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Fuel Cells in Offshore Oil and Gas Production

Camilla Bjølverud Nyberg

Marine Technology
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Supervisor: Arne Ulrik Bindingsbø, IMT

Norwegian University of Science and Technology
Department of Marine Technology

Preface

This master thesis has been written to conclude a five year integrated master's program in Marine Technology, with specialization within technical operations of marine systems, at the Norwegian University of Science and Technology (NTNU). This thesis is a result of autonomous work with the support of my supervisor Arne Ulrik Bindingsbø. The period of work extends from January to June 2017.

I selected the topic of fuel cells because of my interests in how the development and application of new technology can secure long-term value creation in the petroleum industry while addressing the need to cut greenhouse gas emissions. The petroleum industry is confronted with a two-faced challenge: the industry needs to increase production to accommodate for the world's growing energy demand while it simultaneously has to take action to reduce carbon emissions in order to combat global climate change.

This sparks the need for new technologies in energy systems in offshore activities. Such an energy system may be fuel cells. While fuel cell technology has been applied in portable and stationary applications, the technology has never been used offshore. I therefore wanted to look further into the possibility for using fuel cell systems in offshore oil and gas production, and map out the potential challenges, obstacles, advantages, and disadvantages.

Firstly, I would like to express my deepest gratitude to my supervisor Arne Ulrik Bindingsbø for his valuable help and guidance throughout the semester. He has provided me with constructive and concise feedback, and his guidance has been essential. Secondly, I wish to express my sincerest gratitude to my family, who has been my biggest supports, not only through this thesis, but through my entire studies. Lastly, I would like to thank my office crew at office A 2.015 for support along the way, and especially for all the coffee they have made during the last year. A special thanks to all my co-students, the last five years would not have been the same without you.

Camilla Bjølverud Nyberg
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Summary

The petroleum industry is confronted with a two-faced challenge as global energy demand is set to increase simultaneously as greenhouse gas emissions must be reduced in order to combat global climate change. With the signing of the Paris climate agreement in 2015, the world's nations agreed to implement actions to keep the global temperature below 2 °C above pre-industrial levels. Future emissions from the petroleum industry must be reduced as a key way of combating global warming, but also to ensure the future financial viability of the industry as the cost of emitting carbon is likely to increase as governmental regulations on greenhouse gas emission will be tougher. Increased public pressure for environmental friendly choices will also force the petroleum industry to incorporate environmental considerations into their business models. The petroleum industry is therefore searching for ways to improve energy efficiency while reducing costs and emissions.

The most significant emitter of greenhouse gasses on offshore installations is gas turbines, which alone account for 81% of total greenhouse gas emissions. Fuel cells are more energy efficient and less carbon intensive than gas turbines as a result of different conversion processes when the chemical energy in the fuel in converted to electrical energy. For gas turbines is this process performed through a combustion, while it in fuel cells occurs through a chemical reaction between positively charged hydrogen ions and oxygen. This master thesis considers the possibility for fuel cells to replace gas turbines as power generating system on offshore installations in the future. The thesis explores the main challenges the fuel cell technology faces if applied offshore.

A SWOT analysis is conducted in order to map the strengths, weaknesses, opportunities, and threats for the fuel cell technology. Requirements such as demands of output, efficiency, emission, costs, maintenance and downtime placed on power generating systems offshore are especially emphasized in the analysis in order to evaluate if the fuel cell technology is a viable option.

The analysis indicates that the fuel cell technology is equally, if not even better, than gas turbines in some areas while it in other areas is unable to meet the demands. The technology is competitive with gas turbines regarding efficiency, emission, maintenance and downtime. However, it does not meet the requirements set for costs and output. Based on the results from the SWOT analysis it can be concluded that the fuel cell technology is able to meet parts of the demand placed on power generating systems offshore, but far from all. Based

on the position of the technology and its area of application, it is challenging to conclude whether or not the technology is better than gas turbines for power generation offshore. The technology has never been applied offshore; hence it is challenging to compare the two technologies. However, it can be concluded that none of the existing fuel cell technologies are able to satisfy all the demands offshore alone. In order to apply the technology offshore a fuel cell system combining two or more of the already existing technologies has to be developed.

However, the technology has future potential. If the environmental benefits are as significant as expected, the fuel cell technology could be an important way in which the petroleum industry adjusts to global climate change.

Sammendrag

Petroleumsindustrien står ovenfor en tosidig utfordring; verdens energibehov vil øke, samtidig som utslipp av klimagasser må reduseres for å bekjempe klimautfordringene. Parisavtalen ble signert i 2015. Gjennom avtalen ble verdens nasjoner enige om å implementere tiltak som vil bidra til at den globale temperaturøkningen ikke overstiger 2 grader Celsius. Reduksjon av fremtidige utslipp er én måte å bekjempe global oppvarming. Kostnadene for karbonutslipp vil trolig øke siden myndighetenes krav til utslipp av klimagasser forventes å bli strengere. En reduksjon av utslipp vil derfor ikke bare være en måte å bekjempe global oppvarming, men også en måte å sikre industriens fremtidige finansielle levedyktighet. Et økende press fra offentligheten om miljøvennlig energi vil tvinge petroleumsindustrien til å innlemme miljøtiltak i sine forretningsmodeller. Petroleumsindustrien søker derfor etter ulike tiltak for å forbedre energieffektiviteten samtidig som kostnader og utslipp reduseres.

Den største utslippskilden på olje og gassinstallasjoner er gassturbinene. Disse står for 81% av det totale utslippet. Brenselsceller er mer energieffektive og mindre karbonintensive enn gassturbiner. Dette er et resultat av forskjeller i omformingsprosessen av den kjemiske energien i brenselet til elektrisk energi. I gassturbiner skjer denne ved hjelp av en forbrenning, mens den i en brenselscelle foregår gjennom en kjemisk reaksjon mellom positive hydrogenioner og oksygen. Denne masteroppgaven undersøker muligheten for å erstatte gassturbiner med brenselsceller som kraftgenererende systemer på olje og gassinstallasjoner i fremtiden. Oppgaven ser nærmere på hovedutfordringene brenselscelleteknologien står ovenfor dersom den skal benyttes til havs.

En SWOT analyse er utført for å kartlegge styrkene, svakhetene, mulighetene og truslene til brenselscelleteknologien. Krav som stilles til kraftproduserende systemer, som for eksempel levert effekt, effektivitet, utslipp, kostnader, vedlikehold og nedetid, er spesielt vektlagt i analysen for å kartlegge om brenselscelleteknologien er et levedyktig alternativ.

Analysen viser at brenselscelleteknologien er like god, om ikke bedre, enn gassturbiner på enkelte områder, mens den på andre punkter ikke tilfredsstiller kravene. Teknologien er konkurransedyktig med gassturbiner når det gjelder effektivitet, utslipp, vedlikehold og nedetid, mens den ikke tilfredsstiller kravene til kostander og levert effekt. Basert på resultatene fra SWOT analysen kan det derfor konkluderes med at brenselscelleteknologien dekker deler av kravet som stilles til kraftgenererende systemer på olje og gassinstallasjoner, men langt ifra alle. Ut ifra teknologiens posisjon og bruksområder er det utfordrende å konkludere

med om brenselceller er bedre egnet enn gassturbiner til kraftproduksjon til havs. Dette fordi teknologien ikke er benyttet på olje og gassinstallasjoner tidligere, og det er dermed vanskelig å sammenlikne de to teknologiene. Det kan likevel konkluderes med at det ikke per dags dato eksisterer en brenselscelleteknologi som alene kan dekke alle kravene til kraftgenererende systemer på olje og gassinstallasjoner. Dersom teknologien skal benyttes til havs må det derfor utvikles et brenselscellesystem som består av en kombinasjon av to eller flere av de allerede eksisterende teknologiene.

Teknologien har uansett et stort potensiale for fremtiden. Dersom de miljømessige fordelene er så store som de forventes å være, kan brenselscelleteknologien være en viktig bidragsyter når petroleumsindustrien skal tilpasse seg de globale klimaendringene.

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Abbreviations

AC	Alternating current
AFC	Alkaline fuel cell
BEV	Battery electric vehicle
CCP	Combined cooling and power
CCS	Carbon capture and storage
CHEOP	Clean, Highly Efficient Offshore Power
CHIC	Clean Hydrogen in European Cities
CHP	Combined heat and power
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct current
DMFC	Direct methanol fuel cell
EMF	Electromotive force
EU	European Union
EU ETS	European Union's trading scheme
FCEB	Fuel cell electric buses
FCH JU	Fuel cells and Hydrogen Joint Undertaking
HHV	Higher heating value
HRS	Hydrogen refuelling station
HT PEMFC	High temperature proton exchange membrane fuel cell
HVDC	High voltage direct current
ICE	Internal combustion engine
IEA	International Energy Agency
LHV	Lower heating value
LNG	Liquefied natural gas
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
MTBF	Mean time between failure
NCS	Norwegian Continental Shelf
NIP	National Innovation Program
OECD	Economic Co-Operation and Development
OCV	Open circuit voltage

PAFC	Phosphoric acid fuel cell
PACE	Pathway to a Competitive European FC mCHP market
PEMFC	Proton exchange membrane fuel cell
PPM	Parts per million
RCL	Royal Caribbean Cruises Ltd.
REDOX	Reduction - oxidation
SOFC	Solid oxide fuel cell
SWOT	Strengths, weaknesses, opportunities and threats

Nomenclature

E	The voltage of the fuel cell
F	Faraday constant, the charge on one mole of electrons, 96.485 Coulombs
$\overline{g}_f$	Gibbs free energy of formation per mole
$\overline{h}_f$	Enthalpy of formation per mole
I	Current
I_{eff}	Effective current
I_P	Primary current
I_S	Secondary current
N_P	Number of primary windings
N_S	Number of secondary windings
R	Resistance
T_1	Maximum temperature of the heat engine
T_2	Temperature of the heated fluid released
V	Voltage
V_c	Average voltage of one cell in a stack
V_{eff}	Effective voltage
V_P	Primary voltage
V_S	Secondary voltage
Q	Reactive Power
$\triangle$	Change in
ε	Induction
η	Efficiency
ϕ	Phase displacement between current and voltage
Φ_B	Flux
μ_f	Fuel utilization

Chapter 1

Introduction

1.1 Background

As global warming is becoming a reality at the same time as the world's energy demand increases, there is a pressing need to accelerate the development and application of greener technology in the petroleum industry. Global warming is our time greatest challenge. As anthropogenic activity pushes the Earth's systems outside of natural variability, human survival is threatened. In order to address global climate change, our energy systems need to change and become more carbon neutral and carbon effective as global warming is fueled by fossil fuels.

Fossil fuels are our number one energy source, accounting for more than 80% of global energy consumption [2]. While renewable energy sources increasingly are becoming more important, renewable will only supply 33% of the world's energy in 2040[11], which means that fossil fuels continue to dominate the energy sector. The World's Energy Outlook estimates that fossil fuels will account for around 55% of global energy consumption in 2040, thus the global economy will continue to be dependent on hydrocarbons[11]. Emissions are projected to increase as global energy demand is expected to increase by 37% by 2040[11]. This means that without technological advancements and improved efficiency, the world will not reach its 2 °C target set at the Paris Climate Conference in 2015[2]. Development of new technologies to reduce carbon and methane emission as well as innovations to improve production, transportation, and usage of fossil energy sources are therefore necessary in order to halt global warming.

The petroleum industry is a significant polluter of greenhouse gasses as a quarter of Norway's greenhouse gasses are emitted by this industry[2]. The largest emitter offshore is gas turbines, which alone accounts for 81% of the emission from the Norwegian Continental Shelf (NCS)[2]. Gas turbines are used to generate heat, electricity, and power for on-site operations offshore. Gas turbines are fueled by natural gas or other fossil fuels, and are therefore a contributor for emission of carbon dioxide (CO_2) and methane.

1.2 State of the Art

Emissions from the Norwegian petroleum industry are largely determined by production level and the development of carbon reduction and energy efficient technology. Since the world's energy supply is dependent on hydrocarbons and the world's energy demand is set to increase in the coming decades, the petroleum industry will continue to extract new fossil reserves to prevent energy shortage as long as it is profitable. While a growing commitment to gas and oil over coal to a limit extent aids carbon cut, the majority of the emission cuts need to be facilitated by technological advancements as production is unlikely to decrease. The ability to establish good external conditions, develop new technology and commercialize innovations for cost efficient and competitive solutions are therefore the foundation for future value creation and emission reduction. Several alternative energy solutions, including wind, hybrid, fuel cells, and offshore carbon capture and storage (CCS), can be utilized in order to reduce emissions from the NCS. As emissions from the use of gas turbines is such a significant polluter and reducing greenhouse gasses is desirable, a feasible solution may be to replace gas turbines with fuel cells[2].

Fuel cells convert chemical energy from the fuel into electricity through a chemical reaction without combustion. The conversion occurs through a chemical reaction between positively charged hydrogen ions and oxygen, or another oxidizing agent. Fuel cells have a higher conversion efficiency compared to other conventional thermo-mechanical systems since the reaction occurs directly. A fuel cell consists of two electrodes, an anode and a cathode, an electrolyte and a catalyst. Fuel cells differ from batteries since they require a continuous source of fuel and oxygen or air to sustain the chemical reaction, while the chemicals present in a battery react with each other to generate an electromotive force (EMF). Fuel cells are able to produce electricity continuously for as long as these inputs are supplied. Currently, six different fuel cell technologies exist, and as they fluctuate in operating temperature, efficiency, and output, they therefore vary in use and application[12].

While the principal behind fuel cells was invented in 1838, the first commercial use of fuel cells came about more than a century later in 1933[13]. However, fuel cells are mostly used to provide power in stationary and portable power applications[13].

There are both ongoing and feasible projects regarding application of fuel cell technology in the petroleum industry. One promising project is the Clean, Highly Efficient Offshore Power (CHEOP). CHEOP works on developing a hybrid system, which combines the solid oxide fuel cell (SOFC) and the high temperature proton exchange membrane fuel cell (HT PEMFC) technology. The aim of the project is to develop a compact fuel cell with an output of 3 MW, with a size and weight equal to one tenth of a 30 MW turbine. This could potentially increase the efficiency from 35% to 65%[2].

Fuel cell technology will have an important role in future energy systems because of its high energy efficiency and low emission. The offshore and maritime sector are identified as a market where implementation of compact fuel cell systems can contribute to cost efficient reduction of fuel consumption, and lower CO_2 and NO_x emission. Currently, none of the six main fuel cell technologies are individually able to satisfy the desired weight, power output and efficiency requirements offshore. It is therefore necessary to combine the different technologies in order to achieve a fuel cell system suitable for application on offshore installations.

1.3 Objective

Since fuel cells have not yet been tested in offshore oil and gas production, the main objective of this thesis is to consider the characteristics of the different fuel cell technologies in order to evaluate if the fuel cell technology can be utilized instead of gas turbines as power generating system offshore. The thesis will look at the strengths, weaknesses, opportunities, and threats to the technology and examine how these may affect oil and gas production. This thesis will also consider the implications for climate, efficiency and money saved by using fuel cell technology as well as examine if fuel cells is a principal way in which the petroleum industry may address climate change.

