Coproduction with Molten Carbonate Fuel Cells

Utkarsh Shikhar

Exploring the feasibility of coproducing hydrogen and electricity from internal reforming molten carbonate fuel cells.

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by

Utkarsh Shikhar

to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Monday September 28, 2020 at 02:00 PM.

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An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

TU Delft

Acknowledgement

We are living through some challenging times during this ongoing pandemic and it it more important now to be thankful and appreciative of everything. This thesis marks the end of my time at TU Delft as it is the final step towards graduation. This fun and yet challenging journey would not have been possible without the support from numerous people.

I would like to first thank my thesis supervisor Dr. Kas Hemmes for your constant support and guidance throughout this journey. Even as we adjusted to the new normal because of the lockdown, I could always rely on your support through emails or via skype meetings. Your feedback along this journey helped me stay on the right path that has led to this final step.

I would also like to especially thank Mr. Theo Woudstra for being available to answer any questions I had regarding the Cycle-Tempo software. Understanding the workings of a software from scratch can be complex, so your guidance were truly invaluable.

I would also like to express my gratitude to Dr. A. Purushothaman Vellayani and Dr. Lindert van Biert for agreeing to be members of the thesis committee. I am truly grateful to you both for taking time out of your busy schedules to make this possible.

Last but certainly not the least, I would like to express my ultimate gratitude to my family for always being there for me. This would not have been possible without the unwavering support from Mom, Dad, and my sister Prerna. Thank you for always listening to me, encouraging me whenever I felt low, and motivating me whenever it was necessary. To Waldemar, Renata, and Sanjay, thank you for being the pillars of strength that I could rely on whenever needed. Finally, I would like to give a special shout out to my little niece Aashvi, because sometimes talking to a three year old about absolutely nothing can be an extremely efficient de-stressing tool. Thank you.

Summary

The Paris agreement of 2015 brought together most nations of the world with a common goal of combating climate change. It highlighted the urgency of the climate crisis and has shifted the global attention to cleaner energy sources and technologies. Electricity is still the most important energy carrier and it is mostly generated through fossil fuels. Over the years, the importance of hydrogen has been recognized in energy transition. It is a clean fuel and can find application in a variety of sectors.

Fuel cells are electrochemical devices that can produce electricity at much higher efficiency than conventional power plants while operating without combustion. In internal reforming high temperature fuel cells, heat that is liberated can be utilized to produce hydrogen. Molten carbonate fuel cells along with solid oxide fuel cells are considered high temperature fuel cells. As these fuels can generate hydrogen, flexibility in energy output is possible. These fuels are capable of coproducing hydrogen, power and heat while utilizing few different fuels. Due to this the overall efficiency of such fuel cell systems increases.

The concepts of coproducing hydrogen, power and heat with high temperature fuel cells have been studied by various researchers over the years. However, most of these studies have been based on solid oxide fuel cell technologies. Molten carbonate fuel cells provide a stable technology that can support internal reforming as well, but articles available on these fuel cells in literature are far fewer in number. Moreover, the operation principle between the two fuel cells differ as well. Even within the literature available, the most do not provide the importance of other factors needed for the growth of these technologies. Based on these gaps in the literature, investigating the feasibility of flexible coproduction of hydrogen and power using molten carbonate fuel cells is the main goal of this report.

Molten carbonate fuel cells differ from solid oxide fuel cells on factors such as operating temperature, electrolytes and the operating ions. The carbonate ions in molten carbonate fuel cells travel from cathode to anode in the electrolyte. This has opened up the possibility of using molten carbonate fuel cells in carbon capture applications. Besides this, they have been conventionally used in stationary power and marine applications as well. There have been at least two instances where these fuel cells have been considered in hydrogen and power coproducing projects, both of which have been associated with FuelCell Energy. An innovative concept known as the Superwind concept has also been proposed where these fuel cells can be used to mitigate the drawbacks associated with fluctuating renewable energy sources such as wind and solar while flexibly coproducing hydrogen and power.

To analyze the technical feasibility of molten carbonate fuel cells, Cycle-Tempo based flowsheet calculations using molten carbonate fuel cells has been considered in this research. This study has been based on a paper published by Hemmes et al. titled ”Flexible Coproduction of Hydrogen and Power Using Internal Reforming Solid Oxide Fuel Cells System”. Their study has been based on solid oxide fuel cells, where three different modes of operation have been analyzed with a range of fuel utilization values. Using their model as an inspiration, the performances with molten carbonate fuel cells with the same three modes were examined. It was found that the molten carbonate fuel cells can achieve very high overall efficiencies of over 80% while coproducing hydrogen and power. In the high power mode where fuel cell operates at low voltage, overall electric power can even be found to be twice of what is possible in the conventional mode. Moreover, when total gas power is considered, the power output can be almost three times the conventional electric power. When compared to the performance of the solid oxide model, molten carbonate fuel cells produced lower outputs, which could be due to a variety of reasons including difference in cell operations, modelling and recycling parameters specified, and lower fuel intake.

When its socio-economic feasibility is considered, secondary research approach has been used. Molten carbonate fuel cells are a mature technology but the annual growth rate in their production is much slower than other fuel cells like the solid oxide fuel cells. While it was observed that the coproduction technologies are most likely to benefit the society, and due to slow growth of green hydrogen technologies, hydrogen is likely to be produced by natural gas for years to come. Due to the limited availability of molten carbonate fuel cells and their extremely high costs, coproduction systems based on these fuel cells cannot be considered feasible today. The role of actors and stakeholders will play an important role in their diffusion into the socio-technical regime in the future. In the early stage of the development like they are currently, government support in research and development is needed. Based on the existing government policies and the nature of the inputs and ouputs from the coproduction systems, such technologies maybe eligible for support from the policy makers. However, while natural gas based technologies have been supported, when it comes to hydrogen generation, often governments focus on green hydrogen technologies based on only renewable sources. So their socio-economic development will depend on the rate at which MCFC technology develops, the rate at which hydrogen market grows, support from the policymakers and other stakeholders for a natural gas based technology.

The coproduction systems are technically feasible but they will not be socio-ecomically feasible in the short run. In the long run feasibility maybe possible but the speed of infiltration depends on external factors which is likely to vary with time and place.

Contents

1

Introduction

Fuel cells are devices that typically convert chemical energy of the fuel into electricity. However, it is possible to utilize fuel cells for cogeneration applications to produce additional output like hydrogen to improve the overall efficiency of the system. This thesis explores this possibility with molten carbonate fuel cells (MCFC). In this chapter the social context and motivation needed for cleaner energy fuel like hydrogen is provided. After a brief summary on the current global energy scenario and fuel cells, the drivers for this thesis has been deduced.

1.1. Motivation and context

Despite the rise in clean alternate energy technologies, most of the global energy demand today is still met through fossil fuels. As seen in Fig. 1.1 almost 85% of the energy in 2019 came from fossil fuels, namely oil, coal and natural gas.

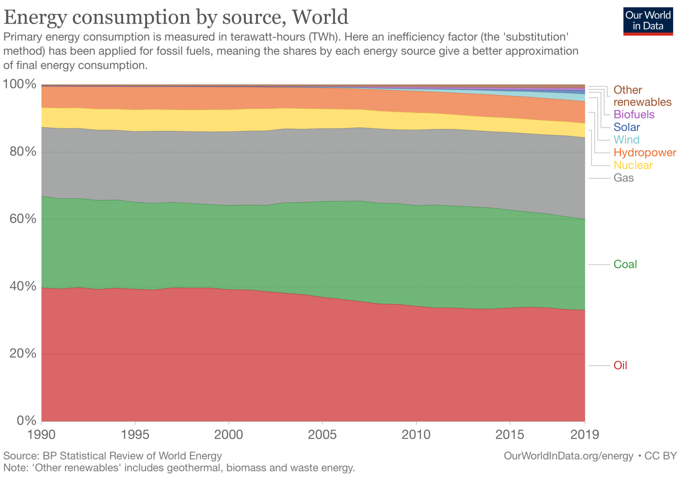

Figure 1.1: Global energy consumption by source since 1990. Fig from Ref.[113]

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In 2015, the Paris agreement brought together almost all nations with a common goal of combating climate change with ambitious efforts focusing on climate change mitigation, renewable energy and energy security. It highlighted the urgency of the climate crisis and required all countries to update their strategies to fight this crisis by cutting down greenhouse emissions. This has contributed to shifting of the global focus towards alternate energy sources. Moreover, alternate renewable energy sources are also needed because fossil fuels are limited and their supplies are running out. Thus, the energy systems need to be efficient, reliable, sustainable and affordable.

Electricity is extremely important in today's society as it finds applications in homes and buildings for lighting and appliances, industries for processing and producing goods and even in transportation for powering railways and light-duty vehicles. As the society develops the need and dependence on electricity will only rise further. According to an article published by Energy Information Administration (EIA) of the United States, global electricity consumption is rising much faster than the global population which has resulted in the increased amount of electricity consumed per person (per capita electricity consumption) [68].

While electricity generated mostly comes from fossil fuels or nuclear energy, there has been an increase in the installed capacity of renewable energy sources in the recent years as shown in figure 1.2. At the end of 2018, renewable generation capacity had climbed to 2,351 GW with over 50% that coming from hydropower [65]. The same report also showed that solar and wind constituted 84% of the new installed capacity.

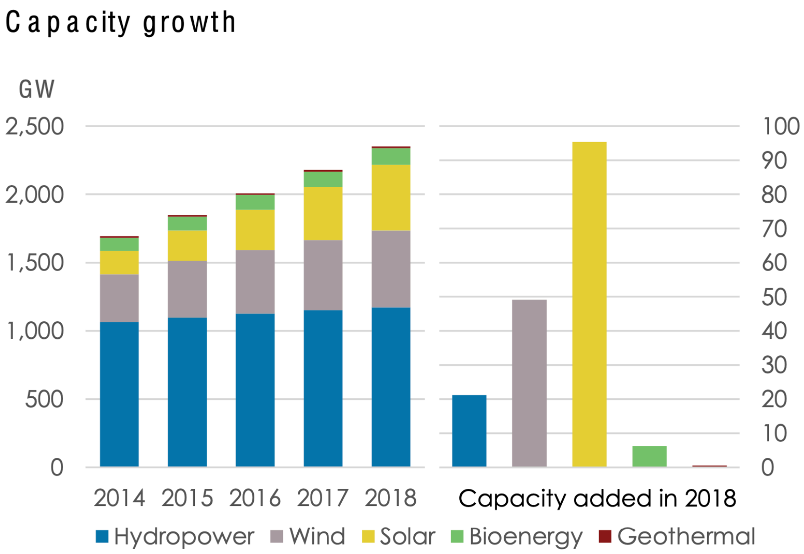

Figure 1.2: Capacity growth for various renewable energy sources. Fig from Ref.[65]

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Energy obtained from solar and wind energy sources are intermittent as they depend on the conditions of their surroundings at any given time to produce useful energy output. This makes them unreliable to meet the power demands as there could be periods of extreme peaks or extreme lows in their outputs. While this can be handled to an extent through storage or backup power technologies, it highlights the fact that for an energy system to be successful, a balance between demand and supply in required in the grid and power markets. Traditional power grids that provide electricity from coal, natural gas or nuclear power are stable but are outdated as they are operating in a top-down manner where energy produced is inefficiently utilized. This obstructs the integration of cleaner renewable technologies that could generate, supply and manage energy locally. This difficulty in integration of cleaner technologies into the grid could contribute in slowing down the transition to cleaner energy.

While the end goal for many countries maybe to achieve net zero carbon emissions in the next few decades, the focus cannot only be on renewable energy based technologies. Steps towards decarbonization would also require contribution from highly efficient technologies, especially in heating and transport sectors, which are two of the largest contributors of greenhouse emissions. These two sectors together contributed to about 22.88 billion tonnes of CO_2 equivalents of green house emission in 2016 [114].

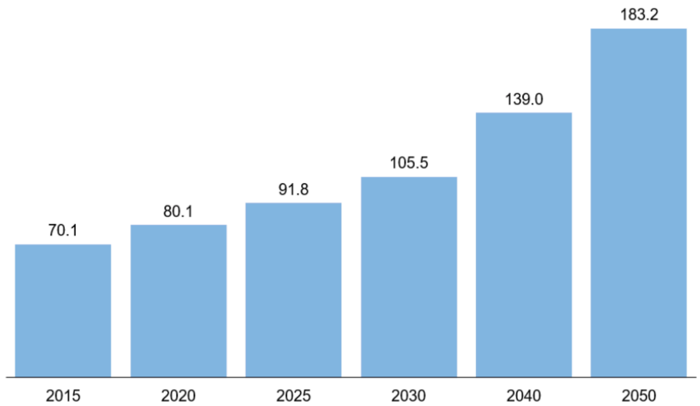

Figure 1.3: Global hydrogen demand (million tonnes per year). Fig from Ref.[49]

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In the last few decades the demand for hydrogen has constantly risen as it is a clean fuel which upon combustion releases only water and heat as byproducts. Figure 1.3 shows the rise of hydrogen demand over the years and it is expected to reach 183.2 million tonnes per year by 2050 [49]. It is a versatile fuel and can find application in transportation, heating and power sectors. Hydrogen can play a significant role in the future energy matrix as it is one of the few options, especially in transportation that at the point of use, can provide power with zero pollutant and greenhouse gas emissions [12]. However, producing hydrogen to be used as a fuel is not simple and it is generally produced from fossil fuels contributing to about 830 million tonnes of CO_2 equivalents of emissions per year [61].

Fuel cells are devices that can operate on a variety of fuels and can achieve electric efficiency of up to 60% which is much higher than 35% that can be achieved from combustion based power plants [98]. High temperature fuel cells also give off substantial heat that can be utilized to further improve efficiency. With internal reforming in high temperature fuel cells, they can produce hydrogen directly from natural gas. Since fuel cells operate without combustion the pollution levels are very low even when operating with natural gas and depends directly on the natural gas fuel extraction method. With fuel cells the following options are possible:

- Flexibility in fuel input.
- Flexibility in energy output.
- Increased efficiency of the system used.
- Production of hydrogen.

Due to these factors high temperature molten carbonate fuel cell has been considered in this thesis.

1.2. Research Drivers

The previous section provided a brief background on the energy situation in the world today and the status of hydrogen and fuel cells. They help with establishing the drivers for this research. These drivers are the concerns that need to be addressed when evaluating a new energy generating system.

- It was seen that despite the growth in alternate energy technologies most of the energy and electric demands are still met through fossil fuels hence not only cleaner technologies but also efficient fuel utilization is needed.
- As renewable technologies like wind and solar provide intermittent supply of energy and the electricity grid is outdated. Thus, a new flexible energy source could be required to match the varying energy demands.
- The potential of hydrogen has been recognized and the demand for hydrogen as a fuel is increasing. Thus, there is a need for cheap and reliable method of hydrogen production with minimal environmental impact.
- Fuel cells are a mature technology and have various characteristics that could make them favorable for flexible energy production so their potential needs to be explored.

With a glimpse into the energy situation and the drivers for this thesis in mind, in the following chapter the research question is defined. The information on methodology and the structure of the thesis has also been provided for the subsequent chapters.

2

Research Methodology

In this thesis report molten carbonate fuel cell has been considered for flexible cogeneration of hydrogen and electric power. Having identified the drivers for the research in the previous chapter, it is necessary to investigate the presence of cogeneration concept in literature before defining the research question. This chapter presents the literature study, derivation of the research question, research methodology and the structure of the report.

2.1. Literature Study and knowledge gap

There are problems with hydrogen production like when produced by natural gas reformation, it struggles with the use of fossil fuels, greenhouse gas production, challenges with regard to sustainability. When hydrogen is produced through electrolysis of water, though more sustainable, the technology can be expensive and inefficient [12]. For hydrogen to find widespread application as a energy carrier, various technological advancements in production, storage and distribution needs to take place. While fuel cells have been recognized as high efficiency generators, high temperature fuel cells have also been recognized as possible hydrogen co-producers to meet the hydrogen demands in the future [12].

High temperature fuel cells like the molten carbonate fuel cells or the solid oxide fuel cells (SOFC) are capable of extracting electric power from fuel at a higher efficiency than the conventional combustion based power plants. They use hydrogen as the energy carrier and can provide continuous energy. However, as the MCFC requires temperature above 650°C and the SOFC can operate in a temperature range between 500-1000°C, a lot of heat is liberated as byproduct during the operation. Over the last two decades various studies have been conducted on utilization of heat from these fuels effectively to improve the efficiency of the fuel cell systems further. For example, the internal reforming fuel cells can produce hydrogen within the fuel cell through endothermic reforming reaction. This results in additional output or multiple outputs besides just electric output. In literature various terms like cogeneration(E.g. Ref. [16]), coproduction (E.g. Ref. [73], [55] and [118]), trigeneration (E.g.ref. [105] and [16]) or polygeneration (E.g. Ref. [10] and [82]) have been used to indicate two, three, or multiple outputs from the fuel cell systems. While some of the papers only talk about the fuel cells others consist of systems in which fuel cells are a part of a combined plant. As there are many papers published on fuel cells, for this literature review only papers with SOFC and

MCFC were considered where hydrogen was a byproduct.

There have been numerous papers written on coproduction of hydrogen over the years with their focus on SOFC. In fact, back in 2000 Vollmar et al. recognized that by utilizing the high temperature heat to produce hydrogen-rich synthesis gas, the range of applications with fuel cells could be expanded [128]. They showed that SOFC reformer operating at low electrical efficiency has the potential for developing highly efficient combined processes plant for the generation of electricity and syngas (or hydrogen) and is more efficient than their separate production. Few years later, Leal and Brouwer using SOFC demonstrated a method for the study of hydrogen co-production, and simulation results to gauge the impact of reformer placement on the performance of the system [73]. They simulated six different cycle configuarations that use the heat from the fuel cells to drive the hydrogen production. Both internal and external reforming was considered and they showed that highest electrical and overall efficiency of 45% and 80% respectively was achieved in the case of internal reforming case.

In 2008, the work of Hemmes et al. showed the technical feasibility of internal reforming SOFC in flexible coproduction of hydrogen (or syngas) and power [55]. The possibilities and limitations of such a system were explored by simulating the system to operate in three different modes namely high efficiency mode, constant current mode, and high power mode. The fuel cells were operated for a range of fuel utilizations from 60% to 95%, with 60% representing highest hydrogen production and 95% representing standard fuel cell operation. It was noticed that a overall efficiency of up to 95% in terms of hydrogen production and electric power generation could be achieved by effectively utilizing waste heat in endothermic reforming reaction [55].

In the last decade various other authors have published works to explore the concept of flexible coproduction of hydrogen and power using SOFC in one way or another. The work of Perdikaris et al. shows a trigeneration system for producing hydrogen, power and heat [105]. They proposed a carbon free combined system consisting of SOFC and solid oxide electrolyzer cells (SOEC) running on natural gas, where upon coupling SOFC provided the heat and power that SOEC required. Two modes of operation: one that produces power and heat, and the other that consumes electricity and heat for electrolysis of water to produce hydrogen have been mentioned. Around the same time the work of Margalef et al. showed an analysis of polygenerating high temperature fuel cells based on SOFC stacks [82]. This study analyzed and compared six different SOFC system configuration, with internal and external reforming options. From all their performance analysis they concluded that the highest electricity and hydrogen production efficiencies are achieved through internal reforming due to the highly synergistic and integrated nature of production. They also highlighted the difficulty associated with transferring heat from fuel cell to external reformer at high enough temperatures, that could result in substantial hydrogen production without compromising the system performance.

In another paper, Becker et al. demonstrated a polygeneration system operating at a steady state for combined production of heat, hydrogen and electric power [10]. They analyzed two methods of hydrogen recovery and purification from the SOFC tail gas: pressure swing adsorption and electrochemical hydrogen seperation. Their system achieved electrical efficiency at rated power of about 49% and overall heat, hydrogen and power efficiency of about 85%. As hydrogen can be produced through shift reaction from CO it might be useful to note the work of Xie et al. where they demonstrated electricity and CO cogeneration through direct carbon SOFC [133]. They used a SOFC with ion conducting oxide membrane as electrolyte and the device which is completely in solid state, operates with solid carbon as fuel. They demonstrated that electricity and CO gas can be cogenerated in direct carbon SOFC through electrochemical oxidation of CO and the Boudourd reaction. When the emitted CO was considered to be part of the power output, their system was found to achieve efficiency of upto 76.5% [133].

In some cases the coproduction of hydrogen and electric power have been studied for specific applications. Shaffer and Brouwer studied and developed a dynamic internal reformimg SOFC model with electricity and hydrogen coproduction to meet dynamic building demands [118]. Their work showed that operating fuel cells at lower utilizations results in higher electrochemical efficiency due to the production of excess hydrogen for later use. During highly dynamic processes, the models they developed retained capabilities to resolve information about intra-cell distributions which allows for further understanding of such systems and controls development. Last year Perez-Fortes et al. presented a pilot hydrogen and electricity producing plant based on SOFC as the principle technology [106]. They proposed a system that would produce hydrogen for fuel cell electric vehicles, hot water for retail stations like a car wash facility and electricity that can be used by retail station or hydrogen refueling stations with excess that could be injected into the grid. They deviced a multi-objective multi period optimization approach for the conceptual design of this SOFC based system. Their system could reach efficiencies exceeding 60% to up to 80% when heat utilization was considered. There was another paper published last year by Ramadhani et al. that proposed a novel polygeneration system using SOFC for homes and vehicles power supply. This system would provide electricity, hot water, cooling and hydrogen. They investigated the best configuration of the polygeneration by considering two aspects, namely grid connection and type of vehicle supply station. They also considered a multi-objective evaluation by considering the energy, economic and environmental impacts. With their system they were able to achieve primary energy saving of 73%, cost saving of 50% and emission reduction of 70%.

Moving on to MCFC based systems, the literature available is scarce in comparison to SOFC systems for cogeneration of electricity and hydrogen. As with the SOFC the concept of coproduction using MCFC has been around for a while now as indicated by the paper published by Silveira et al. in 1999 [119] where the concept of utilizing waste heat from fuel cell was recognized. While in this study hydrogen was not produced, the waste heat from the MCFC was used to run an absorption refrigeration system to produce cold water necessary for the building. They showed that the overall efficiency of 86% could be achieved.

When considering hydrogen and electric coproduction, few papers have been published with regards to the MCFC system in the past decade. Verda and Nicolin studied a hybrid system with a micro turbine, MCFC and a pressure swing absorption systems. Overall efficiency of 62% was observed through their thermodynamic model . The work of Margalef et al [126]. compared the efficiency of trigeneration high temperature fuel cells using MCFC to other hydrogen production technologies [83]. This study compared the production of hydrogen from a MCFC that tri-generates power, heat and hydrogen to the steam methane reformation supply chains that were centralized and distributed. The supply chain for hydrogen production was said to include: production, treatment, distribution, storage, dispensing and use. They concluded that the highest chain efficiency of about 76% corresponded to distributed hydrogen production via tri-generating system with the fuel cell.

In the paper published by Li et al., they analyzed a tri-generating molten carbonate fuel cells systems for ”big box” store businesses that combine grocery, retail business, and sometimes gasoline retail [77]. They used an internal reforming MCFC and the amount of hydrogen which is a byproduct along with heat varies according to fuel utilisation. They were able to show net efficiency of 50.2% when considering hydrogen plus electricity and a overall net efficiency of 65.66% when heat was considered along with hydrogen and electricity production. They also recognized that such a tri-generation system offers an innovative approach to reduce CO_2 emissions. They concluded that MCFC based technology provides lower emission electricity, hydrogen production and heat. Depending on how the grid electricity is generated, it was found that with natural gas as feedstock, CO_2 emission could be reduced by 10% to 43.6%. They also showed that CO_2 emission can be further reduced to nearly zero when renewable methane feedstock is used.

McLarty and Brouwer proposed a poly-generating fuel cell system capable of achieving a co-producing efficiency of over 80% with carbon capture and liquefaction [86]. They proposed a system with a air separator unit which supplied pure oxygen to the fuel cell and liquid nitrogen to a hydrogen separator unit. This system was designed to be suitable for operation using both MCFC and SOFC. However, when using with MCFC a portion of the recovered CO_2 is recirculated by injecting CO_2 back into the air separator unit oxygen stream at 5:1 molar ratio to provide the species necessary to form the carbonate transport ion [86]. In this system the hydrogen was recovered from the hydrogen separator unit instead of it being oxidized as is the case in most fuel cells. This system could produce electricity from the fuel cell, hydrogen from the hydrogen separator unit, heat from anode outlet and CO_2 for utilization or storage.

Carbon dioxide recovery has been a focus of another tri-generating plant based on MCFC. In their work, Rinaldi et al. explored the possibility of separating and recovering CO_2 in a biogas plant that would produce electricity, hydrogen and heat [112]. As stated by Li et al. with natural gas as the feedstock, the high temperature fuel cells can reduce CO_2 emissions by 10-43%, when renewable biogas feedstock is used the emission can be near zero [77]. Having that in mind Rinaldi et al. investigated further greenhouse gas emission reduction by including recovery of CO_2 from the tri-generation MCFC plant. The carbonate ion transfer mechanism of MCFC significantly reduces the energy required for CO_2 separation. In their model the MCFC was fed with biogas produced onsite from anaerobic digestion of sludge supplied from the wastewater treatment plant. Their study outlined the feasibility of applying carbon sequestration to an already existing MCFC trigenerating plant producing electric power, hydrogen and heat to explore the synergies and limitations of integrating CO_2 recovery. They studied CO_2 recovery from MCFC trigenerating system using three different configurations and concluded that carbon separation and hydrogen co-production processes are indeed compatible and they do benefit from carbonate ion charge carrying property of MCFC. It was also found that excess hydrogen can be produced at lower fuel utilization which reduces electric efficiency, this could be seen as a drawback in some cases. Other drawbacks of this system according to the authors would be related to thermal integration due to additional heat exchange steps or additional compression that could be needed for CO_2 or hydrogen production.

These studies have recognized that hydrogen as a fuel would be an important energy source as it does not produce greenhouse gases upon combustion. However, as conventional methods of hydrogen production are energy intensive processes, that require fossil fuels. There is a need for cleaner and more efficient method for hydrogen production. The hydrogen economy will only be feasible if clean hydrogen is easily accessible, is cheap and the method of production and distribution does not have adverse effect on the environment.

High temperature fuel cells like SOFC and MCFC are mature technologies for converting chemical energy of the fuel into electricity at a much higher efficiency than conventional combustion systems that produce energy. They produce high temperature waste heat during this electrochemical energy conversion. From the literature review of studies mentioned in this section, it is obvious that high temperature fuel cells are suitable for coproducing hydrogen by using the high temperature heat that is liberated. This improves the overall fuel efficiency and flexibility in production of hydrogen and electric power can be achieved. It was also observed that in general, internal reforming fuel cell that are capable of producing hydrogen directly from fuels like natural gas, within the fuel cells, were used in these studies. In the studies with high temperature fuel cells, the overall efficiencies when considering hydrogen and electricity production were generally found to be over 70% and even was found to be up to 95% in one of the cases.

It is seen that while considering high temperature fuel cells in co-production of hydrogen and electric power, most of the studies have been based on SOFC systems. These SOFC based studies were often detailed and described the concept of cogeneration of hydrogen and electric power with the help of various system configurations, and were operated at various levels of fuel utilization. It was also possible to find papers that dealt with the potential of SOFC based systems in specific applications. These included possible use to meet dynamic building demands and hydrogen production for fuel cell electric vehicles.

Even though MOFC system is a mature technology, studies based on MCFC on this particular topic of coproduction of hydrogen and power are far fewer than those that can be found related to SOFC. While few papers based on SOFC have recognized that the systems similar to the ones designed with SOFC are possible with MCFC, not enough research works have been published. From the papers gathered, it was noticed that the contribution of hydrogen production has been recognized in improvement of the overall efficiency. For the distributed trigenergation systems, hydrogen production chain was found to attain an efficiency of over 75% in one of the cases. The major difference from the SOFC was the recognition of the role of carbonate ions in the working of MCFC systems due to the difference in operations. Thus, the application of MCFC in carbon capture was also combined with the trigeneration applications in these studies.

From these studies a clear knowledge gap can be recognized between the use of SOFC and MCFC in cogeneration systems published. The need for studying MCFC system arises due to the following factors:

- While possibility of coproduction of hydrogen and power using MCFC has been recognized, the number of papers available for MCFC in comparison to SOFC is lacking.
- Like SOFC systems, MCFC systems produce large quantities of waste high temperature heat but differ in operation from SOFC and that needs to be analyzed.
- There is not enough evidence on other factors that could play a role in widespread development (other than economic analysis in a few cases) found in these papers.

2.2. Research Question

From the drivers and the literature review the following research question was attained.

What is the feasibility of flexible coproduction of hydrogen and power using Molten carbonate fuel cells (MCFC)?

This question has been answered by answering the following sub questions.

1. What is a molten carbonate fuel cell and what is its significance today?

This question is answered by first describing fuel cells and MCFCs. After which, their significance is determined by comparing them with SOFC and studying their applications today.

2. What is a cogenrating/trigenerating IR-FC system and what are the existing examples of MCFC in hydrogen and power cogeneration?

To answer this question cogeneration/trigeneration with IR-FC is first defined. The available examples in this field including a pilot project and a currently developing commercial project has been highlighted. Their potential application in the Superwind concept has also been presented.

3. What is the technical feasibility of flexible coproduction of hydrogen and power using a MCFC system?

This question is answered by running simulations of the proposed system on the software Cycle-Tempo and analyzing the results through plotting graphs.

4. How does the coproducing MCFC system perform in comparison to a similar SOFC system?

This is done by comparing the results obtained from the MCFC simulation with the results from a SOFC based study.

5. What are the socio-economic feasibility factors that would affect these MCFC systems?

The socio-economic feasibility analysis has been done through analysing information available trough research to draw conclusions regarding the economic factors, hydrogen market, actors and their involvements and policies. This has been followed by a section justifying natural gas use and another highlighting the impact on the society.

2.3. Methodology

This research is inspired by the work of Hemmes et al. presented in Ref. [55]. In their paper based on coproduction of hydrogen and power with SOFC they simulated a system in three different modes of operations with different fuel utilization values. They have used a software called Cycle-Tempo for their simulation. The methodologies used in this report include literature study, flowsheet calculations using Cycle-Tempo simulations, and secondary research.

Literature review is important as it helps to place a research within the context of existing literature while also helping in setting up a theoretical framework. It helps to lay the foundation by identifying gaps in knowledge, setting up the methodology and developing the research questions. It is the nucleus of a research and helps in making a case for why further study is actually needed. Through literature review, available information on a given topic can be studied. In this thesis through literature review, the research question was derived,as research on MCFC in high temperature coproduction applications are lacking in literature. Moreover, through literature review the existing status, working principles and applications of MCFCs have been identified and presented.

The use of software such as Cycle-Tempo in flow sheet calculations can be justified for two main reasons. First, it is the basis of the paper on which the technical feasibility of this thesis is based. Having an identical approach is beneficial, especially where comparisons are needed to be made, like in this thesis. Second, software simulations of a technology is usually an important step in the pre-prototype stage of the development as it gives the researchers an idea of how a system could behave in a real life setting. This would help in identifying and rectifying issues before prototypes are built, thus saving time and resources.

The other approach used in this thesis is the secondary research approach, which helps to qualitatively analyze the information available. This is particularly beneficial in analyzing topics where conducting primary research is difficult due to the lack of sufficient information. Since MCFC are still not widely used, this type of research can be helpful to make valuable conclusions.

These research methods together would help to answer the research sub questions, and ultimately help in answering the main research question.

2.4. Structure of the Report

In this chapter the research question were presented. The research question will be answered by answering the five sub questions presented in section 2.2 earlier. The report follows the following structure.

