelling infrastructure with an EU area coverage of 75 % is assumed suitably covering the needs of 97 % of all FCEV-s. This prognosis also assumes the continuation of the current regulatory trend, where conventional propulsion is slowly pushed out of the market due to environment protection policies, mainly in the form of driving restrictions, pollution taxation schemes and parallel incentives for alternative propulsion.

Prognosis 3 An FCEV-dominant prognosis with 50 % of FCEV penetration. This case assumes both an aggressive regulatory push for alternative propulsion and some technological or infrastructural limits for BEV penetration for the small vehicle segments, which could arise from environmental considerations or supply shortages of large battery systems or limitations of the charging capacity due to an overload of the electricity grid with no possibilities for intermediate electric energy storage.

4.1.2 Austrian FCEV scenario based on ÖAMTC study

The more recent expert mobility study conducted by the ÖAMTC[2] for the Austrian market and accounting for Austrian regulatory assumptions outlines a similar scenario set to the FCH JU study, with a detailed composition of propulsion technologies of newly registered vehicles as shown in Figure 7.

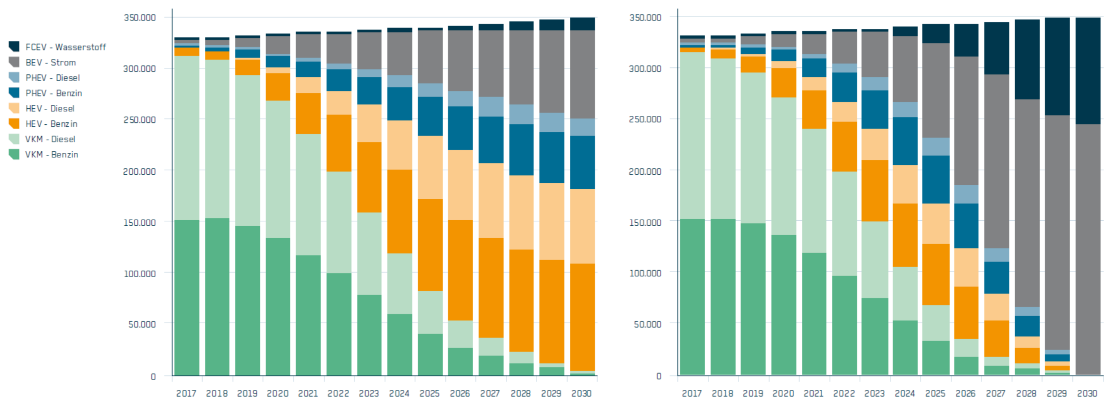

Figure 7: Prognosis: number of newly registered vehicles / year in Austria, grouped by propulsion technology, source: ÖAMTC[2]

Scenario 1 Projection of the current regulatory incentives until 2030, where BEV-s are promoted and ICE-s are not directly banned but taxed according to their pollution class, giving rise to hybrid propulsion technologies. Based on the strong competition of concurring propulsion technologies and the fact, that only a very limited H_2 fuelling infrastructure is available in Austria, registration of FCEV-s only accounts for 3 % of the annual Austrian vehicle market of 350 000 newly registered vehicles, accounting for overall 50 000 FCEV-s in 2030. Meanwhile, BEV-s will make up around 25 % of the market by 2030 with the remaining dominant share split between different hybridization technologies combined with diesel and gasoline combustion engines.

Scenario 2 The core assumption of this scenario is a total regulatory ban of combustion engines with 2030, including hybrid technologies paired to combustion engines. This scenario creates an aggressive shift towards BEV-s starting with 2023, splitting the Austrian market of newly registered vehicles purely between BEV-s and FCEV-s by 2030 with a ratio of 70 % to 30 % in favour of BEV-s. Thus, overall around 350 000 FCEV-s would run on Austrian roads by 2030. Similarly to the FCH JU study, the ÖAMTC also states concerns about the sustainability of such a rapid increase in BEV-s, mainly due to limitations of the electric infrastructure, including CO_2-neutral electricity production, opening the path for the uptake of FCEV-s.

As the Austrian target market has been chosen to be discussed in the course of this thesis, the above scenario set from the ÖAMTC study will be taken over as a representative scenario set for the forthcoming feasibility modelling of decentralized H_2 electrolysis systems. The corresponding low and high projection of the two abovementioned scenarios is presented in Figure 8 for the accumulated number of FCEV-s between 2020 and 2030, based on the year-by-year accumulated ÖAMTC study data for the projected number of newly registered FCEV-s as shown in Figure 7. As the demand for H_2 fuel will be driven by the accumulated number of FCEV-s, Figure 7 clearly shows how a potential change in regulation affecting the newly registered vehicle propulsion technologies can lead to an exponential increase of accumulated FCEV numbers, even when only assuming around 5 % of the newly registered vehicles as FCEV-s from year 2025.

4.2 Scenarios for large-scale H_2 fuel cost

As discussed in Section 3.2, different technologies exist for producing large-scale hydrogen fuel. The FCH JU[14] study gives ample insight in the economically feasible production mixes in two distinct prognoses, as detailed below. Furthermore, the effects and proportions of distribution costs in the overall hydrogen fuel price needs to be assessed.

Based on data from FCH JU[14], gaseous trucks are only able to transport around 10 % of hydrogen in mass units compared to liquid H_2 transport and less than 2 % compared to a fossil fuel transporter, making this type of transport considerably inefficient. As the liquification of H_2 is extremely energy intensive, the underlying

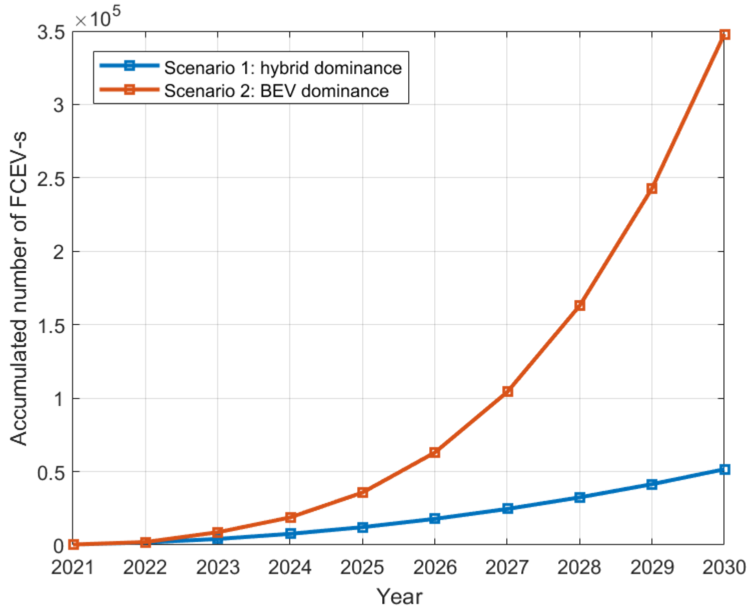

Figure 8: FCEV projection for the Austrian market, based on chosen scenario set

study suggests that by 2030, distribution of large-scale H_2 fuel will mainly take place over pipelines, requiring further capital investment.

In addition to any differences in the delivered price at a H_2 fuelling station, including transportation and infrastructure costs, the study does not consider taxation, neither in the form of a fuel-based tax common for fossil fuels, nor in the form of VAT. As the different production technologies have considerable differences not only in the cost of produced hydrogen, but in their CO_2 emissions as well, this assumption does not correctly account for the advantage of water electrolysis cells, which can be run completely CO_2-neutrally in case of utilization of renewable electricity only. This relation is shown in Figure 9.

A further point to note: the FCH JU study assumes widespread adoption of around 70 % of CO_2 capture and storage (CCS) systems, which would ensure CO_2-neutral operation of inherently non-CO_2-neutral SMR and coal gasification systems by capturing and storing the emitted CO_2 by-product in underground chambers instead of emitting it to the atmosphere. Although the technology itself is already practised in the oil and gas industry for storing natural gas, it is currently not adopted for large-scale hydrogen production systems and would require additional investments as also reflected in the higher cost of hydrogen produced by such systems in Figure 9.

Prognosis 1 Hydrogen is produced utilizing all available technologies and using both fossil fuels and renewable energy sources. In the adoption period of

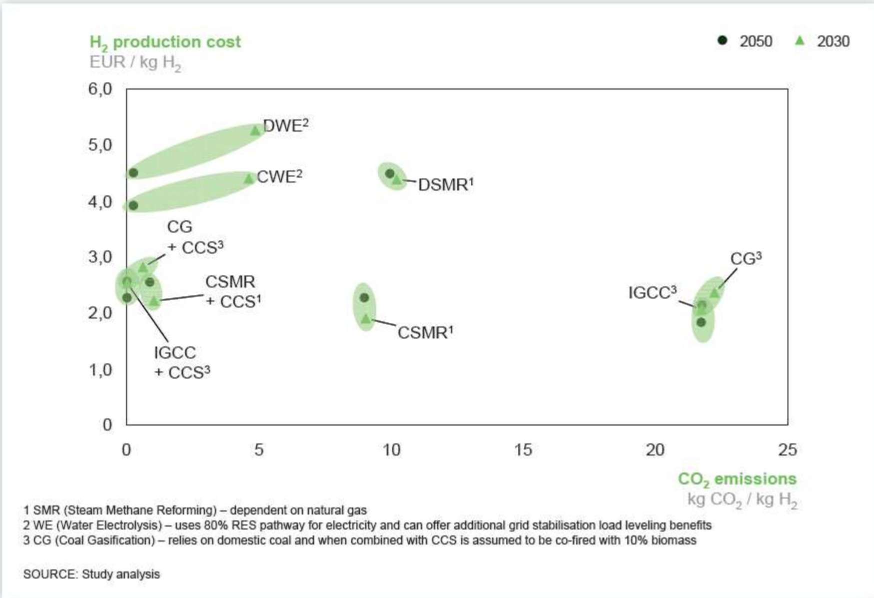

Figure 9: Cost of H_2 from different production technologies, source: FCH JU[14]

FCEV-s, a production relying mostly on SMR technology (70 %) without CCS is dominant, with the remaining 30 % produced by water electrolysis. As FCEV-s become more widespread and H_2 demand rises, coal gasification technologies take over 40 % of the production in combination with CCS, reducing SMR to 30 %. It is also assumed, that SMR plants will be continuously equipped with CCS to meet CO_2 targets. Due to the high ratio of cost-effective hydrogen production technologies, an average price of € 4.00 per kg H_2 is assumed by 2030 in this prognosis.

Prognosis 2 Only water electrolysis with 80 % renewable electricity is utilized for H_2 production, in a mix of centralized and decentralized production facilities, resulting in an average price of € 5.30 per kg H_2 by 2030.

For the purpose of this thesis, following adjustments will be made for the above scenarios in order to match the generally EU-focused projections from 2010 by the FCH JU to the current standings of the Austrian market:

- Define the starting point for the H_2 delivered price prognoses as the current price of € 9.00[2] per kg H_2 fuel in Austria. The price prognoses for year 2030 will be set according to the FCH JU as described in the previous paragraph.
- Assume a market-driven price consolidation of H_2 fuel, based on the projected market demand of FCEV deployment as described in Section 4.1.2. This

[2]Price retrieved from www.omv.at for the OMV fuelling station at Shuttleworthstraße 10, 1210 Vienna on 29.12.2018

scaling establishes a direct link between the market demand factor driven by FCEV deployment and the H_2 delivered price. The scaling assumes a linear dependence between the number of FCEV-s and the price of H_2 fuel, meaning that the starting price € 9.00 per kg H_2 fuel will converge to the projected year 2030 price based on the increasing accumulated number of FCEV-s for the given prognosis set.

- Correction for an assumed CO_2 emission-based taxation of H_2 fuel. By taking the current values of the Austrian mineral-oil tax (MÖSt.) for gasoline and diesel fuels and back-calculating on the incurred tax per emitted kg of CO_2, a proportional tax value can be calculated for the different production technology mixes of H_2 fuel, creating a more realistic customer price per kg H_2 when delivered at a hydrogen fuelling station. This step is especially important when assuming a difference in the taxation scheme for centralized and decentralized production, which is very likely for the case of household or small-industrial applications for self-sustaining provision of hydrogen fuel compared to large-scale commercial distribution of centrally produced hydrogen fuel at fuelling stations.