A part of the literature study in this thesis is obtained from the project thesis written during the fall 2016. However, the master thesis includes further research upon the subject such as electrical integration of fuel cells. A SWOT analysis is conducted in order to examine if the technology is able to meet all the demands placed on power generating systems offshore.

1.4 Limitations

Some limitations with the work of the thesis should be mentioned. The thesis was based on an idea of solving an upcoming challenge in the oil and gas production, mainly emission of CO_2. Using innovative technology to solve a challenge is both interesting and hard and there have not been many, if any, studies of application of fuel cells in offshore oil and gas production.

It is difficult to compare gas turbines and fuel cells since it currently does not exist any fuel cell systems for application offshore. However, the technology has been applied onshore but application offshore brings with it several challenges such as delivery of fuel. Hydrogen should either be stored at the installation, which may be a challenge since space and weight is limited, or it has to be delivered through pipelines. However, there do exist a project working on utilization of waste heat in production of hydrogen. The reforming process can then be performed on the installation.

Retrieving information about certain areas, such as costs, has been one of the greatest challenges during the process. Since application of fuel cells in large power generating systems is a relatively new are of research, the different suppliers of the technology are reserved with this type of information. Hence, the costs of fuel cell systems are not emphasized too much in this thesis.

1.5 Structure

Chapter 2 provides a discussion of the greenhouse gas emission from the petroleum industry. The chapter consider the emission sources, the consequences of emission and possible reduction methods.

Chapter 3 explains the working principle of a fuel cell. The efficiency of a single fuel cells is discussed, as well as voltage and fuel cell stacking. The different fuel types for fuel cells are explained regarding extraction, storage, and transportation. The six different fuel cell technologies are also explained, examined, and compared regarding fuel, operating temperature, electrolyte, efficiency, output, and application.

Chapter 4 presents the different application areas for fuel cells, as well as the background history of the technology.

Chapter 5 looks at the electrical demand on offshore installations and the electrical integration of fuel cells.

Chapter 6 presents a SWOT analysis conducted in order to examine the strengths, weaknesses, opportunities, and threats for the fuel cell technology. The results from the analysis is used to discuss whether the technology is able to meet the specific demands for a power generating system offshore, and whether the technology is competitive with gas turbines in order to replace them in the future.

Chapter 7 contains concluding remarks and recommendations for further work.

Chapter 2

Greenhouse Gas Emission

2.1 Greenhouse Gas Emission in the Petroleum Industry

Global climate change is our time greatest challenge. With the signing of the Paris climate agreement in 2015, the world's nations agreed to implement actions to keep the global temperature below 2 °C above pre-industrial levels. The realization of the Paris climate agreement consequently requires substantial changes in our energy systems as burning of fossil fuels is a significant driver of global climate change. In order to remain within the agreed two-degree limit, carbon emissions have to be greatly reduced since burning of fossil fuels currently contributes with 81% of global carbon emissions[14]. Thus, the world economy needs to shift from a carbon dependent economy to a more carbon efficient and neutral economy in order to combat climate change[2].

However, fossil fuels are our number one energy source, and carbon will continue to play a key role in delivering energy in the coming decades despite the rise of renewable energy sources. The International Energy Agency (IEA) estimates that petroleum will account for at least 54% of total energy consumption in 2035[15]. Long-term investments in fossil fuels are thus necessary to meet future energy demand, and the petroleum industry's focus must therefore be on making the production, transportation, and usage of fossil energy sources as efficient as possible. The industry has a responsibility to invest in low-carbon technologies and increase fuel efficiency to reduce emissions, and it is likely to see an energy future where natural gas becomes increasingly important because of its lower carbon footprint while the shares of coal and oil decreases[2].

At the same time as carbon emissions need to be reduced, global energy demand is set to increase. The world's economy is likely to double by 2035 at the same time as the world population is predicted to reach 8.5 billion by 2030 and 9.7 billion by 2050, which will drive the world's energy demand up[15][16]. The IEA estimates that global energy demand will increase by 37% by 2035 with the non-OECD countries representing 96% of the growth[15]. Access to secure, reliable, and affordable energy is essential for economic growth, which means that the energy industry plays a key role in making global development and economic growth possible. As a consequence, the petroleum industry is confronted with a two-faced challenge; the industry needs to increase the energy production to accommodate for the world's growing energy demand while it simultaneously has to take action to reduce carbon emission in order to tackle global climate challenges[2].

2.2 Greenhouse Gas Emission in the Norwegian Petroleum Industry

The petroleum industry contributes with around a quarter of Norway's total CO_2 emission of 53.9 million tonnes CO_2-equivalents[2]. The petroleum industry emitted 14.1 million tons of greenhouse gases in 2015, which is an increase of 2.5% from 2014, and 83.3% from 1990[1]. This means that despite technological advancements, growing production of gas over oil and an increased focus on cutting emissions, emissions increased as production increased.

Compared to other emitters of CO_2, the petroleum industry has, together with energy supply, seen among the highest percentage growth in CO_2 emissions since 1990[1]. The percentage change is presented in Figure 2.1. While the petroleum industry has increased its emissions with 83.3% since 1990, Norwegian manufacturing industries and mining has decreased its CO_2 emission with 39.9% in the same time period. Residential and industrial heating decreased with 56.7%, while agriculture decreased with 5.3%[1]. Thus, increased oil and gas production and extraction is largely responsible for increased emissions of greenhouse gases from Norwegian territory over the last two decades. Interestingly, increased oil and gas production has an indirect domino effect as greenhouse gas emission from the offshore industry grows proportionally with increased production, which further contributes to increased CO_2 emissions[1].

Emissions and sinks of greenhouse gases. Million tonnes CO2 equivalents			
	2015	Change in per cent	
		Since 1990	2014 - 2015
Emissions from Norwegian territory	**53.9**	**4.2**	**1.1**
Oil and gas extraction	15.1	83.3	2.5
Manufacturing industries and mining	11.9	-39.3	2.5
Energy supply	1.7	311.3	-0.6
Heating in other industries and households	1.2	-56.7	-1.2
Road traffic	10.3	32.6	0.3
Aviation, navigation, fishing, motor equip. etc.	6.4	15.3	-0.6
Agriculture	4.5	-5.3	1.0
Other	2.8	5.2	-3.2
Sinks and emissions from forest and land areas in Norway [1]	**-26,1**	**147,7**	**2,7**

[1] Figure for the previous year. The change in per cent shows increase in net uptake in forests since 1990.
Source: NIBIO

Figure 2.1: Emissions and sinks of greenhouse gases, measured in million tones CO_2-equivalents and percentage change[1]

While CO_2 accounts for 82.2% of the greenhouse gasses emitted from Norwegian territory, methane represents 8% of total greenhouse gas emissions[17]. Agriculture is the most important emitter of methane; however, the petroleum industry is also a significant contributor as it emits 13.8% of Norway's total methane emission[2].

Methane is the main component of natural gas and is a more potent greenhouse gas than CO_2. Methane's global heating potential is 25 times higher than that of CO_2, which means that even small amounts of methane contributes significantly to enhanced greenhouse effect. Not only is methane a potent greenhouse gas, it is also extremely flammable. When mixed with air, an explosive mixture may be formed. Thus, limiting methane emissions in the petroleum industry is also important because of safety concerns. The Norwegian petroleum industry emitted 28 974 tons of methane in 2015, which is an increase from 2012's 25 600 ton despite the industry's focus on reducing emissions. The increase in emissions can be explained by increased production of gas, but is also due to start-up of new production fields and emissions from valves during operations[2].

Gas turbines are the biggest emitters on offshore installations; accounting for 81% of the CO_2 emissions alone[2]. Gas turbines generate heat and electricity, which are utilized for on-site operations such as pumping and compression. As presented in Figure 2.2, flaring is the second largest emitter on offshore installations with its contribution of 9.7% of greenhouse gas emissions before emissions from engines follow with 7.1%. Gas turbines, flaring and engines are the three significant contributors as they collectively represent 97.9% of total emissions. Boilers, well testing and other sources emit the remaining 2.1% of all emissions. Out of Figure 2.2 comes the idea that the most effective way to reduce greenhouse gas emissions on offshore installations is to make gas turbines less carbon intensive. As gas turbines alone represents 81% of all greenhouse gas emissions, measures to reduce emissions should be directed towards making gas turbines more energy efficient, less carbon intensive and more sustainable[2].

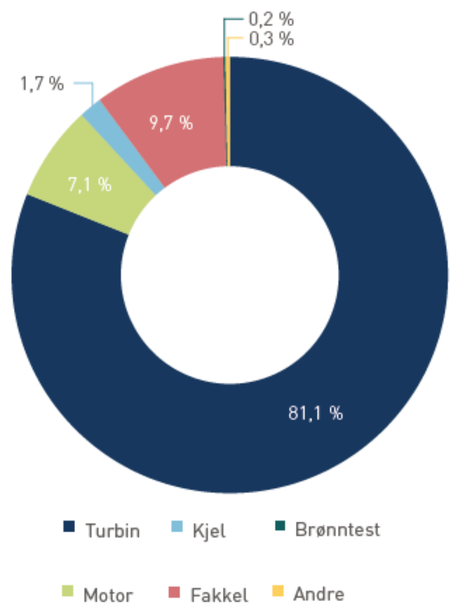


Figure 2.2: CO_2-emission from the Norwegian petroleum industry[2]

However, it is important to point out that the NCS is among the petroleum provinces with the lowest greenhouse gas emissions in the world. The Norwegian average of 55 kg CO_2 per ton oil equivalent is about half of the world average of 130 kg[18]. Essentially three factors determine greenhouse gas emissions from the NCS: production level, political restrictions, and technological advancements. Increased production means that more carbon is extracted and made available for burning, which consequently increases emissions as more hydrocarbons are released. However, emissions can be reduced by political regulations, laws, and incentives as well as by new technology or modifications on existing technologies to make production more efficient, or a combination of both[2].

2.3 Consequences of the Global Climate Change

Global climate change, fueled by increased levels of CO_2 and methane from anthropogenic activity, has severe consequences for both human kind and planet. The atmospheric concentration of CO_2 has increased from pre-industrial levels of 208 parts per million(ppm) to around 380 ppm today as we have extracted and burned fossil fuels[19]. Increased levels of CO_2 enhance the natural greenhouse effect by trapping more incoming solar radiation and thereby heat, which increases global temperatures. Increasing temperatures and changes in the chemical composition of the atmosphere alter the earth's natural system.

One of the most severe consequences of increased temperatures is the melting of the cryosphere. The average surface and ocean temperature rise of 0.85 °C since 1880 has been accompanied by a mean sea level rise of 1.7-2.0 mm pr. year or approximately 0.19 m since 1880[20]. Sea level rise, already posing significant challenges to low-lying countries, island states and coastal regions such as Bangladesh and the Maldives, will continue as the melting of the Antarctic and Greenland ice sheets is expected to increase in the coming decades as a result of heightened temperatures. The Antarctic and Greenland ice sheets have the theoretical potential to raise the mean sea level with approximately 68 m, which would put large coastal areas in every world part under water[21]. Loss of sea ice also creates a positive feedback loop because of thermal expansion and the albedo effect. While ice and snow reflects up to 90% of solar radiation, dark oceans only reflect 5-10%. This means that the loss of ice in Antarctica and Greenland will amplify the rise in temperature as heat is absorbed by the ocean rather than reflected by ice[22][23].

One of the most severe effects of increased atmospheric CO_2 levels from burning of fossil fuels is ocean acidification. The ocean acts as a sink of atmospheric CO_2. Over the past 200 years, the oceans have absorbed approximately one third of anthropogenic CO_2 emissions, and the uptake of CO_2 has lowered the average pH value of the oceans with 0.1 units from pre-industrial levels, meaning that the concentration of H^+ ions have increased with about 30%[19]. A decrease in ocean pH has severe consequences for marine life since a change in ocean chemistry alters the nutrient cycle, affects the biological pump, dissolves carbonated organisms and increases ecological competition. Ocean acidification does not only have biological consequences, but also socio-economic impacts as fisheries, coastal management, water quality and tourism depend on the state of the oceans[22].

As human activity has increased the concentration of CO_2 from 208 ppm to around 380 ppm today, we have pushed the rate of ocean acidification outside the range of natural variability as the current rate is 100 times the maximum rate observed during the last 400 000 years[19]. Because the deep ocean currents that absorb and release CO_2 operate on a timescale of 1000 years, ocean acidification is essentially irreversible during our lifetime even if we stop emitting CO_2. This means that the average ocean pH will fall by 0.5 units by 2100, which will have devastating consequences of marine ecosystems and pose a wide range of biological, economic and social challenges in the coming years[19]. Additionally, global warming further creates a positive feedback loop by rising ocean temperatures. As warm water can hold less CO_2 than cold water, the oceans will absorb less CO_2. This means that more CO_2 remains in the atmosphere, which further enhances the greenhouse effect[19].

Global warming also causes changes in atmospheric circulation patterns. Phenomenon such as La Niña and El Niño as well as the Monsoon seasons are changing in nature, duration, and intensity. As a consequence, traditional weather patterns are transformed, and the climate becomes less predictable and more extreme. Dry areas are getting drier, droughts tend to last longer, flooding have and will become more frequent, bush fires are more common and heat waves are killing more people as they increase in intensity and duration. Extreme weather therefore threatens human health and lives, destroys infrastructure, limits economic growth, and affects food security, which have local and well as global effects[23]. However, climate change affects nations differently since the effects of climate change are not uniform but have strong spatial variations. Some areas will be hit harder than others, which means that global warming is likely to increase global inequalities since some nations, especially the high-income states, are better equipped to address and adjust to climate change than low-income countries[23].

Rising levels of climate gasses also pose significant challenges to biodiversity. As species' habitats changes, species try to adapt to changing environmental conditions. However, as the rate of climate change exceeds the rate of evolutionary change, the Earth is heading towards its sixth mass extinction. Since the Earth's natural systems are interconnected and interlinked, scientists now fear the ”perfect storm scenario” as the challenges we now face feed into each other. The ”perfect storm scenario” is based on the prediction that by 2030 the world will need to produce around 50% more food and energy, together with 30% more fresh water, whilst mitigating and adapting to climate changes[24]. As the planet is pushed outside its natural boundaries unknown territory is entered, thus it is impossible to predict the full consequence of global climate change[22].

2.4 Reduction Methods

Emissions in the petroleum industry can be reduced by governments' adapting a "carrot and stick approach". Governments have to force the industry to cut emissions through tougher regulations, laws and taxes whilst offering incentives, founding and help to aid the transition to a low-carbon production. The petroleum industry operates within the framework set by the government, and corporations base their decisions on what is profitable in the short and long-term perspective. Over the last two decades, it is evident how important the Norwegian government's rulings have been in facilitating emission cuts and technological advancements on the NCS. Especially the CO_2 taxes, the Petroleum act, CCS, and the European Union Emission Trading Scheme (EU ETS) have been important political initiatives to facilitate emissions cut in the Norwegian petroleum industry[2]. The Norwegian government introduced a tax on CO_2 in 1991, which has been a key instrument in reducing CO_2 emissions from the petroleum sector. The CO_2 tax gave the petroleum industry a financial incentive to seek technological solutions to cut carbon emissions, reduce flaring, increase electrification, and look for more efficient solutions for power supply on offshore installations[17].