Chapter 3 first provides a brief introduction to fuel cells. This is followed by a brief description of MCFC and its status today. To help with understanding the significance of MCFC today few major applications of such fuel cells have been presented as well. Since this thesis report is based on a study conducted on SOFC, a brief comparison between MCFC and SOFC is presented. Having introduced the fuel cells, the next part of this chapter defines cogeneration and trigeneration IR-FC systems. This is followed by highlighting the existing research on high temperature fuel cells being carried out around the world. Finally, this chapter ends with a brief section on multi source multi product (MSMP) and superwind concept. This chapter provides answers to research sub questions 1 and 2.

Chapter 4 provides the technical feasibility of the proposed system by first providing a background on the SOFC paper, after which fuel cell theory, and the three modes of operations are described. This is followed by the description of the system model and its operation. After this, results are plotted and compared with those obtained from the SOFC model. The reasons for the difference in performances have also been provided. This chapter answers research sub questions 3 and 4.

Chapter 5 presents the socioeconomic feasibility. In this chapter economic trends and hydrogen market trends have been analyzed. After which the role of actors and their involvement has been examined. This is followed by the investigation of policies that could be responsible for widespread development of the system being investigated. In the section further, the use of natural gas has been justified. Finally, the chapter ends with analysing the impact of such a system on the society. This chapter helps to answer the 5th research sub question.

The answers to these research sub questions forms the basis for answering the primary research question of this report. This has been presented in the report concluding chapter 6 along with discussions, final thoughts and recommendations.

3

Molten Carbonate Fuel Cell (MCFC) Review

As mentioned earlier, fuel cells are devices that convert chemical energy to electricity with the help of electrochemical reactions. Fuel cells have found variety of applications across many sectors as they can achieve high efficiencies and can be scaled in size depending on their use. As MCFC is the main focus of this thesis, this chapter provides a background on MCFC systems. This is done by explaining MCFC technology and its status in the world, after which its current applications have been summarized. As MCFC and SOFC are both high temperature fuel cells that are often considered for use in identical applications, a comparison between the two has also been presented in this chapter as well. This is followed by a section introducing cogeneration and trigeneration principles using internal reformimg fuel cells, with another section after that highlighting existing projects based on these principles. The final section of this project introduces the concept of multi source multi project system and the superwind concept.

3.1. Fuel cells

As the need for electricity has risen in the recent decades, various advancements have been made to produce electric power. Due to a growing demand for cleaner energy, focus has not only been shifting towards renewable energy sources but there is also need for effective utilization of resources available to us. Conventionally internal combustion engines(ICE) have been used to convert the chemical energy of the fuel via combustion into mechanical energy in the form of piston motion. This is then converted into the electric energy by the generator to be supplied to the grid. Electricity can also be obtained from other renewable sources like solar energy, wind energy, hydro energy, tidal energy, geothermal energy and biomass energy through various advancements that have been made and continue to be made. Moreover, electricity can also be obtained directly from chemical energy of the fuels with batteries and fuel cells. While they may seem structurally similar the primary difference between batteries and fuel cells is that, a battery can store its energy, while a fuel cell generates electricity and heat as long as fuel (like natural gas) and air supply is available. As a result of fuel cell consuming fuel and air, there are products of the reactions that are generally released into the atmosphere. The Greenhouse gas emission can be completely eradicated when hydrogen is produced from a renewable energy source or by using CO_2 capture and sequestration. Fuel cells can reduce the dependence on existing electricity grid that is usually outdated and is often pressed beyond capacity. They can function with various fuels that are readily available as well as with waste exhaust streams from industries.

While various types of fuel cells are available today, all fuel cells consist of an anode and a cathode separated by an electrolyte which permits ion conduction and is electrically insulating. At the anode the oxidation of the fuel occurs, this generates ions (usually positively charged hydrogen ions) and electrons. The electrolyte facilitates the movement of ions from anode to cathode as it is an ion conducting medium while forcing the electrons to flow from anode to cathode through the external circuit. At the cathode the available ions react with electrons and oxygen to produce water and sometimes other products. The working principle of a fuel cell is illustrated in figure 3.1. Additionally, the fuel cell theory is briefly explained in chapter 4.

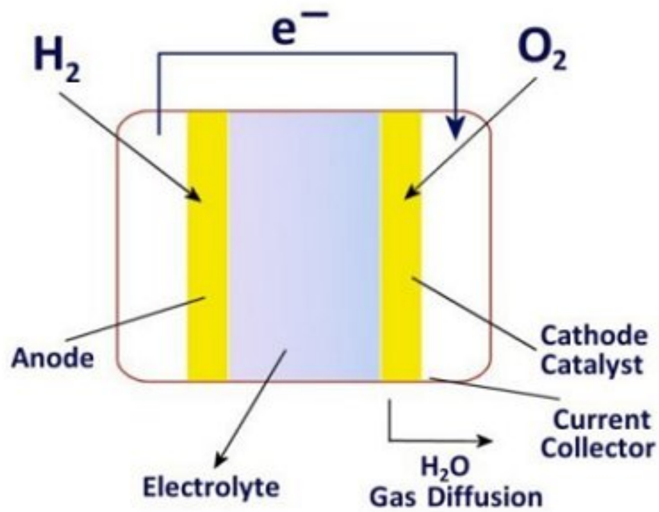

Figure 3.1: Working of a fuel cell. Fig from Ref.[72]

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Fuel cells can be used in stationary applications for generating electricity and heating buildings, in portable applications for powering laptops and phones, and in transport to power electric vehicles and material handling equipment. These applications are provided by various types of fuel cells based on factors like the type of electrolytes and electrode materials used, their operating temperatures, the fuel cell designs and the reactions that occur in the fuel cells. While fuel cell technologies continue to develop, few of these fuel cells are technologically more mature than others. The United States Department of Energy lists Polymer Electrolyte Membrane Fuel Cells (PEMFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), MCFC and Solid Oxide Fuel Cells (SOFC) as the main types of fuel cells [98]. Among the fuel cells mentioned above, PEMFC, AFC and PAFC function at much lower temperatures (<200°C) than MCFC (600-700°C) and SOFC (500-1000°C), due to which the fuel cells mentioned can be classified as low temperature and high temperature fuel cells. The low temperature fuel cells usually have the advantage of quick start up time but require expensive catalysts for their operation and they can be used for distributed power generation, backup power and transportation. The high temperature fuel cells usually do not need expensive catalysts and they offer fuel flexibility in their operation. However, as they operate at high temperatures, they suffer from long startup times, corrosion of electrolytes and the possibility of breakdown of fuel cell components. They find applications in electric utility and distributed generation [98].

Fuel cells have significant advantages over conventional combustion based technologies used in power plants and transportation. Conventional power plants typically generate electricity at about 35% efficiency, while fuel cells can reach electric efficiencies of upto 60% [98]. When cogeneration is considered, efficiencies can be much higher as demonstrated with MCFC and SOFC systems simulations in chapter 4. The electrochemical reactions taking place in the fuel cells are carried out without combustion, and with only few moving parts so they produce low emissions and are favorable from the energy and environmental point of views. As the result of process simplicity in the conversion of chemical energy into electrical energy with fewer moving parts, fuel cell can operate while producing very little noise pollution. Some types of fuel calls may also have the advantage of fuel flexibility and the already available infrastructure of hydrocarbon fuel supply, co-generation capabilities and relatively quick load response [120]. Due to the similarities in construction, fuel cells can power almost all machines that use batteries. However, unlike batteries that die after a certain amount of time, fuel cells supply energy as long as the fuel and oxidant are supplied. Despite the advantages mentioned above, fuel cells have a few disadvantages like high costs due to need for expensive catalysts such as platinum, the lack of infrastructure needed for hydrogen distribution, and high cost of hydrogen production and storage, Moreover, since many of the fuel cell related technologies are in various stages of development, fuel cells are not as widely available as other energy producing technologies.

Mature fuel cell technologies such as PEMFC in mobile applications and fuel cell vehicles or MCFC in stationary power production are nearing cost competitiveness with conventional combustion engines. The cost of technologies related to fuel cells have reduced significantly in the recent years according to various studies. A study published in 2017 by the Department of Energy of the United States, had shown the cost of fuel cell systems had reduced by 60% since 2006 [131]. This study using PEMFC system showed the net cost of operation was down to \$45-\$50/KW in 2017 and was expected to further decrease by 2020. They attributed this reduction in cost to improved research and developments of catalysts, increased durability of components, and improved electrode performance. In transportation the cost of of fuel cell vehicles have decreased significantly as well and according to Ballard, a leading fuel cell manufacturer, the cost of fuel cell vehicles have dropped by 65% in the last 10 years and this was partly due to the innovations in technology and product improvements related to the fuel cells [107]. According to them by 2030 it will be possible to make fuel cell vehicles competitive with battery electric and ICE vehicles. These studies give a glimpse into the possibility of decreasing fuel cell costs significantly in the near future.

Fuel cell technologies will benefit from the increased focus towards hydrogen production. While high temperature fuel cells are capable of internal reforming to produce hydrogen needed for operation, most of the hydrogen is produced through external reforming of natural gas. For instance, in the United States 95% of the hydrogen is produced by reforming natural gas in large central plants [97]. While natural gas is easily available, natural gas reforming requires a large amount of energy and produces CO_2 as a byproduct. The CO_2 produced can be reduced by carbon capture, utilization and storage (CCUS), or by using renewable sources to produce "green hydrogen" by supplying energy for the electrolysis of water to produce hydrogen. The European Union (EU) expects investment in hydrogen will provide jobs and help in sustainable growth, which will be crucial for recovery from the ongoing COVID-19 pandemic. The EU has set a target of installing 40GW of electrolzyers within its boarders by 2030 to produce green hydrogen [19]. Germany as a part of the "National Hydrogen Strategy" has also invested around €7 billion on new business and research around green hydrogen [35]. Since currently hydrogen produced from renewable energy sources constitute only a tiny amount, from these reports we can see an increased interest in not only hydrogen but in hydrogen that can be obtained in a cleaner manner.

Fuel cells have more advantages than disadvantages over the conventional energy producing systems. Having seen the decreasing trends in fuel cell costs and increased interest in hydrogen fuel, it can be said that fuel cells will play a huge role in the energy infrastructure in the future.

3.2. MCFC technology

Molten carbonate fuel cells are high temperature fuel cells that operate at temperatures around $650°$C. The electrolytes found in these fuel cells are usually carbonate salts (like LiK or $LiNa$ carbonates) which have been stabilized in an alumina based porous matrix (e.g. $LiAlO_2$ with Al_2O_3 inserts) [25]. The electrodes used in MCFC are generally made from inexpensive nickle based materials that can be constructed as stacks or bipolar plates. Since these fuel cells operate at high temperatures, they do not need expensive elctro-catalysts like Pt in the electrodes.

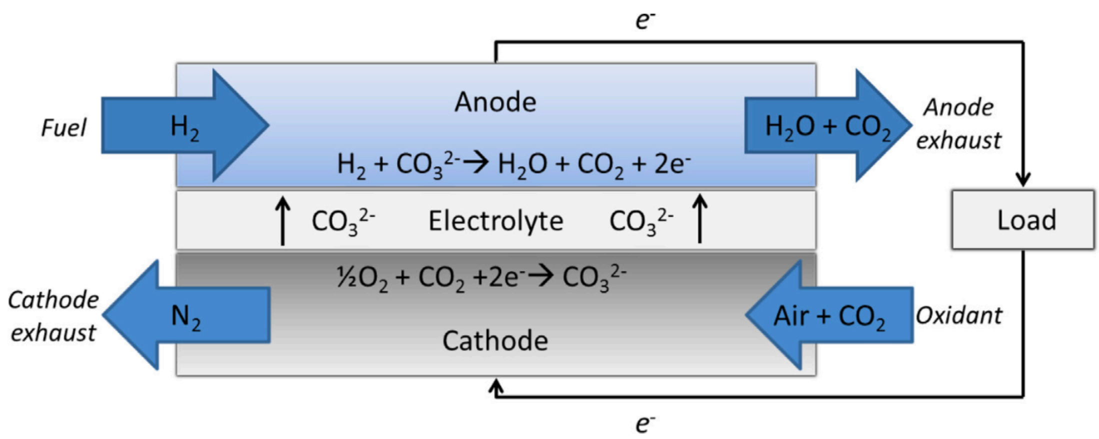

Figure 3.2: The working principle of MCFC. Fig from Ref.[111]

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The carbonate salts melt when operating MCFC at high temperatures of about $600°$C. This is necessary as in the molten state the conductivity of the electrolyte improves and carbonate ions can be transferred from cathode to anode. At very high temperatures of above $700°$C, there is a possibility of increased corrosion and electrolyte vaporization. Therefore, such fuel cells operate within a range of temperature between $600°$C and $700°$C. This range of higher operating temperature also provides for fuel flexibility, as a variety of hydrocarbon fuels like natural gas, alcohols, synthetic fuels from petroleum coke, coal and biomass can be reformed to generate hydrogen required by the fuel cells [127].

The working principle of MCFC is shown in figure 3.2. As seen in the figure, hydrogen is oxidized at the anode to produce water and carbon dioxide. Meanwhile, at the cathode, reduction of oxygen with carbon dioxide takes place. During these processes electrons are liberated at the anode and carbonate ions are produced at the cathode. The carbonate ions travel from cathode to anode through the ion conducting electrolyte while the electrons travel from anode to cathode in the external circuit and generate electric power. Water that is produced at the anode is removed with CO_2. Additionally, CO_2 and air needs to be supplied to the cathode. Therefore a part of CO_2 from the anode exhaust is usually recycled back into the cathode to maintain the electrolyte composition. This can result in complexity associated with the MCFC systems [127]. The reactions at anode, cathode and the overall cell reaction has been shown in equations 3.1, 3.2 and 3.3 respectively.

Anode reaction:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \tag{3.1}$$

Cathode reaction:

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \tag{3.2}$$

Cell reaction:

$$H^2 + \frac{1}{2}O_2 + CO_2(cathode) \rightarrow H_2O + CO_2(anode) \tag{3.3}$$

The normal supply of hydrogen to MCFC, which is usually from reformed natural gas contains some carbon monoxide. It is possible to utilize this CO by oxidation at the anode or through water-gas shift (WGS) reaction when mixed with water vapor. These reactions are shown in equations 3.4 and 3.5. Carbon monoxide is a catalyst poison in low temperature fuel cells. However, the insensitivity of MCFC to CO poisoning offers a significant advantage to MCFC over other fuel cells like the Proton-Exchange Membrane Fuel Cells (PEMFC) and the Phosphoric acid fuel cells (PAFC).

CO oxidation at anode:

$$CO + CO_3^{2-} \rightarrow CO_2 + 2e- \tag{3.4}$$

Water-gas shift (WGS) reaction:

$$CO + H_2O \rightarrow H_2 + CO_2 \tag{3.5}$$

Conventionally, a carbonaceous fuel is supplied to a fuel processor where hydrogen is produced after it has been steam reformed. The hydrogen that is produced is then fed to the fuel cell for the electrochemical reaction taking place in the fuel cell. With internal reforming MCFC, it is possible to eliminate the need for a separate fuel processor for the carbon rich fuel. This concept is feasible and practical in a high temperature fuel cell like a MCFC where steam reforming reaction can be sustained with catalysts. The concept of internal reforming MCFC is fully realized when the reforming reaction and the electrochemical oxidation reaction within the fuel cell are closely coupled [92]. The internal reforming approach provides a highly efficient system which is simple, more reliable and cost effective in comparison to the conventional MCFC system. In case of direct internal reforming, hydrogen consumption at the anode reduces the partial pressure and drives the reforming reaction to the right as shown in equation 3.6. This results in higher fuel utilization and increased efficiency.

Methane steam reforming:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \tag{3.6}$$

Methane is a common hydrocarbon fuel utilized in internal reforming MCFCs, but $650°C$ is a sufficiently high temperature for steam reforming with other hydrocarbon fuels which makes these internal reforming MCFCs flexible in terms of fuel supply. In internal reforming fuel cells the steam reforming reaction like the one shown in equation 3.6 occurs simultaneously with the electrochemical oxidation of hydrogen at the anode. The reforming reaction is sustained at high temperatures of about $650°C$ by Ni based catalysts to produce hydrogen required by the fuel cell. It is important to note that the steam reforming reaction is endothermic while the overall fuel cell reaction is exothermic. The heat from fuel cell reaction provides the heat needed for steam reforming reaction. This eliminates the need for external heat exchange that is needed in the conventional fuel processor that is a part of externally reforming MCFC systems. Besides, the steam produced in equation 3.1 can be used to generate additional hydrogen by enhancing the WGS and the reforming reactions. The reforming reaction shown in equation 3.6 favours high temperature and low pressure for the forward reaction to occur. Thus, these internal reforming MCFC benefit from operating close to atmospheric pressure [92].

3.3. Status of MCFC

Molten carbonate fuel cells operate at high temperatures, have slow-start up time and are usually heavy. Due to the relative complexity of these fuel cells, they are not suitable for manufacturing and operating very small units for domestic operations. Most of the MCFC units that have been developed are over 100kW in capacity [11]. MCFC are suited for large stationary power applications. FuelCell Energy is the main manufacturer and is responsible for almost all the MCFC systems for stationary application installed today. As shown in figure 3.3 MCFC contribute a very small percentage in the total global fuel cell capacity of over 1,100KW [27].

The most significant step in commercialization of MCFCs has been due to the collaboration between the United States Department of Energy (US DOE) and the company FuelCell Energy. In 1993 they started testing an internal reforming MCFC stack that ultimately formed the basis for the 2 MW demonstration project in Santa Clara, California in the United States between 1999 and 2000. With further financial assistance from the US DOE, FuelCell Energy was able to develop MCFC with capacity of 50MW/year by 2002 [11]. Figure 3.4 shows the global rise in MCFC systems is dominated by the United states and South Korea.

By the end of 2007 with the help of FuelCell Energy, the number of installed MCFC plants had increased to 40 in the United States with the total capacity of 11.5MW, 15 in Asia amounting to 8.5KW and an additional 12 in Europe corresponding to 4.5MW [90]. In the last decade the company has had three products with generating capacities of 300kW, 1.4MW, and 2.8MW that can achieve electric efficiency of 47% [11]. FuelCell Energy has also collaborated with few other major companies producing MCFC over the years. Fuel Cell Energy Solutions acquired the fuel cell activities of MTU Friedrichshafen FmbH (MTU) in 2012 which was a joint venture between FuelCell Energy and Fraunhofer IKTS. They are now the main suppliers of MCFC in

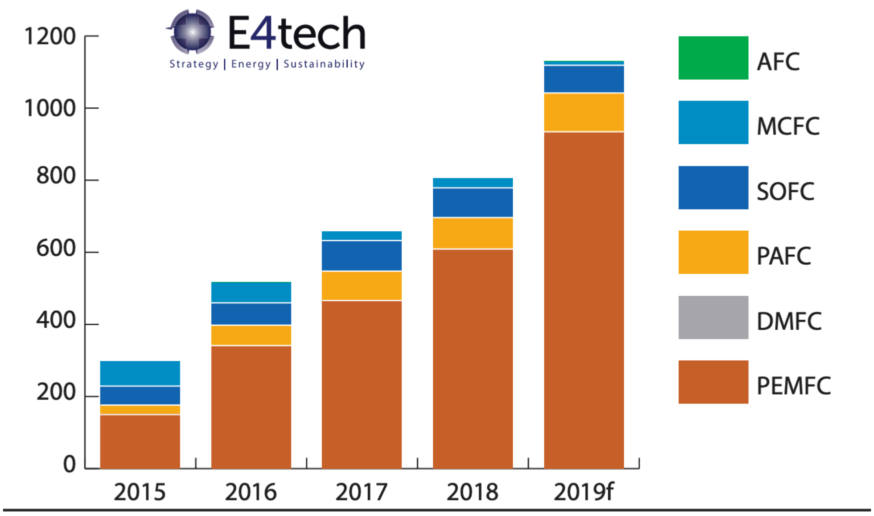

Figure 3.3: Megawatts by installed fuel cell types in the last five years. Fig from Ref.[27]

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Europe [11].

FuelCell Energy also formed a distribution and manufacturing agreement with a South Korean Company known as Posco Energy in 2007. South Korea is the other main center of MCFC technology after the United States. Posco Energy has collaborated with Korea Electric Power Corporation (KEPCO),which is the largest electric utility in the country since 2000. Together they develop and operate a 125 KW MCFC prototype with external reformer in 2010 [11]. The manufacturing capacity in South Korea had reached 100MWe per year and the country had installed a total of 150 MWe of MCFC plants for stationary applications at 23 different cites by 2015 [63]. The world's largest fuel cell park is in South Korea and is operated by Gyeonggi Green energy consists of 59 MW MCFC systems from FuelCell Energy and Posco Energy collaboration [27].

Elsewhere a French company, Franco Cell, is working on a MCFC system based on external ethanol reformation to provide methane that is well suited to feed a standard MCFC stack. They hope that these external reforming MCFC plants with generating capacity of 3.3MW can find applications in small power plants in French Caribbean Islands [11].

FuelCell Energy continues to be the primary manufacturer of the MCFC technology in the world today. Recently, FuelCell Energy has shown interest in the carbon capture capabilities of MCFC and on 2016 they announced a collaboration with ExxonMobil to test carbon capture technology on a power plant at the James M. Barry Electric Generating Station operated by Alabama Power [99]. Fuelcell Energy which has helped install close to 150MW of MCFC in the United States aims to install additional 150 MW by 2021 in the state of Connecticut [129]. The company has recognized the need for further reduction of the total cost of ownership, continued education and acknowledgement of the value their solutions provide as the primary challenges it faces regarding MCFC systems[99]. FuelCell energy has also shown interest in tri-generation plant that will produce hydrogen, power and heat by announcing collaboration with Toyota [31].This development was approved to proceed in December 2017 at the Toyota's Port of Long Beach facility in California and has been briefly summarized in section 3.7.

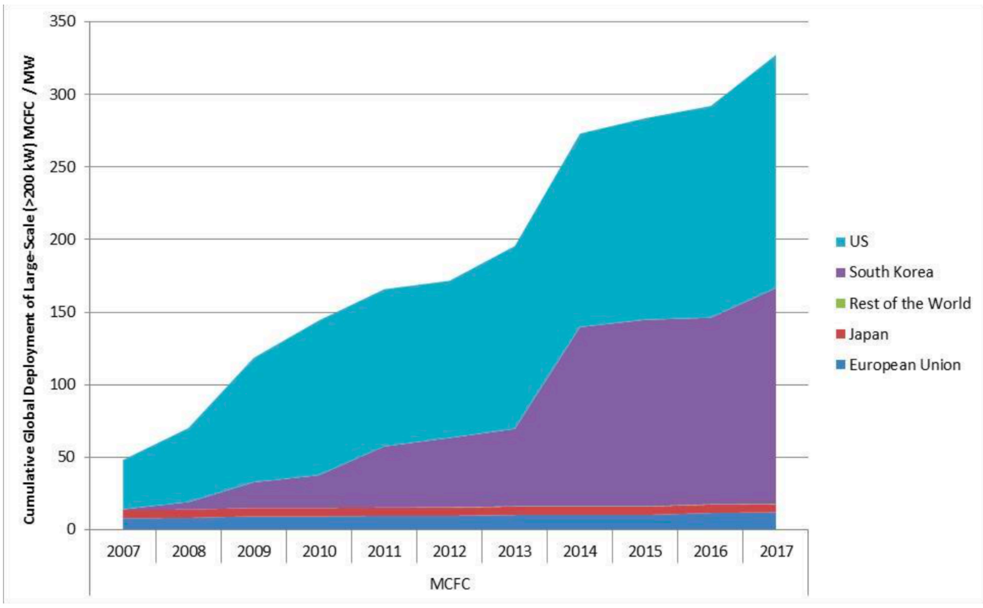

Figure 3.4: Global deployment of MCFC in stationary application. Figure shows the cumulative capacity from 2007 to 2017. Fig from Ref.[129]

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From this section it is evident that most of the developments taking place in the field of MCFC have been carried out by FuelCell Energy. The United States and South Korea are the leading geographical regions where these fuel cell technologies are deployed.

3.4. Applications of MCFC

As MCFC are complex fuel cells and are only economical when they are over 100KW in capacity when they are more suited for larger applications. Having discussed the status of the MCFC, in this section few of the applications of MCFC is mentioned.

High temperature fuel cells like MCFC are suited for use in hospitals, school and other larger commercial operations where they can provide power and heat to their customers. In South Korea several MCFC plants provide power and district heating to the city of Hwaseong [11]. Large MCFC based stationary plants have the potential of reducing load on the outdated transmission grid. With concept of distributed generation, such plants can improve transmission reliability and efficiency when the power plants are installed near consumers. In Europe, MCFC are also being developed for marine applications. The European Union contributed nearly €10 million into the project titled Molten-Carbonate Fuel Cells for Waterbourne Applications (MC-WAP) in 2005 [18]. This project analysed the performance of MCFC among other things through real-life and real-size tests. Through these tests and demonstrations they explored the future potential of MCFC fuel cells in marine applications. Typically MCFCs are generally suited for large stationary power generation where they can attain combined efficiency of over 80% by producing heat and electric power while reducing primary fuel consumption and emissions. Despite their highly efficient application in stationary power, its their operating principle their has made them popular for carbon capture studies. The concept of carbon capture using MCFC is explained in the following subsection.

MCFC in Carbon Capture

One of the most important challenges associated with power generation systems today is the reduction of green house emissions, and in particular CO_2 emissions. Carbon dioxide can be reduced by increasing the efficiency of the power generating systems, switching to cleaner renewable energy sources or by CCUS.

There are three main approaches to carbon capture for industrial and power plant applications and they have been described in [87].In the first approach, the pre-combustion systems process the primary fuel in a reactor, and separate streams of hydrogen and CO_2 is produced. Hydrogen that is produced is then used as a fuel and the CO_2 produced is stored. The second approach involves oxy-fuel consumption where oxygen is used instead of air for combustion. The flue gas that is produced contains mainly H_2O and CO_2 that can be easily captured. The third and final approach involves post-combustion systems that separate CO_2 from the flue gases produced from the combustion of primary fuels in air.

Generally, the carbon capture is applied post combustion. It is because this approach involves only a few modifications in the power generating systems since it can be adapted to easily retrofit in them. Usually this ”passive” method of post combustion capture require chemical solvents to absorb CO_2 and this method can yield up to 90% removal of carbon dioxide [14]. Though high separation efficiencies can be reached, the major drawback of this method is that it is responsible for considerably reducing the plant power output and its efficiency. This is because large amount of energy is needed to regenerate the chemical solvents.

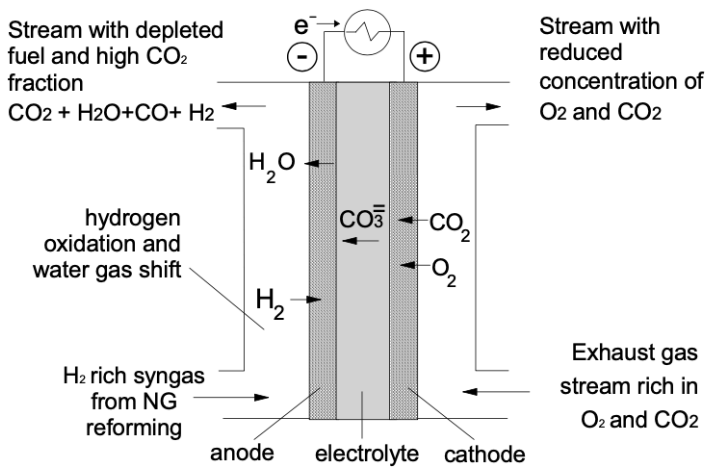

Figure 3.5: Schematic representation of carbon capture using MCFC fed with externally reformed natural gas. Fig from Ref.[14]

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From the electrode reactions shown in equations 3.1 and 3.2, it can be observed that in a MCFC system carbon dioxide is transferred from cathode to anode side. From the cell reaction in equation 3.3 it is also seen that for each mole of hydrogen reacting in a cell, a mole of CO_2 moves from cathode to anode. In considering the use of MCFC in carbon capture, the idea is to feed the cathode of the MCFC with exhaust gas from conventional power plant operating with fossil fuels to filter out the CO_2 content. In this case the MCFC is the ”active” component as it adds power to the plant energy balance while acting as a CO_2 concentrator [14]. Figure

3.5 shows the movement of gases and the carbonate ions in a MCFC that is fed with externally reformed natural gas. The concentration of CO_2 takes place in the anode off-gas from where it can be separated. The overall energy balance for the CO_2 transfer is positive since the fuel cell produces additional "CO_2-free" power [15]. Moreover, the specific emissions kg_{CO_2}/MWh_{el} is also reduced in comparison to passive methods that use chemical solvents.

As the CO_2 is supplied by the exhaust from a conventional combustion process, the concentration of CO_2 at the cathode plays an important role in the performance of the fuel cell. It is shown in equation 3.2 that O_2 and CO_2 are needed for the cathode reaction to occur. If the concentrations of CO_2 and O_2 present in the exhaust gas stream entering the cathode is too low, it could affect the fuel cell performance negatively. It should be also noted that MCFC cannot separate all of the CO_2 entering the cathode, neither can it oxidize all the fuel entering the cell. Therefore, when operating MCFC in carbon capture and storage applications the operating conditions and performance is determined by the trade off between MCFC output and CO_2 separated. While a high CO_2 separation efficiency of over 50% due to structural working features can be obtained, it is not comparable with the passive approach of separation using chemical solvents. Another issue with such systems is that while CO_2 is concentrated at the anode, significant fractions of residual CO and H_2 or other unburned gases are still present that needs to be removed from the anodic off-gas rich in CO_2 .

Despite the few drawbacks the advantages offered in terms of added power output, increased efficiency and the ability of MCFC to be applied to existing plants, the possibility of using MCFC systems in carbon capture has been reviewed by few author over the years. Amorelli et al. studied hybridized systems for CO_2 using MCFC systems developed by Ansaldo Fuel Cell S.p.A. with British Petrol [7]. The Hybrid system combined MCFC technology with a conventional gas turbine. They fed the CO_2 and the remaining oxygen in the off gas from the fossil fuel plant to the cathode of the fuel cells. This resulted in additional power at high efficiency from the hybrid system instead of decreased efficiency and power if a existing passive carbon capture technology was used. They were able to show a 45% reduction of CO_2 emission per KWh produced at 4% vol CO_2 in the cathode input. At levels of CO_2 below 2% by volume, power density fell away dramatically resulting in negative overall performance [7]. In their work, Descepoli et al. reviewed carbon capture with MCFC with experimental tests and performance assesments and found that the MCFC is strongly affected by cathodic carbon dioxide concentration [26]. They observed that voltage drops gradually until a certain threshold (<8%), after which a sharp drop in voltage occurs. They were also able to show a maximum of 70% CO_2 with their system. The work of Campanari et al. proposed a natural gas combined cycle with a MCFC placed between the gas turbine and the heat recovery unit. They showed the possibility of CO_2 reduction between 58% to 68% and increased power output of up to 20% by operating their system in different configurations [14]. Similarly, Desideri et al. studied MCFC based CO_2 capture systems for small scale CHP plants and were able to achieve a 60% CO_2 removal efficiency, with a CO_2 purity of 82.2% from a CHP plant operating at an overall 85% efficiency (electric and thermal combined) [24].

These studies have offered a few possibilities of utilizing MCFC in carbon capture applications but more research is needed in this field. While the CO_2 concentration is possible at the anode, there needs to be a better understanding of lower CO_2 tolerance limit in the cathode input. Better understanding of other factors such as the effects of fuel utilization, loads, cell designs, flow rates need to be further examined. Additionally, the drawbacks associated with these systems need to be further evaluated to determine their competitiveness against other carbon capture methods.

3.5. Comparison between MCFC and SOFC

Just like the molten carbonate fuel cells, solid oxide fuel cells are electrochemical devices that operate at high temperature to convert chemical energy of the fuel directly into electrical energy. Both these fuel cells have been considered for use in similar applications like in stationary power generation and typically distributed cogeneration systems where waste heat from these systems is utilized as well. Since the technical feasibility chapter of this thesis is based on a paper primarily on SOFC, in this section the comparison between the two fuel cells has been presented.