The CO_2 emissions for different hydrogen production technologies can be derived based on FCH JU[14] study as shown in Figure 9. As Austria utilizes a very high rate of renewable sources for electricity generation (83.71 %) in an overall EU comparison, a comparably low rate of 64 g/kWh CO_2 are emitted, which creates an advantage for H_2 production based on water electrolysis.[3] The Austrian MÖSt. regulation subsidizes diesel fuel with a lower tax rate of 0.397 €/l (compared to 0.482 €/l for gasoline)[4], thus it is further assumed, that any tax on H_2 fuel would be subjected to at least a similar subsidization. By taking the CO_2 emission per burned litres of diesel fuel (2.68 kg/l), a CO_2 emission based tax rate can be determined for the different H_2 production mixes as shown in Table 2.

Clearly, the combination of different H_2 production mixtures result in a considerable effect on the delivered H_2 fuel price when a CO_2 emission based taxation scheme is deployed. As the choice and deployment of these technologies are highly depending on the demand for FCEV-s as described in Section 4.1.2, the scenario set for describing a realistic projection range for H_2 fuel price is reduced based on the following underlying assumptions:

[3]Data for 2017, retrieved from `https://www.e-control.at/industrie/oeko-energie/stromkennzeichnung` on 30.12.2018

[4]Data retrieved from the current corresponding law, `http://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10004908` on 30.12.2018

70 % SMR without CCS, 30 % electrolysis	1.06 €/kg H_2
30 % SMR, 40 % coal gasification, both without CCS, 30 % electrolysis	1.8 €/kg H_2
70 % SMR and coal gasification, both with CCS, 30 % electrolysis	0.24 €/kg H_2
100 % electrolysis	0.46 €/kg H_2

Table 2: CO_2 emission-based taxation per kg H_2 fuel

Scenario 1 High adoption rate of FCEV-s according to BEV-dominant scenario, lowest cost H_2 production technologies deployed regardless of CO_2 impact, no tax on H_2 fuel.

Scenario 2 Low adoption rate of FCEV-s according to hybrid-dominant scenario, highest cost H_2 production technology (100 % water electrolysis), no tax on H_2 fuel.

Scenario 3 Low adoption rate of FCEV-s according to hybrid-dominant scenario, mixed H_2 production with 70 % SMR not utilizing CCS and 30 % electrolysis is deployed and a CO_2 emission based taxation is continuously introduced as the number of FCEV-s rises.

Scenario 4 Same as Scenario 1, CO_2 emission of H_2 is not captured by CCS and a CO_2 emission based taxation is continuously introduced as the number of FCEV-s rises.

Scenario 5 Same as Scenario 1, CO_2 emission of H_2 is fully captured by CCS and a CO_2 emission based taxation is continuously introduced as the number of FCEV-s rises.

Figure 10 shows the resulting projections of the H_2 delivered price under the above scenario set. Opposed to the projection in the FCH JU study, where the H_2 price is assumed to flatten out to a minimal value between 2030 and 2050 when not accounting for tax effects, the previously introduced steps of correlating the FCEV deployment rate and a possibility of CO_2 emission based taxation creates a considerable spread in the price prognosis. As it is evident that governments will not be able to sustain the loss of tax revenues which could reach overall 17 % to 36 % in mobility-related tax for Austria[2, p. 47], this assumption needs to be followed up in the forthcoming feasibility study. For the underlying scenarios, this has a considerable effect with the possibility of increasing the H_2 delivered price over time as FCEV and BEV adoption decreases current mobility-related tax revenues. As

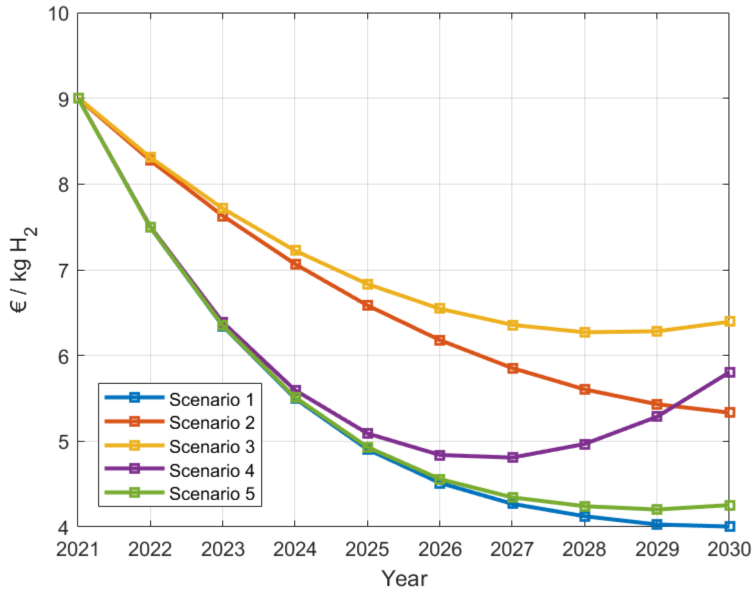

Figure 10: H_2 delivered price projections under different scenarios

no clear taxation schemes have yet been presented and future FCEV deployment is also dependent on different unforeseeable factors, the feasibility calculations in Chapter 5 will be concluded with the highest possible spread (Scenario 1 & Scenario 3) when accounting for the H_2 delivered price.

4.3 Scenarios for the capital expenditure of water electrolysis systems

As described in Section 3.3, the choice of electrolysis cell stack technology is a key factor not only for a proper assessment of necessary capital expenditure, but for key operational attributes like lifetime, maturity, scalability and efficiency. The expert elicitation study by O. Schmidt, et.al [16] gives a comprehensive overview and projections for all relevant technologies, whereas minimizing bias both in technology preference and projection data scenarios due to the methodology of an expert elicitation from both academic and industry institutions. In order to lock in a small but relevant scenario set for the capital expenditure of a water electrolysis system for the purposes of this thesis, the most suitable electrolysis stack technology for small-scale operation needs to be chosen. As SOEC systems are currently not mature enough for industrial application, this technology is disregarded, although potential advantages would include high electric efficiency and low material costs.

> *"AEC is the incumbent water electrolysis technology and widely used for large-scale industrial applications since 1920. AEC systems are read-*

ily available, durable and exhibit relatively low capital cost due to the avoidance of noble metals and relatively mature stack components." [16, p. 30471]

The above statement positions AEC systems towards large-scale applications, leaving PEMEC systems the technology of choice for the intended small-scale application in the course of this thesis, as also backed by expert opinion, industry deployment and the following attribute set:

> *"Key advantages are high power density and cell efficiency, provision of highly compressed and pure hydrogen, and flexible operation. Disadvantages include expensive platinum catalyst and fluorinated membrane materials, high system complexity due to high pressure operation and water purity requirements, and shorter lifetime than AEC at present. Current development efforts are therefore targeted at reducing system complexity to enable system scale-up and reducing capital costs through less expensive materials and more sophisticated stack manufacturing processes."* [16, p. 30471]

From the above attributes the provision of highly compressed H_2 and the flexible operation are highly beneficial for a small-scale operation. If an electrolysis stack already provides highly compressed H_2, the overall efficiency towards the required high pressure storage tank and dispenser can be increased, as less power is needed for operating an additional compressor, also positively effecting the proportion of compressor cost in the BoM. Flexible operation on the other hand allows for efficient utilization of low-cost electricity, when the actual electricity cost is low either due to low power demand or high supply of intermittent renewable sources, as the load switching costs and the transient time for reaching an efficient operation on a PEMEC system are the lowest when compared to the other two technologies.

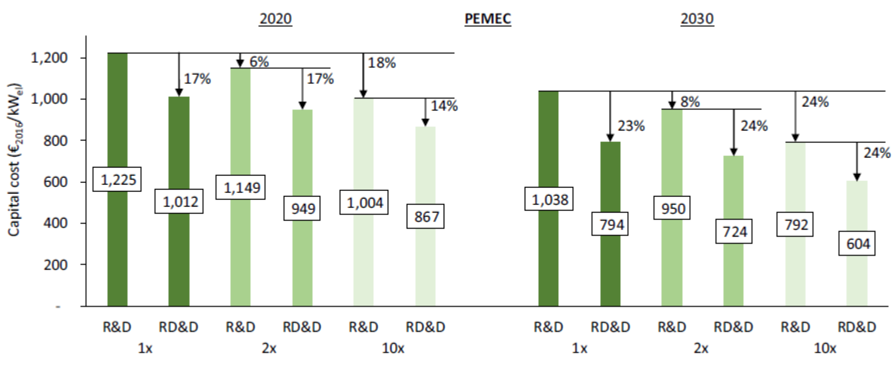

Figure 11: CapEx of PEMEC stacks as per expert elicitation, source: [16, p. 30476]

When assessing the maturity of a PEMEC system, the median of the experts' 50th percentile estimates show a lifetime of 50 500 hours by 2020 and 66 125 hours by 2030 in case of unchanged R&D expenditures, with a potential increase of 14-19% if R&D expenditures would double.[16, p. 30478] As this lifetime would already allow for > 5 years of operation in 2020, no scenarios for a changing technological maturity affecting the operational lifetime of PEMEC systems will be considered in the course of this thesis.

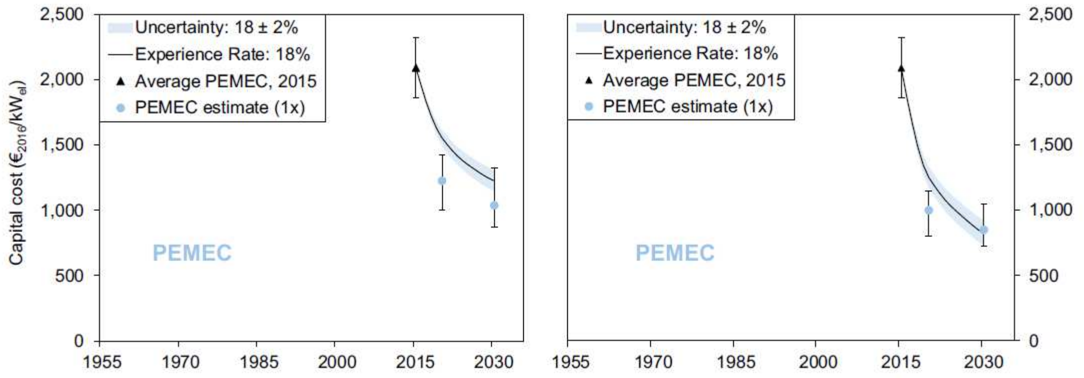

Figure 12: CapEx of PEMEC stacks, overlay of expert elicitation and experience curve, source: [16, p. 30480]

The development of capital expenditure for the PEMEC stack is projected using two different methods in O. Schmidt, et.al [16]: first, the median of the experts' 50th percentile estimates is aggregated while accounting for different scenarios in R&D expenditures and production scale-up (RD&D), as shown in Figure 11. Secondly, an experience-rate based projection has been concluded while assuming an 18 % learning-rate as derived from the reverse technology of PEM fuel-cells due to the lack of direct experience data for PEMEC. Here a potential for a spill-over effect needs to be noted: as the core technology in PEM fuel-cells and PEM electrolysis stacks is the same and PEM fuel-cells are subjected to mass-production in vehicles with a projected price reduction of 90 % over a period of 10 years, an even more significant jump in PEMEC learning rates is possible.[14] In the last step, the results from the expert elicitation and the experience-rate based projections are compared. Figure 12 shows the overlayed result of the expert elicitation results with the experience curve. The left figure assumes no increase of the annual EU-wide deployment rate of 0.36 GW, while the right figure accounts for production scale-up to due to increased deployment of 1 GW by 2020 and 2.5 GW by 2030 annually. This latter assumption of production scale-up adheres well to the expert projections for 2030, creating a sound basis for the purpose of this thesis.