The CO_2 tax also encouraged the petroleum industry to investigate in CCS-solutions as a price was put on CO_2 emissions. The CCS technology is one of the most important technologies in the long-term in order to reduce the CO_2 emissions. CCS is a way to reduce CO_2 emissions and with that costs as CO_2 is caught, transported, and stored underground instead of emitted to the atmosphere. The CCS technology separates CO_2 from the emission, injects the CO_2 into geological formations where it is stored permanently[17]. Because of its role as a large-scale oil-and-gas producer, CCS has become a pillar in Norway's climate and petroleum policy, and a key way in which the Norwegian government plans to tackle global climate change, exemplified with the implementation of CCS technology on the Sleipner and Snøhvit fields[2].

The Petroleum Act, introduced in 1996, provides the legal foundation for the licensing system, which regulates petroleum extraction in Norway[17]. The Norwegian government has incorporated environmental considerations into its regulatory framework for extraction and production of oil and gas so that the petroleum activity will be as environmental friendly and sustainable as possible. This puts pressure on companies to reduce emissions since they are not only forced to meet the Norwegian government's requirements, but also to compete with each other to be the most environmental friendly in order to be awarded contracts. Additionally, there are several governmental agencies in Norway, such as Innovation Norway and Enova, which further facilitate and aid emission cut in the Norwegian industry by financially supporting new, carbon-saving technology[2].

Norway has a National Emission Trading Scheme in place, which has been linked to the EU ETS since 2005[17]. As a part of the European Economic Area, Norway has to implement directives and regulations from the European Union (EU), and the carbon emissions from the Norwegian petroleum industry must be within the quota set by the EU[2]. The IEA estimates that more than 70% of Norway's greenhouse gas emissions are covered by emissions trading and the CO_2 tax, which demonstrates the central role emission trading and taxation have played in facilitating emission cuts[17].

Other actions, such as energy efficient improvement, energy management and alternative energy solutions, can be implemented in order to reduce the CO_2 emission from the petroleum industry. Energy efficiency improvement is an important priority area for the petroleum industry. The opportunity is huge for new installations, while the energy efficiency improvement for already existing platforms can be done through operational optimization and modifications. Energy management is a tool which goal is continuous improvements of the energy system, and combined with energy efficient improvements an efficient tool for fuel consumption and thereby reduced costs and emission[2]. An alternative energy solution, among others, may be fuel cell systems. These systems may play a key role for the future competitiveness of fossil fuels since they have the potential to contribute with significant emission cuts, which would make utilization of hydrocarbons more attractive[2].

While Norway aims to be carbon neutral by 2050, the Norwegian economy is largely build on gas and oil production. The petroleum industry generated 22% of the Gross Domestic Product and accounted for 26% of investment[17]. A "road map" for the NCS's future has therefore been developed. The road map represents different crossroads for the Norwegian petroleum industry, and it addresses the two main challenges the industry face: emissions and profits. Firstly, as a response to global climate change, the road map sets the targets for reducing greenhouse gas emission emitted by the petroleum industry with specific sub-targets for 2030 and 2050. Secondly, it maps the ambitions for the industry's long-term production, competitiveness, and value creation. The overall ambition is that the NCS will continue to be world leading in reducing carbon emissions, and aims to produce fossil fuels with the lowest carbon footprint as possible. In order to achieve this, the industry will develop and implement technologies and solutions that reduce the average CO_2 emissions per produced unit, which is also a key way in which the industry will be competitive. As long as the world is dependent on fossil fuels, Norwegian petroleum is preferred since it has among the lowest CO_2 emissions per produced unit[2][17].

Chapter 3

Fuel Cells

3.1 Working Principle

The characteristic of a fuel cell is its ability to convert chemical energy from a fuel into electrical energy without combustion and emission of greenhouse gasses. However, it should be mentioned that if the fuel cell utilizes natural gas as fuel, small amounts of CO_2 will be emitted. Nevertheless, these amounts are much smaller than from a combustion. The chemical reaction occurs directly, which gives the cell a much higher conversion efficiency than any other conventional thermo-mechanical system[12].

This conversion is done through a chemical reaction between positively charged hydrogen ions and oxygen, or another oxidizing agent. An oxidizing agent is a substance which has the ability to oxidize other substances, in other words the ability to cause other substances to lose electrons. A fuel cell consists of two electrodes, an anode and a cathode, an electrolyte, and catalysts. The main functions of the electrodes are to bring about a reaction between the reactant and the electrolyte without being consumed or corroded[12].

Both electrodes contain catalysts. The catalyst increases the speed of the chemical reaction, causing the fuel to undergo an oxidation at the anode, as the one presented in Equation 3.1. Electrons and positively charged ions are released. The positively charged ions move through the electrolyte at the same time as the released electrons move from the anode to the cathode through an external circuit, producing direct current (DC). A reduction takes place at the cathode, where the negatively charged electrons react with the positively charged ions and water. The reduction reaction is presented in Equation 3.2 The electrolyte allows the positively charged hydrogen ions to move from one side of the cell to the other, while it prevent the electrons. If the electrons went through the electrolyte instead of around the external circuit, no electrical current would be produced[3]. The electrolyte is therefore electrically conductive. At the same time as it prevents the two electrodes from coming into electronic contact by blocking the electrons[12].

$$Oxidation \qquad 2H_2 -> 4H^+ + 4e^- \tag{3.1}$$

$$Reduction \qquad O_2 + 4e^- + 4H^+ -> 2H_2O \tag{3.2}$$

The electrons flow from the anode to the cathode, but conventional current flows from cathode to anode. Indicating that the cathode is the electrically positive terminal, while the anode is the negative terminal since electrons flow from - to +[3].

The total cell reaction for a hydrogen fuel cell is presented in Equation 3.3. The technolgy is considered a green technology since water is the only by-product.

$$Cell\ \ reaction \qquad 2H_2 + O_2 -> 2H_2O \tag{3.3}$$

The working principle of a fuel cell is illustrated in Figure 3.1. The red arrows represent the negatively charged electrons which move in an external circuit from the anode to the cathode generating electricity. The fuel, in this case hydrogen, is represented with yellow arrows and shows how the H_2 is being oxidized into H^+ ions. It can be seen that the positively charged hydrogen ions move from the anode to the cathode through the electrolyte. The oxygen injected to the cathode is represented by the blue arrows. These arrows also represent water produced as a by-product at the cathode.

3.2 Fuel Cell Classification

Fuel cells can be classified according to various criteria. They might be sorted by their operating temperature, reforming process, fuel, oxidant used, or the nature of the electrolyte. The electrolyte can either be an oxygen ion conductor or a proton conductor. The major distinction between the two types are the difference according to which side the water is

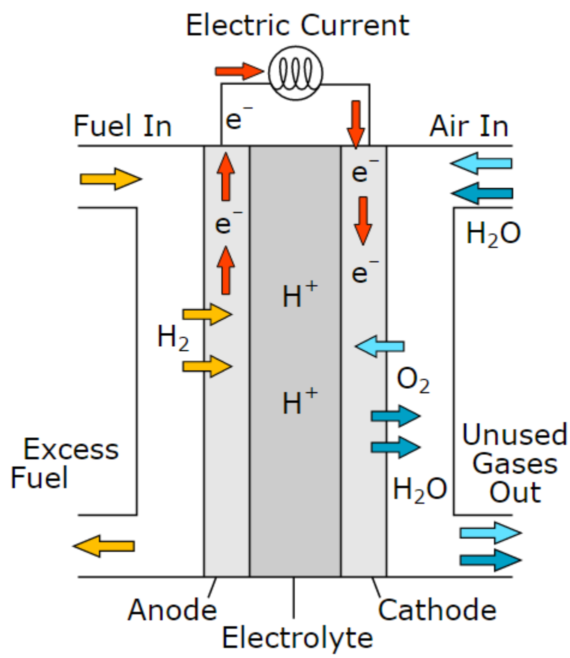


Figure 3.1: Working principle for a fuel cell

produced. The water is produced on the oxidant side in the proton conductor, while it is produced on the fuel side in the oxygen ion conductor[12]. The operating temperature is divided into low and high. For a fuel cell to be categorized as a low temperature fuel cell the operating temperature fluctuates between 50 °C and 250 °C, while the high temperature fuel cells have an operating temperature between 650 °C and 1000 °C[25]. The different fuel cell technologies also fluctuate in power output and efficiency.

Based on the criteria mentioned above, the fuel cells are classified into the six major groups listed below[25]:

- Alkaline fuel cell (AFC)
- Direct methanol fuel cell (DMFC)
- Proton exchange membrane fuel cell (PEMFC)
- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

A description of each of the six groups regarding operating temperature, application, power output, efficiency and fuel type will be given in the following sections. The first four fuel cell technologies are categorized as low-temperature operating fuel cells, while the last two are high-temperature operating fuel cells.

3.2.1 Alkaline Fuel Cell

The AFC utilizes an alkaline electrolyte consisting of potassium hydroxide (KOH) in a water based solution in order to generate electric power. The hydroxyl ions (OH^-) travel across the electrolyte and enables an external circuit to be made, such that electrical energy can be extracted. The water based alkaline solution can absorb CO_2, which means that the fuel cell can be poisoned through the conversion of KOH to potassium carbonate (K_2CO_3), as presented in Equation 3.4. Thus, the AFCs operate on pure oxygen or purified air. The generation and storage of pure oxygen increases the operation costs, and the AFC is therefore expensive[10].

$$2KOH + CO_2 -> K_2CO_3 + H_2O \tag{3.4}$$

Due to the poisoning effect, two main versions of the AFC exist; static electrolyte and flowing electrolyte, with flowing electrolyte as the most common one. In the case with static electrolyte, each cell in the stack has its own, separate electrolyte. The electrolyte is often a thin paste adhering to a porous matrix of asbestos[13]. The electrolyte is held in a matrix material between the electrodes, meaning that it is solid and orientation in any direction is possible. A major advantage with this version is that the electrolyte does not have to be pumped around or dealt with in any way. However, there exist some obstacles related to managing of the product water, the evaporation of water, and the fact that water is used at the cathode. The water is produced at the anode and removed from the cathode[3].

Fuel cells with the flowing electrolyte utilize a more open matrix design. The design allows the electrolyte to circulate continuously between the electrodes[13]. The main advantage is that it allows for the electrolyte to be removed and replaced from time to time. This is essential since the CO_2 in the air reacts with the potassium electrolyte, which is gradually changed to potassium carbonate, as presented in Equation 3.4. The result is a reduction of OH^- ions as they are replaced with carbonate(CO_3^{2-}) ions, and a reduction of the cell performance. Another advantage is that the circulating electrolyte may serve as a cooling system for the cell. One disadvantage associated with a flowing electrolyte are centered around the extra equipment needed. A pump to circulate the fluid is required, and the fluid to be pumped is corrosive. The additional pipework indicates more possibilities for leaks, and it is harder to design a system that will work in any orientation[3].

The redox-reaction taking place at the anode is an oxidation. Hydrogen gas molecules and hydroxyl ions are combined, and water and negatively charged electrons are released.

$$Oxidation \qquad 2H_2 + 4OH^- -> 4H_2O + 4e^- \tag{3.5}$$

The released electrons move through the external circuit, producing electricity. Oxygen molecules and water molecules react with the negatively charged electrons, generating negatively charged hydroxyl ions. The redox-reaction taking place at the cathode is called a reduction, and is presented in Equation 3.6.

$$Reduction \qquad O_2 + 2H_2O + 4e^- -> 4OH^- \tag{3.6}$$

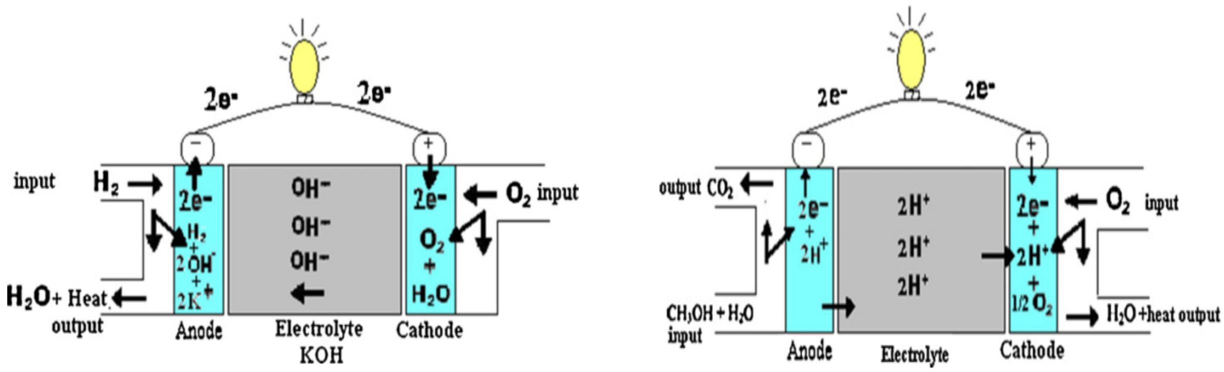
The total cell reaction for the AFC is given in Equation 3.7. The working principle of the AFC is illustrated in Figure 3.2a, with the movement of electrons and ions illustrated with arrows.

$$\text{Cell reaction} \qquad 2H_2 + O_2 -> 2H_2O \tag{3.7}$$

There are both low and high temperature AFCs. Low temperature AFCs operate at temperatures as low as 25 °C and up to 75 °C. The high temperature AFCs have an operational temperature range between 100 °C and 250 °C. Normal operational temperatures for these types of fuel cells are around 70 °C, hence the fuel cell is categorized as a low operating temperature fuel cell[10].

The most efficient way to speed up the reactions at the electrodes is by utilization of a catalyst. The AFC uses Nickel. Nickel is not expensive compared to other types of catalysts, and the AFC is therefore categorized as cost-efficient[10].

AFCs are currently used in submarines, boats, forklifts trucks and in some transportation applications. They have also been used by the National Aeronautics and Space Administration to supply drinking water and electric power for space applications. The AFCs consume hydrogen and pure oxygen to produce potable water, heat, and electricity sources. Due to the utilization of hydrogen and oxygen as fuel, no greenhouse gasses are emitted. This type of fuel cells operate with an efficiency as high as 70%, generating electricity up to 20 kW[10].



(a) Working principle for an AFC[10]

(b) Working principle for a DMFC[10]

Figure 3.2: Illustration of the working principle for an AFC and a DMFC

3.2.2 Direct Methanol Fuel Cell

The DMFC operates at low temperatures, have a long lifetime and rapid refueling characteristics. In addition, it does not have to be recharge and is therefore a suitable source of power for portable energy purposes[10].