The main difference between the two fuel cells is in the operating principle. The working of MCFC systems is shown in section 3.2. The SOFC operates at much higher temperatures than MCFC. For efficient energy conversion the SOFC usually operates in the temperature range between $800°$C to $1000°$C. Typically these fuel cells contain an oxygen ion conducting ceramic electrolyte membrane usually composed of y_2O_3-stabilized ZrO_2 (YSZ) films. The electrodes in these fuel cells are usually comprise of a perovskite cathode, and a nickel cermet anode. The reactions taking place in the SOFC are as follows

Anode reaction:

$$O^{2-} + H_2 \rightarrow H_2O + 2e^- \tag{3.7}$$

$$(4O^{2-} + CH_4 \rightarrow 2H_2O + CO_2 + 8e^-) \tag{3.8}$$

$$(CO + O^{2-} \rightarrow CO_2 + 2e^-) \tag{3.9}$$

Cathode reaction:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{3.10}$$

Cell reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3.11}$$

In the SOFCs, the useful electrochemical driving force is provided by the reducing nature of the fuel fed to the anode. The fuel oxidation occurs at the anode/electrolyte interface as shown by reactions 3.7, 3.8 and 3.9. The anode transfers the oxygen ions to the active catalytic sites and releases the electrons into the external circuit. The cathode operates in an oxidizing environment, in presence of air or oxygen at very high temperatures of up to 1000°C [34]. Electrochemical reduction of oxygen to oxide ions occurs by consumption of two electrons as shown in equation 3.10. These ions formed by reduction are absorbed into the electrolyte through oxygen vacancies which helps them travel to the anode. The overall cell reaction is shown in equation 3.11. The electrolyte YSZ is an ionic conductor and electronic insulator. To achieve good cell performance the electrolyte is kept free of porosity to avoid gas permeation, is thin and uniform as possible to minimize Ohmic losses, and its ion transport number is kept close to unity, while the transport number of electrons is close to zero. Operating the SOFC at high temperature also improves the reaction kinetics and reduces the need for expensive catalysts. Additionally, by operating at high temperatures SOFC systems can tolerate impurities. Sulfur tolerances in SOFC can be up to two orders of magnitudes higher than any other fuel cells due to their high operating temperatures [127].

	Molten Carbonate Fuel Cells (MCFC)	Solid Oxide Fuel Cells (SOFC)
Temperature	$600 - 700°C$	$800 - 1000°C$
Charge Carriers	CO_3^{2-}	O^{2-}
Electrolyte	Liquid Molten Carbonate, $(Li, K, Na)_2CO_3$	Solid Ceramics, $Zr_{0.92}Y_{0.8}O_2$
Electrical Efficiency	45-50% (Ref. [30])	60% (Ref.[29])
Fuel	Offers fuel flexiblity. e.g. H_2, CO and CH_4	Offers fuel flexiblity. e.g. H_2, CO and CH_4
Catalyst	Nickle	Nickle, Perovskites
Reformer	internal or external	internal or external
Typical Operating Voltage	0.8V (Ref.[127])	0.7V (Ref.[127])
Status of development	1.4MW, up to 3.7MW when modules combined (Ref.[30])	up to 300KW in demonstrations (Ref. [29])
Estimated Lifetime	7000-8000h (Ref.[46])	1000h Ref.[46])

Table 3.1: Comparison between MCFC and SOFC.

The main points of comparisons between the two fuel cells have been presented in table 3.1. As both these fuels operate at high temperatures, start up time is long therefore they are both usually suited for stationary power generation applications. Just like the MCFC the cost of production can be lowered as they do not need expensive catalysts like platinum. Fuel flexibility and the option of internal or external reforming is available to both these systems as they operate at high temperatures. When used in cogeneration applications both these fuel cell systems are capable of reaching overall efficiencies of over 80%.

As SOFCs operate with a solid electrolyte, they do not deal with the complications arising from working with a liquid electrolyte like the MCFCs. The primary drawback of molten carbonate fuel cells is its durability. High working temperature along with the use of a corrosive liquid electrolyte can result in electrolyte leakage, component breakdown, and corrosion, resulting in decreased cell life. While the SOFC does not deal with issues related to liquid electrolyte, operating at extremely high temperature still poses problems such as material incompatibilities that could be thermal or chemical, corrosion and cracking. Additionally, thermal shielding is needed to prevent heat loss from the system and retain the extremely high working temperatures required by the SOFCs.

Sulphur poisoning is an issue in both these fuel cells. Although MCFC systems are more resistant to impurities than most other fuel cells, they are highly susceptible to sulphur poisoning. In these fuel cells hydrogen sulphide can interact with anode and negatively effect the fuel cell performance even if only 0.5ppm of it is found in the anode fuel gas [17]. Moreover, recirculation of anode off gas causes sulphur poisoning by SO_2 as any H_2S present in the anode exhaust gas is oxidized to SO_2 before entering the cathode. SOFCs on the other hand have a slightly better lower threshold of 1ppm [135]. At very low concentrations, the adsorption of sulfur on nickle is reversible and can be tolerated by the SOFC if it is found in the feed gas. This is especially true at higher operating temperatures as the catalyst and anode tolerance to sulphur increases with increasing temperatures. However, at higher concentrations irreversible sulfidation process can occur on the anode or the catalyst and hinder the cell performance

[135].

Solid oxide fuel cells can have multiple geometries, which is not the case with most other fuel cells, including MCFC. There are two main geometries of SOFC today commonly found in testing devices. (i) Planer: In this design the components are assembled in flat stacks with fuel and air flowing through the unit via channels built in to the anode and the cathode. (ii) Tubular: In this design the air is supplied to the inside of a solid oxide tube while the fuel is supplied to the outside. A tubular SOFC cell usually consists of long porous YSZ ceramic tube acting as a substrate. The inside of the tube is usually sealed at one end and the cell components, cathode, electrolytes and anode are deposited in layers around the outer surface of the tube. It has been noted that tubular cells experiences lower stresses among the two configurations [34]. This suggests that smarter designs can alleviate possible stresses which can be a major issue in these cells.

The MCFCs and the SOFCs systems have different charge carries, in a MCFC the charge carriers are the carbonate ions and in a SOFC they are the oxide ions. As MCFCs require CO_2 to be constantly supplied at the cathode along with oxygen, they tend to be more complicated. In such fuel cells a part of the anode exhaust is recirculated to be mixed with the cathode gas input to maintain the CO_2 levels required for the optimum functioning of the fuel cells. This not only contribute to the complexity in terms of adding to the physical system but also contribute to sulfur poisoning through SO_2. These problems are not present in the SOFC systems as the cathode reaction only requires oxygen.

Just like with the MCFC technology, for the SOFC to be economically competitive in widespread applications, there is a need for further reduction in materials and system fabrication costs. Currently it is the second most popular fuel cell behind PEMFC with 24,900 units sold in 2018 [27]. Alternate materials as well as designs are being considered and research in these fields are being carried out to reduce cost and improve performance. Developments are also being considered for operating SOFC at lower temperatures between $(550 - 800°\text{C})$ in the recent years [127]. This could support better thermal integration with fuel reformers and sulfur removal systems, lower heat loss, reduce start up time and thermal stress among other advantages.

3.6. Cogeneration/trigeneration using IR-FC

In the case of conventional power plants, the heat that is produced is often not utilized. These energy generating systems produce heat as a byproduct while producing electricity generally from combustion of a fuel. The exhaust gases carrying this ”waste” heat energy would traditionally be disposed into the environment while contributing to lower fuel efficiency. The electricity production efficiency of such plants is low and in the Netherlands it was found to be around 42% [53]. Therefore, there is a need to decrease the exergy loss while increasing the efficiency to make the system more sustainable.

Cogeneration is found to increase the energy conversion efficiency by using heat that would be otherwise lost to the environment [53]. Cogeneration principle is widely utilized in heat and power applications. Through cogeneration practices some of the heat can be recovered to be used for general heating applications, producing electricity, or in other applications that may require additional heat energy. This approach results in higher fuel efficiency, thus reducing cost of operation and impact on the environment.

In the late 1960s and early 1970s interest in cogeneration grew as the need for the conservation of energy resources became obvious [123]. In the United States the Public Utilities Regulatory Policy Act that was passed in 1978 encouraged the cogenerators to connect with the utility network to purchase and sell electricity. In Europe, individual countries where the fuel costs are higher, cogeneration is encouraged. In Denmark for example, 27.5% of all electricity is produced by cogeneration with future energy projects requiring the use of some form of alternate energy or cogeneration technology [123]. In Italy, low-interest loans for building new cogeneration facilities that can cover upto 30% of the cost of construction are available [123].

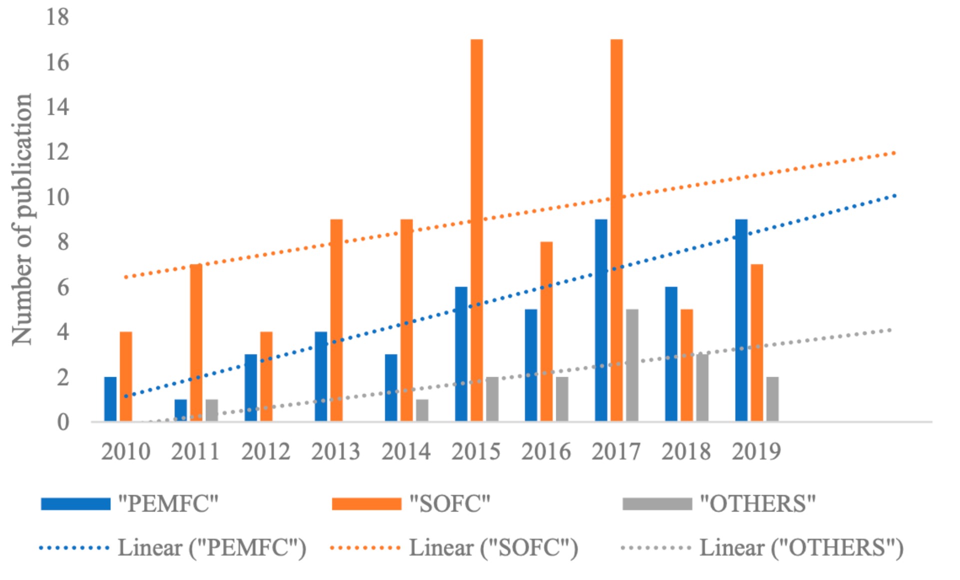

Figure 3.6: Trends in the research publications based on the use of fuel cells in CHP applications in the last decade. Ref. [108].

The applications of cogeneration are typically associated with combined heat and power plants (CHP) plants. By 2016, the United States had 126 fuel cell systems with capacities of 5 to 2800KW, that were configured for CHP applications [96]. The graph shown in in Fig. 3.6 shows that in the CHP applications based on fuel cells, PEM fuel cell and SOFC are significantly more researched than the other types of fuel cells. Almost 90% of all fuel cell technology employed in CHP applications is based on PEM fuel cells [80].This is due to extensive research, besides high efficiency and durability, which has resulted in reduction in cost of these fuel cells. It is possible to expand the concept of cogeneration into tri-generation systems (three outputs) or polygeneration systems (three or more outputs). Essentially tri-generation system is a polygeneration system for power, heating and cooling. However, it is also possible to obtain a fuel like hydrogen along with power and heating from polygeneration systems for which high temperature fuel cells are suitable. Figure 3.7 shows the classification of energy systems based on the number of useful energy outputs along with their efficiencies.

High temperature fuel cells can run directly on natural gas and utilize the heat that would be otherwise wasted to convert natural gas into hydrogen internally. This is an example of polygeneration, as in this case, electric power, hydrogen and heat is produced. The conversion of natural gas into hydrogen within high temperature fuel cells is carried out by an endothermic reaction known as the ’steam methane reforming’, similar to the one mentioned earlier [53].

$$CH_4 + 2H_2O \Rightarrow CO_2 + 4H_2 \tag{3.12}$$

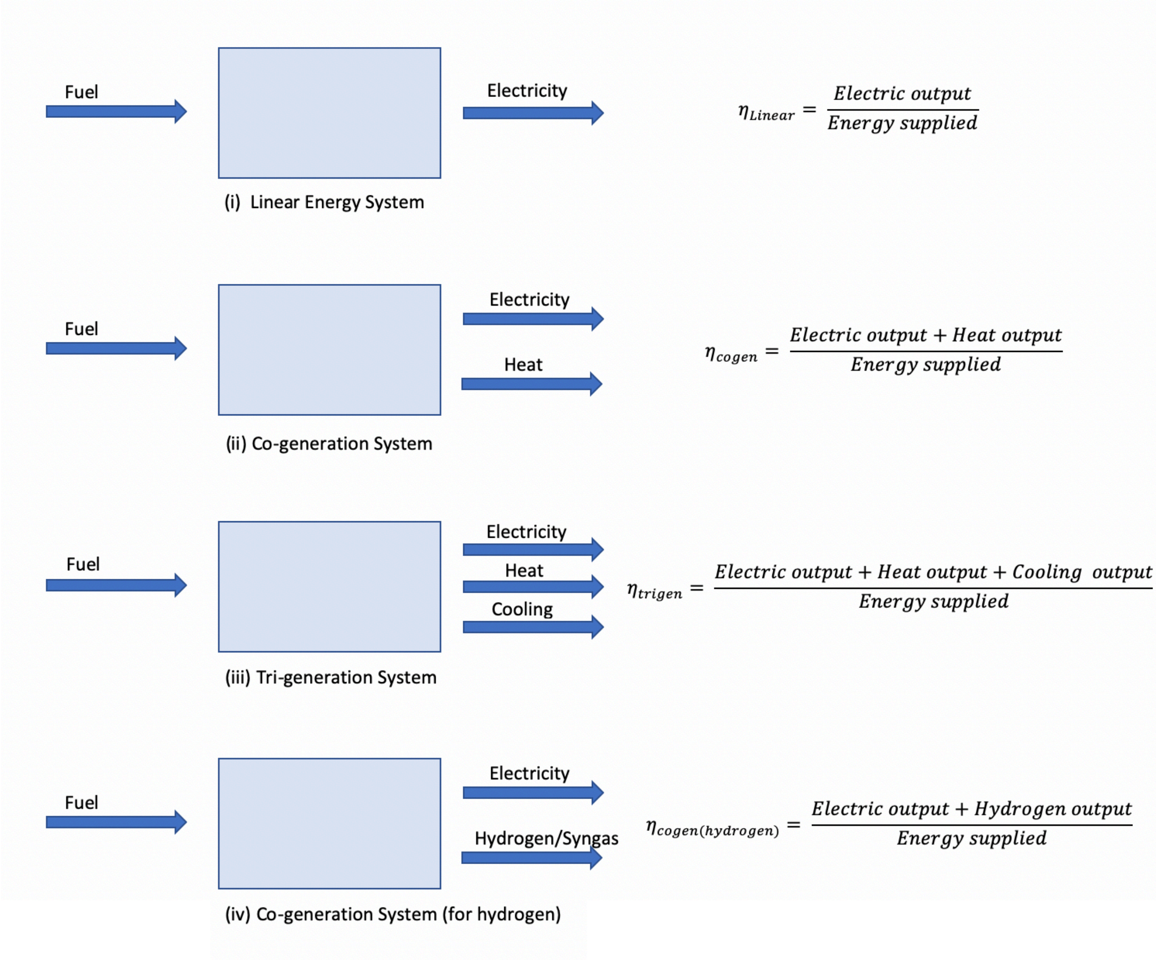

Figure 3.7: Classification of Energy Systems and their Efficiencies

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The hydrogen produced in this reaction is then utilized in the electrochemical reactions in the fuel cell to produce heat and electricity. A part of this heat is utilized in the endothermic reforming reaction mentioned above 3.12. Thus, by reducing the heat loss, overall exergic efficiency of the system is improved. It is possible to increase the amount of hydrogen liberated from the reforming reaction. This can be done by decreasing the electric power output or by increasing the fuel input. The exhaust from fuel cell , which is essentially reformed natural gas, contains a significant amount of hydrogen. Similar to the process of conventional hydrogen production by steam methane reforming of natural gas, hydrogen can be obtained from the off-gas discharged from the fuel cell. In the standard, conventional fuel cell operation, as almost all of the fuel is used for generating electric power, very small concentrations of fuel is available at the fuel cell output. About 50% of the losses in high temperature IR-FCs under such operating conditions are from Nernst losses [53]. These Nernst losses can be reduced significantly by producing hydrogen with IR-FCs and a overall system efficiency of up to 90% can be achieved in flow sheet calculations for producing electric power and hydrogen [55]. In figure 3.7, diagram (iv) represents high temperature IR-FCs in cogenaration configuration where hydrogen and electric outputs are considered as the useful outputs.

Due to the flexibility in the coproduction of hydrogen and electric power, it is possible to operate such IR-FC systems to meet their fluctuating demands and optimize the system for high economic efficiency [53]. Other advantages for using HT-FC like MCFC in cogeneration/trigeneration applications include, fuel flexibility as natural gas or even renewable biogas can be used, near zero emission of criteria pollutants without any water use, availability of clean hydrogen generated near or at the point of use, and the readiness of such systems for immediate deployment [75]. In this thesis this flexible coproduction of hydrogen and power is examined using a IR-MCFC model developed at TU Delft in Cycle-Tempo software. The technical feasibility is found in the next chapter.

3.7. Existing Projects on Coproduction of Hydrogen and Power using MCFC

Currently there are two examples of the use of MCFC in tri-generation systems, both are in the United States. The first one, a pilot project that was situated in Fountain Valley, California was developed with the purpose of demonstrating such systems. The second one is a full scale commercial project currently under development at the Port of Long Beach in California.

World’s First Tri-Gen Energy Station at Fountain Valley

The concept of tri-generation to produce hydrogen, heat and electricity has been studied through a demonstration project that was developed in a partnership involving the United states Department of Energy, Orange County Sanitation District (OCSD), California Air and Resource Board (CARB), South Coast Air Quality Management District, academia and private industry. The project that was the first of its kind was managed by FuelCell Energy, Inc., Air Products, the South Coast Air Quality Management District and the National Fuel Cell Research Center (NFCRC) at the University of California, Irvine (UCI) [75] [95].

The Fountain Valley energy station was supported in part by a \$2.2 million grant from the United states department of energy. It was the first tri-generating system that provided power, heat and hydrogen from stationary, power generating fuel cells [95]. A three year pilot program shown in figure 3.8 was installed at an OCSD facility based on FuelCell Energy’s commercial power plant products. This trigeneration system used a MCFC (DFC-H2® from FuelCell Energy), which was chosen due to its high efficiency and its capacity to coproduce hydrogen. The system was also configured to operate on renewable biogas generated from the wastewater [75].

The parties involved in this project had recognized that conventionally generated hydrogen from methane steam reformation requires large quantities of water and energy and is only economical on a large scale. Similarly electrolysis of water requires high power in addition to water as the process has low conversion efficiency. With renewable energy sources like wind and solar energy, land and capital can still be issues. With this tri-generating system they aimed at providing a practical alternative for clean and affordable hydrogen fuel, suitable for operation even where water availability and space are limited [75].

Their project was a success. They were able to produce 100% renewable hydrogen and the hydrogen that was produced was supplied to a nearby fueling station operated by Air Products which was opened to the public. The MCFC, which was integrated with a hydrogen purification system could produce close to 100kg of hydrogen per day [95]. With the amount of hydrogen

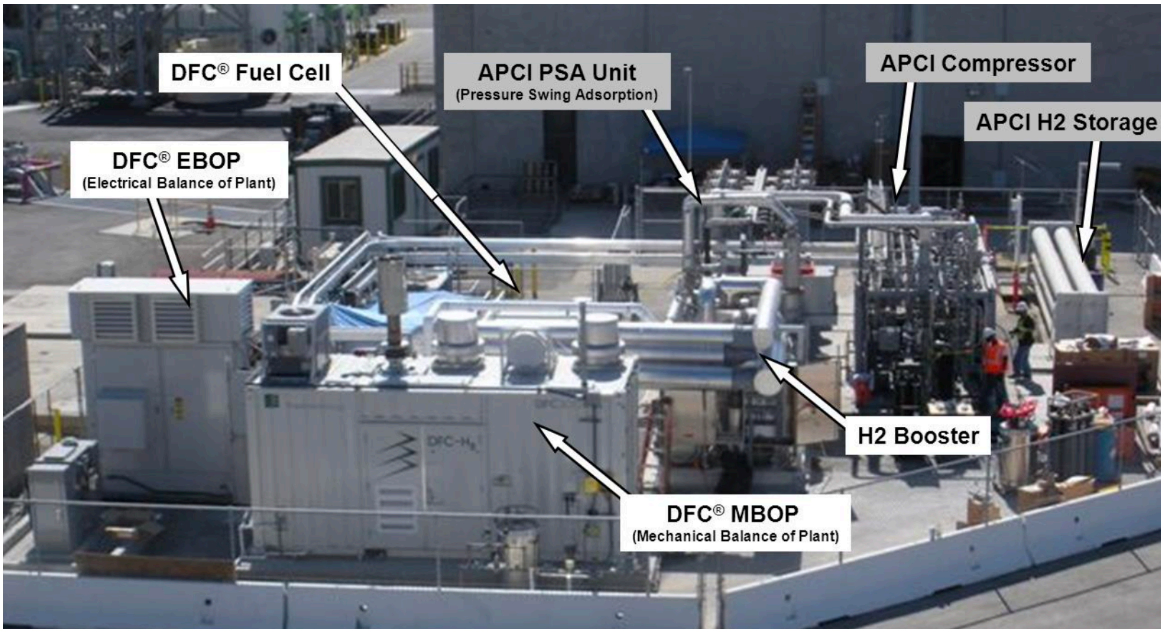

Figure 3.8: The Fountain Valley trigeneration system showing fuel cell from FuelCell Energy and hydrogen seperation and compression equipment from Air Products and Chemicals, Inc. Ref. [95].

that was produced, 25 to 50 fuel cell electric vehicles could be supported daily. The hydrogen that was produced was stored onsite near the tri generation system and next to the fueling station in high pressure tubes at about <7,000psi. [95]. The fuel cell also produced electricity and heat that supported the daily operations of the wastewater treatment plant. This operation cycle was self sustaining and approximately 250kW of power was supplied by the fuel cell to the wastewater treatment plant [95]. The operation is shown with a simple flow diagram in Fig. 3.9.

The system was able to operate with nearly zero criteria pollutant emissions and with substantially reduced greenhouse gas emissions as the power was generated from a renewable waste stream. This trigenerating system was cerified ”carbon negative” by CARB assessment. The CARB evaluates the carbon intensity of an alternate fuel pathways through an established Low Carbon Fuel Standard (LCFS) and comprehensive life cycle analysis [75].

With this 3 year long pilot program, a system was presented that only produced hydrogen when required for refueling otherwise the hydrogen was consumed within the fuel cell to provide continuous streams of heat and electricity. This system also demonstrated the versatility of MCFC to operate with multiple feed stocks. The system that was primarily running on biogas could also use natural gas if there was a disruption in biogas availability or quality [95]. As the hydrogen infrastructure investment needs to occur before the rise in fuel cell electric vehicle demand, the fuel cell and hydrogen industry is being challenged in the recent years. Additionally, auto manufacturers are looking to commercialize fuel cell electric vehicles in the near future and are calling for increasing investment in hydrogen refueling infrastructure. With benefits of low emission, combined with electricity, heat and local hydrogen production, the United States Department of Energy along with its partners were able to successfully demonstrate a tri-generation system that could serve as a bridge technology for introducing and sustaining hydrogen infrastructure. [95]. These systems have the potential for providing hydrogen for both vehicle fueling and industrial applications and can contribute to the growth of distributed

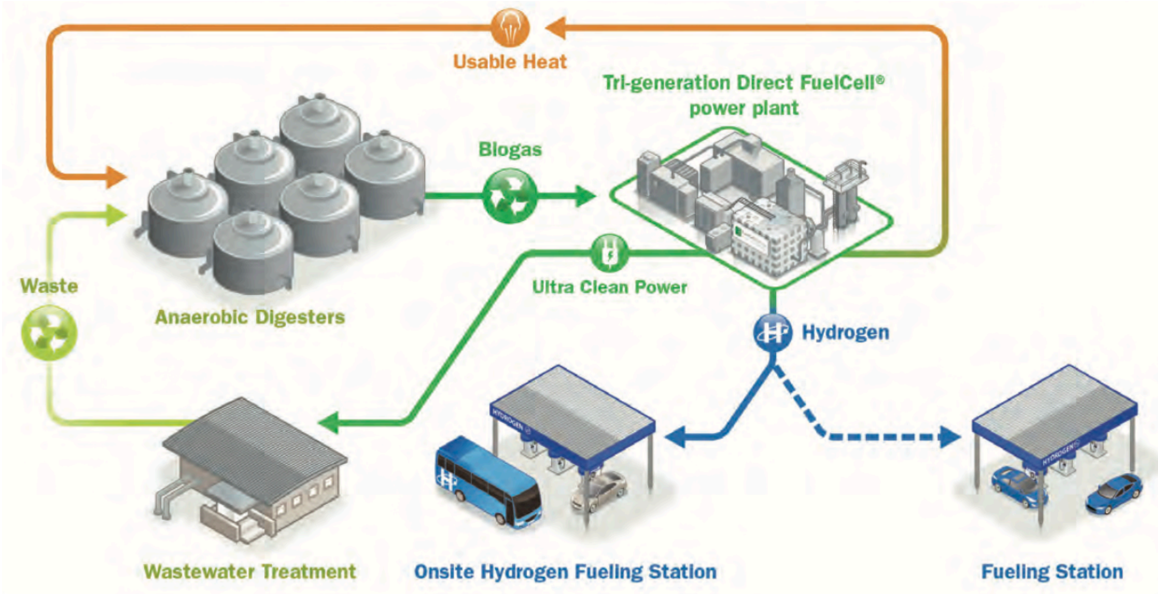

Figure 3.9: MCFC based tri-generation operation using renewable energy from wastewater Ref. [75].

hydrogen markets.

A similar tri-generating unit can be found in FuelCell Energy's North American manufacturing facility to showcase the advantages of hydrogen production on-site. The hydrogen it produced is used as an oxidation preventative in the fuel cell manufacturing process. Simultaneously, the heat and electricity generated are used to provide heating and power necessary for the working of the facility, thus reducing the operating costs [75].

Toyota's Port of Long Beach Trigeneration Project

In December 2017, Toyota, one of world's leading automobile manufacturer announced the construction of a trigeneration power plant and fueling station at one of its North American facilities located at the Port of Long Beach in California. This is going to be the world's first MW-scale MCFC power generation plant with a hydrogen fueling station [13]. This prodject was announced in partnership with FuelCell Energy. Having demonstrated the success their tri-generating pilot plant in the Fountain Valley project, FuelCell Energy is providing the tri-generating MCFC based system for this commercial plant which is expected to produce clean hydrogen, electricity and hot water.

When the plant comes online it is expected to generate an output of about about 2.35MW of electricity and 1.2 tonnes of hydrogen daily. [109]. With these capacities, they will be able to power roughly 2,350 homes and 1,500 vehicles. As this plant will generate electricity,hot water and hydrogen, while consuming bio-material derived from agricultural waste in the state, it is expected to provide 100% clean energy. This facility will meet the energy demands of the Toyota Logistics Services operation at the port, therefore making it the first Toyota business in North America to be 100% operated by renewable power [13].

For Toyota, trigeneration is a major step forward for sustainable mobility and will play an important role their 2050 goal of net zero CO_2 emissions [109]. This trigenerating system supplying hydrogen on a major scale will supply hydrogen for all toyota fuel cell vehicles moving through the port. This includes even the more recent deliveries of Mirai saloon and their Class 8 heavy-duty truck known as Project Portal [109].

This project was initially expected to be completed by 2020. However, as the trigeneration plant would produce far more power than necessary for Toyota's local operations, the excess should be sold to the local utility. For the project to come to fruition, buy-in that was needed from the local utility, Southern California Edison (SCE) was declined by SCE [84]. This delayed the completion of the project. In March 2020 this issue was resolved with the help of California Public Utilities Commission (CPUC) and the project was allowed to proceed with development [31].

3.8. Multi-source Multi-product and Superwind Concept

In section 3.6 the concept of cogeneration and trigeneration were explained. Section 3.7 showcased existing examples of trigeneration applications today showing plants generating multiple useful output streams. However, it is also possible to apply multiple sources on the input side with different levels of integration. This gives rise to the possibility of a multi-source multi-product energy systems.

Multi-source Multi-product Systems (MSMP)

Oftentimes power systems struggle with a mismatch between supply and demand due to mismatch in time, place or energy forms [51]. Even though mismatch in time can be solved by storage, mismatch in place can be solved by transport, and the mismatch of energy form can be overcome by energy conversion, better integration is usually required. A multi-source multi-power approach is a method of integration of energy sources for distributed generation [51].

Even if multiple inputs are present, it is possible to have systems where sources function independently as they are not controlled and integrated. Electricity for example is a mix from sources like fossil fuel, renewable and nuclear sources operating independently. In MSMP systems, more than one energy source is applied on the input side while producing multiple useful output streams. However in such configuration more interaction is possible even on a local scale [56]. Synergy effects can be achieved through coupling energy infrastructures with different energy carriers by taking advantage of their specific virtues. Typically coupling is achieved through energy converter devices that convert power into other forms [45].

These coupled energy systems are the so called energy hubs, where multiple energy carriers can be conditioned, coordinated, stored and dissipated [45]. From a system point of view, a energy hub is a unit that is supplied by more than one energy carrier at its input ports and delivers multiple energy services like electricity, heating and cooling among others [104]. These hubs are the interface between the loads and the energy infrastructures. Usually, the energy conversion and conditioning within the hub is brought about by CHP technologies, power electronic devices, transformers, heat exchangers, compressors and other equipments [45]. An example of a MSMP energy hub operating with a transformer, a microturbine, a furnace, a battery, a heat exchanger, along with a chiller for abosrbtion, and a hot water storage facility is shown in Fig. 3.10.

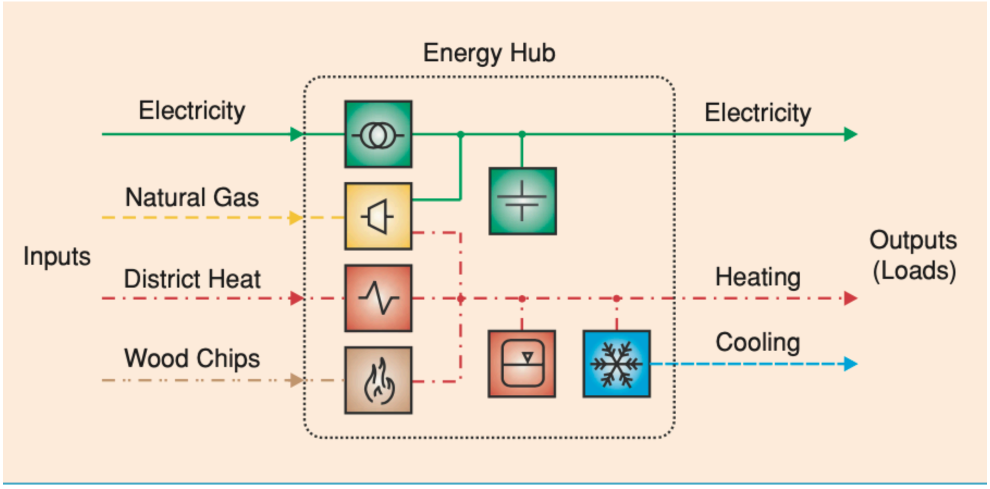

Figure 3.10: An example of MSMP energy hub. Ref. [45].

It is possible for the components within the hub to establish connections between inputs and outputs that maybe redundant [45]. This can be explained with the example shown in 3.10 where the electricity supplied by the hub can be provided completely from the electricity grid, from natural gas, or through a combination of both. There are two major benefits that arise from this redundancy in supply. First, as the load is no longer dependent on a single network and the reliability of supply is increased. Due to this it is also possible to decrease the reliability of a particular infrastructure even when the load is high. Second, optimization of the supply can be achieved due to the additional degree of freedom of the hub. The various different energy carriers that are supplied to the hub can be characterized based on cost, emissions, availability or any other criteria and the input to the hub can be optimally dispatched after the carriers have been evaluated and most suitable option has been determined [45].