The above results only address the capital expenditure necessary for the elec-

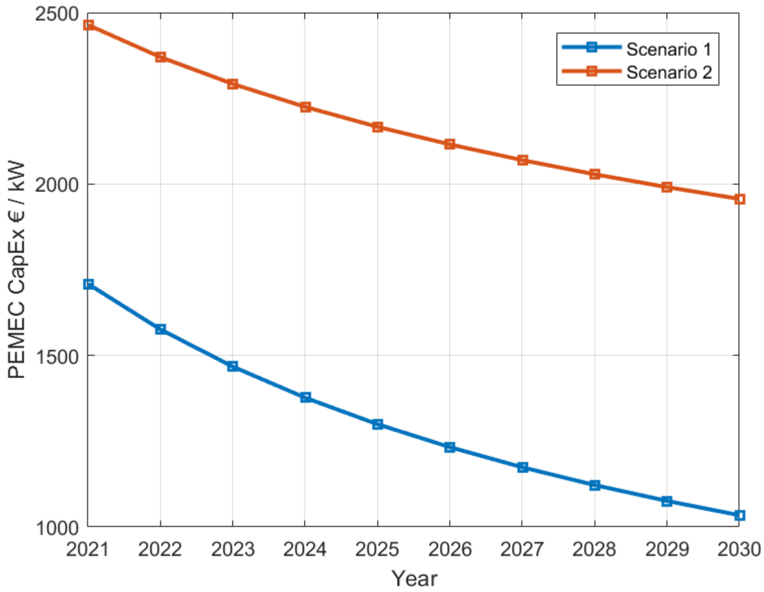

Figure 13: CapEx of a complete PEMEC system under different scenarios

trolysis stack, not the complete system. According to Esposito [8], the BoM for a PEMEC system can be broken down as follows: electrolysis stack - 60 %, power electronics - 15 %, gas conditioning - 10 % and BoP - 15 %, allowing for an extrapolation of the complete system cost based on the nominal power of the electrolysis cell.

Figure 13 shows the projected CapEx of a complete PEMEC system under following scenarios for further use for the feasibility calculations in Chapter 5:

Scenario 1 Rate of EU-wide deployment of PEMEC systems linearly increases from 1 GW per year in 2020 to 2.5 GW in 2030, an optimistic learning rate of 20 % is assumed.

Scenario 2 Rate of EU-wide deployment of PEMEC systems remains constant at 0.36 GW per year, a pessimistic learning rate of 16 % is assumed.

4.4 Scenarios for the operational expenditure of water electrolysis systems

According to Esposito [8], the largest cost in operational expenditure for water electrolysis systems is that of the electricity used. Electricity supply is also the variable with potential additional effects on the operation of the H_2 production plant: depending on the type of deployment, the power tariff scheme is different for households, industrial players and companies with access to the electricity spot markets. Thus, this variable will be handled rather in terms of the applied tariff scheme, in return also affecting the possible business models, while assuming no significant change in average annual electricity prices until 2030 on the Austrian market. This latter assumption can be backed by the fact, that the chosen PEMEC electrolysis systems can utilize intermittently available renewable sources, which are already widely utilized in the Austrian electricity grid and also planned to be expanded in future, leading to falling or stagnating electricity price projections when the connected load is a system adapting to the available renewable energy source.[6]

Scenario 1 PEMEC system deployed at households, fixed electricity tariff during the whole year of 8.1455 c€/kWh.

Scenario 2 PEMEC system deployed at industrial players, staged electricity tariff of 7.2795 c€/kWh during summer, 7.4011 c€/kWh during winter and 4.9611 c€/kWh during night-time (season-independent).[5]

Scenario 3 PEMEC system deployed at companies with access to the electricity spot markets, based on historic 2018 data.[6]

The input material in a water electrolysis system is water, which needs to be deionized by the system itself. As such, the needed water supply of the system is treated as an operational expense, amounting to 1.92 €/m^3. In addition, a projected price increase by 2 % annually is assumed based on historic price developments.[7]

A yet not discussed part of operational expenses are comprised of possible maintenance and service costs. Bertuccioli et.al [5] suggest these expenses proportionally between 2 - 5 % of the capital expenditure per year, depending on the size of the H_2 production plant. As the proportion of maintenance and service costs to capital expenditure decreases with the size of the system and the scope of the current thesis are small-scale PEMEC electrolysis systems, maintenance and service costs of 5 % of the capital expenditure per year are assumed.

[5]The prices for Scenario 1 & 2 have been retrieved from the respective tariffs for Vienna from `www.wienenergie.at` on 2019.01.05

[6]2018 data retrieved from `https://www.exaa.at/de/marktdaten/historische-daten`

[7]Water price and price development derived from `https://www.wien.gv.at/amtshelfer/umwelt/wasser/wasseranschluss/wassergebuehr.html` for Vienna on 2019.01.05

5 Feasibility modelling of decentralized H_2 electrolysis plants

The scenarios of the different parameters influencing the economic feasibility of decentralized H_2 systems from the previous sections clearly picture a very complex problem space, especially in the light of an uncertain environment with regards to the dominating vehicle propulsion technology of the future and the resulting demand-driven price for hydrogen fuel. Thus, in terms of feasibility modelling a staged, backward approach is suggested and followed through in this chapter with the aim to derive the economic viability of decentralized hydrogen fuel production plants in different configurations and under different target segment usecases:

Stage 1 internal feasibility of one single plant, modelling the operational costs for one unit of hydrogen fuel. Any scenario not yielding an equal or lower cost of hydrogen fuel compared to the delivered pump price of large-scale production will be discarded as non-competitive, assuming large-scale produced hydrogen fuel is available. For configurations where internal feasibility can not be reached under any of the studied scenarios and the above restriction, the configuration is also studied under the assumption of an arbitrary value of mobility regardless of the large-scale hydrogen fuel cost, representing non-availability of centralized, large-scale supply in the area.

Stage 2 modelling of investment viability of one single plant. This stage will establish, if it is a viable investment to set up one single plant with the annual operational cash-flow derived from Stage 1 when considering a full net present value calculation for a given investment period.

Stage 3 macro view from a market demand perspective. Although not covered by this thesis, even for the case that there are viable setups of single plants from Stage 2, such plants will not be developed and deployed unless there is demand for a considerable number of plants. Consequently, this stage will have to broadly assess the Austrian market need for such plants and make a recommendation on the overall most feasible deployment, making room for further studies in this field.

Based on the main feedstock and cost driver of the operational expenditure of a decentralized hydrogen fuel production plant as defined in Section 4.4, the availability of different electricity tariffs offer a reasonable segmentation of the target usecase in households, small industries and large entities with access to the electricity spot markets. Such a segmentation relates well with the potential hydrogen production demand of the underlying plant, which in turn is the defining factor for the plant's nominal power, thus the required capital expenditure. As a result, feasibility modelling in this chapter is carried out according to the above segmentation.

5.1 Internal feasibility of a single decentralized H_2 electrolysis plant

As a first stage of internal feasibility modelling of a decentralized hydrogen electrolysis plant, the operational cash-flow modelling based on a plant producing a single unit of hydrogen fuel is carried out. This allows for the assessment of effects due to changes in the operational parameter costs as well as the comparison of different plant configurations based on the normed output of a single unit of hydrogen fuel.

5.1.1 Techno-economic model of a single decentralized H_2 electrolysis plant

A simple techno-economic model of a single decentralized H_2 electrolysis plant models the PEMEC electrolyzer and the compressor necessary for pressurizing the hydrogen fuel for storage and dispensing to the FCEV's fuel tank. For the sake of a feasibility calculation based on the production of one unit of H_2 fuel, the following model parameters and outputs have to be considered:

Parameter 1 electricity need of the electrolyzer and the compressor system for one unit of hydrogen fuel in kWh/kgH_2.

Parameter 2 water need of the electrolyzer, for producing one unit of hydrogen fuel in l/kgH_2.

Parameter 3 cost of electricity at the plant in c€/kWh.

Parameter 4 cost of water supply at the plant in c€/l.

Parameter 5 cost of large-scale produced hydrogen fuel delivered at the pump of a fuelling station in $€/kgH_2$.

Output 1 difference between the resulting cost of hydrogen production at a local decentralized plant and the large-scale H_2 price in Parameter 5, representing the saving which can be realized by H_2 fuel self-supply compared to sourcing from large-scale production and distribution.

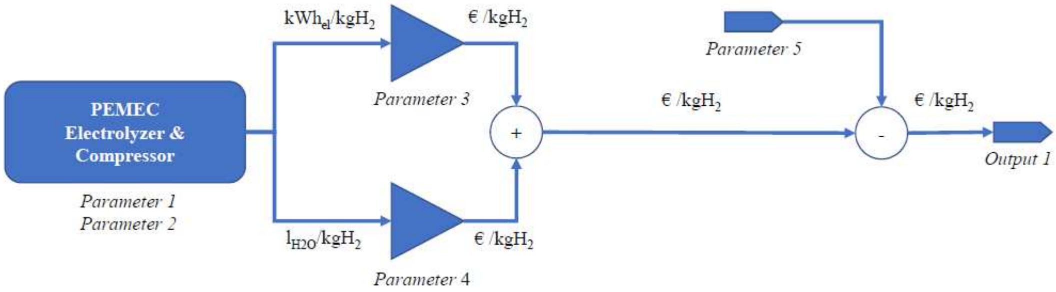

Figure 14: Techno-economic model of a single decentralized H_2 electrolysis plant

A schematic diagram of this model is shown in Figure 14. While varying the inputs and the parameters of the model based on the scenarios from Chapter 4, variations yielding a positive, or at least zero difference in the cost of the plant's produced hydrogen fuel compared to the large-scale cost of H_2 will be considered as feasible, as a cost saving compared to sourcing hydrogen fuel from large-scale production is attainable. In all other cases the underlying setup is considered economically infeasible, as no economic advantage could be achieved by decentral H_2 production, in case an alternative large-scale production supply is available. For these infeasible cases in the strict economic sense, further assumptions in terms of viability can be made, if large-scale hydrogen fuel is not available or other, so far not modelled or intangible value propositions would arise by the utilization of a decentralized hydrogen electrolysis plant.

Based on the scenarios for the different operational expenditure parameters in Section 4.4, the largest variance is expected to be driven by the different electric power tariff schemes for the different potential target segments of decentralized H_2 electrolysis plants. Thus the feasibility results for the current techno-economic model stage is separated according to these target segments as follows: fixed (household) electricity tariff, staged (small-industry) tariff and spot-market tariff.

5.1.2 Internal feasibility of a single decentralized H_2 electrolysis plant with fixed electricity tariff

The target segment for decentralized H_2 electrolysis plant with a fixed electricity tariff would mainly consist of households, producing H_2 fuel for self-sustained supply of 1-2 FCEV-s of the household. Due to this, the resulting plant size would be very small, affecting the overall energy efficiency of the plant and leading to the following parameter set[8] for the techno-economic model of the plant shown in Table 3.

[8]Electric energy consumption data based on [16, p. 30472] for the electrolyzer system and [10] for the compression. Water consumption data based on [7]. Remaining data from Section 4.4.