The DMFC uses methanol (CH_3OH) as energy source, and polymers as electrolyte. Methanol undergoes an oxidation at the anode, where it reacts with water, creating CO_2, negatively charged electrons, and positively charged hydrogen ions. The oxidation-reaction is presented in Equation 3.8.

$$Oxidation \qquad CH_3OH + H_2O- > CO_2 + 6H^+ + 6e^- \tag{3.8}$$

The released electrons move through the external circuit, producing electricity, while the positively charged hydrogen ions move through the electrolyte. A reduction, as the one presented in Equation 3.9, occurs at the cathode where electrons react with oxygen and hydrogen ions, producing water.

$$Reduction \qquad \frac{3}{2}O_2 + 6e^- + 6H^+ - > 3H_2O \tag{3.9}$$

The total cell reaction for a DMFC is presented in Equation 3.10. The final by-products are CO_2 and H_2O, indicating that the DMFC technology is not greenhouse gas neutral as it emits small amounts of greenhouse gasses. The working principle of the DMFC is illustrated in Figure 3.2b, where the arrows illustrate the movement of the electrons and ions.

$$Cell\ \ reaction \qquad CH_3OH + H_2O + \frac{3}{2}O_2 - > CO_2 + 3H_2O \tag{3.10}$$

The DMFC systems are classified into passive and active. Both classification consist of a CO_2 separator, a fuel cell stack, methanol sensor, pump drivers, and controllers. The active DMFCs also have a methanol feed pump and a circulation pump. The circulation pump can increase the efficiency and active DMFCs are therefore highly efficient and reliable systems. They are usually used in control applications for quantities such as flow rate, concentration and temperature[10]. Since the passive DMFC systems do not have a methanol pumping device and external process for blowing air into the cell, the oxygen is defused into the cathode by use of air breathing features of the cell. Simultaneously, the methanol is defused into the anode from an integrated feed reservoir driven by a concentration gradient. Passive systems are therefore cheap and simple. They are also capable of substantial reduction in power loss and system volume[10].

Methanol is utilized in the DMFCs in form of liquid or vapor. Tests performed under similar operating conditions show that the liquid feed DMFCs have a lower achieved cell voltage and power density. This may come from the fact that methanol does not perform perfectly for mass transfer. Also, the extent of methanol cross-over from anode to cathode and poor gas release at the electro-catalyst surface are contributing factors. Methanol cross-over occurs when methanol diffuses through the membrane without reacting, and immediately react with air at the cathode. The reaction of the fuel at the cathode is not only a waste of fuel, but it also contributes to a reduction of the cell voltage[3]. Cross-over is a major factor in inefficiencies, and around half of the methanol is lost to cross-over. This can be reduced by making the catalyst at the anode as active as possible, resulting in a proper reaction of methanol and thereby making the methanol unable to diffuse through the electrolyte and on to the cathode. It should be noted that fuel cross-over reduces as the current from the cell increases[3]. Vapor feed cells are therefore preferred in terms of their cell voltage and power density[26]. Some drawbacks are associated with the vapor feed cells. Dehydration of the membrane, less lifetime and requirement for a high temperature for fuel vaporization are some of them, hence this fuel cell technology is unsuitable for portable applications[10].

The DMFCs operating temperature fluctuates between 60 °C to 130 °C, and the fuel cell is classified as a low operating temperature fuel cell. They have a limited power production, but can store a high-energy content in a small space. This means that they can produce a small amount of power of energy over a period of time. The DMFC is therefore ill-suited for powering large vehicles, but well suited for use in applications with modest power requirements, such as mobile electronic devices or charges, portable power packs, and digital cameras and laptops. DMFCs are an emerging application in the military and in small vehicles, such as forklifts, due to its low noise. The units can have a power output between 25W and 5kW with an efficiency as low as 20% - 30%, making it the fuel cell technology with the lowest efficiency[27].

3.2.3 Proton Exchange Membrane Fuel Cell

The PEMFC uses a solid polymer as electrolyte, while the electrodes are porous carbon containing a platinum or platinum alloy catalyst. The PEMFC consists of bipolar plates and membrane electrode assembly (MEA). MEAs' essential function is to separate reactants and transport of protons, while blocking a direct electronic pathway through the membrane[10]. The bipolar plates, on the other hand, serves as a remedy of feeding fuel to the anode and oxygen to the cathode[3]. The PEMFC has a high power density as well as a low weight and volume compared to other types of fuel cells. Only hydrogen, oxygen from the air, and water are required for the cell to operate and it is typically fueled with pure hydrogen[28].

The oxidation at the anode is activated by a catalyst. Hydrogen forms positively charged hydrogen ions, and ejects negatively charged electrons, as presented in Equation 3.11. The electrons move through an external circuit, producing DC. The hydrogen ions move through the electrolyte and react with oxygen and electrons at the cathode in a reduction reaction. The reduction reaction is given in Equation 3.12.

$$Oxidation \qquad H_2 -> 2H^+ + 2e^- \tag{3.11}$$

$$Reduction \qquad \frac{1}{2}O_2 + 2H^+ + 2e^- -> H_2O \tag{3.12}$$

The total cell reaction of a PEMFC is presented in Equation 3.13. The PEMFC technology is considered a greenhouse gas neutral technology since the only by-product is water.

$$Cell\ \ reaction \qquad H_2 + \frac{1}{2}O_2 - > H_2O \tag{3.13}$$

The working principle of a PEMFC is illustrated in Figure 3.3a, with arrows illustrating the movement of the electrons and ions.

It has been said that PEMFCs only need hydrogen, oxygen from the air and water to operate. In small systems, this will frequently be the case. The situation is different in larger systems where the hydrogen fuel frequently come from some type of fuel reforming[3]. Different fuel reforming processes will be further discussed in Section 3.6. However, these reforming processes nearly always involve a reaction producing carbon monoxide (CO).

High-temperature fuel cells may utilize the CO as fuel. However, fuel cells using platinum catalyst, such as the PEMFC, may not utilize the CO since CO has an affinity for platinum and covers the catalyst, preventing the hydrogen from reaching the electrodes. In situations where reformed hydrocarbons are used as fuel, the CO must be "shifted" to CO_2. This is done through a shifting reaction, as presented in Equation 3.14 below[3].

$$Shift\ \ reaction \qquad CO + H_2O - > H_2 + CO_2 \tag{3.14}$$

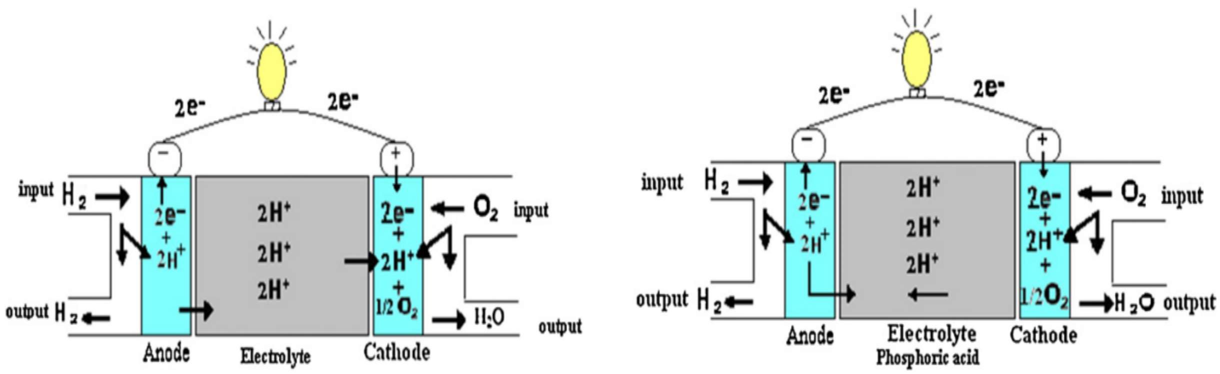
PEMFCs operating temperature fluctuates between 60 °C and 100 °C, thus the cell is therefore characterized as a low-temperature fuel cell. This low-temperature operation allows them to start quickly due to less warm-up time. This results in less wear on system components which again result in better durability. However, this requires use of a noble-metal catalyst, usually platinum, to separate the electrons and protons in hydrogen. If the hydrogen is derived from a hydrocarbon fuel, an additional reactor has to be employed in order to reduce CO in the fuel[28].

A high working temperature results in a higher efficiency due to a higher reaction rate. Working temperatures above 100 °C will vaporize water, resulting in a phase transmission of the water from liquid to vapor. Vaporizing will cause dehydration to the membrane, which will lead to reduction in proton conductivity of the membrane[28].

A variant of the PEMFC may operate at elevated temperatures and are therefore known as the HT PEMFC. This type of PEMFC can operate at temperatures as high as 200 °C. This is achieved by changing the electrolyte from water-based to a mineral acid-based system.

By doing this, some of the current limitations regarding fuel purity is overcome. The HT PEMFC is then able to process reformate containing small amounts of CO. However, the HT PEMFCs are not superior to low temperature PEMFCs, and both technologies have their own strengths and weaknesses[27].

PMEFCs usually have an efficiency between 40% and 50%, and a output power as high as 250 kW. They are usually applied in portable and stationary applications. PMEFCs are particularly suitable for use in transportation due to their fast start-up time, favorable power-to-weight ratio, and because they provide continuous electrical energy supply. Due to no moving parts in the power generating stack, the requirement for maintenance is kept at a minimum[10][28].



(a) Working principle for a PEMFC[10]

(b) Working principle for a PAFC[10]

Figure 3.3: Illustration of the working principle for a PEMFC and a PAFC.

3.2.4 Phosphoric Acid Fuel Cell

The PAFC utilizes electrodes of carbon paper, and liquid phosphoric acid as electrolyte. Phosphoric acid has low ionic conductivity at low temperatures, hence the PAFC has an operating temperature between 150 °C and 220 °C and is characterized as a low-temperature fuel cell[10].

The fuel, in this case hydrogen, is split into positively charged hydrogen ions and negatively charged electrons through an oxidation at the anode. The positively charged ions move from the anode to the cathode through the electrolyte. The electrons on the other hand, move through an external circuit generating DC and heat. The oxidation at the anode is described in Equation 3.15.

$$Oxidation \qquad 2H_2- > 4H^+ + 4e^- \tag{3.15}$$

Water is formed as a result of a reaction between the hydrogen ions, the electrons and the oxygen through a reduction at the cathode, as the one presented in Equation 3.16. The reaction makes use of a platinum catalyst in order to speed up the reaction.

$$Reduction \qquad O_2 + 4H^+ + 4e^-- > 2H_2O \tag{3.16}$$

The total cell reaction for the PAFC is presented in Equation 3.17. The by-product is water, indicating that the PAFC technology is characterized as a greenhouse gas neutral technology due to zero emission. The working principle of the PAFC is illustrated in Figure 3.3b. The arrows represent the movement of the electrons, moving from the anode to the cathode, and the positively charged ions moving through the electrolyte.

$$Cell\ \ reaction \qquad 2H_2 + O_2- > 2H_2O \tag{3.17}$$

The expelled water from the reduction is normally used in heating applications. The generated heat from when the electrons pass through the external circuit is usually exploit for water heating or steam generation. One problem with the steam generation is the production of CO around the electrodes. The CO get attach to the platinum catalyst at the anode, resulting in a reduced performance. The CO absorption is reduced by an increase of the anode tolerance temperature. At high temperatures, the CO is desorbed in a reversed electro-catalyst reaction at the cathode[10].

The PAFCs are CO_2-tolerant and the choice of fuel are therefore broadening. Thus, the PAFC does not require pure oxygen for its operations. They run on air and can easily operate with reformed fossil fuels[10]. The initial cost for this type of fuel cells is high, induced by the fact that PAFC uses air with $\sim$ 21% oxygen instead of pure oxygen. This results in a three times reduction in the current density. Thus, the PAFCs are designed with bipolar plates to increase electrode area, which lead to higher energy production[10]. Requirements for much higher loadings of expensive platinum catalysts increase the costs[28].

When PAFCs are used for co-generation of electricity and heat, they can be more than 85% efficient. However, the efficiency is much lower when generating electricity alone, only 37% - 42%. This type of fuel cell can have an output between 100 kW and 400 kW. Compared to other fuel cells with the same weight and volume, the PAFCs are less powerful[28]. The PAFCs are typically used for stationary power generation and to power commercial premises and large vehicles, such as buses[27].

3.2.5 Molten Carbonate Fuel Cell

The MCFC use an electrolyte composed of a molten carbonate salt mixture. The electrolyte is suspended in a porous, chemically inert ceramic matrix of a beta-alumina solid electrolyte[10]. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate[27].

The MCFC is characterized as a high-temperature fuel cell due to an operating temperature above 600 °C. The high operating temperature removes the requirement for an external reformer to convert more energy-dense fuel to hydrogen. These types of fuels are converted to hydrogen within the fuel cell itself through an internal reformation.

The reformation reaction in the MCFC occurs between the feed gas, normally methane and water, as presented in Equation 3.18. Methane and water are converted to hydrogen, CO, and CO_2[29]. The CO produced in the electrochemical reaction inside the cell is not directly used in the oxidation, but contributes to additional production of hydrogen.

$$Reform\ 1 \qquad CH_4 + H_2O -> CO + 3H_2 \tag{3.18}$$

$$Reform\ 2 \qquad CO + H_2O -> CO_2 + H_2 \tag{3.19}$$

Most of the CO_2 produced in Equation 3.19 is transported in an external circuit to the cathode, as illustrated in Figure 3.4a, where it is combined with the CO_2 input and a small part of it becomes exhaust. At the same time, two oxidation reactions take place at the anode. The hydrogen produced in the internal reforming processes reacts with carbonate ions(CO_3^{2-}) from the electrolyte, producing water, CO_2 and electrons. This oxidation reaction is presented in Equation 3.20. The CO from the internal reforming reaction in Equation 3.18 also reacts with carbonate ions, creating CO_2 and electrons, as presented in Equation 3.21.

$$Oxidation\ \ 1 \qquad H_2 + CO_3^{2-} -> H_2O + CO_2 + 2e^- \tag{3.20}$$

$$Oxidation\ \ 2 \qquad CO + CO_3^{2-} -> 2CO_2 + 2e^- \tag{3.21}$$

Electrons move through an external circuit, producing DC. The reduction reaction presented in Equation 3.22 occurs at the cathode where oxygen, CO_2 and electrons are converted into carbonate ions. The carbonate ions are transferred through the electrolyte to the anode where they are utilized in the oxidation reaction.

$$Reduction \qquad \frac{1}{2}O_2 + CO_2 + 2e^- -> CO_3^{2-} \tag{3.22}$$

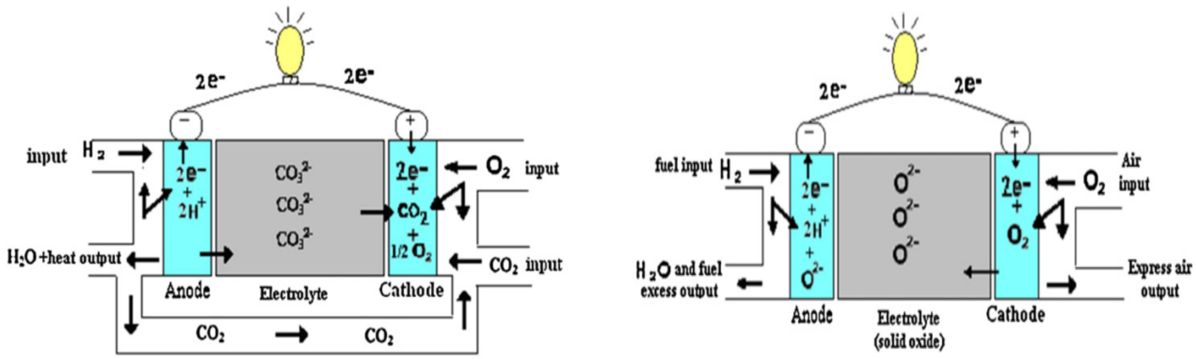
$$Cell\ \ reaction \qquad H_2 + \frac{1}{2}O_2 + CO_2 -> H_2O + CO_2 \tag{3.23}$$

The total cell reaction in the MCFC is presented in Equation 3.23. One of the by-products, in addition to water, is CO. This is a well-known greenhouse gas, indicating that the MCFC technology cannot be characterized as a completely greenhouse gas neutral technology. The working principle of the MCFC is illustrated in Figure 3.4a. The arrows illustrate the movement of the electrons and ions.