The 'Superwind Concept'

The Superwind concept is an example of the MSMP concept using high temperature fuel cells and fluctuating renewable sources like wind energy [51] [54]. As mentioned in sections 3.6 and 3.7, high temperature IR-FCs can flexibly coproduce hydrogen and power (and heat). The quality of coproduction can be advantageously utilized to compensate for the fluctuations in electricity generations from renewable energy sources like wind and solar [54].

Fluctuating energy sources like wind energy are unpredictable and unreliable. Very often the solution proposed to deal with those issues include storing excess energy in batteries, or converting excess wind generated electricity into another form of energy that can be stored for later use. For example, excess electricity can be used to produce hydrogen via electrolysis of water and the hydrogen produced is stored until needed to generate electricity in case of reduced winds. Such complicated storage methods not only increase the steps involved in the operation but also reduce the overall efficiency as efficiency of each additional component has to be taken into account. Moreover, with every increasing component the overall cost of operation increases. It can be said that storage solutions offered today are usually expensive, inefficient and not flexible. Not only is storage a problem but wind fails to deliver power predicted by weather models, wind turbine owners can face financial penalties from electricity traders. Therefore, a technology that 'fills in the gaps' instead of the one that would 'shave the peaks' is needed for them [51].

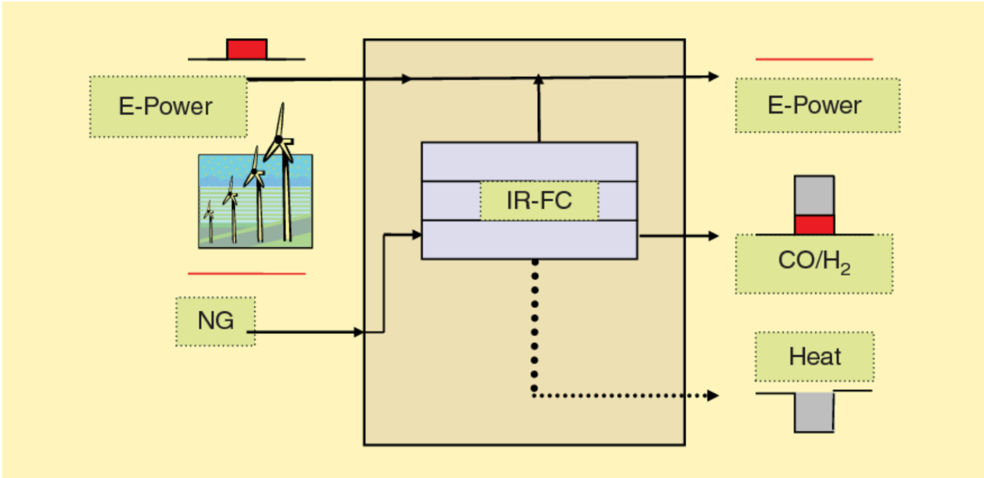

Figure 3.11: Schematic representation of superwind concept. Ref. [48].

For fluctuating energy sources, the Superwind concept can provide an innovative solution for their integration into the grid. As shown in Fig.3.11, it consists of a wind turbine integrated with an internal reforming high temperature fuel cells like MCFC or the SOFC. The operation of this concept has been presented by Hemmes et al. in Ref. [54] and is as follows. The fuel cell power output is reduced to compensate for the peak in wind energy while keeping the input (natural gas, biogas or a mixture of both) to the fuel cell constant. Flow sheet calculations using Cycle-Tempo with SOFC showed that there is a large increase in H_2 (and CO) output relative to a small decrease in electricity power output. From this it was determined that when the fuel input is kept constant, a larger quantity of H_2 is obtained in the anode off gas, relative to the drop in power. The sheet calculations showed that, while compensating wind peak, the increase in hydrogen production was 3-4 times the said peak in terms of energy per unit time. Another way of looking at it is that the peak in wind energy is converted to H_2 (and CO) with 300-400% efficiency [54]. This shows that wind energy is virtually converted into larger quantity of hydrogen and since low heat is produced, it can be said that the system becomes more efficient. In the 'Superwind concept, the fuel cell operates at almost twice the power density than in standard operation because of hydrogen production. This essentially means that with the same fuel cell in coproduction mode, a double electric power output with an equal amount of hydrogen is possible in terms of energy per unit time. Thus, the power output of the fuel cell is almost quadrupled [54].

In the Superwind concept, the heat produced in the fuel cell is utilized by the internal reforming reaction and converted into chemical energy. Moreover, less heat is produced due to lower Nernst loss and polarization loss. Therefore, the first law of thermodynamics is not violated and the sum of energy output remain equal to the sum of energy input [54]. The efficiency vs fuel utilization plot for high efficiency mode (fuel input is kept constant) of operation using internal reforming SOFC is shown Fig. 3.12. In this figure the H_2 and CO output increase being more than the power output decrease is apparent. This is reflected by the steeper increase in gas efficiency line in the graph relative to the decrease in the power efficiency line when the fuel utilization decreases while moving from right to left. The graph also shows the overall efficiency of over 90% can be achieved for the cproduction of electricity and hydrogen. This is because the fuel cell is not idle when wind energy peaks are being compensated but instead it switches to hydrogen production which results in an even higher overall efficiency. In the

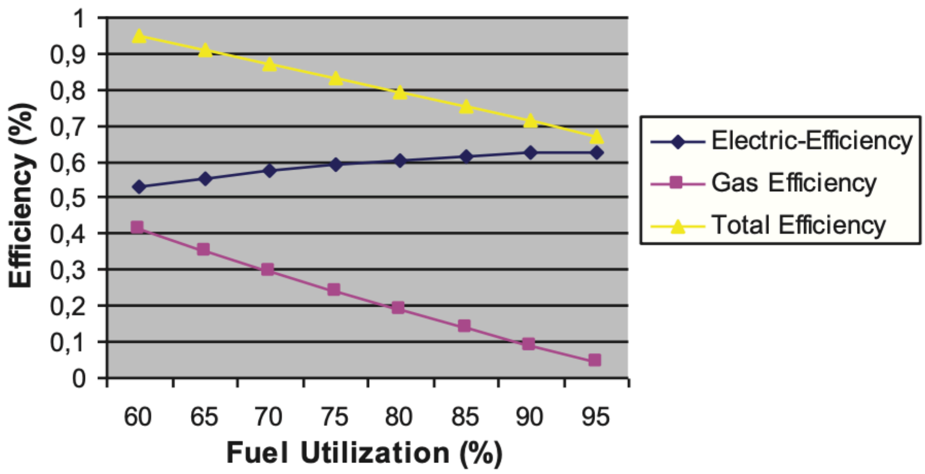

Figure 3.12: Efficiency vs Fuel Utilization for high mode operation using SOFC. Ref. [54].

Superwind concept electricity is never stored as the fluctuations in wind energy productions are compensated by the flexibility of power production in the fuel cell [54].

From reviewing the literature (Ref. [54] and [51]) on the Superwind concept, its advantages can be summarized as follows

- Flexiblity of the Superwind concept can support the growing hydrogen demand and help with widespread adaptation of this relatively new fuel. A cleaner transport sector based on hydrogen as a fuel can be made possible.
- The Superwind concept provides a system that still produces products that are economically valuable like electricity and heat when the hydrogen demand is low.
- It can help minimize the imbalance between the predicted demand that needs to be supplied and the actual electricity productions. This not only helps wind turbine owners avoid penalties but also helps them increase profits by producing more electricity when the demand is high.
- As the electrical output is doubled in comparison to standard operation, the cost of fuel cell per KW is reduced by 50%.
- It also leaves the possibility of utilizing the waste heat for biogas production or for other industrial or residential applications.
- Through this concept, intermittent sources like wind and solar energy can become more reliable. Since no storage is involved, there is no loss in efficiency related to storage as well.
- This concept can help with efficient biomass integration into the transport and energy sectors due to simultaneous production of power and hydrogen.
- This concept will also promote the growth of high temperature fuel cell market resulting in reduced cost of fuel cells due to mass production and also reduced cost of transportation by encouraging distributed generation in medium sized units at a higher efficiency.

These are however still theoretical possibilities and tests and experimentation is still required to determine for the impacts of thermal loads, material degradation, control and seamless interactions among the components. Moreover, its economic feasibility, government policies and role of actors will also play an important role in development of this concept in the future.

This chapter us helped answer the first two research sub questions presented in section 2.2. Through the contents of the chapter a background on fuel cells and MCFC systems in particular were provided from the existing literature. These fuel cells that operate at high temperatures of over $650°C$ can produce electricity at higher efficiency than combustion based energy production systems. Due to their high operating temperatures, internal reforming of hydrogen is also possible within the MCFC. Their demand is constantly growing especially in the United States and South Korea and the global demand is mostly supplied by the company known as FuelCell Energy. These fuel cells have found applications in stationary distributed power generation, marine applications and have been evaluated for carbon capture as the operating ions in these fuel cells are the carbonate ions. Since they are often used in similar applications, this chapter also provided a comparison between the two high temperature fuel cells, SOFC and MCFC in section 3.5.

Cogeneration and trigeneration especially in the CHP applications have been proven to improve the efficiency of the fuel due to their utilization of waste heat for various heating or cooling applications. Similar concept has been adopted by the fuel cell where overall fuel efficiencies of over 80% can be achieved by producing hydrogen, heat and electricity from internal reforming high temperature fuel cells. This concept has been supported by two existing examples. First, a demonstration project at Fountain Valley, California successfully showcased a tri-generating plant producing electricity, hydrogen and heat. This plant based on MCFC had produced a daily output of about 100kg of hydrogen and 250KW of electricity from biogas obtained from wastewater treatment. This successfully showcased the possibility of a fully renewable tri-generation operation for future applications. Second, the example of Toyota's Long Beach project for trigeneration has been presented. This project, currently under development is expected to produce about 1.2 tonnes of hydrogen and 2.35MW of electricity daily. With the energy supplied they can power the facility and completely fuel all their fuel cell vehicles. This chapter also provided a possibility using these fuel cells in MSMP applications by elaborating the 'Superwind Concept'. This concept that integrates fluctuating energy sources like wind (or solar) would have many benefits. Most importantly, it would help make wind energy be more reliable by removing the need for storage as excess energy can be converted to hydrogen that can be stored. This would also make the availability of hydrogen more accessible.

4

Technical Feasibility and Comparison with the SOFC Model

In this chapter the technical feasibility of the MCFC fuel cells in cogeneration of hydrogen and power is analyzed. The performance of these internal reforming fuel cells (IR-MCFC) is also compared to that of the internal reforming solid oxide fuel cells (IR-SOFC). This is done by first providing a background on the SOFC paper, this is followed by a brief section on the Fuel Cell Theory and the three modes of operation. Having defined the three modes of operations, a section on system description and operation has been presented. This is followed by results and comparisons. Finally, conclusions and highlights from the simulation are presented.

4.1. Background on the SOFC paper and the modes of operation

This chapter on technical feasibility has been based on the paper "Flexible Coproduction of Hydrogen and Power Using Internal Reforming Solid Oxide Fuel Cells System" which serves as the inspiration for this paper [55]. There, sheet calculation on an IR-SOFC system has been used to show a flexible coproduction system that has been designed to operate in conventional modes producing mainly electric power with heat, and in high power mode in which hydrogen is also produced besides electric power and heat. As most of the heat has been effectively utilized in hydrogen production, hydrogen and power have been considered for the overall efficiency.

The goal of that paper was to study the technical feasibility of an internal reforming system and explore its possibilities and limitations for a flexible coproduction. It was also shown that such systems can operate in a wide range of fuel utilization ranging from 60% representing highest hydrogen production mode up to 95% which corresponds to standard fuel cell operating mode. Three different modes of operations have been considered

- High Efficiency Mode: Current is is kept constant to 2MW equivalent.
- Constant Current Density Mode: Current density is fixed at 1500 A/m^2.
- High Power Mode: Cell voltage is fixed at 0.5V.

These systems showed very high overall efficiencies of over 90% could be achieved in terms of hydrogen and electric power production [55]. The paper showcased that with the flexibility provided by the coproducing systems, varying demands for hydrogen and/or electric power could be achieved in accordance with their fluctuating market prices through operation optimization.

In this paper coproduction with IR-MCFC has been explored using the software 'Cycle-Tempo' while keeping the parameters close to those used in the IR-SOFC for the sake of comparison. The flexible coproduction of hydrogen and power is examined by using an IR-MCFC energy system developed at TU Delft and modeled in the flowsheet program Cycle-Tempo; also developed at TU Delft. Cycle tempo is now distributed by Asimptote [8]. Using the IR-SOFC calculations as the reference IR-MCFC is run for the same three modes- high efficiency mode, constant current density mode, and high power mode while varying the fuel utilization factor from 60% to 95% [55].

4.2. Fuel Cell Theory

In this section Fuel Cell theory is briefly presented for a better understanding of the IR-MCFC model presented in the following sections. Detailed version of this can be found in Ref. [50] and Ref. [54].

From the fuel cell model derived in Ref. [121] by Standaert et al., the cell voltage of a MCFC is approximately estimated by

$$V_{cell} \approx OCV - \frac{1}{2}\alpha u_f - ir \tag{4.1}$$

This equation 4.1 was later verified and was found to be accurate and has been used for similar study conducted with the IR-SOFC model [9] [55] . For convenience, an quasi ohmic resistance 'r' constitutes irreversible ohmic, kinetic and diffusion losses. In the second term on the right, α is the slope of Nernst potential as a function of fuel utilisation given in volt. The open cell voltage (OCV) for fuel cell in general and for MCFC is given by the following equations 4.2 and 4.3 respectively.

$$OCV = E_0 + \frac{RT}{nF} ln \frac{\prod\left[(P_{reactants})^x\right]}{\prod\left[(P_{products})^y\right]} \tag{4.2}$$

Here E_0 is the standard cell potential, $P_{products}$ and $P_{reactants}$ are the partial pressure or activity of species involved. n is the number of electrons involved, x and y are the stoichiometric coefficients, F is the Faraday's constant, R is the universal gas constant and T is the absolute temperature of the cell. This equation will vary according to the overall cell reaction of different fuel cells. For MCFC it is given by the following equation (Eq. 4.3) based on the overall cell reaction given by Eq. 3.3 in the previous chapter.

$$OCV_{MCFC} = E_0 + \frac{RT}{2F} ln \frac{(pH_2)_a (pO_2)_c^{1/2} (pCO_2)_c}{(pH_2O)_a (pCO_2)_a} \tag{4.3}$$

The potential at standard state (E_0) is dependent on the Gibbs free energy (G) of the overall Fuel cell reaction.

$$E_0 = -\Delta G/nF \tag{4.4}$$

$$\Delta G = \Delta H - T\Delta S \tag{4.5}$$

Where ΔH is the change in enthalpy. The TΔS term in equation 4.5 is the reversible heat production. The irreversible heat production is due to the polarization losses other than the Nernst loss and it increases with the increase in current drawn from the cell. The fuel cell efficiency is also proportional to the change in Gibbs free energy and is given by

$$\eta_{fc} = \Delta G/\Delta H = 1 - T\Delta S/\Delta H \tag{4.6}$$

The fuel utilization (u_f) is determined by the the combination of input fuel flow and the current output and can be shown as

$$u_f \equiv \frac{i}{i_{in}} \tag{4.7}$$

where i is the actual current density and i_{in} is a hypothetical term known as 'equivalent input current density'. It can be defined as current produced by the fuel cell when all the input natural gas is electrochemically converted (i.e., at (u_f) =1) divided by the active cell area of the fuel cell. The equivalent input current density i_{in}, can be calculated with the following equation

$$i_{in} = \frac{n \cdot F \cdot m_{in}}{A} \tag{4.8}$$

where m_{in} is the number of moles of fuel entering the fuel cell per second.

Going back to equation 4.1, it can be seen that by keeping the resistance constant, V_{cell} can be calculated by inputting values of i and i_{in} into the equation. Similarly 'i' can be calculated if the values of i_{in} (or u_f) and V_{cell} are given. Therefore, the fuel cell system has two independent variables which can be seen as two control knobs that can be varied independently. With the help of these 'control knobs', various operating conditions are possible for the production of hydrogen, electric power and heat at different efficiency rates.

4.3. MCFC system description and operation

High temperature IR-MCFCs operate at about 650◦C and produce heat from reversible and irreversible processes that is used for the reforming reaction of the fuel to produce hydrogen. It is possible to obtain more hydrogen than necessary for the operation of the fuel cells by adjusting the operating conditions. In this section, the IR-MCFC model developed in Cycle-Tempo is briefly explained. As this report is based on the IR-SOFC study, the SOFC Cycle-Tempo model used by Hemmes et al. in Ref. [55] has been provided in Appendix A.

Similar to the IR-SOFC system in Ref. [55], the flow sheet system layout shown in Fig.4.1 was designed in TU Delft to be as simple as possible. This design has not been optimized economically or for high efficiency. The choice of natural gas composition was based on the gas composition from the largest Dutch source ' Slochteren' as it is selected to be the standard gas composition in the Netherlands. This low calorific gas was found to contain about 14% of nitrogen.

Recycle loops have been applied to the anode and the cathode as shown in Fig. 4.1. In IR-MCFCs, the CO_2 that is liberated at the anode needs to be recycled back to the cathode to improve performance. This is done through the separator (apparatus 19) as shown in Fig. 4.1. The role of the separator is to isolate out the CO_2 from the anode output that is required to be supplied to the cathode input. The separator has a separation efficiency of 80% in this model. Recycling has three main benefits. First, a better temperature distribution can be achieved inside a fuel cell stack because recycling provides necessary heat for the endothermic reforming reaction [54]. This is beneficial as these reactions occur at rapid speeds, thus they predominantly occur towards the inlet of the fuel cell stack. Second, the necessary steam required by the reforming reaction is also provided by recycling. Input gas streams are preheated by the output streams through various heat exchangers present in the model. Third CO_2 recycling provides the CO_2 required by the cathode in the MCFC operation. A part of the remaining gas from the anode output, after CO_2 removal is recycled back to the anode and the rest exits through sink 9 where syngas is obtained. A valve (Apparatus 16) determines the amount of gas exiting through the sink 9 and the amount of gas being recycled into the anode. In this case the recycle value is set to 0.3 kg/s for all three modes of operation. This value was chosen to obtain results in all three modes of operation in the required range of fuel utilization values for comparison with the SOFC study.

The output from pipe No. 17 contains hydrogen and other gases like CO, CO2 and H2O. Hydrogen can be separated from this mixture externally but that is excluded in this study. In order to stay consistent with the IR-SOFC model, only the amounts of hydrogen and CO are considered in the results for being components of the fuel containing chemical energy and knowing that CO can be used to produce hydrogen via the shift reaction with steam. Most of the heating value of the off-gas is contributed by hydrogen, while CO contributes about a quarter to a one-third. The IR-MCFC model shown in Fig. 4.1 is used to examine the influence of changing fuel utilization, gas input rate, cell voltage and current density on the production of power and hydrogen. In the model, apparatus 5 is the MCFC that operates near atmospheric pressure. The natural gas and air are supplied through sources 1 and 10 respectively. Air from source 10 is compressed by an air blower (Apparatus 11). The natural gas from source 1 is already available at a slightly elevated pressure as it is in the gas distribution grid and does not need further compressing. An air blower (Apparatus 4) is needed to drive the anode recycle circuit and one other (Apparatus 20) is used to drive the CO_2 loop to the cathode. There are three heat exchangers in the model, two of which (Apparatuses 13 and 7) are used to heat the cathode inlet air, while the third (Apparatus 2) is used to preheat the fuel flow. Other fixed parameters include the fuel cell outlet temperature which is fixed at 700°C, Cell resistance which is assumed to be 1ohmcm^2 and cell area which is 1200cm^2 to be consistent with the SOFC model.

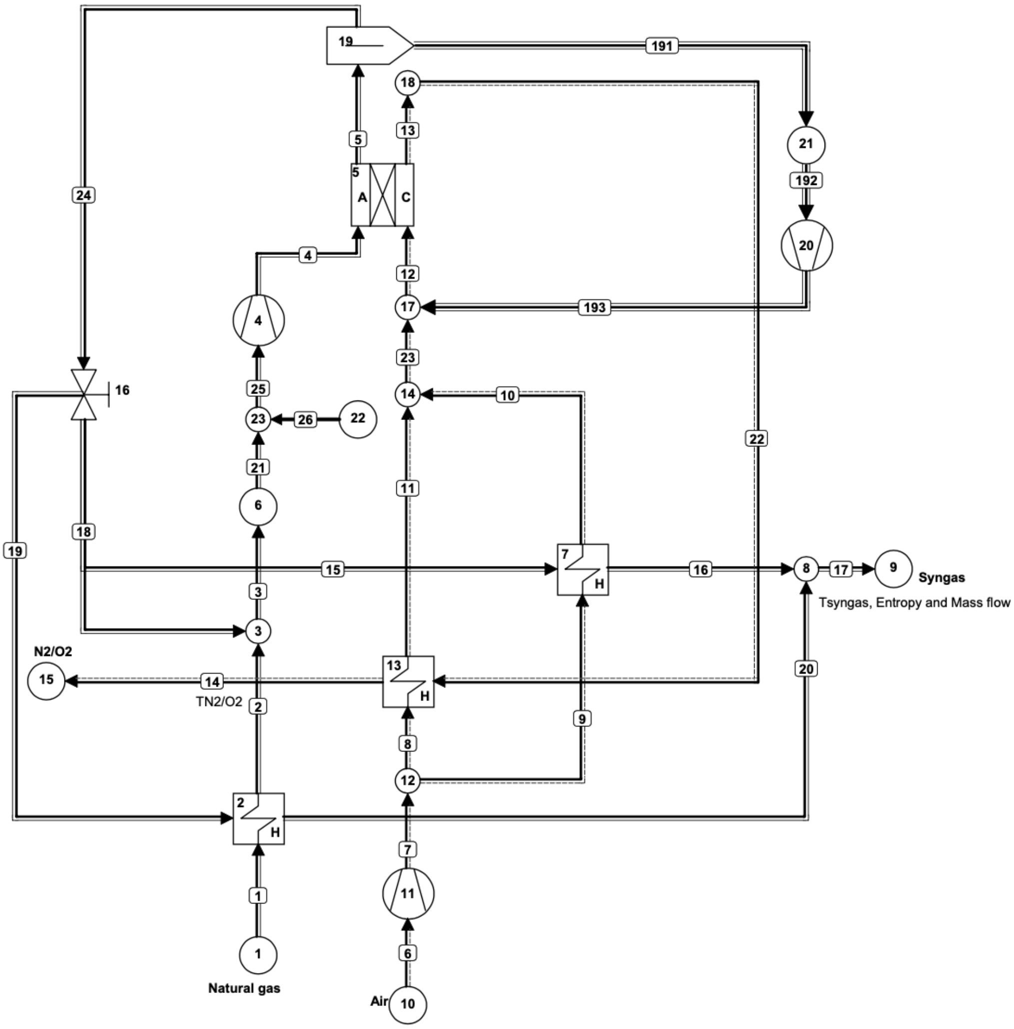

Figure 4.1: Cycle -Tempo flowsheet diagram of an internal reforming MCFC system for coproduction of hydrogen and power.

4.4. Results and comparison with IR-SOFC study

In this section the results obtained from the flow sheet calculations on the IR-MCFC shown in Fig. 1 are presented. Three different modes of operations have also been explored in accordance with the IR-SOFC model in Ref. [55]. In each mode the fuel utilization is reduced from 95% to 60% to showcase the gradual shift from conventional power production setting to hydrogen and CO production setting. The fuel utilization here refers to the fuel utilization of the fuel cell. Finally, to make the comparison between two IR-FC models, the readings obtained from both models are plotted together in one figure for each mode of operation.

Efficiency definitions in these graphs are as follows.

Electric Efficiency:

$$\eta_{Elec} = \frac{P_{elec,fc}}{P_{in,system}} \tag{4.9}$$

Gas Efficiency:

$$\eta_{Gas} = \frac{P_{gas,system}}{P_{in,system}} \tag{4.10}$$

Total Efficiency:

$$\eta_{Total} = \frac{P_{elec,fc} + P_{gas,system}}{P_{in,system}} \tag{4.11}$$

In equations 4.9, 4.10 and 4.11 variable $P_{in,system}$ is the power input into the system through source 1 as shown in Fig. 4.1, it is the MW equivalent of the natural gas that is entering the system. $P_{elec,fc}$ is the electric power output from the fuel cell and $P_{gas,system}$ is the $H_2 + CO$ power output from the system obtained at sink 9 as shown in Fig. 4.1. The fuel utilization values considered in all three modes of operations are the fuel utilization of the fuel cells.

4.4.1. High Efficiency Mode

In this mode of operation the input fuel flow is kept constant to about '2MW equivalent' (0.053kg/s at Source 1) in order to match the arbitrarily chosen fuel cell size in conventional operation. After which, the fuel utilization (u_f) is decreased in steps from 95% to 60% while keeping the total cell area constant as in the SOFC study. This is accomplished by a decrease in current density, which here decreases from 1586A/m2 to 1343A/m2. In practice this can be achieved by adjusting the electric load. At very low utilization, it is possible that the fuel cell does not produce enough heat for the endothermic reforming reaction. Although in some cases a fuel utilization below 60% is possible, it is not considered in this study as such very low utilizations cannot be reached in all modes.

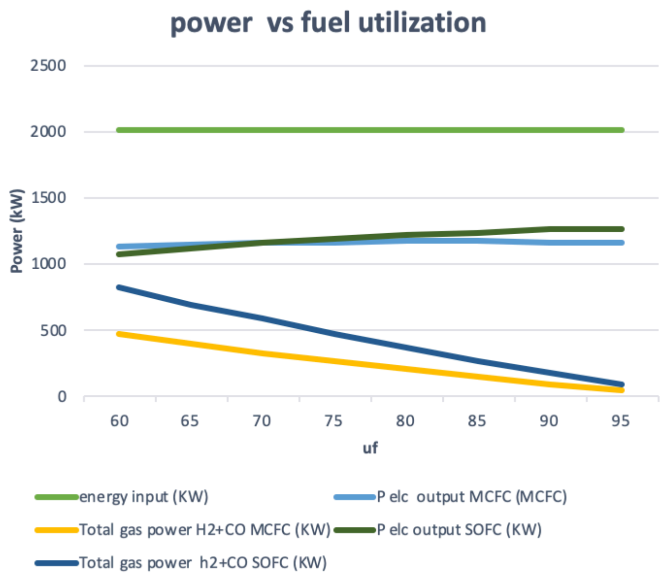

Figure 4.2: Power output vs Fuel utilization for High-Efficiency Mode

Although the current density decreases by reducing u_f, the electric power does not decrease proportionally since V_{cell} increases simultaneously as indicated by Eq. 4.1. In Fig. 4.2 a plot of the power output in the form of H_2+CO and electric power vs u_f is shown. It can be seen that there is a slight decrease in electric power output with the decrease in fuel utilization

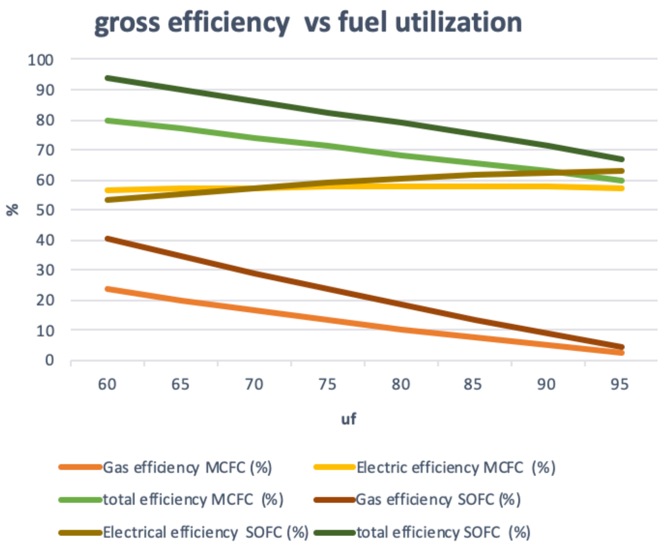

Figure 4.3: Efficiency vs Fuel utilization for High-Efficiency Mode

values, which is compensated by the increase in H_2 power output. The electric output can be considered to be more or less constant. However, the total power output (not counting heat) is more than what can be attained in conventional fuel cell operation with only electric power output and an overall efficiency of over 80% (at low fuel utilization uf = 60%) can be achieved as shown in Fig. 4.3. As stated before the enthalpy carried by hydrogen is almost twice that of CO.

Fig. 4.3 shows a graph of gross efficiency vs u_f for the high efficiency mode. Here gas efficiency is defined as H_2+CO power output divided by the power input. From the figure it can be seen that the total efficiency increases at a higher rate than the decrease in electric power efficiency as the u_f decreases. There is a very slight decrease in the electric efficiency (about 59% to 56%), so it can be assumed to be almost constant in this case. This mode maybe the most efficient, but it might not be the most economically favorable mode. From the calculations it can be also determined that it is possible to trade power for hydrogen, but it is not one-to-one trade off. This means that the sum of electricity and hydrogen power is not constant. As the heat loss across the system boundary is greatly reduced, a maximum total efficiency of 80% is obtained at 60% fuel utilization. It is important to note that this efficiency is the total efficiency for the production of hydrogen + power excluding heat, so not the total efficiency of all power output including heat, which is usually defined as total efficiency in CHP fuel cell systems.

In this mode of operation, the input natural gas flow was kept constant at 2MW equivalent to match the more or less arbitrarily chosen fuel cell size used in conventional operation. As shown in Fig. 4.2, at low fuel utilization of below 75% the IR-MCFC system produces higher electric power output than the IR-SOFC system. As the fuel utilization increases above 75%, the electric output from the IR-SOFC increases at a higher rate than IR-MCFC system, producing slightly higher electric power output at higher fuel utilization. The maximum electric efficiency achieved by the IR-MCFC is about 59% and for the IR-SOFC it is about 63%.

From figures Fig. 4.2 and Fig. 4.3 , observations regarding the coproduction of H_2/CO can also be made. The values of H_2 + CO are represented as "total gas power" and "gas efficiency” in the graphs plotted for the fuel cells. As expected at low fuel utilization, the total gas power is higher as more H_2/CO is produced at lower u_f. At lower fuel utilization uf = 60%, the total gas power is much higher for IR-SOFC system (816KW) than it is for the IR-MCFC system (475KW). At higher fuel utilization, as the fuel is mostly utilized for producing electric power, the moles of H_2/CO liberated from the fuel cell system approaches zero.

The overall energy efficiency which has been calculated as the sum of electric efficiency and the total gas efficiency in this paper is also plotted in Fig. 3. There is a difference ranging from roughly 13% to 8%, with the increase in u_f between the two fuel cell systems, and with the IR-SOFC model having higher overall efficiency throughout. The maximum overall efficiency is achieved at u_f = 60%, being 93% for the IR-SOFC model, and 80% for the IR-MCFC model. From Cycle-Tempo, the maximum exergy efficiency observed from the IR-SOFC system was about 59% while the IR-MCFC system achieved a maximum of about 54%.

From these observations it can be concluded that in the High Efficiency Mode, in the range of observed fuel utilization values, the electric efficiencies from the IR-MCFC systems lie in the range of efficiencies achieved by the IR-SOFC systems. The overall efficiency and the exergy is much lower for the IR-MCFC system, which results from the significantly reduced gas efficiency. Despite this, an overall efficiency of over 80% is possible with IR-MCFC.