Electric energy consumption of plant	95 kWh/kg H_2
Cost of electric energy (fixed rate)	8.1455 c€/kWh
Cost of water feedstock	1.92 c€/l
Water feedstock consumption	18 l/kg H_2

Table 3: Internal parameter table of a single decentralized H_2 electrolysis plant with fixed electricity tariff

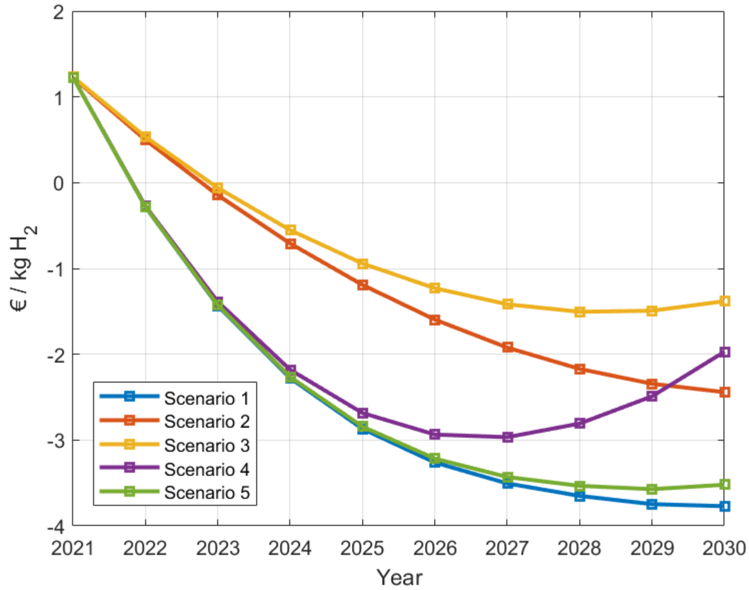

Figure 15: Internal feasibility of a single decentralized H_2 electrolysis plant with fixed electricity tariff

Figure 15 shows the resulting difference in the cost of the plant's produced hydrogen fuel compared to the large-scale cost of H_2 between years 2020 and 2030 when varying the scenarios for large-scale H_2 cost according to the scenario set from Section 4.2. In all of the scenarios a positive price difference in favour for the decentralized production is only reached for the first 1 - 2 years, when assuming a demand-based decrease of hydrogen fuel prices even at a low adoption rate of FCEV-s. Due to the nature of centralized, large-scale production this result is to be expected on the long-run. The short-term advantage in favour of decentralized plants in the first years can be explained based both on the scarce demand and availability of hydrogen fuel, as well as the current monopolistic situation of OMV in the Austrian market. As the sole current provider of centrally produced hydrogen fuel and the fact, that most of the production is sustained through utilizing hydrogen as a by-product of petro-chemical processes, the current hydrogen price is rather based on an arbitrary value of mobility than a market-driven price development.[1, 2]

A further important difference in the comparison of the operational feasibility of decentralized and centralized plants in the underlying household scenario is where possible cost reductions over time can be realized. As the scenario projections for the operational feedstock do not expect a reduction of the cost of neither electricity nor water and the fact, that a fixed electricity tariff does not allow for any operational optimization either, long-term competition with centralized hydrogen production can not be sustained based on this alone. This can lead to the conclusion, that until the time where the hydrogen fuel market stabilizes, the investment in a decentralized system under limited operational flexibility carries increased risks, if the sole driver of the investment decision is economic viability without the consideration of other possible value propositions. Some examples for such value propositions would be local balancing of the electricity grid, independent paths towards energy supply and environmental aspects.

During the current stage of assessing internal feasibility of a single decentralized H_2 electrolysis plant the necessary capital investment for setting up the plant has not yet been considered, already allowing for the assumption of these results not being a feasible investment in case large-scale produced H_2 would be available at a given plant location. Nevertheless, this setup will be followed through in Stage 2 of the investment feasibility model, addressing the option for deploying decentralized H_2 electrolysis plants in areas not sufficiently covered by H_2 fuel stations.

5.1.3 Internal feasibility of a single decentralized H_2 electrolysis plant with staged electricity tariff

As a staged electricity tariff is only available for businesses in Austria, the target segment for a decentralized H_2 electrolysis plant with such a tariff would be businesses with an internal fleet of FCEV-s which they would fuel with H_2 in a self-sustained manner. For this segment, a clear economic benefit needs to be attained by investing in such a plant, thus it is assumed that the underlying mobility or logistics need of the business requires a larger plant size compared to the household plant from the previous section, leading to a higher overall energy efficiency of the plant as suggested by O. Schmidt, et.al [16]. The staged electricity tariff also allows for operational flexibility in terms of utilization rate (annual average hours of operation per day) versus average electricity cost of the plant, as the available night tariff creates a considerable cost advantage when operating the plant exclusively on this tariff. On the other hand, this would automatically restrict the maximum utilization rate of the plant to 33 %, as the night tariff is only available for 8 hours per day.

Based on the above, Table 4[9] defines the parameters for the techno-economic model of a H_2 electrolysis plant when assuming industrial usage with a staged electricity tariff.

Electric energy consumption of plant	78 kWh/kg H_2
Cost of electric energy (mixed rate at 100 % plant utilization)	6.5472 c€/kWh
Cost of electric energy (night rate only at 33 % plant utilization)	4.9611 c€/kWh
Cost of water feedstock	1.92 c€/l
Water feedstock consumption	18 l/kg H_2

Table 4: Internal parameter table of a single decentralized H_2 electrolysis plant with staged electricity tariff

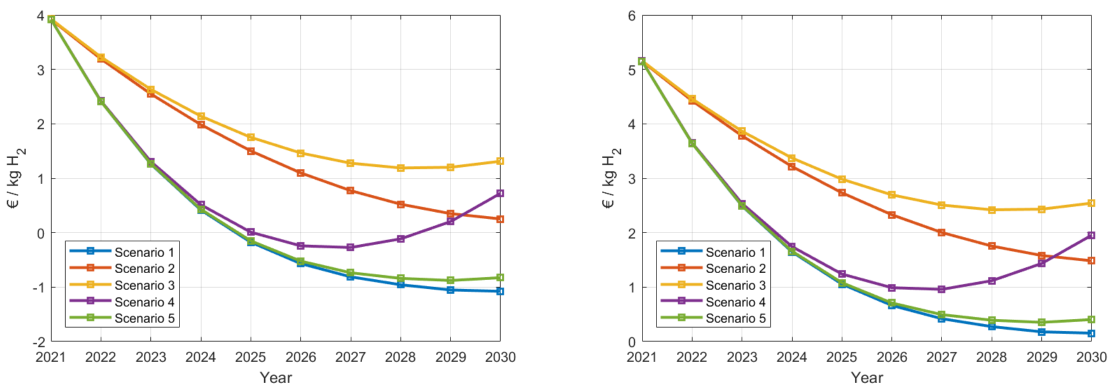

Figure 16: Internal feasibility of a single decentralized H_2 electrolysis plant with staged electricity tariff

The importance of the target utilization of the plant already becomes apparent in the current stage of operational feasibility modelling, when comparing the two sub-figures of Figure 16. For both cases, the scenarios for large-scale H_2 cost according to the scenario set from Section 4.2 are varied, while assuming 100 % plant utilization with the resulting average mixed electricity rate of 6.5472 c€/kWh in the left sub-figure and 33 % plant utilization only fed with electricity from the night rate of 4.9611 c€/kWh in the right sub-figure. When assuming 33 % plant utilization and night electricity rate, the difference in the cost of the plant's produced hydrogen fuel compared to the large-scale cost of H_2 is positive in the full time range between years 2020 and 2030, yielding operational feasibility regardless of the applied scenario. On the contrary, for the case of 100 % plant utilization, Scenarios 1 & 5 yield infeasible operational results.

[9]Electric energy consumption data based on [16, p. 30472] for the electrolyzer system and [10] for the compression. Water consumption data based on [7]. Remaining data from Section 4.4.

Both of these scenarios occur in the case of high FCEV adoption rates, with no or very low taxation on H_2 fuel when dispensed at fuelling stations. As Scenario 4 is also assuming a high FCEV adoption rate but also a CO_2 emission based taxation for the non-CO_2 neutral part of the centralized large-scale H_2 production plants, the importance of assessing future change in mobility taxation schemes for the feasibility calculation of decentralized H_2 electrolysis plants becomes apparent, as Scenario 4 yields feasible operation in case of applying the reduced night tariff, but crosses the line of infeasibility in case of full utilization and thus a higher cost of electricity in the periods of changing taxation schemes on hydrogen fuel. A possible case for such a tipping point could be, if large-scale H_2 fuel is produced utilizing non-CO_2 neutral technologies and taxed accordingly from a certain point in time, while for decentralized electrolysis-based production and a staged tariff this effect would only apply as far as already considered in the electricity cost of the staged electricity tariff. Furthermore it is worthwhile to note, that both Scenarios 2 & 3, which assume low adoption rates of FCEV-s and thus a higher price for hydrogen fuel, are operationally feasible regardless of the applied taxation scheme and average electricity rate over the complete plant utilization range.

Compared to the household electricity scheme, the increased operational flexibility of an industrial plant with staged electricity tariff allows for better compensation of the expected reduction of large-scale hydrogen fuel prices. On the other hand, this flexibility is reached by trading off in terms of utilization, which on the other hand will have an effect on the required capital expenditure for setting up the plant. Based on this, it is to be expected that the assumed reduction in terms of capital expenditure from learning effects and economies of scale will be the defining factor for long-term viability of such a plant on top of a feasible operation, in case competition from large-scale hydrogen fuel production is available.

5.1.4 Internal feasibility of a single decentralized H_2 electrolysis plant with spot-market electricity tariff

As spot-market electricity tariffs are only available to large industrial consumers with mega-Watt scale connection, the application of such a tariff for a decentralized H_2 electrolysis plant is arguably a border case. A possible target segment though would be chains of regional fuelling stations, jointly applying for spot-market electricity market access, while producing H_2 fuel locally at each fuelling station in a decentralized manner. This way a distributed production and supply of H_2 fuel could be established, while benefiting both from the efficiency increase of larger electrolysis plants as well as the flexible access to spot-market price based electricity. As the feasibility of such a plant will largely depend on the cost of electricity, it is essential to operate the plant as much as possible at times with a below-average spot-market price. On the other hand, this will - similarly to the staged tariff in the previous section - lead to a trade-off in terms of maximum possible utilization of the plant. This effect can be assessed based on Figure 17.

The left sub-figure shows the histogram of the Austrian hourly spot-market electricity price over year 2018[10], clearly showing the benefit of being able to flexibly operate according to spot-market prices when considering the spread of the histogram between -50 - 120 €/MWh, negative price values meaning that the electricity provider would pay the given amount for consuming power at that given hour for stabilizing the power grid at times with low consuming loads or high oversupply of unregulable, intermittent renewable sources, e.g. wind turbine power.[6]

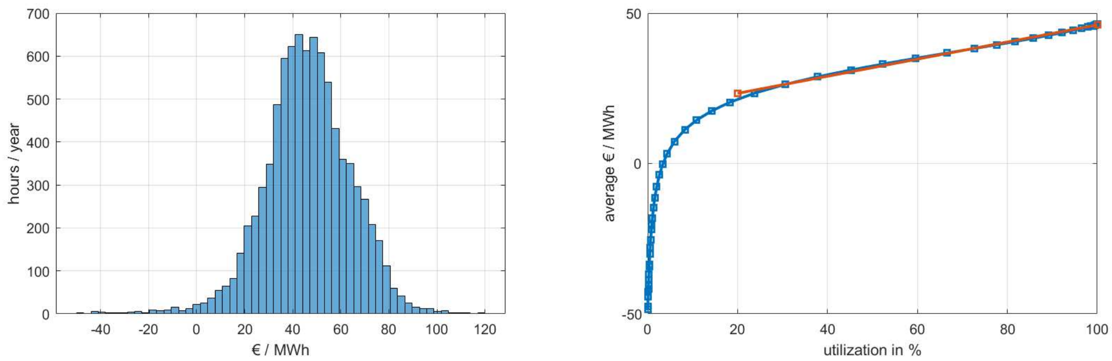

Figure 17: Left: histogram of the Austrian spot-market electricity price in year 2018. Right: average electricity price over utilization

The right sub-figure of Figure 17 shows the relation between the utilization of a plant supplied by spot-market electricity tariff and the achievable annual average price of electricity when optimizing operation in way, that the time intervals with minimal electricity spot-market prices are aggregated for the targeted utilization. The chart can be divided into two sections: below 25 % utilization, where a non-linear relation between utilization and average electricity price exists; and the right section above 25 % utilization, where this relation becomes linear, approximated by the trend-line shown in red. Due to this linear relation, it is sufficient to examine the internal feasibility of a single decentralized H_2 electrolysis plant at discrete points of utilization (in this case at 25 % and 85 %) to assess the differences in feasibility. Although the assessment of feasibility of a certain target utilization will be assessed in Section 5.2, the assumption of having economically non-viable plant investments

[10]Data retrieved from `https://www.exaa.at/de/marktdaten/historische-daten`

below 25 % target utilization is already made at this point. Table 5[11] defines the parameters for the techno-economic model of a H_2 electrolysis plant when assuming industrial usage with a spot-market electricity tariff.