Both the advantages and disadvantages related to the MCFC technology are closely related to its operating temperature. The high operating temperature dramatically improve reaction kinetics, and a catalyst to boost the oxidation and reduction is therefore unnecessary. The high temperature also makes the MCFC resistant to poisoning by CO or CO_2, hence, the MCFC system can be directly fueled with hydrogen, CO, natural gas, propane, and coal-derived fuel gas[10].

The primary disadvantage associated with use of MCFC systems is durability. Due to the high operating temperature and the corrosive electrolyte, component breakdown and corrosion are accelerated, which decreases the cells lifetime. Another obstacle is the use of a liquid electrolyte rather than a solid. Combined with the requirement to inject CO_2 at the cathode, carbonate ions are consumed in reactions occurring at the anode. The MCFC also requires long time to reach operating temperature and to generate power[10]. It is also a disadvantage that the MCFC produces greenhouse gasses since CO_2 is produced during the reformation of the fossil fuels, as presented in Equation 3.21.

MCFC systems are currently used in large stationary power generation. They are employed for natural gas and coal-based power plants in electrical utility, industrial and military applications. MCFC systems are applied for plants of megawatt capacity, for large combined heat and power (CHP), and combined cooling and power (CCP) plants. The efficiency for these types of fuel cells can be up to 60% for conversion of fuel to electricity, and in CHP and CCP where heat is utilized as well, the overall efficiency can be above 80%[27].



(a) Working principle for a MCFC[10] (b) Working principle for a SOFC[10]

Figure 3.4: Illustration of the working principle for a MCFC and a SOFC.

3.2.6 Solid Oxide Fuel Cell

The SOFC utilizes a solid ceramic electrolyte instead of a liquid or a membrane. The most common one is the yttria stabilized zirconsia due to its high chemical and thermal stability and pure ionic conductivity[10]. The SOFCs are based on the concept of an oxygen conducting electrolyte. The oxide ions migrate from the cathode to the anode through the electrolyte before they react with the fuel. The oxidation occurs at the anode. Hydrogen reacts with the negatively charged oxide ions, and ejects electrons, as presented in Equation 3.24. The electrons move through an external circuit where DC is produced. Oxygen from the air reacts with negatively charged electrons at the cathode, as presented in Equation 3.25[30].

$$Oxidation \qquad O^{2^-} + H_2 - > H_2O + 2e^- \tag{3.24}$$

$$Reduction \qquad \frac{1}{2}O_2 + 2e^- - > O^{2-} \tag{3.25}$$

$$Cell\ \ reaction \qquad H_2 + \frac{1}{2}O_2 - > H_2O \tag{3.26}$$

The total cell reaction for a SOFC can be seen in Equation 3.26. The SOFC technology is considered a greenhouse gas neutral technology since the only by-product is water. The working principle of the SOFC is presented in Figure 3.4b, where the arrows illustrate the movement of the electrons and ions.

SOFCs operating temperature is the highest of all fuel cells, with a temperature between 800 °C and 1000 °C. The high operating temperature removes the need for catalysts since the reaction kinetics improve with temperatures. Due to the high operating temperature, fuels can be reformed within the cell itself, eliminating the need for an external reforming and allowing the unit to be used with a variety of hydrocarbon fuels. Some inconveniences are related to the high temperature. These types of fuel cells take longer to warm up and use longer time before reaching operating temperature. The construction has to consist of robust, heat-resistant materials, and they need to be shielded to prevent heat loss[27][28].

Different configurations have been proposed for the SOFC. The main differences between these designs are the method of connection between each cell, the shape of each cell, as well as the flowing of fuel or oxidant through their channels. The four main stacking arrangements are seal-less tubular design, segmented cells in series, monolithic design and flat plate design[31]. The tubular design is further explained in Section 3.5. The segmented cells in series configurations is similar to the tubular design except that the fuel is introduced through the center of the tube, while the oxidant flows at the outside. The monolithic configuration works in the same way as a heat exchanger, with electrodes, electrolyte, and interconnection in a compact corrugated structure. The last type of configuration, the flat plate design, consist of a flat multilayer ceramic plate composed of electrodes and electrolyte. Interconnected plates with gas flow channels for fuel and the oxidant are covering the multilayer ceramic plate[31]. Fuel cell stacking will be further explained and discussed in Section 3.5.

SOFCs are well adopted within large scale distributed power generation systems with capacity of hundreds of MWs. These type of fuel cells have an efficiency of more than 60% when converting fuel to electricity. If the by-product heat is exploited, their overall efficiency can be above 80%. SOFCs are reliable systems with low harmful gas emissions, noise free operations, and low maintenance costs[10].

3.3 Efficiency

Efficiency is categorized as the level of degree of effectiveness the energy is extracted, converted from one form to another, or delivered in the form of services. The energy efficiency of a device or system converting mechanical energy into electricity is given by the ratio between the amount of useful energy put into the system and the useful amount of energy delivered by the system[32].

3.3.1 Efficiency Limits

Defining the efficiency of a fuel cell is not straight forward. The Carnot limit, presented in Equation 3.27, is used to calculate the efficiency for steam and gas turbines.

$$Carnot\ \ limit = \frac{T_1 - T_2}{T_1} \tag{3.27}$$

Where T_1 is the maximum temperature of the heat engine, while T_2 is the temperature of the heated fluid released. The reason for the efficiency limit is that some heat energy, proportional to the lower temperature T_2, is always "thrown away" or wasted[3].

The situation is not so clear with fuel cells since they are not subjected to the Carnot efficiency limit. Since fuel cells use materials that are usually burnt to release their energy, electrical energy produced may be compared with the heat that would be produced by burning the fuel in order to calculate the efficiency. This is presented in Equation 3.28

$$\frac{Electrical\,energy\,produced\,per\,mole\,of\,\,fuel}{-\triangle\overline{h}_f} \tag{3.28}$$

where $\triangle\overline{h}_f$ is the enthalpy of formation, and the minus sign indicating that energy is released[3].

However, even this is not without obscurities since there exists two different values for the $\triangle\overline{h}_f$. The $\triangle\overline{h}_f$ - value is either the higher heating value (HHV) or the lower heating value (LHV). The difference between these two values represents the molar enthalpy of vaporization of water. It should be said whether the LHV or the HHV is utilized to calculate the efficiency. If this information is not stated, the LHV has normally been used in order to achieve a higher efficiency figure[3].

If the efficiency is calculated as in Equation 3.28, a limit to the efficiency exist. The maximum electrical energy available is equal to the change in the Gibbs free energy, and is therefore calculated by use of Equation 3.29.

$$Maximum\,efficiency\,possible = \frac{\triangle \overline{g}_f}{\triangle \overline{h}_f} x100\% \tag{3.29}$$

where $\triangle \overline{g}_f$ represents the change in the Gibbs free energy and $\triangle \overline{h}_f$ is the change in the enthalpy of formation[3].

The maximum efficiency limit is sometimes called the "thermodynamic efficiency"[3]. The values for the efficiency limit, relative to the HHV, for å hydrogen fuel cell is presented in Table 3.1. The form of the water product, the temperature, the change in the Gibbs free energy of formation per mole, as well as the maximum EMF is also presented in Table 3.1. The EMF describes the potential differences arising when chemical energy is being transformed into electrical energy[33].

Table 3.1: $\triangle \overline{g}_f$, maximum EMF, and efficiency limit(HHV basis) for hydrogen fuel cells

Form of water product	**Temp** [°C]	$\triangle \overline{g}_f, [kJmol^{-1}]$	**Max EMF [V]**	**Efficiency limit** [%]
Liquid	25	-237.2	1.23	83
Liquid	80	-228.2	1.18	80
Gas	100	-225.2	1.17	79
Gas	200	-220.4	1.14	77
Gas	400	-210.3	1.09	74
Gas	600	-199.6	1.04	70
Gas	800	-188.6	0.98	66
Gas	1000	-177.4	0.92	62

It can be seen from Figure 3.5 that the efficiency limits vary with operating temperature. The efficiency limits for water product in liquid form and gas form can be compared against the Carnot limit, which is also plotted in Figure 3.5. It should be noted that fuel cells do not always have a higher efficiency limit than heat engines, and it can be seen from the figure that the theoretical maximum efficiency of a fuel cell is less than for the heat engine at temperatures above 700 °C[3].

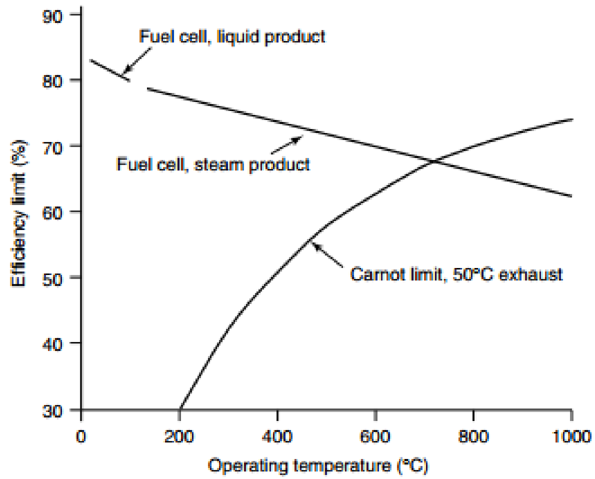


Figure 3.5: Maximum H_2 fuel cell efficiency at standard pressure, with reference to HHV. The Carnot cycle is shown for comparison, with a 50 °C exhaust temperature[3]

Based on this, it might seem unwise to operate fuel cells at temperatures above 700 °C. However, these problems are often outweighed by the benefits of operation at higher temperatures. Such advantages might be that the electrochemical reactions proceed more quickly, and thereby remove the need for catalysts. Another advantage is that the high temperature of the cell facilitates the extraction of hydrogen from other more available fuels, such as natural gas[3].

3.3.2 Efficiency and Fuel Cell Voltage

It can be seen from Table 3.1 that there is a clear connection between the maximum EMF for a fuel cell and its maximum efficiency, the higher the EMF the higher efficiency. This can be proved by application of Equation 3.30. If all the energy from the hydrogen fuel were transformed into electrical energy, the EMF or reversible open circuit voltage (OCV) of a hydrogen fuel cell would be as shown below[3].

$$E = \frac{-\triangle \overline{h}_f}{2F} \tag{3.30}$$

$$= 1.48 \text{ V if using the HHV}$$

$$\text{or} = 1.25 \text{ V if using the LHV}$$

The F is the Faraday constant or the charge of one mole of electrons, given the value 96485C.

Since 1J = 1C*1V, the constant is equal to 96.485 KJ/V*mole. The fuel cell voltage is represented by the E[3].

These voltages would be obtained from a 100% efficient system. The actual efficiency is the actual voltage(V_c) divided by the EMF value, depending on whether the LHV or HHV value is employed. The formula for the cell efficiency can be found in Equation 3.31[3].

$$Cell\, efficiency = \frac{V_c}{E} * 100\% \tag{3.31}$$

The cell efficiency in Equation 3.31 is the theoretical efficiency, and it is found that not all the fuel fed to a fuel cell can be used. Some of the fuel is passing through un-reacted. A fuel utilization coefficient may therefore be defined, and this is done in Equation 3.32.

$$\mu_f = \frac{mass\, of\, fuel\, reacted\, in\, cell}{mass\, of\, fuel\, input\, to\, cell} \tag{3.32}$$

The fuel utilization coefficient is equivalent to the ratio of fuel cell current and the current that would be obtained if all the fuel were reacted[3]. Thus, the fuel cell efficiency is given by:

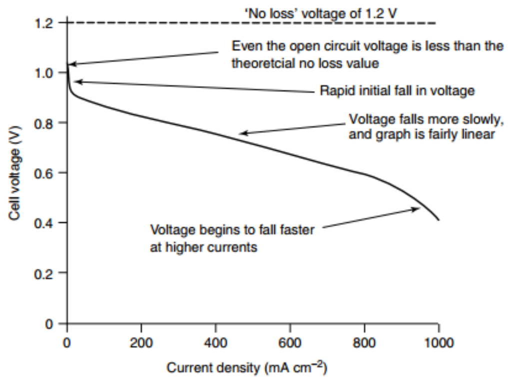
$$Efficiency, \eta = \mu_f \frac{V_c}{E} x100\% \tag{3.33}$$

0.95 is a good estimation for μ_f, allowing the efficiency of a fuel cell to be exactly estimated from the very simple measure of its voltage[3].

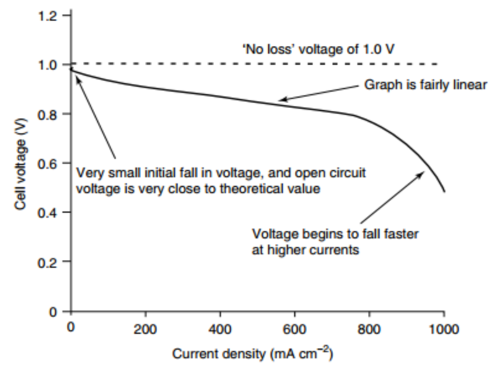
3.4 Operational Fuel Cell Voltages

The formula for the OCV of a hydrogen fuel cell, Equation 3.30, was presented in Chapter 3.3.2. By use of Table 3.1, it can be seen that the theoretical OCV for a cell operating below 100 °C is around 1.2 V. However, it is found that the voltage is less than this when the fuel cell is put to use. The performance of a single cell operating at low temperatures at normal air pressure is presented in Figure 3.6a, where the current density is plotted against cell voltage. It might be worth noticing that the OCV is less than the theoretical value of 1.2 V, and that there is a rapid initial fall in the voltage. The fall becomes more linearly after the rapid fall. The higher the current density, the more rapid fall in the voltage[3].

The theoretical OCV for a cell operating at temperatures above 600 °C is around 0.98 V. However, as in the case with cells operating at low temperatures, it is found that the voltage is a little less than this when put to use. The performance of a single cell operating at high temperatures at normal air pressure is presented in Figure 3.6b. It can be seen that the OCV is either equal or a little less than the theoretical voltage. The graph is more linear than for cells operating at low temperatures and the initial fall is almost non-existing. As with low temperature cells, the voltage falls rapidly with higher current density[3].



(a) Voltage for a typical low operating temperature fuel cell, at normal air pressure[3]



(b) Voltage for a typical high operating temperature fuel cell, at normal air pressure[3]

Figure 3.6: Illustration of the voltage for a low and high operating fuel cell, at normal air pressure.

By comparing Figure 3.6a and Figure 3.6b, it can be seen that although the reversible or "no loss" voltage is lower for the higher temperature cells, the operating voltage is generally higher. Since the voltage drop or irreversibilities are smaller. Four major irreversibilities contribute to the shape of the voltage/current density graphs in Figure 3.6a and 3.6b. These will be briefly outlined in the following[3].