4.4.2. Constant Current Density Mode

In this mode we keep the current density constant and the fuel utilization is decreased by increasing the natural gas input flow. The current density is kept constant at 1500A/m_2 as it represents conventional operation at reasonable power density. In this mode, Cycle-Tempo is allowed to change the gas input flow to meet both the fixed values of u_f and i. Therefore, in Fig. 4.4 it is seen that at lower u_f, the gas flow input is higher, hence more power enters the system. The results obtained in this mode are found to be in between high-power (see next section) and high-efficiency mode. From Fig. 4.5 it can be noticed that the rate at which the total efficiency increases with the decrease in u_f is higher than the decrease in electric power efficiency.

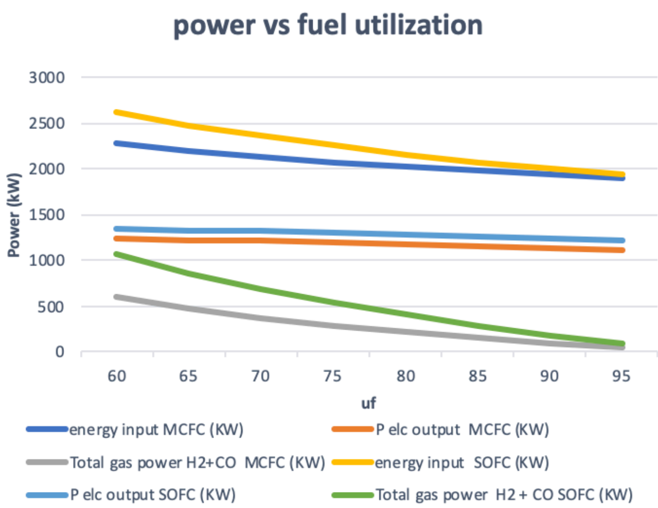

Figure 4.4: Power output vs Fuel utilization for Constant Current Density Mode

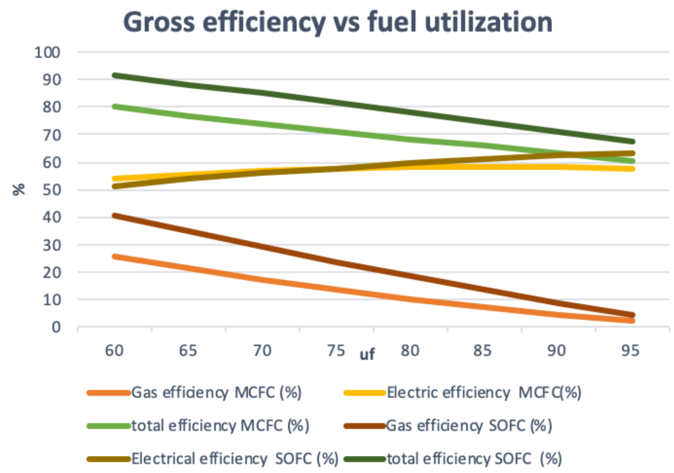

Figure 4.5: Efficiency vs Fuel utilization for Constant Current Density Mode

In this mode the input flow is not fixed and is allowed to increase, resulting in high electric power output at low u_f for both the fuel cell systems. The maximum electric power output is obtained at u_f = 60% instead of uf = 95% as in the case of the high-efficiency mode and is higher than the maximum of the high-efficiency mode. The maximum electric power output in the IR-SOFC system (1347 KW) is found to be higher than the IR-MCFC system (1245 KW) at u_f = 60%. The electric efficiency varies similar to that of the high-efficiency mode with maximums of 57% (for IR-MCFC) and 62% (for IR-SOFC) occurring at uf = 95%. The input flow to maintain constant current density is much higher at lower utilization factor. At uf = 60%, the input flow equivalent to 2291 KW and 2621 KW enters the system for IR-MCFC and IR-SOFC, respectively.

The total gas power from the coproduction of H_2/CO for both the fuel cell systems is higher than what was obtained in the high efficiency mode. As most fuel is supplied at the lowest fuel utilization, conversion to H_2/CO is the highest at u_f = 60%, where a total gas power of 591KW is obtained from IR-MCFC, while IR-SOFC produces almost double this amount by generating 1062KW. This can also be seen in Fig. 4.4. With the increase in fuel utilization, the H_2/CO power converges towards zero. The variation of gas efficiency with u_f gives a nearly identical plot to the one obtained in the high-efficiency mode, and this is shown in Fig. 4.5. Similarly, the overall efficiency is found to closely resemble the values from the high-efficiency mode as well. Its maximum value of overall efficiency is achieved at u_f = 60% for both the fuel cell systems and it is 80% for the IR-MCFC, and 92% for the IR-SOFC. From Cycle-Tempo, the maximum exergy efficiency observed from the IR-SOFC system was about also found to be about 59% like in the high efficiency mode while the IR-MCFC system achieved a maximum exergy efficiency of about 54%.

To conclude, in this mode maximum power output occurs at lowest fuel utilization due to much higher fuel input. Just like in the high efficiency mode, the electric efficiency of IR-MCFC is in the range of what is achieved by the IR-SOFC system between u_f = 60% and 95%. Again the difference in the overall efficiency for the IR-MCFC system can be attributed to the loss in gas efficiency as in the MCFC operations. Even in this case, IR-MCFC was still able to achieve an overall efficiency of 80%.

4.4.3. High Power Mode

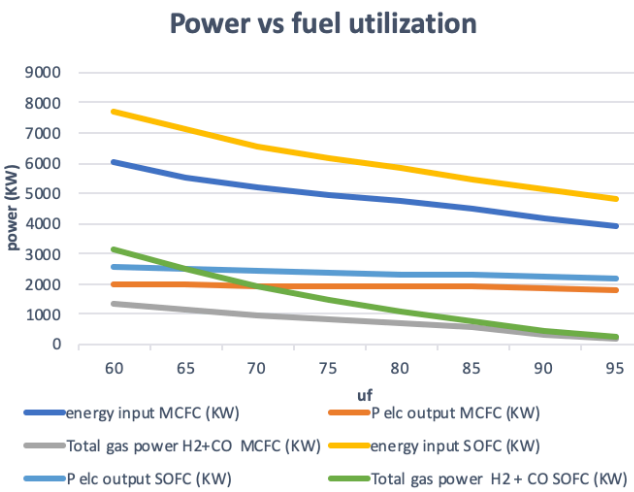

Figure 4.6: Power output vs Fuel utilization for High Power Mode

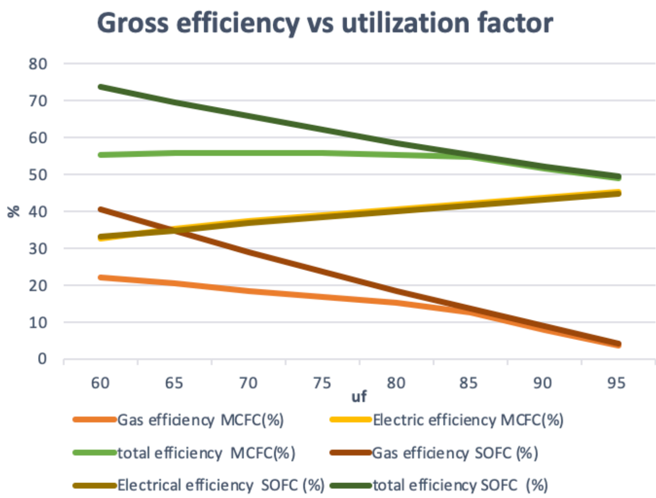

Figure 4.7: Efficiency vs Fuel utilization for High Power mode

High-power mode is of great interest from an economic point of view. In this mode large current densities are obtained by keeping the cell voltage fixed at a very low value of 0.5V. Similar to the constant current mode, this mode achieves a decrease in fuel utilization u_f by increasing the natural gas input fuel flow. The results from this mode of operation are shown in Fig. 4.6 and Fig. 4.7, which are the plots of power output vs fuel utilization, and efficiency vs fuel utilization respectively. As very high power output values are obtained in this mode, this is an extreme operation mode.

It is seen that at u_f = 60% the current density is i = 3428A/m^2. As the cell voltage is low (set at 0.5 V), the amount of heat dissipated is high. This heat can be used for the internal reforming reaction of the natural gas fuel, and a larger quantity of natural gas can be reformed than in previous modes. Despite this, significantly large electric power output is still achieved while operating at a very low cell voltage of 0.5V. In the high power mode the cell operation is carried out near the maximum in the power output vs current density curve at the expense of low electric efficiency [55]. By using waste heat for producing hydrogen we can operate at or near maximum power for electricity production while at the same time producing a similar high output in the form of H_2/CO albeit at the expense of a drop in efficiencies. At low u_f, low electric power output is partly compensated by the higher H_2/CO production, and the total efficiency for coproduction of gas and electric power was found to reach 56%. It is seen that the maximum electric power obtained in the high efficiency mode (1153 kW) is 58% of that obtained in the high power mode (1980 kW). So, roughly estimating, it can be said that high power mode produces electric output that is almost twice that of high efficiency mode. Additionally, 1344KW of gas power is obtained from producing H_2/CO in this mode, bringing the total useful output to over 3300KW. This is 2.9 or about 3 times the electric power output obtained in the conventional operation (1153KW) carried out with the same fuel cell.

It should be noted that although at low fuel utilization the system is in H_2/CO production mode, the electric power increases as well. This is because in this mode of operation, the utilization factor is decreased by increasing the natural gas input. Hence, by allowing more Joules per second to flow into the system, we are increasing both hydrogen production and power output. Moreover, Nernst loss is significantly reduced due to higher partial pressure of hydrogen at lower fuel utilization, resulting in an improvement of cell voltage and thus fuel efficiency as indicated by Eq. 4.1.

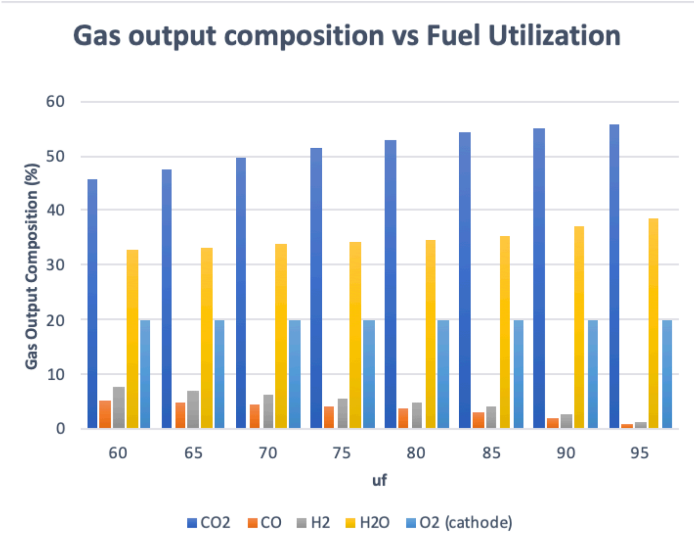

Figure 4.8: Gas output composition vs utilization factor curve for high power mode.

As the fuel utilization value is varied from uf = 60% to uf = 95% the composition of gases in the fuel cell output changes as shown in Fig. 4.8. The anode output is found to contain the gas mixture containing H_2, CO, H_2O and CO_2 with an obvious decrease in H_2 and CO as the fuel utilization increases. The cathode output mainly consists of a mixture of N_2, O_2(N_2 is not shown in Fig.4.8). The cathode output composition is similar to that in the IR-SOFC model however, a major difference observed in the anode side involves much higher CO_2 emissions. This is expected due to the difference in the fuel cell operating principles.

In this mode of operation, the fuel input is found to be the highest among the three modes of operation explored in this paper. The fuel input is maximum at uf = 60%, being 6041 KW equivalent for the IR-MCFC and 7713 KW for the IR-SOFC system. This results in much higher gas and electric output than the other two modes. It is seen that electric output decreases with an increase in fuel utilization, resulting in a maximum output obtained at uf = 60%. This maximum electric output is 1980 KW for the IR-MCFC system and 2542 KW for IR-SOFC system. It should be noted that the minimum electric outputs obtained from this mode of operation at uf = 95% is still much higher than the maximum electric outputs for both the fuel cells in the other two modes of operations as can be deduced from the power output vs fuel utilization plots for the three modes of operations (Figures: 4.2, 4.4, 4.6). The electric efficiency increases with the increase in fuel utilization, but is much lower than in the other two modes; this is expected as fuel is supplied in abundance. The electric efficiency varies almost identically between 32% to 45% for both the fuel cell systems as the fuel utilization increases as shown in Fig. 4.7. From cycle tempo, the system exergy efficiency was also found to be closely identical in both the fuel cell systems and was in the range between 30 and 40%.

Just like the electric output, the total gas output in this mode is the highest among the three modes of operations. The gas output from both the fuel cell systems decreases with the increase in fuel utilization to produce electric output. The maximum H_2/CO output achieved at uf = 60% is 1344 KW for the IR-MCFC system, and 3125 KW for the IR-SOFC system. The difference in gas efficiency between the two fuel cell systems is much larger at lower fuel utilization and is found to be almost identical beyond uf = 85%. Just like in the other two modes of operation, the maximum gas efficiency remains around 25% for the IR-MCFC system, and 40% for the IR-SOFC system.

Maximum total efficiency of the IR-MCFC is found to be over 56% while for the IR-SOFC model it is found to be about 73%. Here, the maximum total outputs from IR-MCFC is 3325 KW, and from IR-SOFC is 5667 KW. While outputs as high as IR-SOFC may not be possible with the IR-MCFC used here, we see that the maximum total output from the IR-MCFC is still almost 3 times that of conventional IR-MCFC operations.

4.4.4. Reasons for loss in efficiency in IR-MCFC

From the three modes of operation, it can be observed that the electric efficiency between the two fuel cells, in all three modes of operation were closer to each other than gas efficiency. It can be implied that the difference in overall efficiencies between the two fuel cell systems are therefore primarily due to differences in the rate of H_2/CO exiting the system. While the IR-SOFC system can achieve a gas efficiency of up to 40%, the IR-MCFC system examined in this paper was able to achieve only 25% at best. The loss in efficiency can be due to a few reasons.

The working principles of the two systems are different. The IR-MCFC system is kept at 650°C while the IR-SOFC is kept at 900°C. From Fig. 4.8 we also see that while operating in the high power mode (also true for other modes), the anode output gas composition obtained from the IR-MCFC system contains a much higher CO_2 concentration, than possible with the IR-SOFC system in Ref. [55], which is much richer in steam. This is due to the difference in the operation of the two IR-FCs systems and the reactions taking place in the fuel cells.

In the case of IR-MCFC the amount of fuel entering the system in the constant current density mode and the high power mode is less than in the IR-SOFC systems for all utilization factors. The difference in the fuel input can be as high as 1700KW equivalent like in the high power mode operating at fuel cell utilization of u_f = 60%. With lower amount of fuel entering the fuel cells, outputs lower than IR-SOFC can be expected.

In the MCFC model as shown in the Fig. 4.1, the CO_2 generated in the anode output is recycled to the cathode through separator (apparatus 19). The separation efficiency of the separator is 80%. The CO_2 that is separated is compressed in a blower (apparatus 20) in the recycle loop to provide CO_2 at the pressure of the air entering the cathode.

The remaining composition of the anode outlet is made to pass through the valve (apparatus 16), where a portion of the gas is injected into the fuel stream through pipe 18. The remaining gas from the valve passes through heat exchangers (apparatus 2 and apparatus 7) through pipes 19 and 15 respectively. These two streams after passing through heat exchangers ultimately combine at the end to supply hydrogen and CO from the outlet of pipe 17.This arrangement through the valve is identical to the SOFC model. The main difference is that in the case of the SOFC model, the input flow to pipe 18 is fixed at 0.4 relative to pipe 5 (anode outlet). This means that 40% of the anode output is injected back into the fuel stream headed to the anode inlet. The recycling into the anode inlet is needed to provide the sufficient steam for the internal reforming reaction. Due to the complexity arising from the recycle loop (for CO_2 to cathode from anode output), similar flow cannot be specified for pipe 18 in the MCFC model. The other option for specifying input data for a pipe (pipe 18 in this case) that is leaving a valve in Cycle-Tempo is by fixing its absolute flow. In the MCFC model the flow for pipe 18 is set to 0.3kg/s, which is a fixed value. This is a ”best fit” value chosen to operate in all three modes, across entire range of fuel utilization values analyzed.

This value also indirectly determines the amount of H_2/CO that is obtained from the system, since it is in the remaining gas from valve 16, which is not flowing in pipe 18, that contains the desired gases. Due to fixing the flow in pipe 18 to 0.3kg/s, majority of gas (like in the high efficiency mode and constant current density mode) from the anode (after CO_2 separation) is actually recycled into the fuel stream headed towards the anode inlet. This means much more of the anode output in comparison to the IR-SOFC is actually getting recycled back into the anode input in the case of IR-MCFC. This stream is rich in hydrogen and thus supplies additional fuel to the IR-MCFC along with the natural gas which is entering the system. By looking at the high efficiency mode where fuels entering the system is constant and analysing the power outputs, it would imply that the IR-SOFC configuration is more efficient. The remaining gas that constitutes the syngas production at sink 9 as shown in Fig. 4.1, which is lower for all fuel utilization values in IR-MCFC than IR-SOFC. As expected with the increased fuel utilization in the fuel cell, the H_2/CO in the anode outlet decreases, this results in the gas power output line of IR-MCFC in the graph (e.g. Fig. 4.2) approaching zero.

Moreover, there are two other blowers, one (apparatus 4) before the anode inlet, that provides pressurized fuel mixture to the anode and the other (apparatus 11) that compresses the air entering the system. As a result of the much higher flow in pipe 18, the flow through the blower 4 is larger in the MCFC model (than the SOFC model), requiring more power for compression than in the SOFC model. Due to the increased mass flow into the anode of the fuel cell, both anode and cathode outputs are larger as well. The mass flow from the cathode output is at high temperature (700°C) and it passes through heat exchanger (apparatus 13) before exiting through sink 15 at reduced temperature of 100°C, which is a lower exiting temperature than the cathode exhaust in the IR-SOFC model. As a result of large amount of heat available at (Heat Exchanger) apparatus 13, there is an increased airflow into the system through compressor 11. This air is ultimately supplied to the cathode inlet. This results in higher power consumption in the IR-MCFC system than in the IR-SOFC case for blower 11.

With an additional blower (apparatus 20) for separated CO_2, along with the higher power consumption by the other two compressors (apparatus 4 and 11), the power consumed by the auxiliary components of the system is much higher than in the SOFC case, resulting in the loss of efficiency in the IR-MCFC systems.

4.5. Highlights and Conclusions

The highlights from the Cycle-Tempo simulations are presented below.

The aim of this chapter was to answer the sub questions 3 and 4 of the main research question. These questions relate to the technical feasibility of the IR-MCFC models and it's comparison to the IF-SOFC model.

It was found through flow sheet calculations on an IR-MCFC system, that it is possible to design a flexible coproduction system that can function in a conventional mode producing mainly electric power and heat and in coproduction mode producing mainly electric power and hydrogen and very little heat. By using waste heat in the endothermic reforming reaction to produce hydrogen, high total efficiency of over 80% for hydrogen + power production is possible. Conventionally, CHP plants operate in the overall efficiency range of 60-80% [4]. This shows that coproduction of hydrogen and power with IR-MCFC achieves efficiencies as high as what can be achieved by the CHP plants. As waste heat is effectively utilized in production of hydrogen, the IR-MCFC can be operated at a very high power density. In the high power mode, it is possible to achieve very high electric power output that is nearly twice that of the same MCFC when operated in a conventional mode, while at the same time an additional large amount of power in the form of hydrogen is co-producted. The total efficiency however, drops below 60% in this high power mode.

- High Efficiency Mode: IR-MCFC achieved a maximum overall efficiency of over 80%.
- Constant Current density: IR-MCFC achieved a maximum overall efficiency of over 80%.
- High power mode: IR-MCFC achieved a maximum overall efficiency of over 56%.

In comparison to the IR-SOFC system, the IR-MCFC system produces similar electric output at similar efficiency but the gas power output in the form of hydrogen and CO; hence the gas efficiency, is much lower. This results in lower total efficiency. In all the three modes of operation, the overall efficiency was over 10% lower than what can be achieved with the IR-SOFC model, which was mostly due to the reduced gas efficiency. The gas efficiencies maybe lower due to reasons associated with operating principles, valve recycling ratio setting, and increased power consumption by the blowers. Despite this, IR-MCFC, like the IR-SOFC system, allows for operation of a flexible coproduction system that can meet varying hydrogen demand and electric demands at high efficiencies. Thus, making them technically feasible for cogeneration applications.

5

Socio-Economic Feasibility

In this chapter the socio-economic feasibility factors are studied by analysing the economic trends and hydrogen market trends, identifying the role of actors and the involvements, investigating the existing policies. Justification of using natural gas fuel and the possible impact of these system on the society have also been presented.

5.1. Economic and Hydrogen markets trends.

Since MCFC is not a widely used technology and the information available is limited, this section makes economic presumption based on current trends with the data that is available. Additionally the hydrogen market is not stable and is rapidly changing so the hydrogen market is analyzed in the second half of this section.

5.1.1. Economic trends based on information regarding costs

For a cogeneration technology generating hydrogen and power with MCFCs to be successful, the system should be economically viable. The MCFC production is dominated by a single company and in comparison to other technologies its quantities are scarce.

PEMFCs dominate the fuel cell industry with an estimated installation capacity of up to 934MW in 2019. They are followed by the PAFC and the SOFC with 106.7MW and 78.1MW respectively, according to the Fuel Cell Industry Review 2019 [27]. The Review also said that the MCFCs were only able to add 10MW in the past year, with production expected to ramp up further. According to them a total of nearly 71,000 fuel cells were shipped last year, which is an increase of nearly 10,000 in the last 10 years. The contribution of MCFC in the fuel sale total has repeatedly stayed under 50 in the last 5 years Appendix B. This small number can also be supported by low increase in MW installations of MCFC shown in Fig. 3.3 in chapter 3.

The cost of construction of various energy generators in the United States of America has been shown in figure 5.1. The cost of installing electricity generators has been shown to be between \$604/KW for combustion turbine to \$1,848/KW for PV. The cost of installing MCFC is not easily

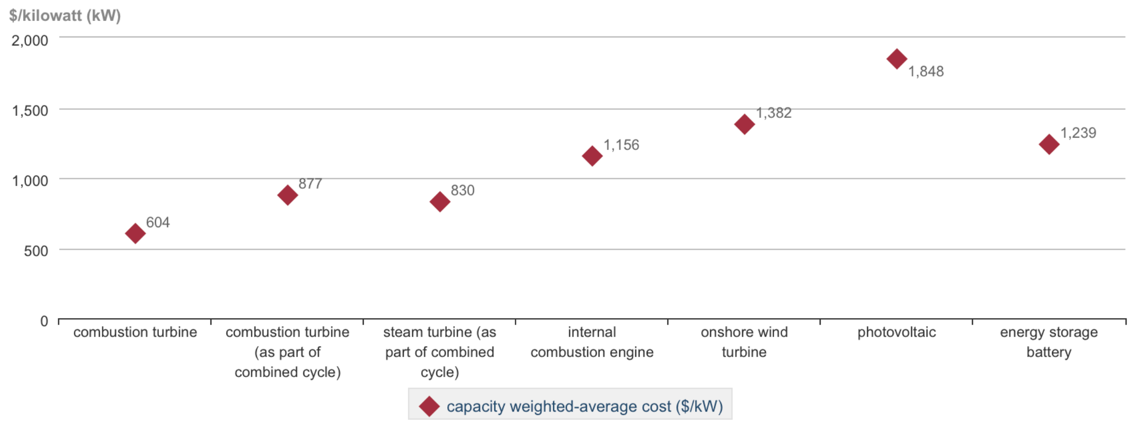

Figure 5.1: Average Construction Cost of electricity generators Ref. [28].

available due to extremely low quantities of production per year which is mostly supplied by a single company. Based on a report published by the National Renewable Energy Laboratory of the U.S. Department of Energy the installation cost of a 1.4MW MCFC model from FuelCell Energy averaged approximately $4,200/KW [110]. The breakdown of this amount involved the cost of fuel cell module being $2,400/KW, balance of plant involved $1,100/KW and $700/KW commissioning, conditioning and installation. This range of product from FuelCell Energy mentioned in the report included a steam-methane reformer that was incorporated into the fuel cell stack module, adding to the cost of the module. According to FuelCell Energy, integration of this MCFC to an anaerobic digester at a wastewater treatment plant or a food processing plant could increase the overall cost to $7200/KW due to the requirement of a custom designed clean up system [110].

It was estimated that the cost of the fuel cell module could be brought down from $2,400/KW through reduction in the overhead costs and material costs. The overhead costs can be reduced by increasing the volume of production and the material costs. High material costs is largely due to low power density of the cells which usually operates at $120mW/cm^2$, being far less than the $600mW/cm^2$ from the PEMFCs [110]. By increasing the power density of the fuel cell, more power output will be possible without increasing the material and therefore, reducing costs. They also estimated that the balance of plant, which is usually fabricated from standard chemical process hardware has the same scaling factor as the chemical process plants. As a result, overall reduction in cost per kilowatt is possible as with the increase in plant size. They also deduced from engineering estimates that the cost of commissioning, conditioning and installation can be reduced at a higher production value without significant modification of the techniques used in the production line. Having had 30MW/year of production in 2010, it was estimated that by 2020 that number could be raised to 100MW/year and up to 500MW/year by 2030. Based on theoretical calculations, they had estimated that by 2020, a cost reduction of $1,370/KW maybe possible and by 2030 the reduction of $2,130/KW can be achieved from the total cost[110].

In the study it was also recognized that fuel cell stack degradation needs to be slowed down to ensure a life span of 10 years. The causes of degradation were identified as electrolyte loss, cathode degradation, and degradation of inert electrolyte support. These topics have been researched on separately and work on such issues are being conducted internationally as well. They also showed the possibility of reduction in operation and maintenance costs by up to 40% by extending stack life to 10 years. They concluded that through increased R&D and volume productions, the costs would be brought down to $2,730/KW by 2020 and $2,030/KW by 2030 with a 10 year fuel cell stack life as shown in Fig. 5.2 [110]. Even if these cost reductions, which are the best case scenarios were achieved, the cost of MCFC would still be too high to make this technology commercially viable. From the cost of energy generators shown in Fig. 5.1, the cost of energy constructor is the highest for the PV based technology at about $1,848/kW, which is still much lower than the projected cost of $2,730/KW with the MCFC.

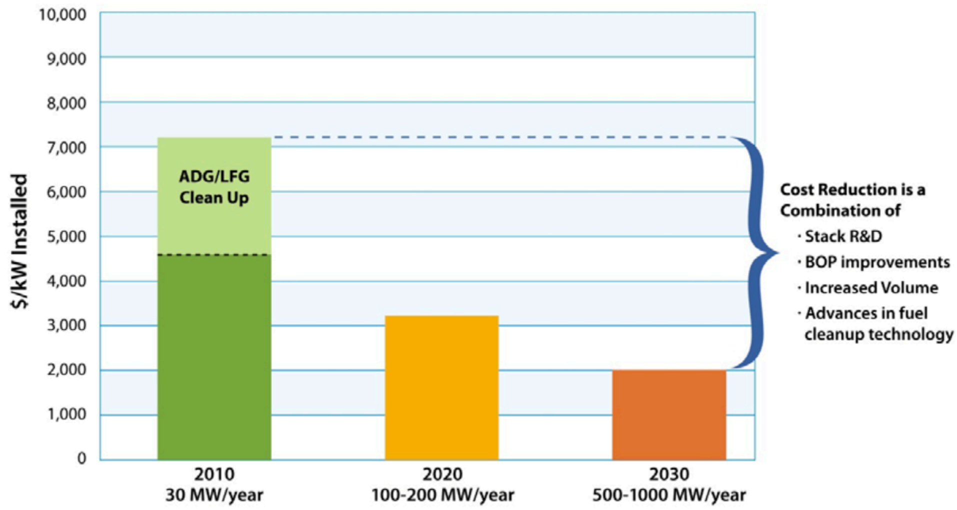

Figure 5.2: Projected reduction in the cost of 1.4MW MCFC with increased installation Ref. [110].

The same study also estimated the cost of electricity generated with a MCFC stack, having an average lifespan of 10 years, operating on natural gas at the cost $\$10/10^6$ Btu (this cost was chosen based on renewable gas certificates cost in the future). It was shown that under the 2020 scenario, the cost would be $0.130/kWh and under the 2030 scenario $0.116/kWh would be possible [110]. If these scenarios are achieved it could make these systems competitive as the average cost of electricity today is over $0.13/kWh in developed economies around the world [47]. However, cost of coal generated power can be as low as $0.07/KWh and conventional natural gas power can be as low as $0.06/kWh [89]. Additionally, cost of power from renewable energy sources like wind and solar have fallen to as low as $0.045/kWh in case of onshore wind and solar PV [66]. In 2013, the cost of electricity from fuel cells was about $0.15/MW [89]. According to FuelCell Energy that primarily deals with MCFC, when the costs have been brought down to between $0.09/KW to $0.11/KW, fuel cell based energy will be able to be competitive with other sources [89]. Between 2003 to 2013, FuelCell Energy was able to reduce cost of producing energy by three quarters of the original value, and with the increase in production this cost could be reduced further [89].

Most of the hydrogen today is produced from fossil fuels. About 48% of hydrogen generated is produced from natural gas, 30% from naphtha and heavy oils, and 18% from coal [93]. The cost of production is strongly correlated to the cost of fuels used. Among the technologies of producing hydrogen from fossil fuels, hydrocarbon reforming and pyrolysis are the most popular. With steam methane reforming, the cost of hydrogen that is produced can be in the range between $2.08/kg (without CCUS) and $2.27/kg (with CCUS) [69]. Through methane and biomass pyrolysis the cost of hydrogen generated can be found to be in the range of $1.25/kg and $2.20/kg [69]. On the other hand the cost of hydrogen generated from renewable sources can be found to be between \$3.0/kg to \$7.5/kg[61]. In natural gas MCFC in trigeneration systems, it has been demonstrated that for a 300KW internal reforming MCFC stack (\$1,400/KW), supported with tax credit, the cost of hydrogen generation can be priced between \$6.5/kg and \$9.5/kg depending on the cost of electricity [5]. It was seen that, increasing hydrogen production reduces cost of electricity more rapidly for given levelized cost of energy. When electricity cost was fixed to \$0.103/KWh,it was possible to set price of hydrogen at \$6.5/kg in the case of 125kg of hydrogen coproduction per day and the price was increased to \$9.2/kg when coproduction was lowered to 75kg of hydrogen per day [5]. The variability in the grid price geographically also effects the minimum cost of production. For example, it was shown that 125kg of hydrogen gas coproduction per day could result in \$4.3/kg for the gas, like the New England Region where the commercial electricity price was close to 0.18/kWh. While, when the electricity price was as low as 0,08/kWh, the gas price was \$7.5/kg in the case of the west south central states of the United States of America [5].

For general cogeneration and trigeneration, the costs not only depend on the cost of the equipment, but it also depends on countries or regions the project is being installed. Due to this, comparing project costs and other related costs are difficult, because different baselines need to be incorporated. These costs include capital cost, financing costs and operation and maintenance costs but they can also include upfront transaction, cost of backup power and outages, and storage [134]. The total cost of cogeneration or trigeneration units can vary significantly between technologies. However, in terms of volume production, the underlying economies of scale is valid for all such cogeneration or trigeneration technologies [134]. For example, the cost degradation with increased capacity installation of natutal gas fired cogeneration unit is shown in Fig. 5.3.