Electric energy consumption of plant	66 kWh/kg H_2
Cost of electric energy (at 25 % plant utilization)	2.4745 c€/kWh
Cost of electric energy (at 85 % plant utilization)	4.041 c€/kWh
Cost of water feedstock	1.92 c€/l
Water feedstock consumption	18 l/kg H_2

Table 5: Internal parameter table of a single decentralized H_2 electrolysis plant with spot-market electricity tariff

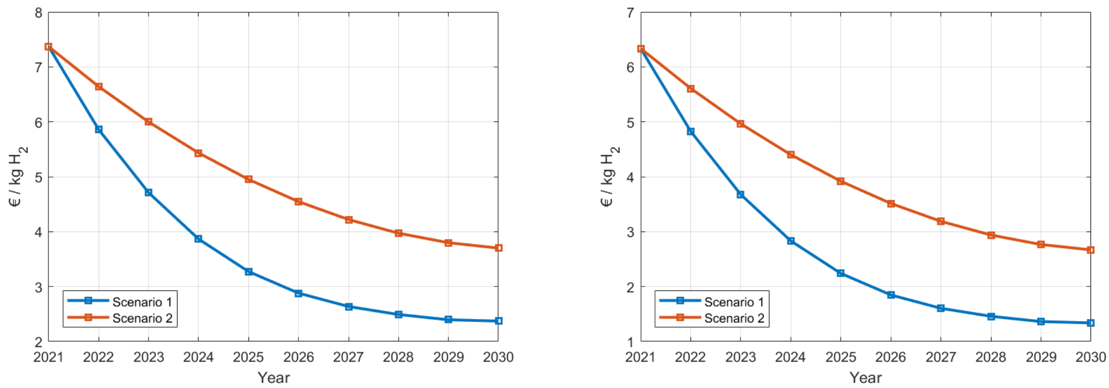

Figure 18: Internal feasibility of a single decentralized H_2 electrolysis plant with spot-market electricity tariff

When assessing the internal feasibility of a decentralized H_2 electrolysis plant utilizing spot-market electricity prices, only Scenarios 1 & 2 are assumed to be relevant for modelling, as these are the scenarios not having any taxation effects on the price. This assumption is made, as the current electrolysis plant usecase is considered to apply to hydrogen fuelling stations producing H_2 fuel on the spot, thus falling under the same taxation schemes as centrally produced H_2 fuel. As the current stage of internal feasibility modelling bases the the feasibility assessment on the achievable price difference between the decentralized and centralized production of H_2 fuel, such effects are assumed to cancel themselves out. Figure 18 shows the resulting price difference for the two disjunct scenarios of low- and high FCEV adoption rates (Scenarios 1 & 2), while utilizing an annual minimal average electricity price from the spot-market according to a target plant utilization of 25 % in the

[11]Electric energy consumption data based on [16, p. 30472] for the electrolyzer system and [10] for the compression. Water consumption data based on [7]. Remaining data from Section 4.4.

left sub-figure and 85 % in the right sub-figure respectively, resulting in a positive operational feasibility for all cases.

5.1.5 Conclusions of the internal feasibility modelling of a single decentralized H_2 electrolysis plant

The previous sections resulted in internal feasibility models for the three chosen usecases for hydrogen fuel production of households or small businesses with a fixed electricity tariff, small industry businesses with a staged electricity tariff and hydrogen fuelling stations with on-site H_2 fuel production and access to spot-market electricity tariffs. As the internal feasibility model is only assessing the operational feasibility of a single plant producing one unit of hydrogen fuel, the results of this section in an economic sense give an outlook on the achievable cash-flows per unit of H_2 fuel produced under different scenarios. Due to this, the projections on the year-to-year time axis are more expressive in terms of showing changes in operational feasibility under changing prices for centrally produced H_2 fuel on a large-scale basis, than in terms of showing projections for best market-entry times or overall market trends. Additionally, it can be concluded, that the operational cash-flows are always decreasing over time driven by the projected decrease of the competing large-scale hydrogen fuel price. As all other operational cost parameters of the decentralized H_2 fuel production plant are stagnating or increasing over time, this effect can not be compensated during operation.

Nevertheless, this perspective has been already valuable at this stage, as the variation in the applied electricity tariffs on one hand and the changing projection of centrally produced H_2 fuel prices under the three chosen scenarios yielded following conclusions:

- Main drivers of the internal feasibility are the competitive factor of cost of large-scale H_2 fuel and the operational expenditure for electricity, where the latter is critically influenced by the applicable electricity tariffs. While cost of large-scale H_2 fuel is projected to decrease over time, operational expenditure for electricity is assumed to be stagnating at best, leading to decreasing cash-flows over time.

- Small plants (household or small business application) utilizing fixed electricity tariffs can only be feasible if the cost of large-scale H_2 fuel does not decrease significantly (more than ca. 1.00 €/kgH_2 from the current level of 9.00 €/kgH_2 or in the case that no local access to large-scale H_2 fuel is given.

- Variation and applicability of taxation schemes on H_2 fuel can tip scales between feasible internal operation in rapidly changing or uncertain market environments, especially if the competitive advantage of decentrally produced H_2 fuel lies in an advantage with regards to applicable taxes. This conclusion especially applies for the usecase of small industrial business with staged electricity tariffs.

5.2 Investment viability of a single decentralized H_2 electrolysis plant

The previous sections have established the internal feasibility of decentralized hydrogen fuel electrolysis plants by studying the operational cash-flows of different possible plant configurations. Although operational cash-flows are important for assessing the long-term feasibility of a plant, the results can only be regarded as a first stage of viability modelling, with the main goal of reducing the number of considered configurations at later modelling stages. This section is taking the operationally feasible configurations to the second modelling stage, where full investment viability is examined under consideration of the required capital expenditure, overall plant size and discount rate for the calculation of the net present value of the investment in a decentralized H_2 electrolysis plant.

In addition to the above, it is worthwhile to mention that this modelling stage will also allow for assessing the investment decision in time. This is mainly based on the fact, that a decreasing capital expenditure over time due to expected learning curves and economies of scale in electrolysis cell stack prices is the variable with the largest presumed cost-reducing effect, which so far has not been considered in modelling. On the contrary, while large-scale hydrogen fuel prices have been used based on their projected price over time in the model, all other operational cost parameter projections are showing a stagnating or increasing cost evolution, reducing the operational cash-flows over time. This development is then only to be compensated by choosing a year of investment, where the required capital expenditure has decreased to a value which is able to sustain lower operational cash-flows in the long-run.

5.2.1 Investment viability model of a single decentralized H_2 electrolysis plant

A model for calculating the investment viability over a certain period of time will need to take into account the overall capital expenditure for setting up the decentralized H_2 electrolysis plant as well as the discounted annual cash-flows from operations during the modelled time period. As an operational model has already been established in Section 5.1.1 when taking one unit of H_2 fuel as a basis, this model will be reused in this section and scaled up with the annual target output of the plant. The additional parameters for the investment viability model are as follows:

Input 1 Capital expenditure for setting up the decentralized H_2 electrolysis plant in €.

Input 2 Annual target H_2 fuel production of the plant in kgH_2/year.

Parameter 1 Annual service & maintenance costs of plant, expressed as percentage of total capital expenditure.

Parameter 2 Total number of years of operation of the plant, resulting in the time horizon of the discounted cash-flow calculation.

Parameter 3 Discount rate for discounting the annual cash-flows in %.

Output 1 Net present value (NPV) of the investment in a single decentralized H_2 electrolysis plant.

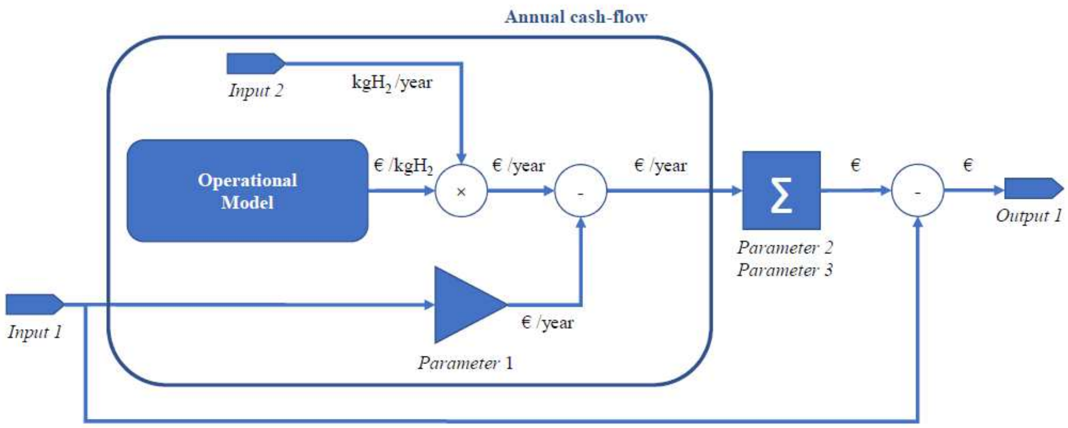

Figure 19: Investment viability model of a single decentralized H_2 electrolysis plant

The resulting model in Figure 19 represents a discounted cash-flow calculation for the assumed years of operations of the decentralized H_2 electrolysis plant. At this point it is important to note, that due to the expected changes of the large-scale hydrogen fuel price over the years of operation of the plant, these cash-flows will not be fixed during the studied period. The investment in such a plant is considered viable, if the difference between the sum of discounted cash-flows over the years of operation and the required capital investment yield a positive net present value. As all considered projections and scenarios from Chapter 4 take a 10 year period between 2020 - 2030 as a basis, the operation period of the plant will be fixed at 10 years for all investment viability calculations. The discount rate for the calculation will be based on the findings from Steinbach & Staniaszek[17], suggesting discount rates in energy system investment analysis of 3 - 6 % for households and 6 - 15 % for commercial and industrial segments. All other parameters will be varied as applicable for the specific usecase. In order to be able to model the changes in investment viability due to the expected reduction of the required capital expenditure due to learning effects, investment calculations will be carried out with different starting points in time in the respective scenario space. For all years where parts of the 10 year period of the investment calculation exceed the projection horizon of 2030 for the given starting year of investment, a flat extrapolation of the last available data point as a fixed value is used.

5.2.2 Investment viability of a single decentralized H_2 electrolysis plant with fixed electricity tariff

In order to be able to define the necessary parameters for performing the investment calculation, the annual production amount of H_2 fuel needs to be assessed. As the target group for the usecase linked to a fixed electricity tariff is mainly consisting of households, data from the mobility study of ÖAMTC[2], shown in Table 6, can be used for assessing the annual H_2 fuel need of this group, as this target group has also been in focus of this study.

Average number of vehicles per household	1.2
Annual mileage per vehicle	13 000 km
Average H_2 consumption of an FCEV passenger car	0.86 kgH_2/100km
Resulting annual H_2 production requirement per plant	134 kgH_2

Table 6: Annual H_2 production requirement per plant with fixed electricity tariff

The internal feasibility results from Section 5.1.1 suggest, that for the usecase of households only a limited scenario set can yield profitable overall operation of a decentralized H_2 electrolysis plant. Based on these results, the original scenarios for the large-scale H_2 fuel cost will be discarded for this usecase. Instead, the following scenario set will be defined, in combination with the scenario sets for the capital expenditure of a PEMEC electrolysis plant from Section 4.3:

Scenario 1 Low adoption of FCEV-s results in a low number of H_2 fuelling stations and consequently the capital expenditure requirements for PEMEC electrolysis plants remains high, with low learning rates over time. Due to the non-existing alternative for available H_2 fuelling, the value of the H_2 fuel produced only correlates with the perceived value of the resulting mobility of the user. For the sake of this thesis, an arbitrary value of 11.60 €/kgH_2 fuel is defined for the investment calculation, corresponding to a variable cost of mobility of 10.00 €/100km when assuming average H_2 consumption of an FCEV passenger car. This scenario would correspond to a worst-case setup, where only a few enthusiasts or otherwise FCEV-dependent individuals would have demand for such a system.