The first is activation losses. These losses are due to the slowness of the reaction taking place at the electrodes. A part of the voltage generated is lost in driving the reaction transferring the electrons from the anode to the cathode. The second one is fuel cross-over and internal currents, where the losses are a result from the waste of fuel passing through the electrolyte. They are also caused, to a lesser extent, by electron conduction through the electrolyte. In theory, the electrolyte should only transport ions through the cell but a certain amount of fuel diffusion and electron flow is always possible. The fuel cross-over and internal currents have a market effect on the OCV for fuel cells with a low operating temperature. The third type are those related to ohmic losses. These losses are due to the electrical resistance of the electrodes, as well as the resistance to the flow of electrons through the material of the electrodes and the various interconnections. This type of voltage drop is proportional to the current[3]. The last one is mass transport or concentration losses. These losses are a result from change in concentration of the reactants at the surface of the electrodes when fuel is used. The concentration affects the voltage and this type of irreversibility may be called concentration loss. Since reduction in concentration is a result of a failure to transport sufficient reactant to the surface on the electrodes, these types of losses are also called mas transport loss[3].

3.5 Fuel Cell Stacking

As explained in Section 3.3, the voltage of a single fuel cell is around 0.7 V, which is quite small. In order to produce a useful voltage, several fuel cells have to be connected in series. Such a connection of fuel cells is called a "stack". The amount of current produced is proportional with the surface area of the membrane and the amount of fuel. Fuel cells are therefore easy to scale; the higher the number of fuel cells connected, the higher the voltage. In addition, the current produced depends on the area. The bigger the area, the more current generated[34].

The most obvious way of connecting the fuel cells are by connecting the edge of each anode to the cathode of the next cell, as presented in Figure 3.7. The main problem with this method is that electrons are forced to flow across the face of the electrode to the current collection point at the edge. Since the cells normally have a small operating voltage, even a small voltage drop is important and affects the output. This method is therefore not applied unless the current flows are very low and the electrode is a particularly good conductor[3].

A more suitable method of cell connection is to utilize a so called "bipolar plate", also called cell interconnects. The bipolar plate makes a connection all over the surface of one cathode and the anode in the neighboring cell. It also contributes to feed fuel gas to the anode and oxygen or air to the cathode. Channels are cut in them in order to make it possible for the gas to flow over the face of the electrodes. They are also made in such a way that they make a good electrical contact with the surface of each alternate electrode, but it is essential that the gas supplies are strictly separated. A simple design of a bipolar plate is presented in Figure 3.8a. As seen from the illustration, the bipolar plate has horizontal grooves on one side and vertical grooves on the other. The vertical grooves are used to feed hydrogen over

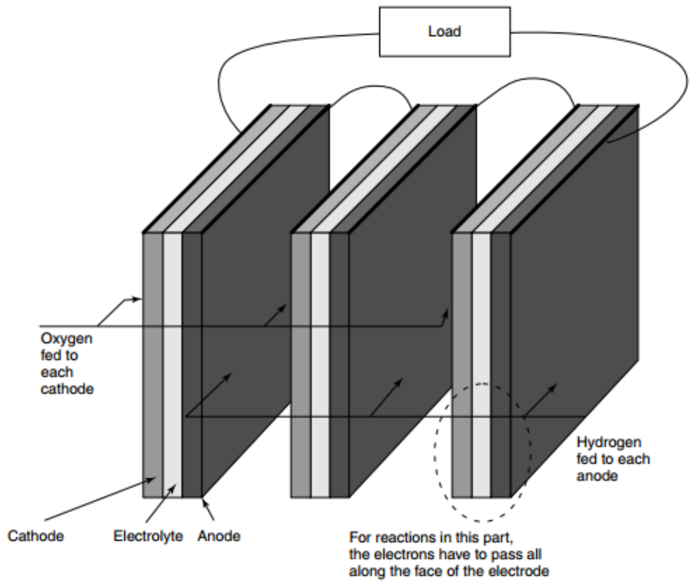
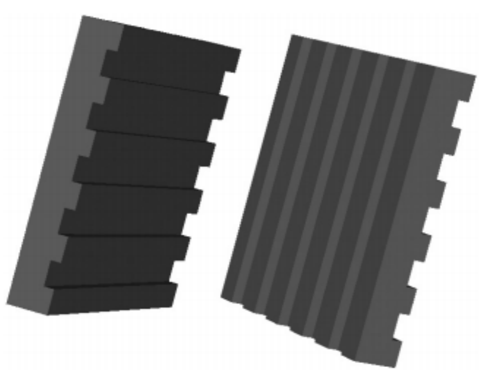


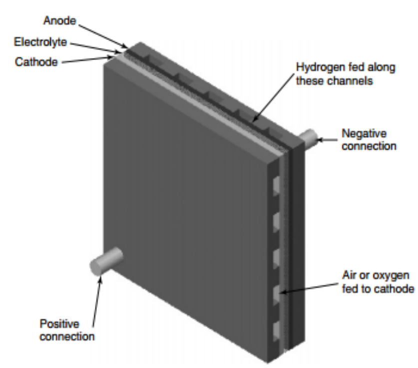
Figure 3.7: A simple edge connection of three-cells in series to create a stack[3]

the anodes, while the horizontal ones are used to feed oxygen or air to the cathodes[3].

The method of connecting end plates to a single cell is presented in Figure 3.8b. It can be seen that the fuel cell is "covered" by the bipolar plates, all over the electrode surface. Air or oxygen is feed to the cathode while fuel gas is feed to the anode[3].



(a) Illustration of two bipolar plates of simple design[3]



(b) Single cell, with end plates to serve as a means of feeding oxygen to the cathode and fuel gas to the anode[3]

Figure 3.8: Illustration of two bipolar plates and a single cell with bipolar plates.

Bipolar plates are applied between the different cells to connect several in series. The cells and the bipolar plates are then stacked together, as shown in Figure 3.9. This "stacking" results in a solid block in which the electric current passes effectively. The design of the fuel cell stack allows the current to move more or less straight through the cells rather than over the surface of each electrode. The whole structure is strong and robust, supporting the electrodes[3].

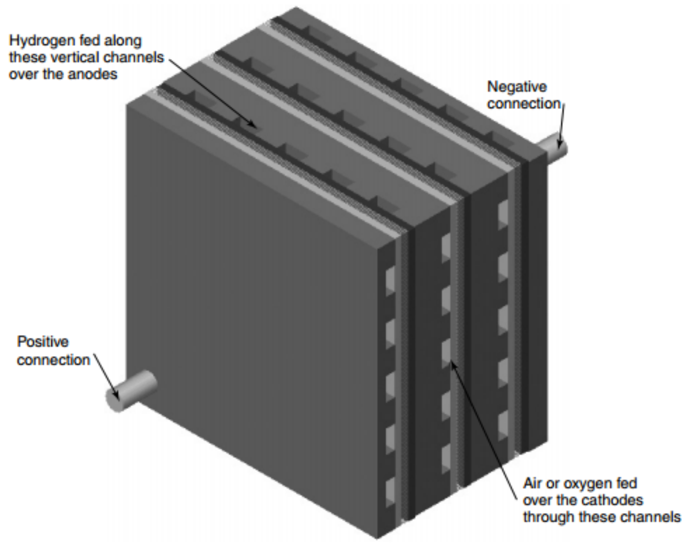
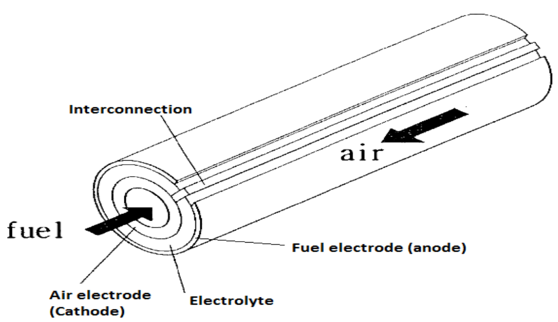


Figure 3.9: A three-cell stack illustrating how bipolar plates are used to connect the anode of one cell to the cathode of its neighbor cell[3]

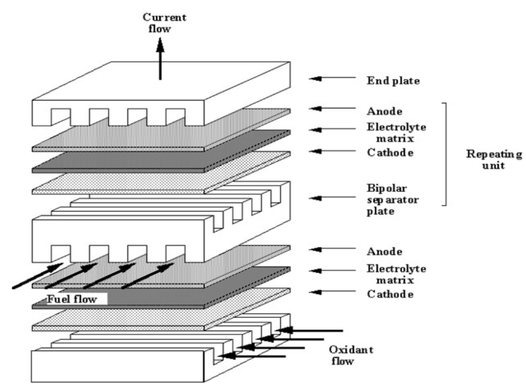
However, the method brings with it several inconveniences. The design of the bipolar plate is not simple, and several factors have to be considered. In order to optimize the electrical contact, the contact points should be as large as possible. One problem with this is that large contact points would mitigate the good flow over the electrodes. The contact points may be small, but they have to be frequent. This result in a more complex, difficult, and expensive manufacturing, in addition to a more fragile plate. Ideally, the bipolar plate should be as thin as possible in order to minimize electrical resistance and size of the fuel cell stack. However, this results in narrow gas channels making it more difficult to pump the gas around the cell. This should be done at a high rate, especially when air is utilized instead of oxygen at the cathode. In the case where fuel cells are operating at lower temperatures, the circulating air has to evaporate and carry away the product water. In addition, further channels through the bipolar plate is necessary in order to carry a cooling fluid[3].

Until now, bipolar stacking has been the most simple and conventional configuration applied in most types of fuel cell systems, especially for those with a low operating temperature. However, sealing issues due to large temperature gradients during operations is a major disadvantage with this type of system design for fuel cell systems with high operating temperature. This problem has driven the research toward alternative arrangements, leading to the development of a tubular design. The design is well suited for systems with high operating temperature due to its ability to minimize the number of seals in the fuel cell systems, and in that way alleviating problems due to different expansion coefficients[35].

When the tubular design is applied in fuel cell systems, the elements of the fuel cell assembly are arranged concentrically forming a hollow cylinder. An illustration of the tubular design can be seen in Figure 3.10a. The fuel is fed to the anode, either through the inside or along the outside of the cylinder. The oxygen or air is fed to the cathode. The tubular design can either be connected in series or in parallel. The cells are connected vertical, with other words in the height direction, when coupled in series. When coupled in parallel, the cells are connected horizontally in the same plane[35].



(a) Illustartion of the tubular design



(b) Illustration of planar stacking[36]

Figure 3.10: Illustration of two fuel cell stacking arrangement, the tubular design and the planar stacking

Planar stacking is another alternative to the bipolar arrangement. This type of stacking has several similarities with the bipolar stacking, but the cells are connected laterally rather than vertically in the planar stacking, as illustrated in Figure 3.10b. The air or oxygen is feed to the cathode while the fuel is fed to the anode. It is possible to stack as many cells as desired by repeating the part of the figure named "repeating unit". Several planar designs exist, such as the banded-membrane design and the flip-flop design. The anode of one cell is connected to the cathode of the adjacent cell across the band in the banded-membrane design, while there is an interconnection of unit cells on the same side of the band due to alternate anodes and cathodes. The main advantage with the planar stacking is a better volumetric packaging, at the sacrifice of increased resistance losses[35].

3.6 Fuel Types

The basic fuel for fuel cells are pure hydrogen or hydrogen-rich synthesis gas. Due to the lack of widely available alternative sources of hydrogen, the hydrogen has to be derived from hydrocarbon fuels. Depending on the applications, there is a wide range of conventional fuels, such as natural gas, light distillates, methanol, ethanol, to mention some[37].

3.6.1 Fossil Fuels

Three major forms of fossil fuels exist: oil, coal, and natural gas. Fossil fuels are fuels formed over a period of millions of years through anaerobic decomposition[37]. Fossil fuels range from volatile compounds with a high ratio between hydrogen and carbon, to nonvolatile materials with a lower proportion of hydrogen and a higher proportion of carbon. A fuel mixture usually contains a wide range of organic compounds, usually hydrocarbons. The specific mixture of hydrocarbons gives the fuel its characteristic properties, such as boiling point, melting point, density and viscosity[37].

The most common fossil fuel used in fuel cells is natural gas. Natural gas is predominantly methane, with small amounts of other hydrocarbons such as ethane, propane, and butane along with inert gasses such as CO_2, nitrogen, and helium[38]. It is a naturally occurring gaseous fossil fuel found in oil reservoirs, natural gas reservoirs, and coal beds. A gaseous fuel is a fuel which exists in the gaseous form and can be isolated from natural sources or by manufacture from other sources. Once the natural gas is brought from the underground, it is refined to remove impurities like water, other gasses, sand, and other compounds[39].

Burning fossil fuels produces CO_2, the most important greenhouse gas. One advantage with natural gas compared to other fossil fuels is that it burns more cleanly. It has a lower emission of sulfur, carbon, and nitrogen, and almost no ash particles left after burning. Use of this type of fuel may therefore contribute to reduce the environmental impact. As with other fuels, natural gas affects the environment when produced, stored, and transported. As mentioned earlier in this section, natural gas is mostly made up of methane, which can leak into the atmosphere from wells, storage tanks, and pipelines and harm the environment. When methane is leaked to the environment, a reaction with oxygen occurs and CO_2 and water are formed. Methane has a shorter lifetime than CO_2, but is more efficient in trapping heat in the atmosphere making it a good global-warming contributor. There is a high attention on emission of methane in the petroleum industry, not only because its climate impact but due to safety concerns. Methane is extremely flammable and when mixed with air it might form an explosive mixture[39].

Storage

Underground storage reservoir can be used to store natural gas. The three main types are depleted gas reservoir, aquifers, and salt caverns. Depleted reservoirs are formations which have already been tapped of all their recoverable natural gas, leaving an underground formation capable of holding natural gas. Aquifers are underground rock formations that act as natural water reservoirs, while salt caverns is underground salt formations. The concept of underground storage is injection of natural gas into the formation. The pressure is built up as more natural gas is added, creating a pressurized natural gas container. The higher the pressure in the storage facility, the more readily gas may be extracted. When the pressure is higher in the wellhead than in the storage facility, no pressure difference is left to push the natural gas out of the storage facility meaning that a certain amount of gas in every storage facilities will never be extracted[39].

Natural gas may also be stored as Liquefied natural gas (LNG). LNG is produced by removal of impurities and liquefying of the natural gas. The gas is cooled to a temperature of approximately $-163\,^{\circ}C$ at ambient pressure in the liquefaction process. The liquefied natural gas is stored in large cryogenic tanks, with a storage capacity of 100 000 m^3[28].

Transportation

Transportation of natural gas is closely linked to gas storage. Storage provides a viable option if gas is not required immediately. Natural gas is not suitable for pipeline transportation straight after extraction, and has to be processed in order to remove unwanted water vapor, solids, or hydrocarbons. With this accomplished, several options for transportation of natural gas may be applied. These include pipelines, or in different forms such as liquefied petroleum gas, compressed natural gas (CNG), and LNG. Transportation of natural gas as hydrate or CNG is believed feasible and cost-efficient compared with LNG, and when pipelines are not suitable[39].