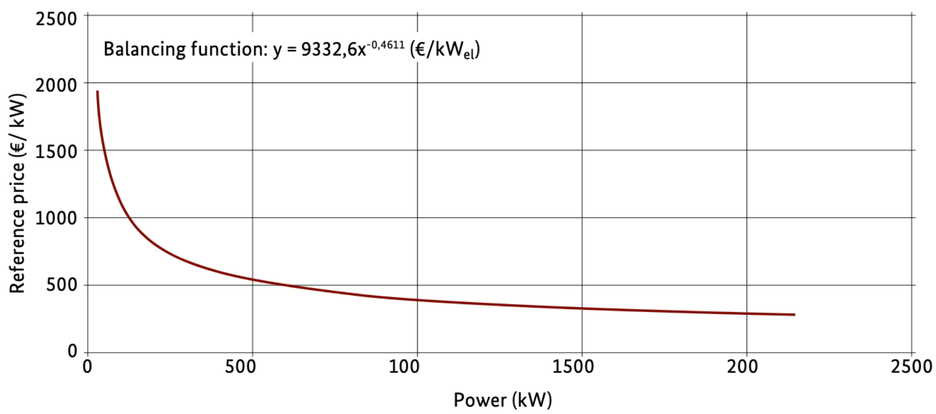

Figure 5.3: general representation of cost degradation of natural gas fired cogeneration plant Ref. [134].

Having seen that the superwind concept is technically feasible in section 3.8, some economic perspective is needed.In the case of the superwind concept, the profitability of a high temperature fuel cell based system has been examined by Hemmes et al in Ref. [52]. In the economic study they needed input data for electricity production forecast of a given turbine as this would be the amount of electricity sold in the market, the actual electricity output of the turbine, the price of APX (energy exchange which operates the spot market in the Netherlands) market and the balancing costs. They based the study on the data they recieved from the Winduine for one month for a 600KW wind turbine so the results are a rough estimate [52]. They established various strategies based on factors like fuel cells compensating for electricity only during shortage, only during surplus, during both shortage and surplus, and if or not the fuel cell is playing on APX. 'Playing' here refers to the adapting of the fuel cell output to APX price in order to achieve maximum possible economic benefits when the knowledge of the price is available in real time. Additionally, decision regarding if hydrogen was to be produced or not was needed. These decisions need to be made beforehand as the economic performance of the system depends on these decisions. Profit in this study was defined as income from wind turbine and fuel cell combination minus income from the wind turbine alone minus fuel cell operation and maintenance cost. From their study, Hemmes et al.(in Ref [52]) determined that (i) Hydrogen production substantially increased the potential benefits of the superwind concept. (ii) Compensating for electricity shortage is favorable only if additional electricity was also sold on the APX market implying that playing on APX market is more favorable. (iii) higher gains are possible when compensating for shortage than electricity surplus. (iv) Best results were obtained when the internal reforming fuel cell was operating in the stand alone mode, selling both hydrogen and electricity, and playing on the APX market, suggesting that playing on APX market gives the highest gains. (v) From the plot of increase in profit per kWh as a function fuel cell capacity they showed that the optimal fuel cell capacity requirement is about 1/3rd of the wind turbine capacity. (vi) The capital cost was not used in this study, since high temperature fuel cells like MCFC are too expensive. They were able to show that for the system to be economically feasible the cost should be in between €800/kW and €900/kW [52]. Although, this study was based on a lot of assumptions and further research is needed, an indication of profitability from the superwind concept was demonstrated.

From the information obtained regarding costs and profitablity, the following inferences can be drawn.

- As the quantities MCFC produced annually is too small (under 50), the installation cost of these fuel cells per kW is too high in comparison to other energy producing technologies (4,200/KW vs 1,848/KW for PV). However, by increasing factors like cell life and production capacities per year, the costs will be significantly reduced in the future and is expected to drop to around 2000/KW by 2030.

- Electricity generated from MCFC systems in test conditions can seem to be competitive when compared to electricity prices from countries with developed economies. However, they are still too expensive in comparison with what is possible with popular fossil fuel or renewable energy generations ($0.13/kWh vs $0.045/kWh for offshore wind). There have been indications of a downward trend in the electricity generation cost per kwh with MCFC in the last few years, and this price can be expected to fall further with improved advancement and production of these fuel cells.

- Cost of hydrogen productions from renewable energy sources are still not competitive with general steam methane reforming ($2.08/kg from SMR vs $3-$7.5/kg from renewables). With MCFC cost comparable to renewable energy sources like wind and solar maybe possible, depending on grid prices and locations.

- While costs can vary between technologies, for all cogeneration and trigeneration technologies economies of scale is valid in terms of volume production. This implies that cost reduction per kW installed capacity, is possible for MCFC based systems that is coproducing hydrogen and electricity (and heat).

- The economic profitability from the superwind concept maybe possible, especially when the output is adapted to electricity price which has been previously known. This could garner further interest in the technology which could inspire other studies.

From these inferences it can be concluded that, the MCFC based hydrogen cogeneration system is unlikely to be economically feasible in the near future, as currently it cannot compete with other technologies due to its high installation costs, which translates to high electricity and hydrogen costs in cogeneration productions. Since in test conditions the cost of hydrogen generated can already compete with renewable hydrogen, the cost of electricity can almost compete with electricity prices of some countries and economic profitability with the superwind concept maybe also possible, the main factor determining the economic feasibility of this technology is the cost of MCFCs. The cost of MCFCs have dropped over the years and this is expected to drop further with time. Moreover, like any trigenration technologies, coproduction technologies including superwind, will benefit from economies of scale. With proper support from the actors, based on the trends in costs available and the inclusion of added benefits of the superwind concept it can be concluded that **MCFC based cogeneration or trigeneration producing hydrogen, electricity (and heat) will be economically feasible in the future.**

5.1.2. Status of hydrogen market

For a MCFC based cogeneration system that produces hydrogen along with electricity to be successful, it has to make positive contribution to the hydrogen market. Primarily it is necessary for newer technologies to provide cleaner hydrogen generation solutions at competitive costs. In this sections we analyse the current hydrogen market and make assumption about the need for MCFC based technology.

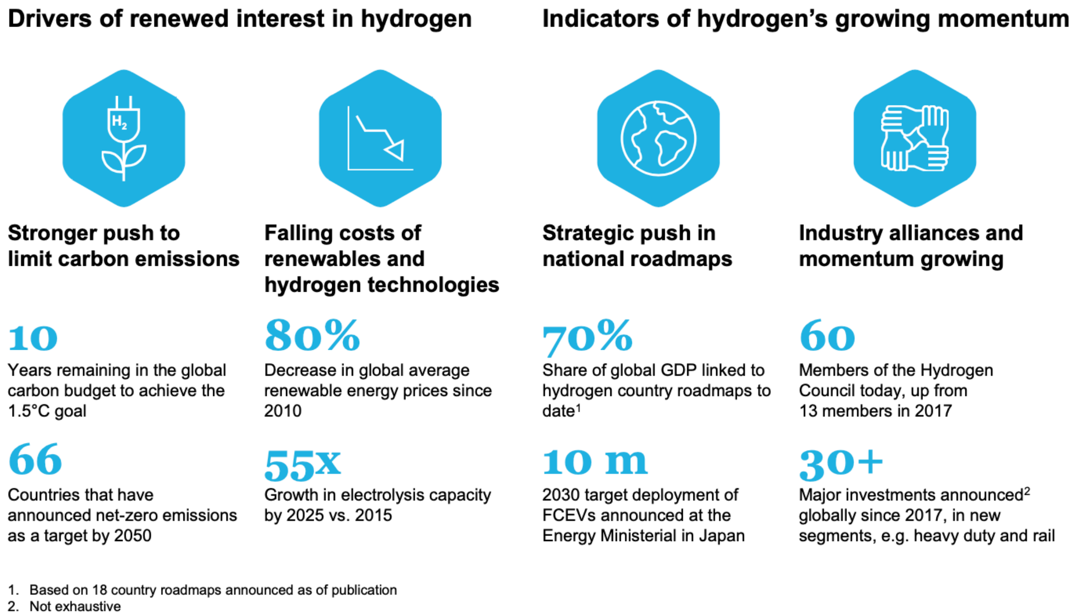

Figure 5.4: The main drivers and indicators of hydrogen's growing momentum. Ref. [20]

The demand for hydrogen has been rising over the years as hydrogen has been recognized as a clean fuel. The hydrogen Council has recognized two main drivers and two indicators of hydrogen's growing momentum in its 2020 report cite [20]. The drivers include (i) There is a stronger push to limit carbon emissions as only 10 years remain in the global carbon budget to achieve the $1.5^{\circ}C$ goal. (ii) Falling costs of renewable (like wind and solar) power, which is the largest driver of renewable hydrogen costs, has decreased significantly in the last decade boosting interest in clean hydrogen production with low carbon electricity. These drivers of hydrogen momentum have been supported by indicators such as (i) tangible government policies that promote hydrogen (ii) and growing industry alliances as the result of falling costs and hydrogen's versatility, resulting in investments in a variety of sectors. These drivers and indicators have been summarized in Fig. 5.4.

Based on the methods of production, colors are often used to refer to different types of hydrogen available today. Most of the hydrogen produced today is 'Grey hydrogen' that is usually from steam methane reforming using natural gas without any CCUS. Grey hydrogen is accompanied by production of a lot of carbon dioxide. 'Blue hydrogen' may refer to hydrogen produced by steam methane reforming with CCUS while using fuels such as natural gas or biomass. In case of blue hydrogen there is very low or no CO_2 emissions. There are many demonstration sized plants that exist and are in development with blue hydrogen technologies [85]. These technologies are proven but needs to be scaled to industrial size . 'Green Hydrogen' is the cleanest variety of hydrogen, with zero carbon emissions. This hydrogen is produced by electrolysis of water which is powered by renewable electricity from wind and solar. Technologies related to green hydrogen are mostly in pilot project stage [85].

As most hydrogen produced today is grey hydrogen, developing low carbon hydrogen production routes is critical in clean energy transition based on hydrogen. This can be done by either coupling conventional technologies with CCUS attachments to produce blue hydrogen or through water electrolysis from low carbon electricity and water. This means that technologies focusing on blue and green hydrogen will play an important role in future hydrogen production. This claim can be supported by the increase in such projects in the recent years. There were six projects that combined conventional technologies with CCUS in 2019, having a combined annual production of 350,000 tonnes of blue hydrogen, with additional 20 new project announced for commissioning in the 2020s [79]. Electrolysis of water to produce hydrogen with electricity is made possible in Electrolysers. Electrolysers when supplied by low carbon electricity from renewable sources, enable the production of clean green hydrogen. While elctrolysers have been used in various applications in the past, their fastest growing market today is for uses with climate and energy goals. Not only has the average electrolyser based project size increased from 0.5MW to upto 6MW in the last decade, but the installed capacity had increased from less than 1MW in 2010 to more than 25MW in 2019 [79]. In March 2020, Japan opened world's largest green hydrogen plant using a 20MW solar array, with back up renewable power from the grid, to run an electrolyser with 10MW capacity [74].However, despite the increased capacities for both green and blue hydrogen, such technologies remain expensive and contribute a very small percentage of total global hydrogen production. It is expected that the cost of producing hydrogen from renewable electricity could decrease by up to 30% by 2030 due to the declining cost of renewable energy and the scaling up of hydrogen production [61]. As a result, related technologies such as fuel cells, electrolysers and refueling equipment can benefit from mass manufacturing.

As the hydrogen markets continue to grow, blue hydrogen could play a major role especially in the short term. This is because a large part of current industrial applications can be decarbonized with minimal interruption to the supply chain [85]. This can be done by increasing the cost efficiency of blue hydrogen production method by adding economical CCUS technology. The cost of CCUS can be brought down if CCUS technology is scaled up or better use of $CO_(2)$ is found. In these natural gas based blue hydrogen generation technologies the cost is mostly influenced the cost of the natural gas. The cost of blue hydrogen could be as low as \$1.40/kg while green hydrogen is estimated to be triple at about \$4.42/kg [116]. In various studies blue hydrogen is often considered as a bridge between grey and green hydrogen. According to one of the studies blue hydrogen production could grow in capacity from 0.6 million metric tons per year to 3.3 million mt/year by 2028, while green hydrogen production would grow from 0.2 million mt/year to 0.6 million mt/year in that span [116].

Besides the high cost of cleaner hydrogen production, and heavy reliance of current technologies on fossil fuels, the other drawback of hydrogen production is the lack of infrastructure. The development of hydrogen infrastructure is slow and the existing regulations limit the development of a clean hydrogen industry [61]. Hydrogen prices for the consumer will likely depend on factors like the number of fueling station, their use frequency and the quantity of hydrogen they can deliver. These factors bring out the necessity of efficient planning and coordination between industry, investors and the government. Government and industry must work together to ensure that unnecessary barriers are removed and trade and investment is encouraged [61].

Hydrogen has the potential to be used in a variety of applications. Fig. 5.5 shows existing and future applications of hydrogen and the expected timeline of when they would be cost competitive. The figure also shows the low carbon competition for each sector. Among the applications listed in the figure, hydrogen has only reached cost competitiveness in applications where it is used used as an industrial feed stock. While the possibility of applications of hydrogen is large, in the short term for most applications, it struggles to compete against conventional alternatives due to its high generation costs and limited infrastructure as seen in the figure. The Hydrogen Council expects most road applications and simple cycle hydrogen turbines for peak power, hydrogen boilers and industry heating to be cost competitive against low-carbon alternatives by 2030 [20]. By 2050 most of the hydrogen technologies in Fig.5.5 are expected to be cost competitive against other low carbon alternatives so as to meet the $2°C$ temperature increase goals, with the CO_2 emissions expected to be reduced by 90% [20]. This will only possible if low carbon solutions are applied with other solutions like carbon sequestration and electrification.

Most of the hydrogen produced today is used in industrial applications where hydrogen is used as a chemical agent. These applications generally include oil refining, ammonia production, methanol production and steel production. The hydrogen that is supplied today consists of two main types: hydrogen that is produced onsite and hydrogen that is produced as a byproduct. Onsite production is often done by large consumers in the chemical industry and constitutes about 64% of total European hydrogen [37]. Hydrogen that is produced as a byproduct in other industrial applications constitutes 27% of the total hydrogen production and is also commercialized. The remaining 9% of the hydrogen that is produced is is found in merchant hydrogen commercialization [37]. Due to these factors the hydrogen market is not transparent. The hydrogen price is highly dependent on local market situation and as there is no reliable database for prices and transactions yet. Therefore, a global, regional, or national price for hydrogen does not exist [91].

It should be also be noted that transport of hydrogen is one of the key challenges to the parties involved in the process chain. Hydrogen is usually transported from the point of production to point of use over road in cryogenic liquid tanker trucks, barge, rail or pipelines. These processes usually have high delivery costs, operate at low efficiency and can suffer from hydrogen leakage or contamination. Low efficiency is partly due to the fact that at the same pressure, hydrogen energy content is less than a quarter of that of natural gas. There have been methods proposed for hydrogen transportation and for building hydrogen infrastructure. These include building a new hydrogen network parallel to the grid or converting existing nat-

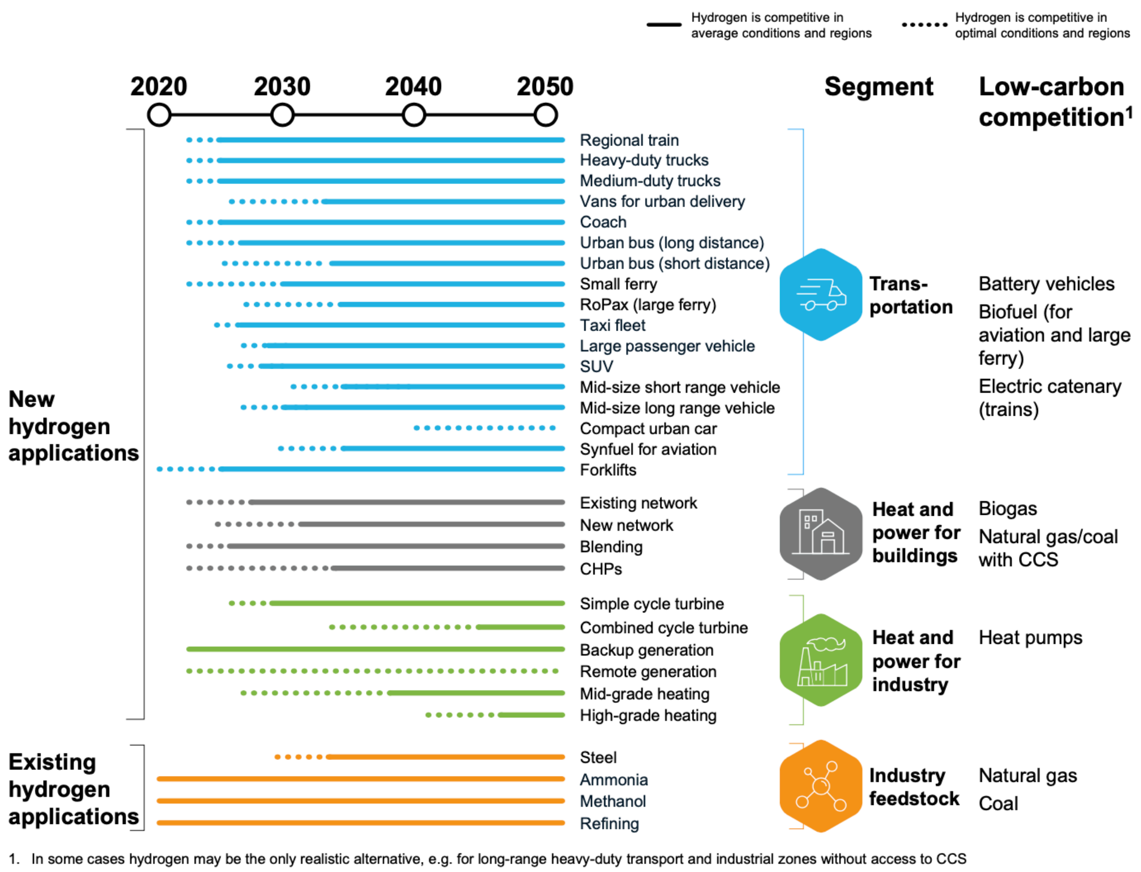

Figure 5.5: Projection of cost competitiveness trajectories of hydrogen applications. Ref. [20]

ural gas grid. The economics of both these options are still uncertain, however the cost of conversion of natural gas grid can be between 5-30% of building a new network [124].

It has also been suggested by experts that a decarbonization pathway that is based on electricity will only be expensive and unrealistic. Hydrogen will be needed to meet industry demands for deep decarbonization to be achieved. There are many applications that technically use electricity, for which hydrogen can be the still cheaper alternative. It has been shown that hybrid electricity-hydrogen models can be far cheaper than electricity only models [85]. There have been studies that have shown hundreds of billions of euros can be saved by the European Union if the hybridized pathway is chosen. A study by Navigant showed that upto €217 billion could be saved annually on a scenario based on hydrogen and electricity [41]. In the Eurogas scenario study conducted using PRIMES modelling they concluded that a strong push for electrification would result in high overall costs and system limitations. A combined hydrogen and electricity scenario was a better approach and it would allow annual savings of upto €335 billion in infrastructure investments until the year 2050 [32]. Moreover, there exists ambitious renewable energy targets, like the European Union's 2030 goal of producing 32% of all energy and more than 50% of its electricity from renewable energy. Since, most of this demand is expected to be met by intermittent sources like wind and solar energy, hydrogen will play a vital role in complementing and balancing these sources and providing a flexible electricity balancing service [85].

In this section information regarding state of the hydrogen market and future market trends have been presented. Summarizing the information, the following inferences can be made:

- The drivers (like carbon emission reduction) and indicators (like government policies and roadmaps) of hydrogen momentum point towards increased focus on hydrogen that would require newer, cleaner technologies and pathways.
- Currently grey hydrogen dominates hydrogen production but there is a push towards developing blue and green hydrogen technologies.
- As green hydrogen technologies are not yet economically feasible, natural gas based blue hydrogen production will dominate in the near future.
- Hydrogen has the potential for use in a variety of applications most of which are not cost competitive currently. Rapid developments of technologies and their mass production would be needed to meet the 2050 climate change targets.
- Due to the lack of proper hydrogen infrastructure, and drawbacks of current transportation methods most of the hydrogen generated is on or near the site of their applications.
- The decarbonization pathway based on hydrogen and electricity is economically more favorable than electricity only pathway. Moreover, hydrogen will play a vital role in complementing and balancing electricity from intermittent sources.

The MCFC technology for coproduction of electricity and hydrogen will benefit from the growing hydrogen momentum as it provides a low carbon solution of producing hydrogen. Additionally, decrease in hydrogen cost will promote MCFC mass production and this will lower the cost of these fuel cells. As blue hydrogen production is expected to dominate in the near future, natural gas based technology will still be encouraged. The MCFC uses natural gas to produce blue hydrogen and electricity but it can also be used with renewable sources like biomass to produce green hydrogen as seen with the Fountain Valley project 3.7. The currently lacking hydrogen infrastructure, makes the MCFC based coproduction system a more suitable solution for distributed generation of hydrogen and power at the the site of operation. The hydrogen that is produced can be used in a variety of applications and is suited for transport as well as industry sector, thus, helping in their development. As the MCFC systems can produce hydrogen as well as electricity they are well suited for a hybrid electricity-hydrogen decarbonization pathway. Additionally, since all these advantages apply to the superwind concept as well, they can also be considered as a solution in hydrogen market development. They have an added advantage because with the superwind configuration, it is possible to balance electricity from intermittent sources like wind energy as well. And they can also help in the transition towards hydrogen infrastructure since they can produce hydrogen by combining natural gas and electric inputs.

Based on the status of hydrogen market it can be assumed that **MCFC systems for cogeneration of hydrogen and power, and MCFCs in superwind configuration are well suited for hydrogen market.** These systems can help bridge the gap between grey and green hydrogen and combat few other concerns in hydrogen market development.

5.2. Actors and their involvement in the superwind generation

There are many stakeholders compromising of actors from various sectors that play important roles in introducing a new technology and its success. It is necessary to identify these actors involved to make informed decisions needed for managing, guiding and controlling how a technology develops. A stakeholder analysis is usually carried out when a new project develops. As identifying all actors can be complicated, important actors have been identified and their roles summarized in this section.

Actors can be categorized in various ways. The actors can be classified on the basis of the nature of various sectors that are involved like shown by Franzen et al. in Ref. [38]. They categorized the actors into three categories namely public sector actors, private sector actors and civic societies consisting of interest groups and citizens. Elsewhere, Geels identified that actors are embedded in social groups with shared characteristics like roles, responsibilities and norms [43]. He identified that socio-technical systems do not function autonomously but are the result of the activities of actors involved. In his paper the actors are divided into two main groups based on if they can be found on the production side or on the user side of the system. Actors can also be identified based on the the PESTLE analysis. PESTLE stands for Political, Economic, Social, Technological, Legal and Environmental analysis. This method is typically used in business and management to analyze their operating environment but has also been used to analyze the stakeholders involved in renewable energy industry as shown in Ref. [130]. However, this system seems more favorable for an industry on the whole, rather than a single technology, so it has not been considered in this thesis. It is important to note that all these methods will be specific to the technologies, regions and other local factors. Hence, only generalized analysis using them has been indicated here.

Public Sector	**Private Sector**	**Civic Society**
International unions E.g European Union	Energy and gas suppliers	Residents
National governments	Utilities	Public organisations
Local governments	Wind turbine/Solar energy manufacturers (superwind)	Car owners
Energy ministries	Project developers, , designers and architects	Environmental groups
Health ministries	Financial institutions	Non Governmental Organizations
Transport and infrastructure ministries	Builders	Charities
Municipalities	Knowledge institutions	Heavy duty truck owners
Environmental Agencies	housing associations	Energy Transition groups
Power Grid Owners	Chemical Industries	
	Car Manufacturers	
	Gas Stations	
	Wind energy generators (superwind)	
	MCFC Producers	
	Renewable Energy Consultants	
	Hospitals, Schools, Commercial spaces	
	Biomass Generators	
	Engineers and Researchers	
	Uber/Lyft drivers	

Table 5.1: Classification of different actors in MCFC cogeneration based different sectors.

Adopting the method of classification proposed by Franzen et al. (Ref. [38]) for the MCFC based system generating hydrogen, power and heat, the actors involved have been segregated into three sectors as shown in Table 5.1. It is important to identify as many actors as possible but for the sake of simplicity only the more obvious actors have been listed. In the classifications made, the public sector actors are generally the government bodies, private sectors involves actors who are not state controlled and the motive for their action is to earn profits. Civil society consists of actors distinct from government and for-profit actors, these are actors with shared interest and includes profession associations, community groups, non-governmental organizations and citizens among others. In the case of superwind concept, despite the technological differences, most of the actors involved would be the same. The only two other additions that have been considered here are the wind turbine (solar PV if solar energy is used instead of wind) manufacturers and the wind (or solar) energy generators who supply energy from the wind farms. This has been pointed out in the private sector column seen in table 5.1.

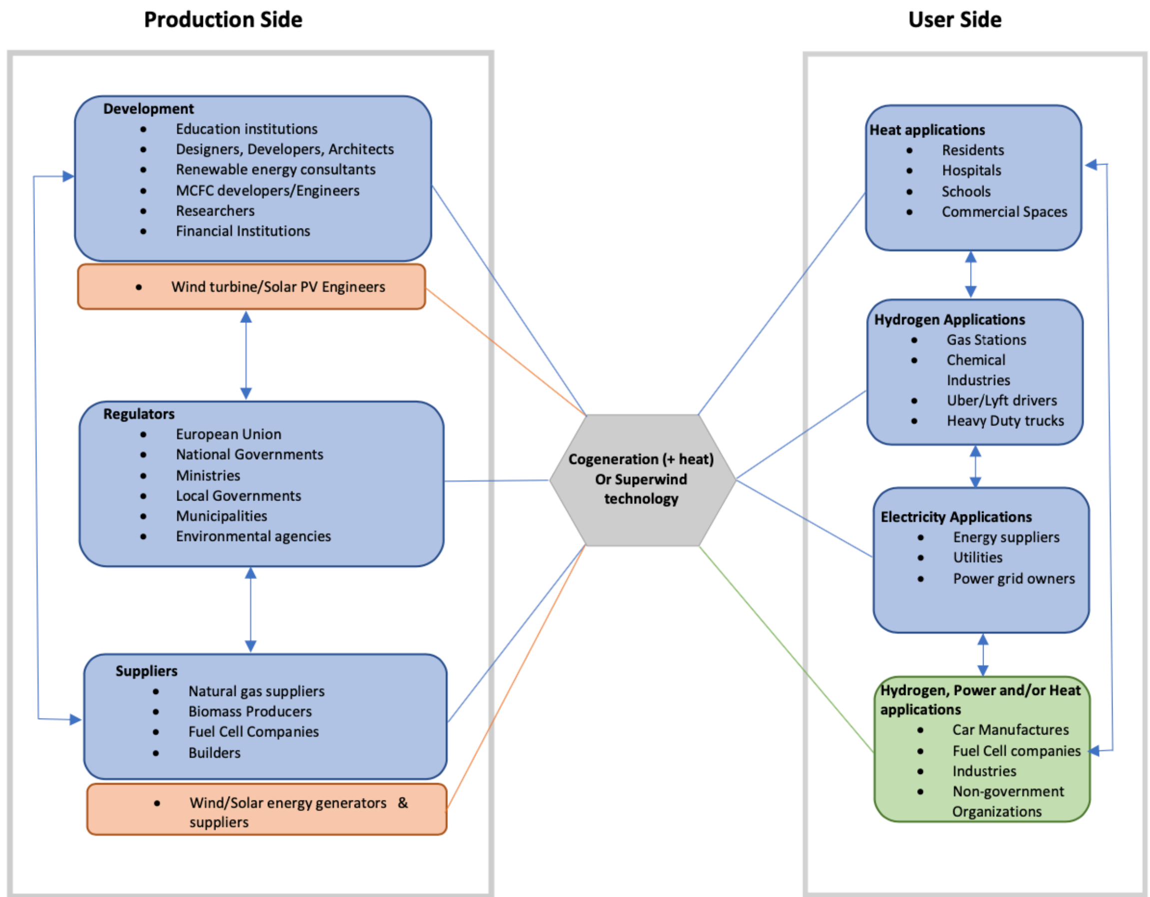

Figure 5.6: Actors involved in MCFC based technology (and superwind) producing hydrogen, heat and electricity.

It is also possible to classify the actors mentioned in table 5.1 based on their roles in either the production side or the user side. This has been presented with the help of a chart shown in Fig. 5.6, which has been inspired by diagrams found in Ref. [81] and Ref. [43]. The production side consists of three main categories based on actors in development, the regulators and the suppliers. The orange blocks on the production side represents additional actors in the development and supply categories when the superwind concept is considered. The double sided arrows in the production side is because each of the categories can separately influence one another. For example, a new stricter policy regulation from the government to cut emission could boost research and development of new cleaner technologies. Similarly, financial institutions can not only provide funds to developers for new research but they can also provide funds to suppliers in the form of loans. On the user side of Fig, 5.6, the consumers have been separated into categories based on the type of energy carrier utilized. These categories are based on hydrogen applications, heat applications, electricity applications and applications combining all three (represented by the green block). The double sided arrows in the user side is because some of the applications can benefit for more than energy carrier. For example, chemical industries that require hydrogen as a raw material can also utilize electricity produced by the MCFC based cogeneration or the superwind technology. Similarly, the consumers of heat can also benefit from electricity generated by these technologies. As the demand for hydrogen and cleaner energy technologies increases, the categories on the user sides are more likely to merge with one another. Combining both methods of classifying actors we see that the actors in the public sectors generally fall in the production side while the actors from the civic society will mostly be the users of the proposed technology. Profit oriented private sector actors can be found on either side.

From Fig. 5.6 we see that introducing a new technology involves a multi-actor network. In networks, the governments (or regulators) alone cannot impose their will upon other actors, and interaction between interdependent actors is necessary in decision and policy making processes [71]. Intensive interaction between actors helps with resource distribution and influences the functioning of a network associated with development of a new technology. The actors play a specific role and their actions determines the success or failures of a project. Without cooperation between actors, especially those who mutually depend on one another to realize their objectives, favorable outcomes cannot be achieved [71]. It is therefore necessary to understand the role of actors and how they can influence the development of MCFC based coproduction and superwind technologies.

From Fig. 5.6, the important categories of actors are the developers, the regulators, the suppliers and the users. Their roles in introducing a new technology would be as follows:

Developers: These actors include those that are responsible for development and designing of a technology. They include scholars, engineers, researchers, consultancies, universities and even companies can be involved. In this stage analysis of current issues and policies are required. New solutions are proposed after issues and the available technologies have been analysed. Additionally, through research, exchange of knowledge, and experimentation the technical feasibility can be determined. In the case of high temperature fuel cells, the concept of cogeneration and trigeneration has been proposed by various researchers, which can be found in literature. For example, Hemmes et al. tested the technical feasibility of SOFC while looking for an alternate method of hydrogen production as fuel cells had not been studied enough for hydrogen generation [55]. Similarly, FuelCell Energy recognized the need for economical hydrogen generation closer to the point of use and also the potential of a sizable new market if the fuel cell electric vehicles adoption was accelerated. This lead to their collaboration with the government in the Fountain Valley demonstration project [75]. The superwind concept was proposed by Hemmes having recognized the drawbacks of intermittent wind energy and the lack of hydrogen infrastructure [51]. Financial Institutions can be considered a part of development if they provide funds for experiment or demonstration projects.

Regulators: The regulators are generally a part of the public sector. They can include multi nation-union like the European Union, the national governments, local governments municipalities, environmental agencies and other authoritative bodies. These bodies not only oversee the progress being made or if the fund is being utilized effectively, but they have other important roles. For instance, European Union's 2050 goal to have net-zero emission by 2050 has increased member nation's focus on cleaner energy generation. The Netherlands, for example has included the rapid development of hydrogen in its long term-growth strategy. The government aims to send a clear signal of their commitment to hydrogen by stating the importance of zero carbon-hydrogen, introducing ambitious policy agenda and taking steps needed to boost infrastructure developments [102]. They have realized this would also benefit the economy by attracting international companies. They hope to announce their hydrogen program, which will be jointly outlined and implemented by the stakeholders next year. These kinds of initiatives will benefit the MCFC based systems studied in this thesis. The local governments may find these systems attractive not only because these systems will supply clean energy but also because they may provide jobs and help in local development.