Scenario 2 Same as Scenario 1, but assuming reduced capital needs for the electrolysis plant. This scenario could be triggered in case of low adoption of FCEV-s, but an otherwise strong deployment of PEMEC electrolysis plants for other applications than producing H_2 fuel, for instance as power-to-gas systems for energy storage.

Based on the production requirement for H_2 fuel from Table 6, the nominal power of the electrolysis plant can be calculated based on the knowledge of power needed per unit of produced H_2 fuel from Table 3 and an assumed annual operation with 80 % utilization for leaving room for times with increased H_2 fuel demand. The complete set of required parameter data for the investment viability model of the current usecase is summarized in Table 7.

Annual H_2 production requirement	134 kgH_2
Electrolysis plant nominal power at % 80 utilization	1.8 kW
Scenario 1: initial capital expenditure	2460 €/kW
Scenario 1: learning rate	16 %
Scenario 2: initial capital expenditure	1710 €/kW
Scenario 2: learning rate	20 %
Annual service & maintenance, % of capital expenditure	5 %
Lower Discount rate (i)	3 %
Higher Discount rate (i)	6 %

Table 7: Parameter table for an investment viability model of a single decentralized H_2 electrolysis plant with fixed electricity tariff

Figure 20 summarizes the result of the investment viability calculations. The horizontal axis represents the assumed year of investment, thus projected future changes in parameters, most notably the capital expenditure for the plant components can be represented. The bar charts for each year show the two investigated scenarios, each also considering the maximum spread in the projected discount rate respectively. As the underlying assumption of both scenarios has been, that no competition from large-scale H_2 fuel exists and thus an arbitrary value of 11.60 €/kgH_2 is expected, the results need to be handled as an indication instead of a sound investment viability projection. Nevertheless, based on the result it can be concluded, that the examined setup of very small-scale plants with a fixed electricity tariff can only yield positive NPV in case of the most optimistic scenario, where the capital expenditure for the plant is assumed to be the lowest and the value of the produced H_2 fuel can be set to an arbitrary value, which is higher than the market price due to an inaccessible market supply.

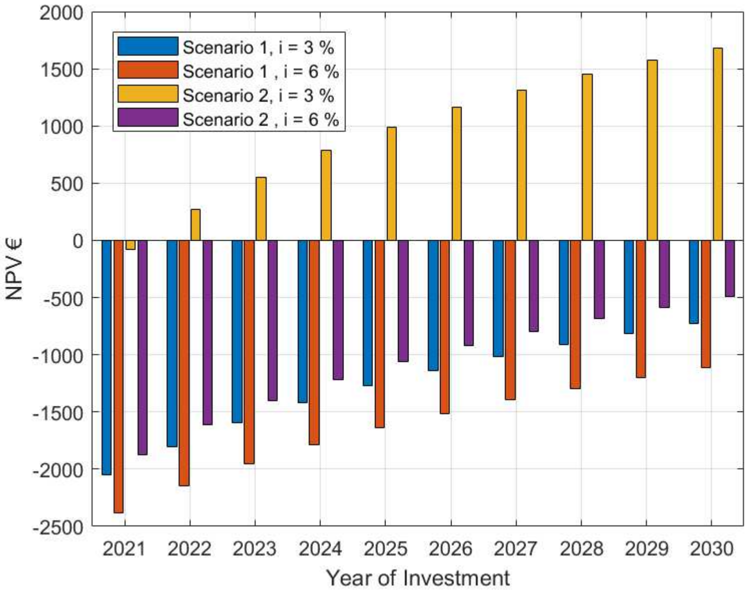

Figure 20: Investment viability of a single decentralized H_2 electrolysis plant with fixed electricity tariff

5.2.3 Investment viability of a single decentralized H_2 electrolysis plant with staged electricity tariff

As previously described, the segment of potential users of H_2 electrolysis plants with staged electricity tariff mainly consist of small- to medium-sized businesses, where the yearly average need for H_2 fuel has to be defined based on the size of the business, the number of vehicles and their average annual mileage. According to the WKO, small- to medium-sized businesses are defined based on the number of their employees in the range of 0 - 249[12], while about 93.7 % of these are having less than

[12] Data retrieved from `https://www.wko.at/service/zahlen-daten-fakten/KMU-definition.html` on 14.04.2019

10 employees. Unfortunately, no direct data for the absolute number of vehicles in the fleet of small- to medium-sized businesses could be found, thus the forthcoming assumption on the average fleet size is based on data from the Corporate Vehicle Observatory[15]. As the smallest segment of businesses up to 10 employees will likely not have fleet sizes over 10 vehicles, these businesses will not be considered as part of the segment with access to a staged electricity tariff, thus assuming that in case of a need for self-supplied H_2 fuel, the considerations for the fixed-electricity tariff from Section 5.2.2 apply. For businesses with 10 - 99 employees, 66 % of the businesses reported a vehicle fleet size of 1 - 9 vehicles, while the remaining 24 % reported 10 - 99. Between 99 - 249 employees, the proportion is the following: 26 % 1 - 9 vehicles, 64 % 10 - 99 vehicles and 10 % over 100 vehicles. As an investment in a self-supplying plant for H_2 fuel only makes sense in case there is considerable fuelling demand from the own vehicle fleet, based on the above data a minimum number of 10 vehicles per fleet is assumed for the investment viability calculation of this segment. In order to be able to estimate the average annual mileage of one vehicle, data for the average leasing duration of 5.9 years and leasing mileage limit of 150 000 km is used, yielding a rough average annual mileage estimate of 25 000 km per vehicle.[15]

The results from Section 5.1.3 showed, that all of the 5 examined competition scenarios with large-scale produced H_2 fuel can result in positive internal feasibility given certain other conditions are met, thus all of them will be taken over for investment viability assessment. As the possible combinations of all variables would lead to an excessive amount of result data, the combinations of worst-case and best-case projections of the relevant variables are considered, leading to the following assessment structure:

- Scenarios 1 - 5 for large-scale H_2 fuel price, mixed-rate electricity tariff with 100 % target plant utilization, lowest capital expenditure scenario for setting up the plant, discount rate effect considered on both ends of the 6 - 15 % range.

- Scenarios 1 - 5 for large-scale H_2 fuel price, mixed-rate electricity tariff with 100 % target plant utilization, highest capital expenditure scenario for setting up the plant, discount rate effect considered on both ends of the 6 - 15 % range.

- Scenarios 1 - 5 for large-scale H_2 fuel price, night-rate electricity tariff with 30 % target plant utilization, lowest capital expenditure scenario for setting up the plant, discount rate effect considered on both ends of the 6 - 15 % range.

- Scenarios 1 - 5 for large-scale H_2 fuel price, night-rate electricity tariff with 30 % target plant utilization, highest capital expenditure scenario for setting up the plant, discount rate effect considered on both ends of the 6 - 15 % range.

With this structure, the effects of counter-acting variables can be examined, most notably the question of utilization versus low electricity input price, as for the staged electricity tariff the restriction of only using the considerably lower night-rate reduces the target utilization of the plant, thus leading to a higher nominal power requirement, meaning a higher capital need for setting up the plant. This effect is then further assessed under the two distinct best-case and worst-case scenarios for the development of the capital expenditure and the discount rate. Table 8 summarizes the parameter data for the investment viability model of a single decentralized H_2 electrolysis plant with staged electricity tariff[13]. When calculating the investment viability across different starting points of the 2020 - 2030 timeline, the projections of changes in variables accounting for cash-flows beyond the year 2030 are not considered. Instead, the respective value at year 2030 is taken over as a flat projection for subsequent years.

Average number of vehicles per business	10
Annual mileage per vehicle	25 000 km
Average H_2 consumption of an FCEV passenger car	0.86 kgH_2/100km
Annual H_2 production requirement	2150 kgH_2
Electrolysis plant nominal power at % 100 utilization	19.0 kW
Electrolysis plant nominal power at % 30 utilization	63.5 kW
Initial capital expenditure (worst-case)	2460 €/kW
Learning rate (worst-case)	16 %
Initial capital expenditure (best-case)	1710 €/kW
Learning rate (best-case)	20 %
Annual service & maintenance, % of capital expenditure	5 %
Lower Discount rate (i)	6 %
Higher Discount rate (i)	15 %

Table 8: Parameter table for an investment viability model of a single decentralized H_2 electrolysis plant with staged electricity tariff

Figure 21 shows the resulting NPV of a single decentralized H_2 electrolysis plant under Scenarios 1 - 5 for large-scale H_2 fuel price, defining the possible returns in terms of savings due to the self-supplied H_2 fuel for the underlying best-case estimates of capital expenditure per unit of plant power and discount rate. The left

[13] Internal operational parameter data same as in Section 5.1.3

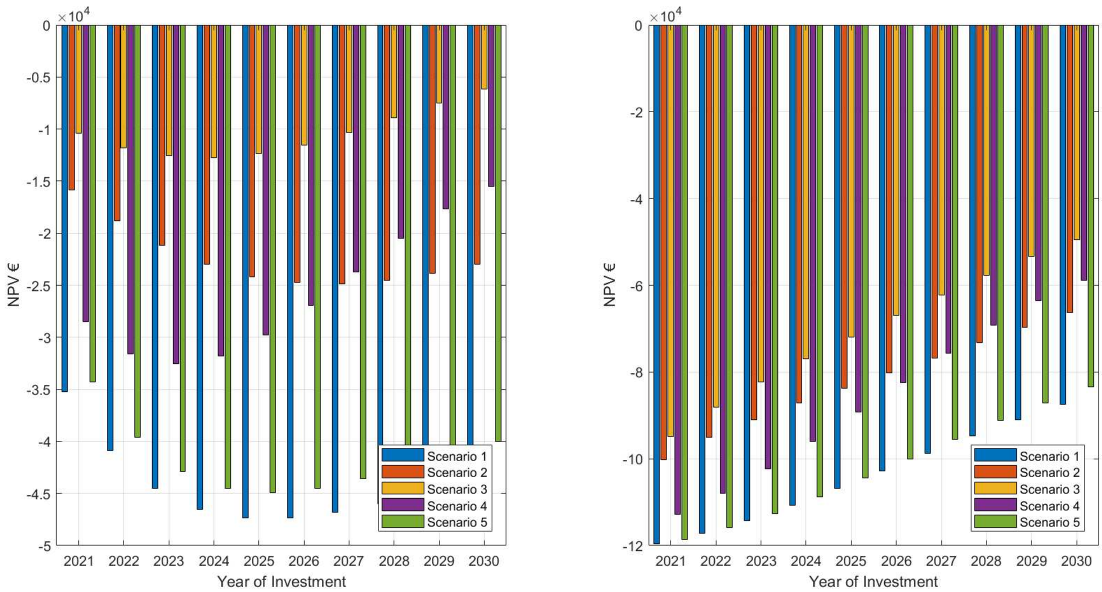

Figure 21: Investment viability of a single decentralized H_2 electrolysis plant with mixed rate (left) and night rate (right) electricity tariff and low estimate for capital expenditure

sub-figure shows the case for 100 % plant utilization and a mixed rate for the cost of electricity, while the right sub-figure represents 30 % plant utilization while only relying on electricity supplied by the lower night rate. Clearly, both cases result in a negative NPV over all studied scenarios, meaning that the accumulated operational savings in terms of price difference between self-supplied and centrally produced hydrogen fuel were not able to overcome the required cost of investment for setting up the electrolysis plant.

Regarding the trade-off between utilization and cost of electricity, the right sub-figure leads to the obvious conclusion that the higher capital expenditure due to the lower utilization could not be compensated by the lower cost of electricity, as the resulting NPV for all scenarios is considerably lower than for the case of 100 % utilization and a higher electricity cost in the left sub-figure. As the above conclusion has been made for the best-case estimates, analysis of further cases with higher capital expenditure will not be conducted.

Based on the high spread of resulting NPV values when varying the scenarios of large-scale hydrogen fuel cost in the left sub-figure, a sensitivity analysis will be carried out, comparing the effects of variations in the parameters large-scale H_2 fuel cost and required capital expenditure for the electrolysis plant while applying both limits of the discount rate range.