A very conventional transportation method is pipelines. However, the transportation method is not very flexible since the gas will leave the facility and arrive at its one destination. The quantities of gas delivered is set by the choice of pipe diameter. Different measures, such as compressors, along the pipeline may be implemented to increase the maximum quantity achieved[39]. Double- hulled vessels are used to transport LNG from the facility to the end consumer. The LNG is typically off-loaded into well insulated storage tanks when the vessel arrives at the port. In order to convert the LNG back into its gas form, regasification is applied. After the regasification, the gas enters the domestic pipeline distribution system and is ultimately delivered to the end-user[39].

When natural gas is used as fuel in existing gas turbines offshore, or as fuel in future application of fuel cells, it is easily accessible on offshore installations extracting natural gas. The need for transportation is therefore removed, making the use of natural gas as a fuel more cost-efficient. The natural gas has to be processed before used, but the processing takes place at the installation.

3.6.2 Hydrogen

Several fuel cell technologies prefer hydrogen as fuel and direct hydrogen or reformed fuels are typically used. Hydrogen is called a secondary energy source since it does not occur naturally as a gaseous fuel, and has to be generated from other fossil fuels. Primary energy sources, such as coal gas made from coal and water, natural gas, and nuclear plant via water electrolysis are required to generate hydrogen. Ideally, hydrogen should be produced from water using renewable energy sources[40].

Extraction From Fossil Fuels

Several techniques can be applied to obtain hydrogen from primary energy sources. The most noteworthy one is extraction from fossil fuels. Other techniques are also applied, such as water electrolysis. This method is, however, employed on a much smaller scale due to the high cost[29]. The different ways which hydrogen may be supplied to fuel cells are presented in Figure 3.11.

Bio-Fuels

Biomass or biomatter is defined as natural organic material associated with living organisms. Due to its high energy content, biomass represents an important source of renewable fuels.

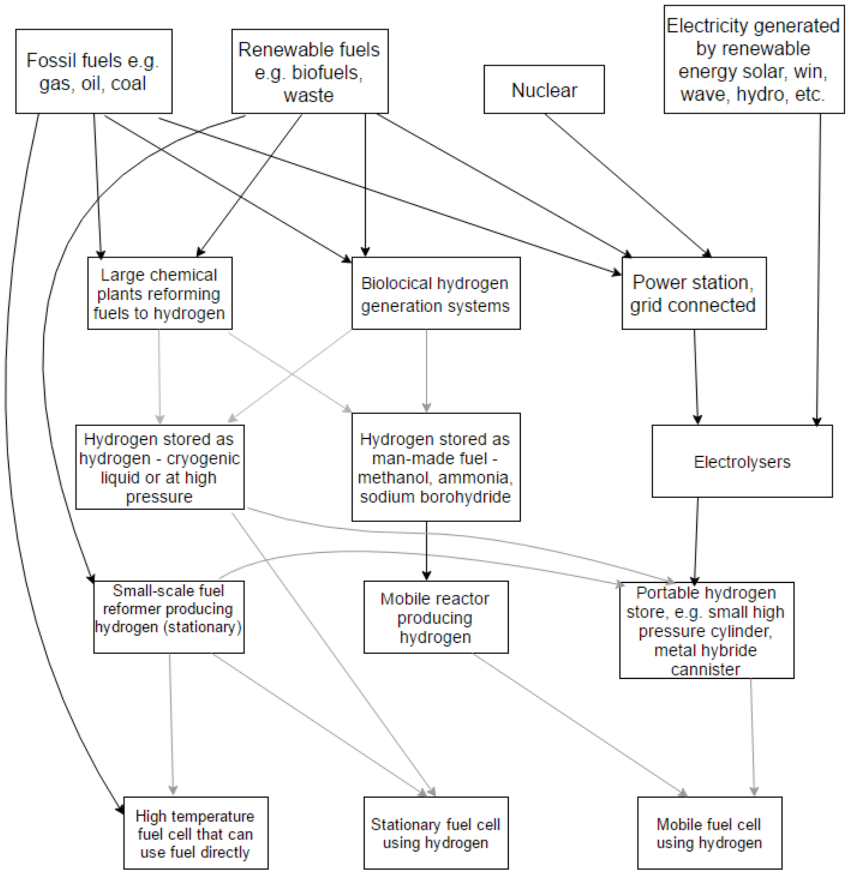


Figure 3.11: A presentation of the many different ways in which hydrogen can be supplied to fuel cells[3]

Bio-gas produced from biomass contains a mixture of methane, CO_2 and nitrogen, as well as a variety of other organic materials[3].

There exists a particular attraction for utilization of bio-gases in fuel cell systems. One characteristic for most bio-gases are their low heating value, making them unattractive for utilization in gas engines. However, this is not a problem for fuel cell systems, especially not for those operating at a high temperature such as the MCFC and SOFC. These fuel cell technologies are particularly well suited to handle fuel with a high concentration of carbon oxides[3]. Bio-liquids, such as ethanol and methanol, may also be attractive bio-fuels for some fuel cell systems due to their ease with which they can be reformed into hydrogen rich gas[3].

As mentioned, several techniques may be utilized in order to convert the primary energy sources into hydrogen. These techniques will be further discussed in the following subsections.

Extraction Methods

Extraction of hydrogen can be performed through application of various techniques, such as steam reforming, partial oxidation, a combination of both, or gasification. A promising way of producing hydrogen, which is not yet commercially used, is application of biological methods to break down the fuel - fossil or bio[3].

Steam reforming is a well-established technology, using natural gas as feedstock. A generic hydrocarbon (C_nH_m) reacts with water over a catalyst and produces hydrogen-rich gas and CO through a reforming process, as presented in Equation 3.34. The reaction is very endothermic, meaning that heat has to be supplied to drive the reaction forward[3]. The hydrogen-rich gas is further used by fuel cells. The CO produced in the reforming process reacts with water and produces CO_2 and hydrogen, as presented in Equation 3.35.

$$Reforming \qquad C_nH_m + nH_2O -> nCO + (\frac{m}{2} + n)H_2 \tag{3.34}$$

$$Shift\ \ reaction \qquad CO + H_2O -> CO_2 + H_2 \tag{3.35}$$

Steam reforming technology has the highest hydrogen concentration compared to other technologies based on fossil fuel. One limitations is that it does not offer fast start-up and dynamic response[29].

Both reactions in Equation 3.34 and 3.35 are reversible and equilibrium are normally reach over an active catalyst. The reactions occur at high temperatures, resulting in a high reaction rate[3]. As presented, the steam reforming process takes place in two steps, a reforming process and a shift reaction[29]. A combination of the two reactions result in an overall product gas consisting of a mixture of CO(15%), CO_2(10%) and hydrogen(75%), as well as unconverted fed gas. The actual composition of the product from the stem reforming process is governed by the outlet temperature of the reactor, the operating pressure, the composition of the fed gas, as well as the proportion of the steam fed to the reactor[3].

However, it should be noticed that not all the CO in the shift reaction presented in Equation 3.35 will be converted to CO_2. For fuel cell systems, such as the PEMFC and PAFC, which require low levels of CO, further processing is required. One solution is to lower the temperature of the shift reaction in Equation 3.35, since higher temperatures favor the production of CO. In order to utilize the gas composition in the PEMFC, even further CO removal is necessary. This is usually done in one of the three following ways; Selective oxidation reactor, by Methanation or by utilization of Palladium/platinum membranes. One common disadvantage for all three methods are the expenses related to them[3].

An alternative to steam reforming is partial oxidation. The method can be applied to convert hydrocarbons to hydrogen. This process may be performed within the fuel cell itself when operating at high temperatures. The partial oxidation is presented in Equation 3.36, while the shift reaction needed to convert the CO into CO_2 is presented in Equation 3.35. At high temperatures, typically between 1200 °C and 1500 °C, partial oxidation can be carried out without a catalyst. High-temperature partial oxidation is able to handle heavy petroleum fractions, such as diesel, logistic fuels and residual fractions. One problem with high-temperature partial oxidation is that it does not scale down well, and the reaction may be difficult to control. If the temperature is reduced, a catalyst is required. The process is then called a catalytic partial oxidation[3].

$$Partial\ \ oxidation \qquad C_nH_m + \frac{n}{2}O_2 -> nCO + \frac{m}{2}H_2 \tag{3.36}$$

However, it can be seen that the reforming process presented in Equation 3.34 produces more hydrogen per molecule of hydrocarbon than the partial oxidation reaction presented in Equation 3.36. Meaning that partial oxidation is less effective than steam reforming for fuel cell applications. About half of the fuel converted into hydrogen in Equation 3.36 is oxidized to provide heat for the endothermic reforming reaction. Unlike for the steam reforming reaction, no heat from the fuel cell may be utilized in the partial oxidation reaction and the net effect is a reduced overall system efficiency. On the other hand, a key advantage is that partial oxidation do not require steam, resulting in system simplicity[3].

Another commonly used term in fuel processing is autothermal reforming, describing a process where both steam and oxidant are fed with the fuel to a catalytic reactor. Both the endothermic steam reforming process, presented in Equation 3.34, and the partial oxidation process, presented in Equation 3.36, occur at the same time in a autothermal reforming process, removing the need for heat to be supplied or removed from the system[3].

The third technique is gasification, which breaks down coal or another carbon-based feedstock. This technique offers one of the most versatile and clean ways to convert coal into electricity, hydrogen, as well as other valuable energy products[28]. Gasification is a thermo-chemical process which instead of burning the coal, breaks it down into its basic chemical constituents. Coal is exposed to steam and carefully controlled amounts of air or oxygen under high temperatures and pressure. The molecules in coal are broken apart under the process, initiating a chemical reaction that typically produce a mixture of CO, hydrogen and other gaseous components[28]. The coal gasification reaction is presented in Equation 3.37. The amount of the product depends on type of coal, temperature, and pressure of the reaction, as well as the amount of steam and oxygen injected into the gasifier[3].

$$Gasification \qquad 3C + O_2 + H_2O -> 3CO + H_2 + other\ gaseous\ components \tag{3.37}$$

When the desired end-product is hydrogen, as when gasification is utilized to produce fuel for fuel cells, the CO in Equation 3.37 undergoes the shift reaction presented in Equation 3.35 where more hydrogen is produced.

Different coal gasification systems exist, and they may be classified as one of three basic types: (1) moving bed; (2) fluidized bed; and (3) entrained bed. Steam and either oxygen or air are used in all three types in order to partially oxidize coal into a gaseous product. The main differences between these three types are their operating temperature, the amount of oxidant and steam, and thereby the composition of the product gas. Common for all these gasifiers are that the heat required for gasification is provided by the partial oxidation of the coal. The product gas from the gasifiers contain contaminants, which have to be removed before utilized in fuel cell systems[3].

A common obstacle for all three techniques is the production of CO and CO_2, significant contributors to the environmental pollution. In order to eliminate the by-products, several techniques are being developed as potential solutions for CO_2 - free hydrogen production from fossil fuels[29]. However, these methods will not be further discussed here.

Hydrogen can also be obtained through water electrolysis. All the basic theory and the reactions taking place at the electrodes are the same as for a fuel cell, thus the reactions go the other way. At the negative electrode(cathode), electrons from the external circuit and hydrogen ions from the electrolyte reacts and hydrogen is formed. Water is oxidized into oxygen, negative electrons and positively charged ions at the positive electrode(anode). Both reactions are presented in Equation 3.38 and 3.39[3].

$$Reduction \qquad 4H^+ + 4e^- -> 2H_2 \tag{3.38}$$

$$Oxidation \qquad 2H_2O -> O_2 + 4H^+ + 4e^- \tag{3.39}$$

Steam will have to be supplied if high-temperature systems are applied, which is not so convenient as liquid water. Therefore, the only electrolytes in use are alkaline liquids and solid proton exchange membranes. Heat is added to the process by steam electrolysis, providing some of the energy needed to split water. The heat also contributes to make the process more efficient. Due to the use of electricity as input, the overall costs of producing hydrogen increases. Thus, the technique is only used for small scale production[29][38].

Storage

Hydrogen may be stored in several ways, both as hydrogen and by use of chemical hydrogen carriers. The different storage options will be further discussed in the following. However, several difficulties are associated with storage of hydrogen. Even though hydrogen has one of the highest specific energies, its density is very low. These properties make it difficult to get a large mass of hydrogen into a small space, and high pressure has to be applied. Hydrogen is also difficult to liquefy[3].

When hydrogen is stored as hydrogen, the methods described below are applied. These four methods will be briefly explained in the following [3].

- Compression in gas cylinders
- Storage as a cryogenic liquid
- Storage in a metal absorber - as a reversible metal hydride
- Storage in carbon nanofibres

The most technically straightforward method and the most widely used one for small amounts of hydrogen is to store the gas in pressurized cylinders. Since hydrogen is a small molecule, it is able to diffuse into materials that are impermeable to other gases, which may affect the mechanical performance of a material in many ways. Safety problems related to storage of hydrogen under high pressure have to be taken into consideration. A leakage from a cylinder could generate large forces as the gas is propelled out. However, this method is widely and safely used, despite these problems and brings with it several advantages, such as simplicity, indefinite storage time, as well as no purity limits on the hydrogen. The method is most widely used when the demand for hydrogen is variable and not too high[3].

In order to store large quantities of hydrogen, storage of hydrogen as a liquid is most widely used. The gas is cooled to its liquid state, and are called a cryogenic liquid. The hydrogen is stored in containers, which are large and strongly reinforced vacuum flask. The hydrogen will evaporate after a while and the pressure in the container are normally kept around three bars. The most important thing when the hydrogen is being filled into, or withdrawn, from the container is to prevent air into the system. A mixture of air and hydrogen, as mentioned earlier, will result in an explosive mixture. One problem is that the liquefication process is very energy-intensive. The gas is first compressed, and then cooled before high pressure is used to cool it even further by expanding it through a turbine[3].

Hydrogen may also be stored in metal hybrids. Certain metals, such as mixtures of titanium, iron, nickel, can react with hydrogen through a controlled reversible reaction in order to form a metal hybrid. This reversible reaction is presented in Equation 3.40, where M represents the metal in the reaction[3].

$$M + H_2 <-> MH_2 \tag{3.40}$$

The reaction is mildly exothermic, meaning that small amounts of heat has to be supplied in order to release the hydrogen. Hydrogen is supplied to the metal alloy in a container at a pressure little above atmospheric, and the metal hydride is formed. The main advantage with this method is its safety since the hydrogen is not stored at a significant pressure and can therefore not discharge rapidly and dangerously. The method has a wide range of applications when small amounts of hydrogen are stored, and where space is limited. The disadvantages with the method are particularly noticeable when large quantities of hydrogen are being stored[3].

Hydrogen cannot yet be stored in carbon nanofibers, but several experiments are giving the industry grounds for hope that the technique will be used in hydrogen storage systems in the future. Three types of carbon nanofibers are being investigated for hydrogen storage, and those are graphitic nanofibers, single-walled carbon nanotubes and multi-walled carbon nanotubes[3].

None of the methods for storage of hydrogen is entirely satisfactory and other approaches being developed use chemical hydrogen carriers. Many compounds which can be manufactured hold, but they have to pass three tests in order to be useful: The compounds must easily give up their hydrogen, the manufacturing process has to be simple and utilize little energy, and they must be safe to handle[3].

Transportation

The transportation methods may be the same for hydrogen as for natural gas, either through pipelines or by use of tankers, depending on the quantity and distance. A major disadvantage with hydrogen is its low volume density. One kilo hydrogen has a volume of 11 000 liter at atmospheric pressure and temperature, while the same energy amount in gasoline has a volume of 3.8 liter. The volumetric density has to be increased before hydrogen can be transported, either by compression or cool-down[41].