Suppliers: Not to be confused with energy suppliers that provide electricity and gas to the end users, suppliers here refers to the providers of the input and construction required for installation, construction and running of MCFC systems. These consist of fuel cell companies that are producing fuel cells and accompanying parts commercially, for operations beyond the demonstration projects, like the trigeneration project at Toyota's Long Beach facility [109]. Currently FuelCell energy is the largest supplier of MCFC in the world. Additional actors could be builders responsible for building infrastructures or other necessary components. Suppliers would also include natural gas suppliers supplying to the MCFC systems. As a MCFC can operate with a variety of fuels even biomass plants can supply fuel to the MCFC systems. In case of the superwind operation, wind turbine owners would be the suppliers as well.

Users: Users will play an important role in the market formation since they are the one who would create demand for these technologies by utilizing electricity, hydrogen and heat supplied. The heat can be used for generating hydrogen or it can be supplied for heating applications in residence, hospitals, schools and commercial complexes. Hydrogen can be supplied to the gas station and chemical industries. While the electricity generated can be utilized by energy suppliers, utilities and power grid owners before it can be supplied to the end users. In combined applications, all three forms of the energy can be utilized on site like in the case of car manufacturers [109]. Beyond those consumers, wind turbine owners or solar farm owners would also benefit from the superwind configuration as these systems would reduce the cost of energy storage by eradicating the need for batteries or the balancing costs they might have to pay due to irregular generation and could drive the demand for this technology forward. Moreover, these systems could also benefit from consumers who are part of a energy collective, which is an association of members who aim to facilitate, use and promote sustainable energy. In the Netherlands there were 582 of these energy cooperatives in 2019 and the number is only growing [103].

The network of actors who are responsible for conceptualizing, operating and using the outputs of a new technology are not the only once who influence the success or failure of a project. There are other external factors that need to be taken into account. The interaction between actors and the response to external processes can be demonstrated with the help of multi level perspectives.

Multi-Level Perspective using the Superwind concept

The concept of Strategic Niche Management(SNM) has been recommended for designing and organizing a superwind pilot project in Fryslan by Hemmes et al. in Ref. [52]. Fryslan was selected because of its sustainable energy goals, and Nij Bosma Zathe (NBZ) was chosen as a location that could host the project because biogas was easily supplied. There was also the possibility to utilize waste heat, and deliver hydrogen at a gas station [52]. The SNM approach involves a concentrated effort to develop protected spaces where a promising new technology can develop and be used [70]. These protected spaces are the technical niches. The idea behind this approach is that from these technological niches, an innovation can grow and expand and may ultimately be able to replace the dominant technology. Niches are platforms of interaction and they result from interactions shaped by multiple actors [70]. When Fryslan was proposed for the pilot project, wind energy was still considered a niche technology[52]. However, in the time since that paper was published in 2008 the global wind energy installed capacity has increased from 120GW to 650GW and wind energy is often considered a mainstream renewable energy technology[21] [132]. MCFC are still in niche phase so superwind can still be studied using SNM. Nevertheless, the developments within the niche are not the only important factors, and external factors play a crucial role in bringing about transformation as well. Niche innovations themselves cannot bring about changes in the regime without the help of broader forces and processes from the outside [117].

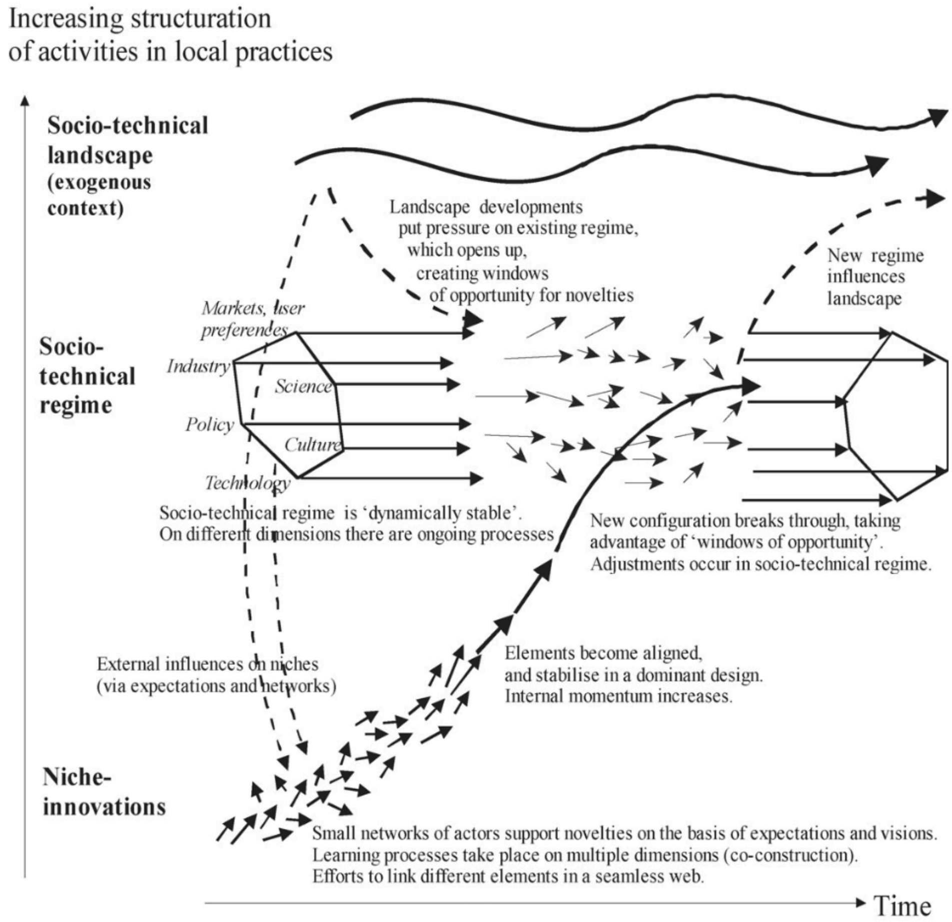

Figure 5.7: Multi-Level Perspective on technological transitions. Ref [42] and Ref. [44].

The Multilevel Perspective (MLP) is a framework that links the internal and external processes of the niche. The MLP frameowrk consists of three levels as explained in Ref. [117] and shown in Fig.5.7. (i) Niches: Micro level where novel sustainable technologies can emerge. (ii) Socio-technical regime: Meso-level accounting for the stability of a large scale systems(e.g. energy). (iii) technical landscape: Macro-level exogenous environment beyond the influence of niche and regime actors. The MLP suggests that transition comes about through interaction between processes and actors at various levels. Changes in the landscape puts pressure on the regime while the niche innovations build up internal momentum. These niche innovations have windows of opportunities to break into the regime when its destabilization occurs [117]. The regime is destabilized because of stress and shocks on the landscape level or through the operations within the the regime.

The interaction between the actors and processes can be elaborated in each level of the MLP framework by using the superwind concept in the Netherlands as the example.

Landscape level

Changes in the landscape levels occur slowly and are usually out of control of regime and niche actors. For this example, on the landscape level is the climate crisis, and limited availability of fossil fuels which has put pressure on the energy systems. Additionally, The Paris Agreement whose long term goal is to limit the global average temperature rise to $1.5°C$ can also be considered part of the landscape here. This landscape development puts pressure on regime to focus on cleaner energy systems. Additionally, the European Union's target of increasing renewable energy share to at least 32% and increasing energy efficiency by at least 32.5% by 2030. This would also form the part of the landscape for all the member countries.

Niche

This stage involves a small network of actors supporting novelties on the basis of visions and expectations. Learning process in this level takes place on multiple dimensions [117]. The example for this can be the superwind concept that was designed with the vision to improve reliability of wind energy while providing hydrogen to boost the growth of hydrogen infrastructure. The actors here are the researchers, engineers, institution, designers and even the NBZ testing facility that was chosen to facilitate the pilot project. As superwind concept aims to produce hydrogen while eradicating the need for electricity storage, it will face competition from other technologies in the niche stage with similar goals. For example a feasibility study stared last year that aims to build a 100 MW hydrogen plant for Westereems Wind farm. The electrolyzers are fueled by wind energy from the farm and hydrogen is supplied for industrial applications, heating and transport [23]. Similarly there are numerous other projects in the various stages of development for potentially producing blue or green hydrogen in the Netherlands that have been listed in Ref. [23]. When it comes to electricity storage, LeydenJar Technologies have made a breakthrough in battery technology that aims to boost the battery energy density by 70% while reducing CO_2 emissions by 62% [62]. Just like these there would be other innovations that are being developed in the niche involving small set of actors.

Socio-technical regime

The regime reflects the interaction between industries, policies, markets, user preferences, science, culture and technologies. These regimes are dynamically stable despite the processes, learning effects and ongoing incremental changes [117]. The government policies can play an important role in either driving regime change or maintaining certain technologies' continued existence in the regime. In the example of the Netherlands, the government has expressed desire to upscale hydrogen development in the country. The superwind concept could benefit from the financial support that includes subsidies up to 25% during research and development of a new technology, the government's increased interest in linking hydrogen to offshore wind energy, and even green hydrogen policies since MCFCs can also be powered with biogas [102]. The speed at which regime can change will also depend on the support offered by the government to the current technologies. According to one study the Dutch government has still on average, offered fossil fuel subsidies worth over €4 billion annually in the last 5 years [125]. Elsewhere in the regime, interactions between science and technology can occur through collaborative initiatives such as the Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), of which the Netherlands is a part of [102]. This initiative aims to support the development of hydrogen and fuel cell technologies and speed up their deployment. Science and technology related actors in the regime can also be the existing industries manufacturing wind turbines and fuel cell technologies in the regime. Advancements made in these industries can boost the opportunities for the applications of the superwind concept. For example, Tennet, a dutch electricity company is spearheading a project based on an offshore windfarm on an artificially developed island, with support equipment that is expected to generate 30GW of power [40]. Having support equipment on the island, makes it easier for the team to operate more turbines at a lower costs. The superwind concept can be suitable for projects such as this as it is equipped for distributed generation since it use MCFCs, and also because transporting hydrogen is considerably cheaper than producing hydrogen. Additionally, since the superwind concept can also utilize natural gas it can support energy transition. Currently natural gas is the main energy carrier in the Netherlands, its unlikely that the actors associated with its generation and distribution will leave the regime in the near future. Market creation will also be necessary for the superwind technologies to develop. The users of heat, power and hydrogen separately or together would be able to drive the development concept further. (Some of the users have already been mentioned earlier in this section 5.2 and their role applies in the regime as well, hence they have not been mentioned again.) While the demand for cleaner electricity is widely discussed, in the Netherlands 93% of the heating supplied is through natural gas based plants, and an additional 4% of the supply is through district heating [33]. District heating generally utilizes heat from cogeneration plants in CHP applications. This heat generation can be considered similar to the superwind generation, as it is the heat that is produced as a byproduct that is being utilized. Since district heating is expected to grow in the future, it shows that heat generation from cogeneration technologies is desired. Hydrogen market is expected to grow as well as the users, who are expected to buy 300,000 fuel cell electric vehicles by 2030 [36]. The existing regime can also be phased out if the preference of the users changes. This can be brought about by creating awareness, through demonstration, education and media by highlighting the benefits of hydrogen and the drawbacks of fossil fuels. This increased awareness can also result in usage of technologies in a new field, especially through proper strategies, policies and collaborations between actors.

In the current Dutch socio-technical regime, fossil fuels (mainly natural gas and petroleum) are the dominant energy carriers as a result of the lock-in effect which has been developed over the decades. This lock-in effect works against the phasing out of fossil fuel by keeping the related technologies in the regime. The stable regime is the result of it resisting pressures from the landscape and the niche innovations for decades through modification strategies, focusing on economics, innovations, and frameworks that maybe socio-cultural and political. This lock-in effect works against the phasing out of fossil fuel by keeping the related technologies in the regime. Usually the transformation of regime occurs through either of the four different transition pathways as proposed by Geels and Schot in Ref. [44]. They are (i) Transformation: In response to moderate landscape pressure when the niche innovations have not yet developed sufficiently, the actors in the regime respond by modifying the direction of innovation activities and innovation paths. (ii) De-alignment and re-alignment path: In this method of transformation, problems in the regime are large. This results in regime de-alignment and ultimately its erosion. There are multiple innovations that emerge, and a single innovation or a combination of multiple innovations co-existing together form the new re-aligned regime. (iii) Technological Substitution: In this pathway, the niche technology that has sufficiently developed replaces the existing dominant technology, in response to landscape pressure. (iv) Reconfiguration: In this pathway, not only does the regime change in terms of technology used, but there is also a substantial change in the regime's architecture and the organizational structures.

It is known that landscape pressure exists as mentioned earlier and in the niche level the superwind technology along with other competing technologies are developing. The list of actors in all the three levels in reality will be longer and their interactions will be more complex. However, from the information gathered above, the suggestions for the expected pathway with the superwind concept can be made. Since MCFCs are not yet produced on a large scale and are expensive, technological substitution pathway can be ruled out. Additionally, the superwind concept cannot be considered as a fully developed technology yet. The de-alignment and re-alignment pathway can be ruled out, as it is unlikely that superwind technology is the dominant or one of the dominant innovations in the niche because of limited experimentation and other constraints due to availability of wind farms, location and MCFCs. Moreover, as over 80% of the energy demands of the Netherlands is still supplied by fossil fuel based technologies, their de-alignment is unlikely to happen in a relatively short duration of time like a decade or more. Reconfiguration and Transformation are the most likely pathways through which superwind concept can be absorbed into the regime. In both these concepts the regime evolves due to efforts of the actors in the regime towards innovation activities. This results in a new regime growing out of the old one as the result of new technologies moving into the regime from the niche level. Once the superwind concept is ready for commercialization it can be slowly absorbed into the regime. As the demand for hydrogen is expected to increase, the superwind concept will in turn benefit from the growth of competing technologies that produce hydrogen. This is because as hydrogen applications become more mainstream, it will result in increased interest in clean hydrogen, MCFCs, and hence the superwind concept. The additional characteristic of the reconfiguration pathway that separates it from the transformation pathway is that regime reconfiguration involves change in regime's architecture and organizational structure. This has always been a possibility with increased technological advancement, focus on efficient methods of operation and the ever growing climate concerns. However, with the ongoing COVID-19 pandemic, the impact of which is not entirely understood, reconfiguration of the regime's architecture and operation is a possibility. With the pandemic effecting almost every sector and having influenced energy consumption, economy, trade, operations, energy generation and technology development among others, it is likely a new regime structure would emerge.

To bring about change in the current regime various actors are involved. In this section, the actors were first identified based on if they are part of the public or private sector after which they were also classified based on their role in production or consumption. This gave some idea of their role in the network around a technology. Since a breakthrough in technology is usually based on the response of regime actors to internal and external factor, MLP framework was applied using the superwind concept in the Netherlands as an example. Having considered a limited number of actors due to the complexity involved in the actor interactions, the paths of diffusion for the superwind concept is expected to be reconfiguration and transformation.

With the uncertainties created by the ongoing COVID-19 pandemic, it is most likely to be the reconfiguration pathway.

5.3. Investing policies and their role in hydrogen cogeneration

While many actors are involved in the network interacting with and influencing a new technology, governments play an important role. A new technology can greatly benefit from the government policies if its principles and aims align with their goals. In this section the suitability of the MCFC based cogeneration system is analysed based on the existing measures that would effect the development of this technology.

Cogeneration and trigeneration are not new concepts, they have been used in CHP applications for a while now. Hence, there are various policies in countries around the world that support these concepts and related technologies. In Germany for example, the share of electricity generated from cogeneration increased from 13.6% to 16% between 2003 and 2011 [134]. In 2012 a new act was passed in support of cogeneration that stated that required the increase in electricity generation to be 25% through cogenerating plants by the end of 2020 [134]. This increase was brought about through government support such as bonus paid per kWh generated, and capital subsidy for small cogeneration plants. In India, cogeneration is promoted through several policies and regulations on both central and state level. Subsidies of 5% to 25% can be availed on the total costs by the central government [134]. Capacity grants, feed-in-tariffs, and tax incentives have also been used in India to promote cogeneration plants. However, in the Netherlands where active CHP market was once thriving, lack of government support financially and an unfavorable market resulted in its stagnation and decline. In 2013 the Dutch National Energy Agreement halted the CHP cogeneration support in the Netherlands [94]. Despite the partial similarity between CHP plants, cogeneration using MCFCs, and the superwind concept in terms of input (natural gas) and outputs (power and heat) same cogeneration policies cannot be applied.

The MCFC based cogenration/trigeneration technology and the superwind concept is likely to be impacted by the policies associated with the following characteristics of these systems.

- These are highly efficient technologies. Highly efficient technologies will play in fundamental role in meeting climate change goals, strenghten energy security, improve energy access and reduce local air pollution.
- Natural gas is the primary fuel. These technologies will be impacted by the level of support and policies on natural gas.
- Carbon emission is low. In such technologies (i) no combustion occurs during operations and there is no need for additional CCUS technology. (ii) wind energy can also be used in the superwind configuration.
- Hydrogen is flexibly generated. Hydrogen fuel will play an important role in achieving net zero emission and quicker progress towards that emission target will depend on faster innovation in hydrogen generating technologies, bioenergy and CCUS among others.
- Electricity is flexibly generated. This method of electricity generation is more energy efficient than conventional combustion generation.

The European frameworks largely determine the Dutch energy policy. However, there is scope for developing national policies within the international framework. As policies vary among countries, just like with the CHP systems, the level of support for the cogeneration technology can vary from country to country. Therefore, using the Netherlands as an example, the degree of support offered by the government in their energy policy to each of these characteristics of the hydrogen and power cogenneration and superwind systems needs to be examined.

Support for efficient technologies

The Energy Agenda recognizes that the development of the technologies that are needed for low carbon by 2050 is not yet complete. It has been recognized that innovations aimed at sustainable and efficient heat use is needed. This includes focus on electrification of heat, sharing of residual heat and energy efficiency [88]. The Netherlands is also committed to 1.5% increase in energy savings annually and has made agreements with industry and economic sector. The Netherlands aims to produce 16% of all energy sustainably by 2023, and for this it is offering renewable energy grants for businesses to invest in technologies that combine production and storage among others [100]. Potential for energy saving is highest in built environments, manufacturing and transport, with an estimated 250PJ that could be saved annually from technologies in these sectors [57].

Policy on natural gas

Natural gas provides about 40% of the primary requirement in the Netherlands. Most of the gas extracted in the country comes from the Groninger field near Slochteren, and is the cause of in earthquakes in this area. Due to this limitations on the production in the area has been set to 24 billion m^3 per year [88]. The cabinet has also decided to phase out production from this site by 2030. The support for natural gas is decreasing. The Gas Act prohibits any new houses and buildings to be connected to the gas grid. The Mining Act requires companies to carry out studies extensively before applying for permits to extract gas [100].

Support for reduction in carbon emissions

The Dutch government plans to achieve net zero emissions by 2020. The government is promoting clean energy technologies through subsidies like the Sustainable Energy Transition (SDE++).This SDE++ subsidy is suitable for companies and organizations in sectors such as industry, mobility and electricity that aim to produce renewable energy or provide CO_2 reducing techniques. A budget of €5 billion has been made available for SDE++ [3]. Other measures taken by the dutch government to limit emissions includes a proposal to introduce a targeted carbon levy in the industrial sector. It is expected to be €30 per ton in 2021 and would increase to €125-130 per ton in 2030 [101]. The government has also placed a limitation on CCUS subsidies to promote technologies needed for long-term transition and is expected to reduce the expenditure on CCUS by half in 2030, which will be about €275 million [101].

Support for Hydrogen

As indicated in the government strategy on hydrogen document, rapid hydrogen development is in line with the country's long term growth strategy. In the first phase of hydrogen, the government has recognized that it is crucial to reduce the costs of clean hydrogen, which would be possible through upscaling of generation technologies in regions where there is demand for hydrogen (e.g. Industrial cluster). The blue hydrogen generating projects are permitted to receive support from the SDE++ subsidy [102]. The government also supports research and developments of hydrogen production in various Mission-oriented Research, Development and Innovation (MOOI) tenders. Additionally, innovative pilot projects related to hydrogen are encouraged through the Energy Innovation Demonstration Scheme (DEI+). Within the DEI+ scheme, the projects will be eligible to receive a 25% subsidy on the eligible costs. This amount maybe up to 45%, up to a maximum of €15 million per project [102]. The government is also planning to support projects with scaling up through temporary operating cost support in addition to the investment support. For this the government will be allocating €35 million per year by making use of Climate Budget funds [102]. The government has also been carrying out a study looking into the advantages and disadvantages of linking hydrogen production to offshore wind via integrated tenders. This study if successful, could benefit from reduced cost of landing renewable energy which would reduce the congestion on the electricity grid. This is because hydrogen transport is cheaper than transporting electricity [102].

Support in the Electricity Sector

The electricity sector platform has formed an agreement to produce more than 70% of electricity through renewable sources by 2030. The CO_2 free electricity is expected to be made possible through green hydrogen, nuclear power and from fossil fuel sources with CCUS or reduced emissions. Subsidies to be provided to renewable sources like wind and solar until 2025 [101]. The government also supports the idea of residents being involved in the local energy generation projects, with municipalities and provinces playing important role in energy transition through the Regional Energy Strategies (RES) approach. The security of electricity supply should not be jeopardised by a higher percentage of renewable electricity. The government continues to monitor the security of supply and the development of new technologies involving green hydrogen, supply, hybrid generation, and their applications [101].

Support for wind energy and biomass

As the result of various initiatives from the government, the onshore wind energy capacity is expected to be 6,000MW by the end of 2020. The measures involved in this process includes a better information and communication to overcome the resistance from local residents, and a fast track procedure for introducing wind farms [100]. For offshore wind energy, the government has proposed a roadmap after consulting with various actors involved. This would help the Netherlands generate 11GW by 2030 from offshore windfarms [100]. The government has recognized the importance of biomass in a range of applications and the support for new technologies is provided through SDE++ grants. Biomass is used for energy generation by combustion. Biomass that is cofired in coal fire plants need to meet higher standards and the companies need to prove that greenhouse gas emission is at least 70% than coal fired fuels. The government also requires that patrol and diesel are blended with 10% biofuels as of this year [100]. The government expects that the demand for biomass is expected to increase in the future for both export market and local market. The Netherlands Programme Sustainable Biomass (NPSB) by the Netherlands Enterprise Agency has supported over 40 projects over several years.

For a MCFC based system with high costs, policies will play an important role in its growth and development. From analysing the existing policy measures based on the characteristics of the MCFC cogeneration system, most policy tools seem to be favoring the technology.

These technologies satisfy the requirement of highly efficient innovations that use residual heat efficiently. They can also be considered to be technologies that combine production and storage. Even though electricity is technically not stored, the hydrogen generated can be stored. For that they may be eligible for the grants from the government. Since these technologies provide solutions with reduced CO_2 emissions, they can be suitable for the SDE++ subsidy from the government. The SDE++ subsidy would also apply because they generate blue hydrogen. Innovative pilot projects related to hydrogen is also supported through the DEI+ scheme where 25-45% subsidy on eligible costs is possible. The electric sector policies include the importance of CO_2 free electricity, local generation and electricity security of supply. All of which are can be made possible through these technologies, especially through distributed stationary generation. Additionally, the Dutch government strongly supports both onshore and offshore wind farms. This would benefit the superwind technology.

There are two drawbacks that were noticed when evaluating these technologies against the existing Dutch policy measures. (i) These technologies use natural gas, which has been phased out in the country. (ii) The Netherlands favours green hydrogen technologies more than the blue hydrogen technologies, with government providing temporary support schemes for operating costs related to the scaling up and cost reduction process for green hydrogen [102]. These drawbacks can be overcome by using biofuels. As internal reforming MCFC can operate with a variety of fuels and the dutch supports the development of biogas generating technology, this could be a possibility worth exploring.

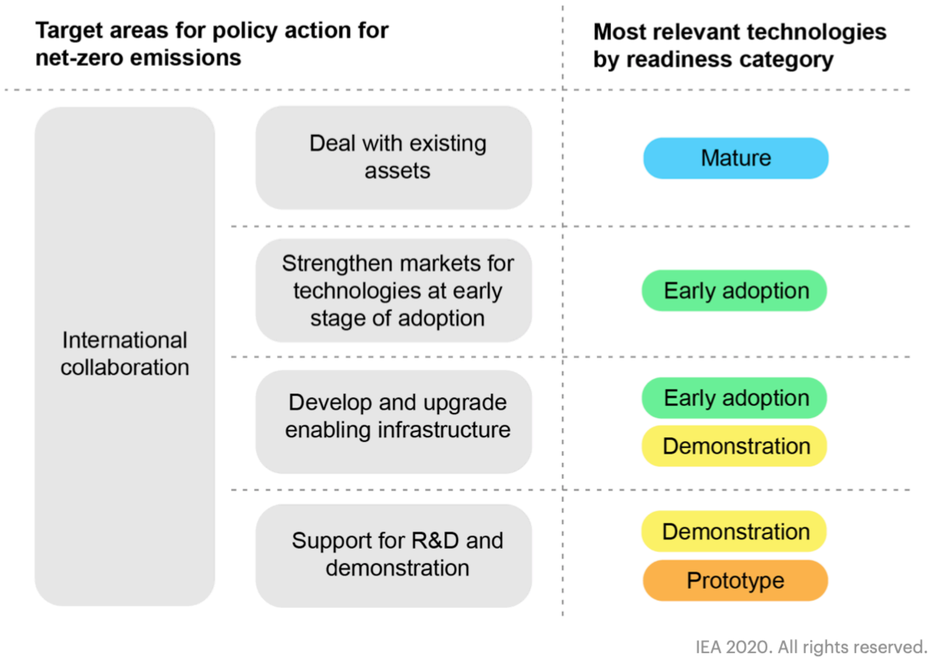

Figure 5.8: Government policy requirement for technologies at various levels of maturity. Ref. [60].

The International Energy Agency (IEA) recommends that the governments need to design policies for technologies based on levels of maturity when strategies are developed to achieve net zero emissions as shown in 5.8. For the mature technologies, IEA recommends policies dealing with assets, these are the existing capital stock for which CO_2 emissions is considered to be "locked-in". As they can remain in operation decades into the future this can be a problem. The solutions recommended by them include early retirement, refurbishment and retrofitting, and switching fuels. Early adoption can be an option for technologies who have progressed beyond the demonstration stage. The role of the government here is to accelerate the uptake of clean energy technologies by maximizing private capital through appropriate policies. These technologies can benefit from market-pull policy instruments (e.g. tax rebates and purchase incentive) and through continued support towards research and development after introduction [60]. Based on the the success of solar PV and lithium-ion batteries in the past, IEA expects fuel cell to be one of the technologies with potential to be adopted at early stage through proper government support [60]. In the level between early adaptation and the prototype stage, technologies will benefit from investment in infrastructure or upgrades in existing networks. This will result in the availability of alternate fuel distribution, smart grids, CO_2 transport and storage. The government policy here needs to encourage owners and operators to adapt and enhance existing infrastructure. This can be done by integrating clean energy technologies into existing pipelines and grids for example. The government also needs to provide initial investment needed for new infrastructure to mitigate investment risks by the entrants [60].

In their current state, the MCFC based hydrogen cogeneration technology and the superwind technology fall into the lowest section of Fig. 5.8. In this stage the prototypes are developed from the pre-prototype stage and demonstrations are conducted. The government policies at this stage should focus on providing support for research, development and demonstration and ensure that the knowledge from publicly funded research and development projects is openly shared with the research community and the taxpayer value is maximized (e.g. for European Union Grants, open access publishing is mandatory) [60]. Similar to the level just above, the government policies should help mitigate risk of large demonstration projects on clean energy technology. The cogeneration technology and the superwind technology satisfy many criteria to be eligible for government funding as mentioned earlier. They are clean technologies that would benefit from financial support and sharing of knowledge among researchers. Government support in R&D will especially be more important in the wake of the Covid-19 pandemic as it is likely that companies face lower revenues and cash flow to invest into research, development and project capital costs.

Another thing to note that by the time the system is ready for early adoption, it could be affected by the state of the grid and the policies around it. In the Netherlands, the electric grid is dated and just last year it was reported that the Dutch grid was struggling to cope with the increase in supply from more diverse sources, limitations in transportation and increase in energy use [67]. The Dutch grid may need €20-70 billion by 2050 towards infrastructure for the energy transition so this is a major issue going forward [88]. In the case of these technologies it is important to consider the state of heat and natural gas grids too. With the Netherlands expected to completely phase out unabated natural gas by 2050, Groningen field expected to be completely shut off by 2030, and the implications of gas demands in the coming decades being uncertain,it is hard to predict the state of the natural gas grid in the future. Having recognized the importance of residual heat streams, the Dutch government has planned to upgrade the heat grids [88]. The biggest challenge task for them is to provide low carbon heat to existing buildings. The best possible implementation of energy conservation also varies locally and customized solution maybe needed. While this the systems proposed maybe suited for decentralized generations, grid connections maybe essential for large plants. For example the delay in the Toyota Long Beach project was due issues with the utility.

As seen in Fig.5.8, a technologies will benefit from international collaborations at all stages of development. This could be through good policy practice exchange so a successful approach can be adopted from elsewhere, harmonizing standards and codes with countries, collaboration between institutes and through support networks where knowledge could be rapidly exchanged [60]. This will be particularly important for the concepts proposed in this thesis as they are based on MCFCs. The information on MCFCs are not as easily available as the global markets are dominated by very few suppliers. Moreover, through collaborations it would also be possible to test prototypes and conduct pilot demonstrations elsewhere in the world where MCFC maybe more widely available. Since these demonstrations would be performed over a long duration of time, exchange of knowledge would be important.

Currently, it is evident that MCFC based technologies proposed here provide many advantages that governments and policymakers are looking for in new technologies to meet emission targets. At this stage of the technology, more investment is needed in the field of research and development which maybe provided. However, a country's support for natural gas based hydrogen generating technology maybe favored less than green hydrogen technologies in development. Additional drawbacks may include, lack of the proper grids to support these technologies, especially in the case of large projects. Sharing of knowledge and international collaboration is also needed to advance these technologies further.

5.4. Justifying the natural gas based technologies examined

Natural gas is not a renewable energy source. Therefore, it is necessary to justify its use in technologies that are being recommended in this thesis, especially since countries around the world are focusing on renewable energy sources and its applications.

Natural gas is inherently cleaner than other fossil fuels. The carbon and hydrogen content of a fuel largely determines the amount of energy produced or the heat content, generally when the fuel is burned. The amount of CO_2 emission from a fuel is essentially a function of the carbon content of the fuel. Natural gas, which is primarily composed of methane, has a higher energy content relative to other fossil fuels, and therefore lower CO_2-to-energy content. Noncombustible elements, sulphur and water in fuels can reduce the heating values of the fuel and increase their CO_2-to-energy contents. Due to this, different amounts of CO_2 is produced by fuels during combustion in relation to the energy that is produced. This has been shown in table 5.2.

Type of fossil fuel	pound of CO_2/ million Btu of energy
Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (subbituminous)	214.3
Diesel fuel and heating oil	161.3
Gasoline (without ethanol)	157.2
Propane	139.0
Natural gas	117.0

Table 5.2: Pounds of CO_2 emitted per million British thermal unit of energy generated for various fossil fuels. Adapted from Ref.[2].

The emissions from natural gas fuel can be nearly half of that of CO_2 emissions from coal. However, in the MCFC based technologies analyzed in this thesis, combustion does not take place. Energy transformation from natural gas within the fuel cell takes place due to electrochemical conversion in MCFCs. This reduces the emissions even further. Almost all of hydrogen generated today is from fossil fuels, with 6% of total natural gas consumption globally going into hydrogen production [61]. This accounts for about 830 million tonnes of CO_2 per year from hydrogen generation globally [61].