For the sensitivity analysis, the underlying plant model has been exercised at

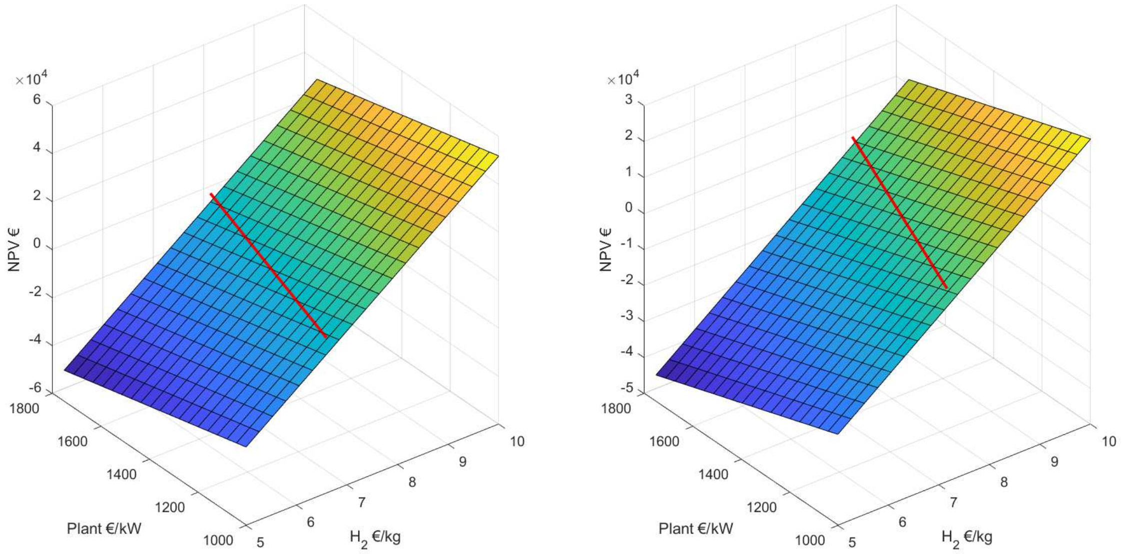

Figure 22: Investment viability variation of a single decentralized H_2 electrolysis plant with mixed rate electricity tariff under low (left) and high (right) discount rates

20 different points of both parameter dimensions: large-scale H_2 fuel cost and the required capital expenditure per unit of plant nominal power. The resulting surface in Figure 22 then shows the respective NPV value for all points, while assuming that the parameters do not change over the studied 10 year discount period as opposed to the cases shown in Figure 21, leading to fixed annual cash-flows over the discounting period. As the model under these conditions is linear, the effect of the variation of both parameters can be revealed by studying the coefficients p_n of a linear surface $z = p_{10}x + p_{01}y + p_{00}$ fitted to the results by linear regression, with z representing the NPV, x the large-scale H_2 fuel cost and y the required capital expenditure. The resulting surface is depicted in Figure 22, with the lower discount rate of 6 % in the left sub-figure and 15 % in the right. The red line marks the break-even point of the investment with NPV of zero along the surface.

	p_{10}	p_{01}	p_{00}
Discount rate 6 %	15824	-26	-80408
Discount rate 15 %	10790	-24	-54830

Table 9: Coefficients of the linear surface fit for investment viability variation of a single decentralized H_2 electrolysis plant with mixed rate electricity tariff

With the help of the linear surface fit and its coefficients in Table 9, proportionally equal variations along both parameter dimensions lead to the following conclusions:

- Regardless of the applied discount rate, an increase of the large-scale H_2 fuel cost by a given percentage has a stronger positive effect on the investment viability of the plant than a reduction of the initial capital expenditure by the same percentage.

- The effect of a higher discount rate is twofold: the attractiveness of the investment is diminished regardless of other parameters and the effect of a variation of the large-scale H_2 fuel cost is reduced compared to the effect of the initial capital expenditure while still remaining the stronger driving factor.

Further conclusion of this section based on Figure 22 is the fact, that regardless of the projections used for both large-scale H_2 fuel cost and the required capital expenditure per unit of plant nominal power, a considerable part of the NPV surface remains above the red break-even line, when assuming no change in the large-scale H_2 fuel cost over the studied discounting period. This again has the consequence, that the competition factor of both availability and the development of the cost of large-scale H_2 fuel is a crucially important factor for the viability of decentralized hydrogen electrolysis plants. In case the projections on the price reduction of large-scale H_2 fuel are not realized, such plants can become viable for small industry businesses with at least 10 vehicles to supply with H_2 fuel under the current conditions for all other model parameters. Due to this, an especially interesting point of the red break-even line in Figure 22 is represented by the minimal large-scale H_2 fuel price necessary for yielding a positive NPV regardless of the development of capital expenditure need per nominal plant power. For the lower discount rate scenario, a large-scale hydrogen fuel price of 8.00 €/kgH_2 would correspond to this point, while for the higher discount rate this would rise to 9.00 €/kgH_2. Comparing these values with the current market price of hydrogen fuel in Austria, the conclusion, that decentralized H_2 electrolysis plants can be a viable alternative for bridging the shortage of the current hydrogen infrastructure is further enforced.

5.2.4 Investment viability of a single decentralized H_2 electrolysis plant with spot-market electricity tariff

Chapter 5 introduced the applicability decentralized hydrogen electrolysis plants at fuelling-stations, where the competitive advantage compared to large-scale produced H_2 fuel would mostly lie in saving on distribution, transport and logistics infrastructure costs of the fuel. As such plants would be in optimal positions for supplying H_2 fuel to a large number of vehicles, the resulting electric power need would allow access to the electricity spot markets, which in turn enables further reduction of operational costs when optimizing the plant operation for times with a lower spot-market electricity cost. The crucial parameters for this usecase will be the utilization of the fuelling station in terms of H_2 fuel dispensed per day and the balance of plant utilization against the achievable operational cost reduction. The FCH JU[14] study categorizes H_2 fuelling stations in small, medium and large stations, based on the amount of H_2 fuel dispensed per day. Based on the suggested data of 400 kgH_2 per day for small stations, Table 10 shows the parameters of investment viability modelling for the two relevant large-scale H_2 fuel cost scenarios and different plant utilizations.

Daily H_2 production requirement	400 kgH_2
Electrolysis plant nominal power at % 80 utilization	1.4 MW
Electrolysis plant nominal power at % 50 utilization	2.2 MW
Electrolysis plant nominal power at % 25 utilization	4.4 MW
Initial capital expenditure (worst-case)	2460 €/kW
Learning rate (worst-case)	16 %
Initial capital expenditure (best-case)	1710 €/kW
Learning rate (best-case)	20 %
Annual service & maintenance, % of capital expenditure	5 %
Lower Discount rate (i)	6 %
Higher Discount rate (i)	15 %

Table 10: Parameter table for an investment viability model of a single decentralized H_2 electrolysis plant with spot-market electricity tariff

First, the results of the investment viability model will be assessed under the assumption of the best-case projection for the required capital expenditure of H_2 electrolysis plants as shown in Figure 23. The left sub-figure shows the NPV under the lower discount rate of 6 %, while the right sub-figure is calculated with the higher discount rate of 15 %. Following conclusions can be made when assessing the result under different aspects:

- A target plant utilization of 25 % can never yield a positive NPV of the investment.
- Scenario 2, representing a higher cost of large-scale produced H_2 fuel, results in a positive NPV at 80 % target plant utilization, regardless of the discount rate. Under high discount rates, all other cases become non-viable.
- Under the low discount rate case, Scenario 2 can yield positive NPV even at 50 % target plant utilization, either at high large-scale produced H_2 fuel cost

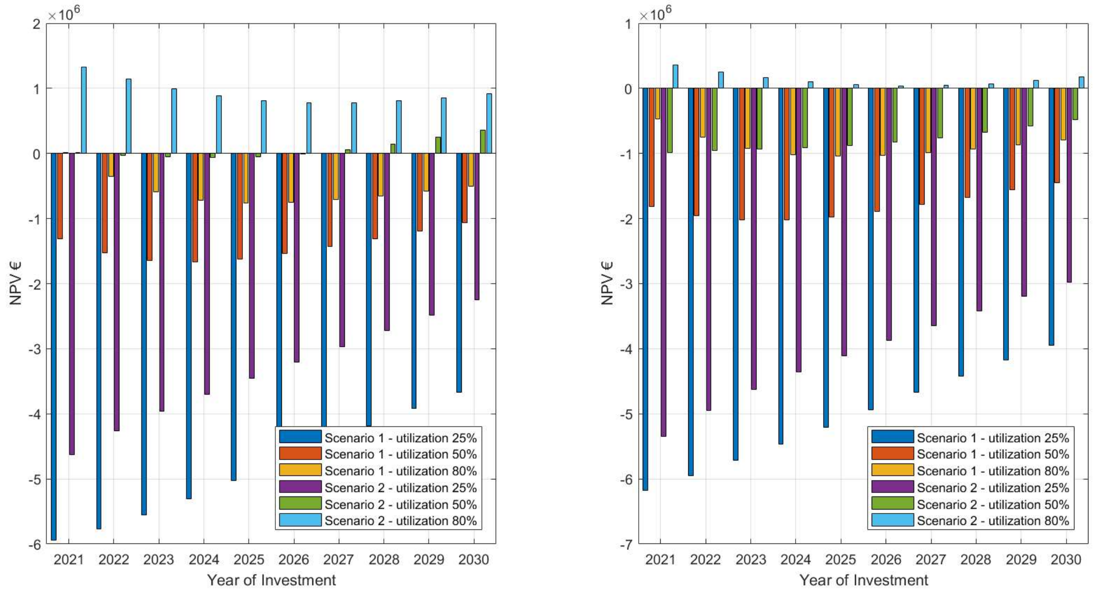

Figure 23: Investment viability of a single decentralized H_2 electrolysis plant with spot-market electricity tariff and low estimate for capital expenditure

at the beginning of the studied timer period or after sufficient reduction of the required capital expenditure due to learning effects at the end of the period. This statement has special importance when acknowledging the potentially fluctuating transient demand at a fuelling station and also the fact that during the adoption period of FCEV-s a high plant utilization rate will likely not be reached.

- Scenario 1, representing a lower cost of large-scale produced H_2 fuel, shows a slightly positive NPV at the initial time period with 80 % target plant utilization and a low discount rate condition.

In the light of these results, where only a few cases yield a viable investment, it is to be expected that changing the assumption on the required capital expenditure of H_2 electrolysis plants to the higher cost projection will turn the results towards an overall negative NPV. This expectation is fulfilled when assessing Figure 24, where even the absolute best-case conditions for the remaining parameters can not compensate the high capital expenditure.

Thus, as a summary for the underlying section the conclusion can be made, that H_2 fuelling stations with on-site H_2 fuel production can be a viable investment for utilization rates above 80 % in case the cost of the underlying hydrogen electrolysis system is following the lower cost projections.

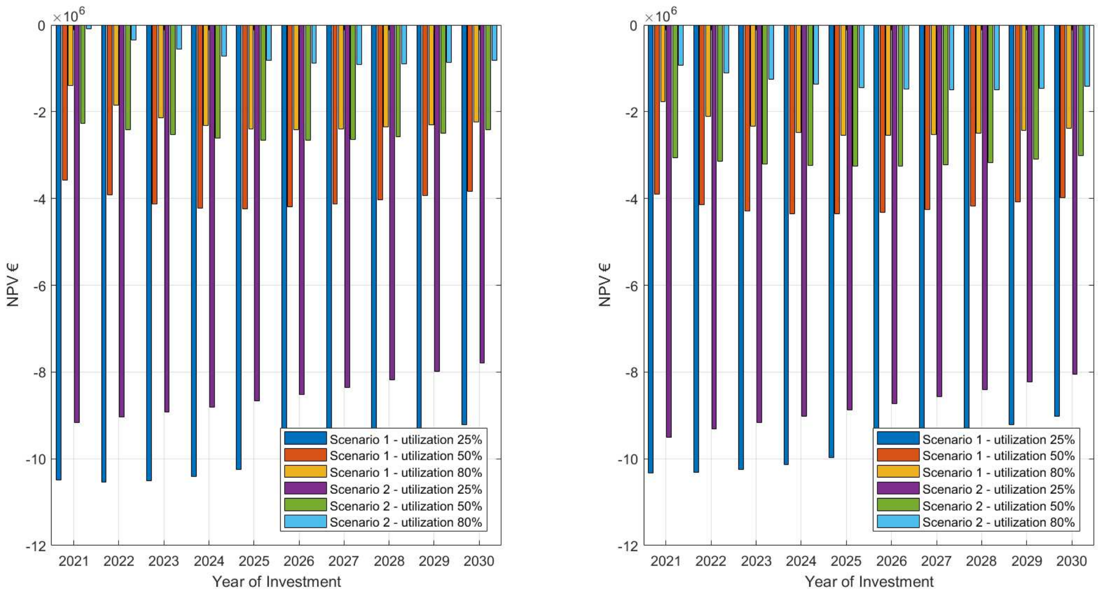

Figure 24: Investment viability of a single decentralized H_2 electrolysis plant with spot-market electricity tariff and high estimate for capital expenditure

6 Conclusion and outlook

Finally, the last chapter of this thesis is compiling all key results in a conclusion section, while also giving an outlook on further studies to be carried out relating to the topic of decentralized hydrogen fuel production in the Austrian market.

6.1 Conclusions of the investment viability modelling of a single decentralized H_2 electrolysis plant

In the previous sections, investment viability modelling has been carried out for the three chosen usecases of decentralized hydrogen electrolysis plants: household usage for 1-2 FCEV-s, self-supply of small business fleets with around 10 vehicles and on-site hydrogen fuel production at fuelling stations. Regardless of the usecase, it now can be concluded, that the initial assumption of defining the large-scale H_2 fuel price and the capital expenditure for the plant as two main driving factors from the complex set of parameters is valid. Based on the study projections of these parameters, the overall investment viability for the underlying usecases remain questionable, unless specific conditions of deployment and operation of the respective plant are met.

The household usecase is a good example for such specific conditions: this usecase can only be viable in case there is no other available hydrogen fuel source for the given household, thus creating an independence of the variable of the large-scale H_2 fuel price market projections and changing it to a new variable of an arbitrary value of mobility. Nevertheless this still can pose an interesting market opportunity of such electrolysis plants for regions without sufficient coverage of hydrogen fuelling stations. A similar situation can be observed in case of small businesses: under the applied market projections for the studied set of variables no viable plant setup can be achieved. On the other hand, based on the sensitivity analysis in the respective section, it can be concluded that considerable areas of the variable state space would correspond to a viable investment, if the restriction on one or more variables with regards to the market projections can be removed. Again, the most straightforward condition for this case would be the unavailability of large-scale H_2 fuel.

For the case of the on-site production of hydrogen fuel at fuelling stations, the results are more favourable in terms of restrictive conditions. As clearly viable plant deployment scenarios can be found even under projected market conditions, such a setup poses a real alternative to central production of H_2 fuel. Considering the already outlined difficulties in terms of transportation of gaseous hydrogen and the associated investment needs in the supporting infrastructure, it can be concluded that on-site production of H_2 fuel at fuelling stations is an opportunity worth considering with increasing FCEV deployment both in short-term and long-term. In addition to the results from the viability calculations, this statement is further enforced by the results of the two other studied deployment usecases of decentralized hydrogen electrolysis plants, as those are only viable in case of unavailability of a hydrogen fuelling station. As the viability the deployment of an electrolysis plant at a fuelling station is already given from 50 % plant utilization under high-cost scenarios of large-scale H_2 fuel prices, such a deployment can both support the spread of hydrogen fuel availability during the uptake period of FCEV-s and the long-term sustainable supply of decentralized H_2 fuel after future consolidation of the market and the H_2 fuel price with plant utilizations of above 80 %. In addition, future scaling of the production capabilities in-line with the market demand for H_2 fuel and the anticipated decrease of capital expenditure requirements for hydrogen electrolysis cells is a more flexible option at a plant deployed at a fuelling station compared to the household or small business usecase.

To conclude all findings, this thesis was able to provide viable deployment schemes for H_2 electrolysis plants for the Austrian market. While the case of viability is not overwhelming for most of the studied usecases, certain realistic market conditions are expected to yield profitable investment results. Furthermore, it is worthwhile to note, that in case of an emerging technology with a not yet established market environment, all results are subject to considerable uncertainty, especially when trying to extrapolate from the status quo. In order to handle such an uncertainty, all projections have been based on expert studies instead of own research, nevertheless these studies are still subject to errors when trying to predict future market environment. Due to this, further research is suggested in the upcoming final section for establishing a sound basis for the economic viability of small-scale decentralized hydrogen fuel electrolysis in the Austrian market.

6.2 Limitations and Outlook

Due to the complex problem space of hydrogen economy and the broad aspects of decentralized H_2 electrolysis plants, the scope and as such the addressable questions needed to be limited in this thesis. As already stated above, one of the greatest limitations of this thesis is the currently scarcely available data for projecting the development of important parameters of the techno-economic model, leading to systemic uncertainties in the results. While this is a natural restriction when handling emerging technologies, it has to be emphasized repeatedly. Additionally, this leads to the necessity of reiterating on the models and calculations as soon as new data is available or the expert projections for future development are changing.

As already outlined in the introduction of Chapter 5, the macro view in terms of overall market demand for decentralized electrolysis plants still needs to be assessed as a missing pillar of the viability question. Depending on the chosen most viable market segment, differently sized electrolysis plants needs to be developed and deployed, whereas the cost of this product development phase has not yet been established. Compared to the default situation, where development and deployment costs of a product are distributed over the number of produced units of a given period, for the case of decentralized electrolysis systems different research grants and subsidies might be applied due to the increased focus on renewable and CO_2-neutral energy systems. Thus, following aspects would require further studies:

- number of deployable decentralized electrolysis systems in the Austrian market, projections on the development of the chosen market segment
- cost of product development based on the actual technological standing
- possibility of using grants and subsidies for product development of green energy projects
- underlying business model, while considering the possibility of collaboration

between players in different industries (most notably the energy and the automotive sector)

Based on the overall conclusions for the three studied plant configurations, a so far not considered hybrid deployment option could materialize. From the aspect of the operating costs, we can conclude, that any deployment allowing access to the electricity spot market is the most favourable one. A condition for this on the other hand is a large-scale electricity usage. A natural player in this segment are local electricity providers, owning parts of the local infrastructure and supplying electricity to both households and businesses in the given area. As such, they also participate in the load regulation of the electricity grid, which either requires the regulation of the electricity supply or the demand, with the former being the more challenging option, especially in case of the intermittent and uncontrollable availability of renewable sources. This is very well reflected in Figure 17, where negative prices on the spot-market correspond to cases of electricity oversupply, with the need of controllable electricity loads to match in demand. We have already concluded, that the deployment of a decentralized H_2 electrolysis plant is a good candidate for such a controllable electricity load and feasible for the case of on-site hydrogen fuel production at fuelling stations. Taking this idea further and also considering the fact, that a so far not considered hurdle for the deployment of decentralized H_2 electrolysis plants at households and small businesses surely would be the necessary upfront investment need for the plant, an interesting deployment scheme could be established through the local electricity provider by deploying the plant to households and small businesses on a hydrogen fuel as a service basis. In this scheme, the users of the plant would commit to a certain monthly hydrogen fuel amount and be charged for this and any exceeding amount by the electricity provider, without the need of a substantial upfront capital expenditure in the plant itself. As long as the resulting fuel unit cost is below the perceived value of mobility and there is no other available fuelling option, such a deployment is equal to the viable outlined options in this thesis. For the electricity provider, a sufficient grid of decentralized H_2 electrolysis plants can pose a viable investment for the following reasons and as such be a topic of a dedicated study on this deployment option:

- better utilization of a larger amount of intermittent renewable sources, without incurring costs with the downside of oversupply, as directly usable by the grid of decentralized electrolysis plants
- current costs for offering negative electricity prices in case of oversupply will be buffered by own grid of decentralized electrolysis plants

- reduced investment in electricity grid infrastructure (electricity lines) for electricity transport, as locally generated power can be utilized by local grid of decentralized electrolysis plants

- government incentives and grants awardable for the investment in green energy projects

- further scale-up options by combining the deployed decentralized H_2 electrolysis plants with locally renewable supplies, as local photo-voltaic electricity generation for harvesting the sun's energy from rooftop modules

A further key conclusion of this thesis is the possibility of decentralized H_2 fuel electrolysis plants posing as an alternative for large-scale hydrogen production opportunity for regions without sufficient coverage of hydrogen fuelling stations, alleviating the confirmed key competition factor. Although this opportunity has been addressed in the course of the feasibility modelling in this thesis, the arbitrary value of mobility, which has been used as a substitute parameter, has been defined in a very simplistic way. As such, further studies could focus on the feasibility of decentralized H_2 fuel electrolysis plants specifically targeted as a supply alternative for regions without hydrogen fuelling stations.

As a final outlook, as opposed to this thesis, which strictly focuses on the economic value of an investment in a decentralized H_2 fuel electrolysis plant, more intangible value propositions of such plants could be assessed in further studies. Chapter 3 already maps out several of these aspects, most notably the questions around environmental friendliness and as such the effects on the society due to the influence on the quality of living. Due to the intertwining nature of modern energy systems, further research on these intangible value propositions in a broader context than hydrogen as vehicle fuel would be beneficial. One good example for such research is provided by Fowler et al.[9] for the utilization of hydrogen as energy carrier in the existing natural gas network. Tying together various such applications as heating of households and fuelling vehicles with decentralized hydrogen production plants powered by renewable sources as solar panels while considering the overall feasibility of such systems not only in monetary terms is certainly a topic for further studies as well.

Summarizing the above, the current thesis is considered as a basis for assessing the viability of decentralized hydrogen fuel electrolysis systems in the Austrian market, while additional studies are necessary for establishing a full picture of the underlying complex topic from all different viewpoints.

Glossary

ÖAMTC Österreichischer Automobil-, Motorrad- und Touringclub 2, 3, 14, 16, 23, 25, 26, 48

AEC Alkaline Electrolysis Cell 19, 20, 32

BEV Battery-Electric Vehicle 12, 13, 15, 16, 24, 25, 26, 30

BoM Bill of Materials 19, 20, 32, 34

BoP Balance of Plant 20, 34

CapEx Capital Expenditures 3, 20, 32, 33, 34

CCS CO_2 storage and capture 10, 27, 28, 30

CG Coal gasification 10

CO_2 Carbon-Dioxide 4, 6, 10, 11, 17, 19, 26, 27, 28, 29, 30, 42, 60

FCEV Fuel-Cell Electric Vehicle 12, 13, 14, 15, 16, 17, 21, 23, 24, 25, 26, 28, 29, 30, 31, 37, 38, 39, 40, 42, 44, 48, 49, 52, 57, 58, 59

FCH JU European Fuel-Cell Hydrogen Joint Undertaking 2, 3, 16, 17, 23, 24, 25, 26, 27, 28, 29, 30, 56

H_2 hydrogen 2, 3, 4, 5, 9, 10, 14, 15, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62

ICE Internal Combustion Engine 11, 15, 16, 17, 24, 25

IEA International Energy Agency 24

MÖSt. Mineralölsteuer - Austrian mineral-oil tax 29

NPV Net Present Value 47, 50, 52, 53, 54, 55, 56, 57

OMV Österreichische Mineralölverwaltung - Austrian Mineral Oil Administration 14, 28, 39

OpEx Operational Expenditures 3, 20, 21

PEMEC Proton Exchange Membrane Electrolysis Cell 3, 19, 20, 32, 33, 34, 35, 37, 48, 49

PHEV Plug-In Hybrid-Electric Vehicle 12, 15, 16, 17, 24

SMR Steam Methane Reforming 10, 17, 18, 19, 27, 28, 30

SOEC Solid Oxide Electrolysis Cell 19, 20, 31

WKO Wirtschaftskammer Österreich - Austrian Chamber of Commerce 50

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