Carbon storage technologies are currently expensive and can have drawbacks. CCUS technologies and solutions have been proposed for conventional technologies running on fossil fuels. The resulting blue hydrogen technologies with CCUS are not yet commercially feasible. In fact, only 35 million tonnes of carbon was captured from power and industrial sectors in 2019 [59]. In conventional hydrogen generation technologies, addition of CCUS could add up 30% to the the cost of the hydrogen product [87]. Carbon capture technologies can also have drawbacks such as emission of other greenhouse gases, land use change, emissions and leakages from subsequent increase in emissions in other parts of the process, and also impermanent disposal (emission is only delayed instead of being avoided or good) [1]. Due to these factors selection of CCUS technologies and methods depend on energy source, location and land availability, labor cost, scalability, permanence of capture among others. Currently, many available technologies offer capture at over $100 per tonne of CO2 [1]. This is much higher than the estimated value of approximately $25-30/tonne needed for CCUS system to start being significantly impactful [87]. The MCFC based cogeneration technology can operate at overall efficiency of over 80% and energy transformation occurs through electrochemical reactions. Both these characteristics contribute to much lower emissions which can help eliminate the costs and drawbacks associated with CCUS. It is likely that many CCUS technologies will take decades to be commercially feasible, which also gives an opportunity to the cogeneration MCFC technology to possibly develop in parallel with them.

Switching to natural gas and renewables has slowed the growth in CO_2 emissions, hence natural gas will be important for energy transition. Despite the decline in the Dutch natural gas consumption, the overall consumption of natural gas is increasing globally. In 2018 the global natural gas consumption rose by 4.6% and it accounted for nearly of the global energy demand [58]. In the same year the renewable electricity generation saw a growth of 7% in comparison to the previous year [58]. These increasing numbers are contributing to CO_2 emission reductions. The global average carbon intensity of the electricity generated in 2019 was 450g of CO_2/kWh which is 12% less than in 2000 [60]. Due to the increasing demand of natural gas and the positive effect it has on reduction in emissions, natural gas is likely to play an important role in energy transition to fully renewable technologies.

Natural gas grids are widely available. Another advantages of using natural gas is that natural gas grid network is large and has a wide reach. This would help reduce geographical restriction of setting up new projects. Additionally, these grids provide opportunity for decarbonization to the hydrogen producers since they can distribute some hydrogen by blending it into existing grid without the need for major upgrade. Several successful projects around the world are already blending hydrogen into the natural gas grid, with installations that can blend 2,900 tonnes of hydrogen already in place around the world [79]. The European Union has also recognized that ultimately these natural gas grids could be converted to supply pure hydrogen [115]. Additionally, 15% of European Union's power generation currently requires hydrogen and biogas is unlikely to be available at the required scale [115].

Green hydrogen has its problems. Despite the significant improvements in the green hydrogen technologies, their development has been slow and has few major drawbacks. Some of these technologies consume significant amount of electricity and can suffer from toxicity (e.g. photo-reduction technologies can suffer from toxicity of the products that have been generated in the photo arsenic electrodes) [22]. Technologies such as photovoltaic water splitting have very high production costs, low efficiency and challenges associated with developing stable and active catalysts [22] [78]. Moreover, electricity is needed for electrolysis of water to generate hydrogen. Due to which, cost of hydrogen production via electrolysis would vary significantly depending on the source of the electricity. Therefore, it is essential to acknowledge the emissions associated with the electricity used as well as the CO_2 emissions from the electrolysis process. Costs associated with mitigation of such emissions during any part of the operation pathway need to be acknowledged. The costs associated with hydrogen production from electrolysis remains significantly higher than hydrogen generated from fossil fuels in most locations around the world. The cost of hydrogen produced from electrolysis can vary up to a factor of ten based on the location and the source of electricity [78].

Hydrogen has been recognized as the only at-scale technology available to deal with time related fluctuations of renewable energy [115]. With the increase in electricity supply from renewable energy sources, both long and short duration supply and demand imbalances can be expected to increase. This will result in the need for for increased balancing across the year and the possibility of seasonal energy storage. Batteries and demand-side control measures can only provide short term flexibility and hydrogen is expected to be utilized for long term energy storage for longer period of time at lower costs [115]. This is likely to happen when excess energy from renewable sources is converted into hydrogen and stored in salt caverns or depleted natural gas fields for longer duration.

Availability of both hydrogen and electricity can be beneficial to the consumers. The demand for both electricity and hydrogen is expected to increase in the coming decades. Currently, natural gas based technologies play important roles in the generation of both these energy carriers. Often electric generation plants and hydrogen generation plants or both can be located away from the place of consumption. This results in increased capital and transportation costs. Having a cogeneration plant that operates on the existing natural gas grid can be beneficial for the consumers. This is because costs, especially on transport can be lowered while having the option of utilizing different energy carriers.

As natural gas is cleaner than other fossil fuels and its growth has contributed to slowing down of CO_2 emissions, it is likely that it will be a part of the future energy matrix for at least a few decades. Moreover, the natural gas grid is far reaching and countries continue to further invest in expanding their grids. This is going to benefit the MCFC based cogeneration technology with or without the application of the superwind concept. Availability of the operating natural gas fuel in the future, while not being constrained by the location will increase the suitability of the MCFC systems in various applications. As the carbon storage technologies and the green hydrogen technologies are currently in the early stages of development, and are not yet cost effective, this gives the MCFC based cogeneration technologies the room needed for its development and growth. Being in the early stage of development as well, these cogeneration technologies can develop parallelly with those technologies with the right support. As hydrogen has been recognized to play an important role in long term energy storage, the superwind concept, while utilizing natural gas, can provide the solution needed for the fluctuating energy storage. The superwind concept can reduce the requirement of batteries or electrolyzers while being able to still assist in hydrogen generation from renewable sources. While flexibility in the cogeneration of energy carriers based on demand is a key characteristic of the superwind concept, hydrogen can be generated for storage as well. Lastly, cogenerating hydrogen and power flexibly the MCFC based technologies can provide consumers with multiple energy carriers while reducing costs associated with multiple plants and transportation.

5.5. Impact of these cogeneration systems on society

A technology is not sufficient on its own, as it cannot solve anything on a larger context with the support from the actors involved in energy transitions. The interactions and roles of actors have been explained briefly in section 5.2. The support from actors can only be gathered if a technology has an overall positive impact on the society.

The primary impact these MCFC cogeneration technologies can have on the society is through their flexible hydrogen production. Hydrogen has been considered as the fuel of the future however, the rise in the growth of efficient technologies producing hydrogen have been slow. These technologies can not only produce hydrogen more efficiently but the superwind concept can also integrate renewable energy sources into hydrogen generation. Such hydrogen generating technologies can help solve the chicken and egg problem associated with fuel cell electric vehicles and hydrogen filling stations [53]. The development of fuel cell electric vehicles have been limited by the availability of the fueling stations. Countries are hoping to increase the number of fuel cell electric vehicles in the coming years. For example, the United States of America which hopes to have up to 500,000 fuel cell electric vehicles by 2030 [76]. This is an ambitious target, which can only be possible if there are increased number of fueling stations in place.

While the MCFC's Fountain Valley and the Port of Long Beach projects have shown the possibility trigeneration, one was a pilot project and the other is being developed for Toyota facility exclusively. It is unlikely that fossil fuel stations would be replaced by hydrogen stations in the near future however, trigenerating fuel cell based stations gaining momentum. A SOFC based initiative known as the CH2P (Cogeneration of Hydrogen and Power using SOFC based system fed by methane-rich gas) is being currently tested the Shell Technology Center in Amsterdam, the Netherlands. Similar to the MCFC based technologies discussed in this paper, this initiative developed for hydrogen refueling stations aims to cogenerate hydrogen, heat and electricity. As of July this year, the technology was in prototype stage with one generating up to 20kg of hydrogen per day is expected to be tested soon [39]. These examples based on MCFC and SOFC show that interest in such fuel cell based hydrogen technologies are growing in different parts of the world and such technologies coiuld play a significant role in the future of hydrogen stations. This would ultimately speed up the diffusion of fuel cell vehicles in the market.

Elsewhere, fuel cell based technologies are being considered for developing smart communities. For example, Toshiba's plan for implementing a hydrogen based energy society includes including renewable energy sources such as wind and solar to create hydrogen, the hydrogen that is produced is stored, and during peak demand fuel cells can be used to create electricity [6]. A MCFC based technology like the superwind concept can be used in similar applications, while reducing the need for storage. These MCFC based cogeneration (and superwind) technologies can be utilized in smart grids where the actions of the consumers are intelligently integrated. These technologies are well suited for the so called ”prosumers” that can produce electricity as well as consume it, while ensuring the requirements of smart grids through sustainable electricity supply, reduced losses, increased supply and reliability. The smart grid concept integrates meters, sensor and other communication technologies needed to share information, with the physical infrastructure responsible for generating, transmitting and distributing electric power. Unlike the conventional grids, the smart grids can accommodate changes in the end user behaviours in real time. Such grids allow for demand side management, energy savings and cost reduction among other benefits. The MCFC cogeneration technologies can successfully contribute to the demand side management through flexibility in electricity and hydrogen generation, while operating at high efficiency resulting in lower fuel consumption and lower costs. The demand for smart grids has increased over the years and the European Commission expects about 50% of electricity network to be operating on 'smart' principles by the end of this year [122].

Energy efficient technologies are expected to be crucial in energy transition. As these MCFC based cogeneration technologies achieve efficiencies of over 80% the owners will benefit from the advantages of efficient technologies. These includes increased profits from existing market prices, giving them a competitive edge over their rivals. As a result of higher energy efficiencies, utilities and hydrogen distributors could require distributors reduce their prices. This would result in consumers and produces mutually benefiting from such technologies. Additionally, environmental benefits arising from cleaner fuels and increased efficiency would results in lower emissions. This would benefit any society in current times, but especially those of the developing countries that are heavily reliant on fossil fuels. Through highly efficient technologies such as these, import of both electricity and hydrogen could be reduced. This increases the security of these energy carriers.

These systems can play an important role in off-grid or stand alone decentralized energy systems. Like with the superwind concept, off-grid energy systems often consists of technologies dependent on renewable energy sources like wind or solar energy. Between 2011 and 2016, over 9 million people have benefited from being connected to a mini-grid [64]. Off-grid renewable energy grid also grew from 2GW in 2008 to over 6.5 GW in 2017, with a majority of the deployed capacity being dedicated to industrial applications like cogenration [64]. While the MCFC based cogeneration solutions in this thesis generally utilize natural gas, MCFC offers fuel flexibility which can be beneficial in off-grid applications. Through cogeneration solutions, electrification and development in hard to reach areas, islands or even socio-economic development of rural communities can be achieved. The distributed and decentralized nature of such technologies allows for engaging local capacities along the value chain. Opportunities for skills needed in installation, operation and maintenance of these systems can be developed locally. Off-grid solutions have successfully created job opportunities, with an estimated 1.5 million full time jobs with solar value chain expected by by 2022 [64]. Success of such systems can inspire opportunities with MCFC based cogeneration systems. Direct jobs maybe possible downstream with distribution, sales, installation (e.g. hydrogen station) of hydrogen as well. Indirect job opportunities can also be provided as the result of economic activities from increased access to hydrogen and electricity. For example, industries in such areas could benefit from supply of hydrogen, electricity and available labour. With industries needing constant supply of energy and usually employing large number of people, this would result the overall economic development in the region through sale of energy carriers and increased employment.

With the help of the points made in this section, it can be argued that the MCFC hydrogen and power cogenerating technologies are going to positively impact the society. These technologies can contribute to the transition towards hydrogen economy while facilitating smart grids, efficient energy generation and local socio-economic developments through off-grids.

5.6. Chapter Conclusion

In this chapter the last research sub question found in section 2.2 has been answered.

With MCFCs, the generation of hydrogen and power have been shown to be approaching cost competitiveness, possibility of profitability with superwind has also been shown to be possible in literature. There have been decrease in the costs of MCFCs based on improvements in technologies, and reduction in costs are also associated with increase in volume of production. Based on these factors it can be said that MCFCs and hence the technologies based on these fuel cells can be economically feasible in the future.

Natural gas has been found to have its own set of benefits (e.g. properties, ease of avilability). However, some of the benefits offered by natural gas in section 5.4 are as the result of the state (poor status of green hydrogen technologies,poor hydrogen infrastructure) of hydrogen generation technologies as seen in section 5.1.2. With increasing hydrogen demand, blue hydrogen technologies will actually have an important role to play in hydrogen supply. Natural gas based technologies will not only be needed out of necessity but will also be considered because of the advantages offered by natural gas.

Moreover, both the MCFC cogeneration, and the superwind concept have the potential to positively impact the society by accelerating the diffusion of hydrogen. This would in turn step up the production of fuel cell vehicles. Moreover, such technologies can also contribute towards off-grid power and smart communities.

Having seen that the costs of MCFC can drop in the long run, natural gas will be needed for hydrogen generation and the benefits offered by these technologies on the society. The rate at which diffusion occurs will depend on actor interactions and policies.

Section 5.2 showed the complexity that arises from actor interaction with the example of the Superwind concept with the MLP approach. These technologies are currently in the technological niche level and they could break into the socio-technical regime through few different pathways. However due to the factors like the limited MCFC production, status of coproduction technologies, and the landscape shock provided by the global pandemic, reconfiguration pathway is likely to be possible. This is because change in the structure of regime architecture and organization can be expected during and beyond this pandemic. For this to happen, support from the policy makers are important in research and development. Based on the types of policies in the example of the Netherlands. The cogeneration tick a lot of boxes so they are likely to benefit from government support. The only major concern that was observed that green hydrogen technologies get more support from the policymakers than natural gas based generation.

Finally, these technologies are currently not economically feasible mainly due to the the costs of MCFCs. However, owing to the advantages offered by coproduction on society, the expected role of the natural gas technologies in hydrogen production, promising trends in the support offered by the governments towards research and development of current technologies, expected nature of regime diffusion. These technologies have the potential of being socio-economically feasible in the future.

6
Conclusion

With the demand for cleaner energy technologies and hydrogen rising, the interest in fuel cells have grown in the last decade. Moreover, the importance of energy efficiency has also been recognized resulting in the growth of efficient CHP technologies that can supply multiple energy carries. The concept of cogeneration utilizing waste heat has been explored with high temperature fuel cells. However, most of those studies focus on the solid oxide fuel cells. Molten carbonate fuel cells like the solid oxide produce excess heat in large quantities but differ in operation. This makes them suitable for cogeneration applications. With that in mind, the aim of this thesis report was to answer the following research question:

What is the feasibility of flexible coproduction of hydrogen and power using Molten carbonate fuel cells (MCFC)?

This question is to be answered by answering the following sub questions.

1. ***What is a molten carbonate fuel cell and what is its significance today?***
2. ***What is a cogenrating/trigenerating IR-FC system and what are the existing examples of MCFC in hydrogen and power coproduction?***
3. ***What is the technical feasibility of flexible coproduction of hydrogen and power using a MCFC system?***
4. ***How does the coproducing MCFC system perform in comparison to a similar SOFC system?***
5. ***What are the socio-economic feasibility factors that would affect these MCFC systems?***

6.1. Key Findings from the Report

Before answering the main research questions, in this section the research sub questions are answered with the help of the key findings from the research.

1. Molten Carbonate Fuel Cells and its significance today.

Just like the other fuel cells, MCFCs are electrochemical devices that produce electricity from a fuel like hydrogen with an oxidizing agent through multiple redox reactions. MCFCs specifically are high temperature fuel cells operating at about $650°$C. This is needed to improve the performance of the electrolyte. In such fuel cells, the anode emits CO_2 that is recycled into the cathode input to provide the carbonate ions needed for the fuel cell operations. Due to the high operating temperatures in these fuel cells, internal reforming of fuels is possible. They can also operate at higher electric efficiencies than conventional power plants as they can reach values of about 50%.

MCFCs are rising in significance today, even though the MCFC industry today is very small, with most of the installations today being provided by FuelCell Energy. The United States of America and South Korea are the leading nations with MCFC installations. MCFCs have been considered for stationary power applications. in South Korea, they are being used to provide power and in district heating applications. Owing to their ability of achieving high overall efficiencies, they are also being considered for waterbourne applications. Due to their operating principle which involves the need of CO_2, they have been considered in carbon capture applications. The idea is to feed the cathode of the MCFC with exhaust gas from conventional power plant operating with fossil fuels to filter out the CO_2 content. In this case the MCFC is the " active" component as it adds power to the plant energy balance while acting as CO_2 concentrator. According to studies they can reach carbon reduction efficiencies of 45-70%.

MCFCs and SOFCs have similarities such as high operating temperatures, possibility of internal reforming, flexibility of fuel use, potential for achieving high overall efficiencies, and even increased susceptibility to sulphur poisoning. However, as SOFC operates with solid electrolytes, multiple geometries are possible. Moreover, SOFCs have a simpler operating principle without the need for CO_2 recycling to the cathode. SOFCs are also more popular in stationary applications with nearly 25,000 units sold in 2020 in comparision to <50 MCFCs sold in that span. These advantages give SOFCs an upper hand in new application.

2. Cogenrating/Trigenerating IR-FC system and examples of MCFC in hydrogen and power coproduction

A cogenerating/trigenetrating IR-FC involves a high temperature fuel cell such as a SOFC or a MCFC where more than one energy carrier is produced. Generally, in such fuel cells, heat is utilized for internal reforming. Cogeneration usually involves production of electric power and heat, while in trigeneration application from these fuel cells electric power, hydrogen and heat can be obtained. Moreover, it allows for flexible coproduction of hydrogen and power which is an added advantage.

There are two examples of IR-MCFC in cogeneration applications. The Fountain Valley project and the Port of Long Beach Project. Both of these are the results of collaboration of FuelCell Energy. The Fountain valley involved FuelCell Energy collaborating with the United States Department of Energy on a pilot project that successfully demonstrated flexible coproduction of hydrogen and power from a renewable fuel using IR-MCFCs. The Port of Long Beach Project on the other hand is a full scale 2.35MW, 1.2 tonne (daily) hydrogen generating project being developed as a result of FuelCell Energy collaborating with Toyota. These examples are the real life proofs of such technologies, and their success can enhance the future prospects of coproducing hydrogen and power using IR-MCFC.

A future application of coproducing hydrogen and power technology can be the the Superwind Concept. It is the concept designed to improve the reliability of intermittent sources like wind and solar energy. This concept can provide an innovative solution for integration of fluctuating sources into the grid without the need for storage. These technologies can support the growing hydrogen demand and help with the widespread adaptation of this relatively new fuel, while also integrating renewable energy sources with a natural gas source.

3. Technical feasibility of flexible coproduction of hydrogen and power using a MCFC system

and

4.Coproducing MCFC system's performance in comparison to a similar SOFC system.

The research sub questions 3 and 4 have been answered together here. From the technical feasibility of the the IR-MCFC model on Cycle-Tempo, it was observed that these systems could achieve very high overall efficiencies of over 80%. The amount of electric power generated by these systems is comparable to what can be achieved by very efficient CHP plants, implying that heat has been efficiently utilized in hydrogen coproduction along with power. Even in the high power mode where overall efficiency was still a respectable 56%, the amount of electric power generated was nearly double of what is possible from the high efficiency mode. When hydrogen is considered, the overall power output was found to be nearly three times the electric output from the conventional mode. These factors make IR-MCFC systems feasible for flexible coproduction of hydrogen and power.

Mode	**IR-SOFC**	**IR-MCFC**
High Efficiency Mode (Fuel fixed at 2MW equivalent)	93%	80%
Constant Current Density Mode (i= 1500 A/m^2)	91%	80%
High Power Mode	73%	56%

Table 6.1: Overall efficiencies for all three modes of operations.

The IR-MCFC systems cannot match the IR-SOFC in terms of overall efficiency as shown in 6.1. While the electrical efficiencies are close to what can be achieved by the IR-SOFC, the loss in gas efficiency could be due to a variety of factors. These can include different operating principles, difference in the amount of fuel used, and differences in the modeling setup.

5. Socio-economic feasibility factors

The socioeconomic feasibility depends on the range of factors. Based on the operating nature and the outputs generated, MCFC based coproducing technologies (including superwind concept) will benefit from the following factors. Natural gas offers a range of benefits in hydrogen production based on its properties and availability among others. Moreover, based on the trends observed in hydrogen generation it is evident that the growth in hydrogen demand is expected, and cleaner hydrogen will be blue rather than green. Additionally, these technologies are likely to benefit the society because they offer potential for hydrogen fueling stations and thereby they can contribute towards speeding up the diffusion of electric vehicles. They can also contribute towards off grid energy systems and foster the rise of smart communities.

These technologies also provide qualities needed by the policy makers to offer their support in clean energy generation.

While all that is true, the socio-economic feasibility is likely to depend on the costs of MCFCs which are currently not feasible. The diffusion of MCFCs globally is very slow and these technologies are extremely expensive today. However, these technologies maybe feasible in the long run based on the trends observed in MCFC production, cost pattern associated with coproduction technologies, and costs of electricity and hydrogen generated from MCFCs. Another important factor that would affect the socio-economic feasibility is the contribution from the actors and stakeholders. If these coproduction technologies are to break into the regime it is likely through the reconfiguration pathway. In the early stage of development, like these technologies are currently, government support is mainly needed in research and development. They tick many of the requirements needed for governmental support, but being a natural gas based technology may prove to be a disadvantage as the support for green hydrogen is often more than it is for technologies operating with natural gas.

Having answered the research sub question, the main research question **What is the feasibility of flexible coproduction of hydrogen and power using Molten carbonate fuel cells (MCFC)?** now needs to be answered.

Molten carbonate fuel cells provide an efficient technology, whose potential in power generation has already been applied across the world. Moreover, its stability, versatility and maturity can be confirmed through various applications that have been considered and continue to be considered. Their high temperature operation has made them well suited for cogeneration/trigeneration applications where hydrogen can be coproduced along with other fuel carriers, which can only be further confirmed with existing examples of plants coproducing hydrogen and power.

Moreover, the technical feasibility analysis carried out in this report showed that these technologies can achieve efficiencies of over 80%. This efficiency was found to be lower than what can be achieved by a SOFC system. However, in reference to the conventional CHP plants, it is considered a very good value of efficiency. Based on the results obtained from the flowsheet calculations on Cycle-Tempo it can be said that IR-MCFC systems are technically feasible for hydrogen and power coproduction.

As far as socio-economic factors are considered, the coproduction technologies will benefit from the existing natural gas and wind energy networks (in case of superwind) and they will positively impact the society in numerous ways, but most importantly through hydrogen production in a more convenient and cleaner manner than most of what is available today. However, when it comes to the economic feasibility, the biggest obstruction is the costs associated with the MCFCs. These technogies are not economically feasible currently. Their feasibility in the short run will depend on the role played by the stakeholders and actors in diffusion of this technology into the socio-technical regime, government support for a natural gas technology as well their support especially in research and development.

To conclude, IR-MCFC coproduction systems are technically feasible. However socio-economic feasibility currently is not possible mainly due to high costs. With the increase in the rate of MCFC productions which would ultimately lower costs, increase in demand for clean hydrogen, and support from the relevant stakeholders these technologies have the potential of being fully feasible in the long run.

6.2. Discussions

This thesis set out to explore the feasibility of IR-MCFCs in hydrogen and power cogeneration application.

Based on the results from flowsheet calculations on IR-MCFC conducted on Cycle-Tempo the results obtained were in accordance to what was to be expected. As in, through coproduction with these systems very high efficiencies much higher than what is possible in conventional operation was achieved. With the efficiency of 80% being possible by these systems, they are on par with highly efficient technologies such as CHP plants available today.

However, limitations in the research also needs to be analyzed. The methodology choices were constrained by the following factors.

Flowsheet simulations can involve large number of equations and unknowns with only few degrees of freedom. Various values are needed to be specified and constrained maybe applied. It may so happen that certain values that need to be fixed, can impede the full range of process limitations and the solution is restricted to a small subset of solution space. This was particularly experienced with the settings on the valve that decided the amount of gas being recycled and the amount of gas being liberated from the system, as absolute value was needed to be fixed.

Additionally, as this study involved comparison of outputs with a existing study, the range of operation was constrained by that study. For example it may so happen that the optimum range of fuel utilization may vary between the fuel cells.

Moreover, constraints applied, efficiencies of components, environmental conditions and temperatures within components are most likely to differ in real life applications. The model used for the analysis is usually simpler than in real applications. Efficiency loss due to separation of hydrogen and CO from the exhaust gas rich in syngas has also not been considered. The model used for the analysis is also most likely to be simpler than what would be used in real applications.

Due to the factors mentioned above real life results can be less than what has been achieved through simulation.

Furthermore, the secondary research conducted in this thesis suffered from limited information available on MCFC, especially on the financial aspects.The MCFC supply is extremely low and the global demand is mostly provided by a single supplier severely limits the number of source available. Challenges related to the the information being non timely and incomplete availability were also experienced. Things like actor involvement and future of hydrogen fuel even if influenced by a common goal (e.g reducing emission) will also vary based on geographical location and time besides policies, interaction among actors et cetera. These need to be analyzed more locally. Future estimations also can be challenging to make due to uncertainties associated with the path of energy transformation and the limitation of the MLP concept. Challenges associated with a new coproduction plants add to the complexity, as the response of parties available to a combined operation with two outputs, is hard to gauge.

Despite these drawbacks, in the chapter on socio-economic analysis, important factors that could play a role in successful implementation of these technologies were identified. Insights based on trends and expected targets could be provided to an extent.

6.3. Final Thoughts and Recommendations

In this thesis technologies based on MCFC were analyzed. These technologies are well suited for coproduction applications based on the technical analysis conducted. Their success in widespread applications will depend on the ease with which MCFC can be easily available at a desired location. As MCFC are not being scaled up as quickly as SOFC or PEMFC, this could be an actual hindrance to the development of the cogeneration technologies.

However, with any new technology, more research is needed than what has been presented here.

In case existing Cycle-Tempo model is used, further research maybe needed to establish a more suitable relation between recycling, separation and gas output obtained. Moreover, the effect of lower fuel utilization on efficiency can also be explored.

It could also be important to study and compare the performance of MCFC in CCUS with the technologies suggested in this thesis. This would help establish the more favorable technology, which would specially be be beneficial due to slow growth rate of MCFC installations.

More research on Superwind concept need to be conducted. So far they have been justified almost solely on the performance of SOFCs. Further research could bring to light additional complications.

When it comes to socio-economic feasibility life cycle assessment and cost benefit analysis can be carried out if sufficient data can be availed. Case study on existing IR-MCFC coproducing plants may also be beneficial to get a better understanding of these systems. This would also provide information on the involvement and interactions between various stakeholders and actors .

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A

SOFC model

The flowsheet model used for the SOFC study in the paper "Flexible Coproduction of Hydrogen and Power Using Internal Reforming Solid Oxide Fuel Cells System" by Hemmes et al. in [55] has been presented in this appendix. Just like the MCFC model, this was created on Cycle-Tempo. In this model the recycle ratio of the anode outlet was set to 0.4 during the operation. This was done to optimize the system to achieve the highest efficiencies between 60 and 95% fuel utilization values.

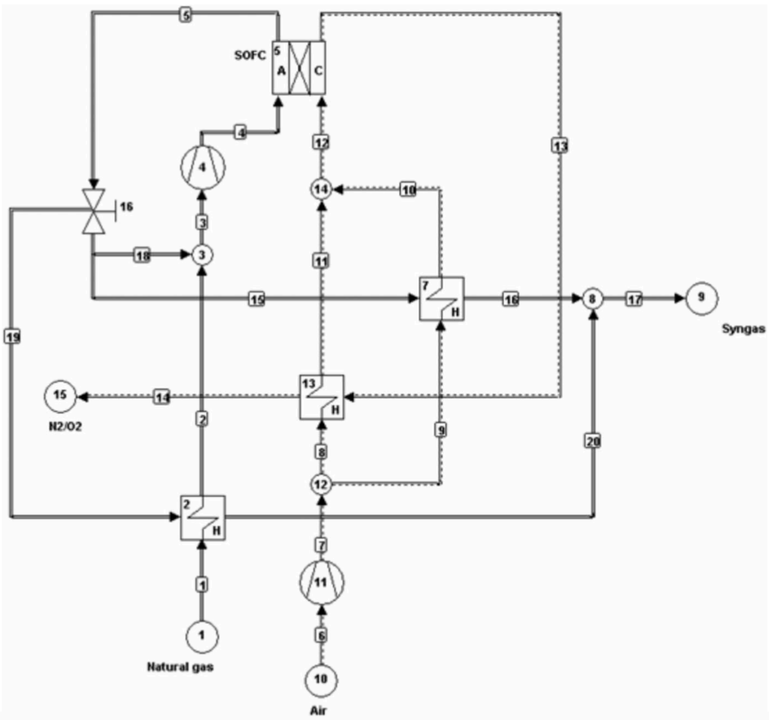

Figure A.1: Cycle -Tempo flowsheet diagram of an internal reforming SOFC system for coproduction of hydrogen and power. Ref. [55]

B

Fuel Cell Shipment

Shipment of Fuel Cell according to their types

Figures B.1 and B.2 have been obtained from The Fuel Cell Industry Review 2019 by E4tech [27]. These figures show the data and the plot of shipment of the various types of fuel cell shipments in the the last 5 years. 2019f represents their forecast for the full year of 2019, based firm data of January to September. These figures represent shipments in multiples of 1,000. These figures show that the numbers of MCFC continues to be very small in the last 5 years and has been rounded off to zero due to it. According to the Fuel Cell Review report unit numbers have been rounded of to nearest 100 unit and an entry of zero represented less than 50 systems shipped in that year.

Shipments by fuel cell type					
1,000 Units	**2015**	**2016**	**2017**	**2018**	**2019f**
PEMFC	53.5	44.5	43.7	39.7	44.1
DMFC	2.1	2.3	2.8	3.7	3.7
PAFC	0.1	0.1	0.2	0.2	0.3
SOFC	5.2	16.2	23.7	24.9	22.8
MCFC	0.0	0.0	0.0	0.0	0.0
AFC	0.0	0.1	0.1	0.0	0.0
Total	**60.9**	**63.2**	**70.5**	**68.5**	**70.9**

Figure B.1: Data table showing of fuel cells showing quantities of their shipment in multiples of 1,000. Ref. [27].

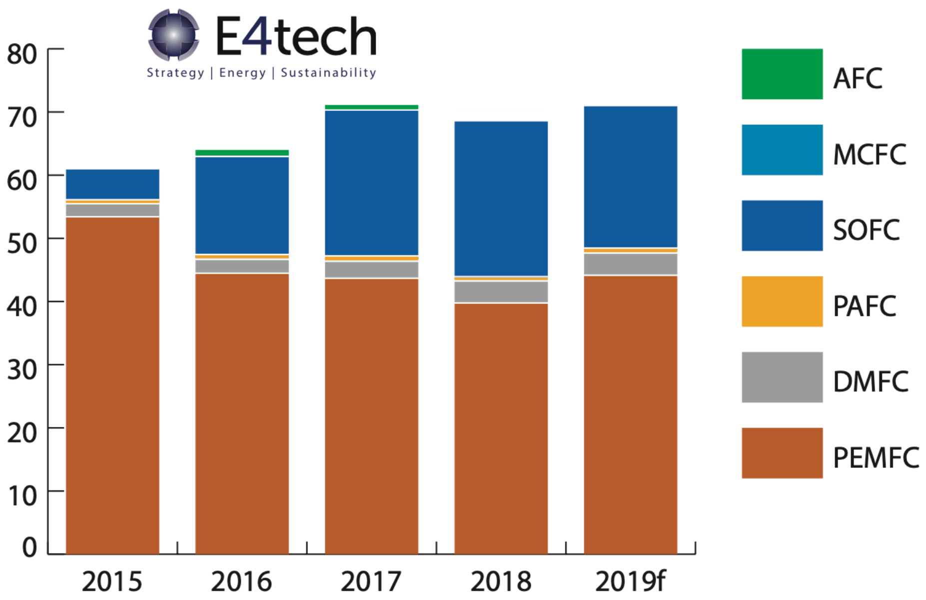

Figure B.2: Shipment of fuel cells according to their types (1,000 units). Ref. [27].