To avoid the need for transportation the hydrogen production may be centralized. The energy would be transported in the form of electricity and the hydrogen are produced locally in an electrolysis tube. The electrolysis tube is relatively easy to scale and may therefore be built in a size suitable for the consumer. Decentralized hydrogen production from fossil fuels may be an alternative option according to transportation. Natural gas and oil have an already existing infrastructure and are therefore easier to transport to the end user than hydrogen. However, a reformer is required in order to convert the fuel to hydrogen[41].

3.7 Other Components in a Fuel Cell System

Different fuel cell systems may have different design, depending upon fuel cell technology and application and the required components in a fuel cell systems may vary. However, a number of basic components are common for many fuel cell systems. Such components may be a fuel cell stack, a fuel processor, power conditioners, air compressors and humidifiers[28].

The core of a fuel cell stack is the electrodes, electrolyte and the bipolar plate, or another arrangement for fuel cell stacking. However, other components make up a larger proportion of the engineering of the fuel cell system, often called the balance of plant. The fuel cell stack often appears to be a small part of the whole system, especially when high-temperature fuel cells, such as SOFC and MCFC, are applied in CHP systems[3].

For all fuel cells, except the smallest, air and fuel need to be circulated through the fuel cell stack by use of pumps or blowers. Compressors are often used, sometimes accompanied by the use of intercoolers. The compressors are used to increase the pressure of the reactant gases in order to improve the fuel cell performance, while the intercoolers are used to cool the fluid or gas[28]. DC is produced by the fuel cell stack, which rarely are suitable for direct connection to an electrical load. If the fuel cell is used to power equipment requiring alternating current (AC), the DC will have to be converted to AC[28]. Some kind of power condition is therefore necessary, such as a voltage regulator and a DC/AC inverter, which will be further discussed in Section 5.4.4. A vital part of a fuel cell system is electric motors. They are used to drive pumps, blowers, and compressors, to circulate reactant gases or to cool fluids. These motors are in use at all times and it is therefore desirable that they have a high efficiency, availability, reliability and thereby a low downtime[3].

A critical problem for fuel cells are the supply and storage of hydrogen. Fuel Cell storage will therefore be a part of many systems. If the fuel cell utilizes some other type of fuel, such as natural gas, some form of fuel processing system will be needed[3].

Other components needed in a fuel cell system are control valves, pressure regulators and a controller. The controller is used to coordinated the different parts of the system, such as start-up and shutdown. This is a complex process, especially for high-temperature fuel cells. A cooling system is also needed, except for the smallest fuel cells. This is usually called a heat exchanger in the case of CHP systems, due to the idea to use the heat in other applications. In case of high-temperature fuel cells, some of the heat generated will be used in fuel and/or air pre-heaters. In cases where the PEMFC is applied, a need to humidify one or both reactant gases exists[3]. Humidifiers normally consist of a thin membrane. Dry inlet air is flowing on one side of the humidifier, while wet exhaust air is flowing on the other side. The PEMFC, for instance, is kept well hydrated by utilization of the water produced by the fuel cell[28].

3.8 Comparison of Different Fuel Cell Technologies

As mentioned in Section 3.2, the main differences between fuel cells are their operating temperature and choice of electrolyte. There are several advantages and disadvantages related to the operating temperature. Fuel cells with low operating temperature have a short start-up time. The disadvantages with these types of fuel cells are that they often require a catalyst, and often a platinum catalyst. These are expensive and consequently increase the cost. Many of these fuel cells are also sensitive to CO or CO_2. On the other hand, fuel cells with high operating temperature requires a long start-up. The advantages with this type of fuel cells are their ability to handle CO and CO_2, and their non-existing need for a catalyst. Their working efficiency is normally higher due to a higher reaction rate.

The majority of the fuel cells have a solid electrolyte, the exception is the PAFC, which uses liquid phosphoric acid. A comparison between the six major groups of fuel cells regarding their type of electrolyte, mobile ion, operating temperature, and type of fuel are presented in Table 3.2.

The different technologies have different efficiency and applications and it is necessary to clarify the technology best suited to a specific application. Since different technologies produce different range of power, from 1kW to 10 MW, they can be employed in almost any application requiring power[10]. The operating temperature is a main contributor regarding application. The PEMFCs, DMFCs, and AFCs operate at a lower temperature and are generating smaller amounts of power, hence, they are best suited for transportation and small utilities. The PAFCs operate at higher temperatures, and are mainly developed for medium-scale power applications. The MCFCs and SOFCs are operating at high-temperatures and generate a higher amount of power, and are designed for large power applications. Generally, higher power output can be achieved at higher operating temperatures[29]. A comparison between the different fuel cell technologies regarding efficiency, application, generated power and by-products is presented in Table 3.3.

Table 3.2: Characteristics of different fuel cell technologies

Fuel cell type	**Electrolyte**	**Mobile ion**	**Operating temperature [°C]**	**Fuel type**
Alkaline (AFC)	Potassium hydroxide (KOH)	OH^-	25 - 250	Pure hydrogen, or Hydrazine
Direct methanol (DMFC)	Polymer	H^+	60 - 130	Liquid methanol
Phosphoric acid (PAFC)	Liquid phosphoric acid (H_3PO_4)	H^+	150 - 220	Hydrogen from hydrocarbons and alcohol
Proton exchange membrane (PEMFC)	Solid polymer	H^+	60 - 100	Pure hydrogen or hydrogen from hydrocarbons or methanol
Molten carbonate (MCFC)	Molten carbonate salt mixture	CO_3^{2-}	>600	Hydrogen, CO, natural gas, propane, or marine diesel
Solid oxide (SOFC)	Solid ceramic (stabilises zirconia)	O^{2-}	800 - 1000	Hydrogen, hydrocarbon, or natural gas

Table 3.3: Efficiency, application, power generation and by-product(s) for the different fuel cell technologies

Fuel cell type	**Efficiency [%]**	**Application**	**Power generated [kW]**	**By-product(s)**
Alkaline (AFC)	60 - 70	Transportation	20	H_2O
Direct methanol (DMFC)	20 - 30	Application with modest power equipment	0.025 - 5	CO_2 and H_2O
Phosphoric acid (PAFC)	40	Stationary and heat applications	100 - 400	H_2O
Proton exchange membrane (PEMFC)	40 - 45	Portable and stationary applications	250	H_2O
Molten carbonate (MCFC)	50 - 60	Medium and large power applications	1000	CO_2 and H_2O
Solid oxide (SOFC)	50 - 60	Medium and large power applications	>1000	H_2O

3.9 Maintenance

Maintenance is defined as "the combination of all technical and corresponding administrative actions, including supervision actions, intended to retain an entity in, or restore it to, a state in which it can perform its required function"[4]. Maintenance is generally performed in order to reduce the risk and ensure safety for people, the environment and assets, to maintain the component or system availability, and to ensure that the system or component is efficient. The higher the availability for the component or system, the higher reliability, hence lower downtime. Availability is defined as the probability that the item, components, or system is functioning at time t[4]. The reliability is defined as "the ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time"[4].

Maintenance is classified as preventive or corrective, where preventive maintenance is planned maintenance performed on a functioning system or component in order to prevent future failures or to reduce the probability for a failure on the item. Corrective maintenance, on the other hand, is performed when the component or system have failed in order to bring the item back to a functioning state[4]. If required maintenance is not performed, it may result in an undesired stop in the production. The time used for corrective maintenance and the start-up time results in a production loss and thereby loss of income.

The failure rate of an item describes the number of failures per time unit. Figure 3.12 may be interpreted as an estimate for the failure rate function of an item, and are usually called a bathtub curve due to its characteristic shape. The failure rate for an item is often high in the initial phase, due to undiscovered defects which will be discovered when the items are activated. This period is often called the infant mortality. After this period, the failure rate often stabilizes at a level where it remains for a certain amount of time until the failure rate starts to increase. It can be seen from Figure 3.12 that the lifetime of an item may be divided into three intervals: the burn-in period, the useful life period and the wear-out period[4].

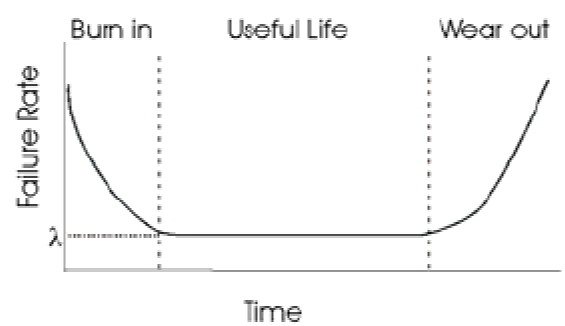


Figure 3.12: The bathtub curve[4]

The working principle of fuel cells are fully described in Section 3.1. The only moving parts in a fuel cell are the once associated with the ancillary systems. Ancillaries can include thermal, heat, and air management systems. Such systems require pumps and compressors, which requires different types of maintenance tasks. In addition, these systems may also generate some noise[42].

However, fuel cells have considerably less moving parts than a internal combustion engine (ICE), and the requirement for maintenance is therefore lower. Routine maintenance may be completed at scheduled intervals, typically quarterly or annually. Periodic cleaning of the air intake and replacement of filters is required when the fuel cell systems performance becomes unacceptably low. Periodic replacement of filters are normally performed at intervals of 2000 to 4000 hours[43]. Fuel cells in fuel cell systems are delivered in modules and maintenance is performed by replacing the module requiring maintenance with a spare one.

Several factors influence the fuel cell operation and maintenance costs, such as type of fuel cell, capacity, and the equipment's maturity. Some of the typical costs which need to be included are maintenance labor, ancillary replacement parts and material, and major overhauls. Major overhauls include shift catalyst replacement, which normally has to be performed every three to five years, reformer catalyst replacement, performed every five years, and stack replacement, performed every five to ten years[43].

3.9.1 Degradation

It is rather difficult to specify the lifetime of a fuel cell. Since a fuel cell's performance gradually deteriorates, a standard engineering measure such as mean time between failure (MTBF) do not apply well. The cells power also drops steadily with time as the electrolyte and electrodes age. Thus, the lifetime of a fuel cell is normally over when it no longer can deliver the rated power, e.g. when a 20kW fuel cell are unable to deliver 20kW[3]. However, a degradation rate of 2 - $10\mu V h^{-1}$ is normally accepted for most applications, and a proven lifetime of 40 000h for stationary applications and 5000h for application in transportation is the target[44].

Several degradation mechanisms exist, some are more common for a specific fuel cell technology while others are more general. These mechanisms will be explained in the following. The first one is membrane degradation mechanisms, a typical degradation mechanism for PEMFC. This type of degradation may be separated into three categories: mechanical, thermal, and chemical/electrochemical. The mechanical degradation results in early life failure due to perforations, cracks, tears, or pinholes caused by congenital membrane defects or improper MEA fabrication processes. Local pinholes and perforations may lead to a physical breach of the membrane, resulting in cross-over of reactant gasses. Hence, the direct combustion of the oxidant and reductant occurs on the surface of the catalyst and thereby generate local hot-points. This will accelerate the degradation of the membrane, as well as the entire cell[44].

Thermal degradation, on the other hand, is a result of overheating. The most favorable working temperature for PEMFCs is between 60 °C and 100 °C. The membrane may be subjected to critical breakdowns at higher temperatures, resulting in a degradation of the membrane. The last category, the chemical/electrochemical degradation of the membrane, may be attributed to cross-over. A combustion between oxygen and hydrogen may result in pinholes in the membrane which are destroying the MEA and causing catastrophic problems. Even more severely, the chemical reactions on the electrodes catalysts may produce peroxide and hydroperoxide radicals, which often are responsible for chemical attack on the membrane and catalysts[44].

Several mitigation strategies may be implemented in order to reduce membrane degradation. The MEA and flow field structure have to be carefully designed to avoid drying of the membrane in order to prevent mechanical failure of the membrane. In order to prevent chemical and electrochemical degradation of the membrane, membranes that are chemically stable against peroxy radicals has to be developed. Several solutions are discussed. One solution may be to develop membranes with higher chemical stability, another one is to modify the structure of the membrane, while a third solution may be to redesign the MEA[44].

Electrocatalyst and catalyst layer degradation may be a problem for fuel cells operating at low and medium temperatures, such as PEMFC, AFC, DMFC and PAFC. The catalyst may be coarsened due to movements in its particles which will result in a decrease of the catalytic active surface area[44]. This type of degradation may also be a problem for fuel cells intolerant to CO_2 or CO since the CO and CO_2 may get attached to the catalyst and thereby reduce the performance. The absorption of CO and CO_2 can be reduced by increasing the tolerance temperature of the electrodes[10].

Bipolar degradation is another degradation mechanism. Bipolar plates are a multifunctional component in a fuel cell stack. They act as a separator between the fuel, oxidant gases and coolant, they conduct current between cells, and facilitate water and thermal management through the cell. High corrosion resistance and mechanical strength, low interfacial contact resistance, high contact angle, as well as no brittleness are the ideal characteristics of a material utilized in bipolar plates. Graphite composite is currently utilized as material for bipolar plates due to its relatively high corrosion resistance. Several other advantages, such as lower interfacial contact resistance and higher electrical conductivity, may be obtained by increasing the carbon to polymer ration in the graphite composite. However, a higher carbon ratio will result in a higher brittleness as well as an elevation of the volumetric power density. Metals are another material which may be suitable for utilization in bipolar plates.

They provide a higher mechanical strength, better durability to vibrations and shocks, as well as a higher flexibility in fabrication. The main challenge is that metals resistant to corrosion develop a passive oxide layer on the surface, leading to a high interfacial contact resistance. The high interfacial contact resistance leads to a conversion of a considerable amount of electric energy into heat, causing a reduction of the overall efficiency of the fuel cell system[45].

Chapter 4

Applications

4.1 Background History

Fuel cell technology is an important aid when it comes to reducing pollution from combustion engines. Since fuel cells run on hydrogen or natural gas, most of the environmental impact depends largely on how the hydrogen or other fuel inputs have been manufactured[46]. For the last 20 years, application of fuel cells has been more common. Fuel cells are mostly used to replace ICE and to provide power in stationary and portable power applications.

Even though the application of fuel cells has been more common for the last 20 years, the development and use extend more than two centuries back[13].

There are some controversies concerning who discovered the principles of fuel cells around year 1838. A British scientist named Sir Anthony Carlisle discovered the decomposition of water into hydrogen and oxygen by using electricity in 1800[13]. This is the inverse process to the one occurring in the hydrogen fuel cell. However, the Swiss chemist Christian Friedrich Schönbein was the first one to carry out systematic scientific investigation on fuel cells. The English scientist Sir William Robert Grove developed the first true fuel cell[46]. Grove discovered that if two platinum electrodes were immersed on one end of a solution of sulphuric acid and the other two ends were separately sealed in containers of oxygen and hydrogen, a constant current was found to be flowing between the electrodes. He then discovered that the voltage drops became higher when pairs of electrodes were connected in series. He called this a gas battery, i.e. the first fuel cell[13].

The term "fuel cell" was not coined until 1889 when the chemists Ludwig Mond and Charles

Langer attempted to build the first practical device using air and industrial coal gas. The interaction of various components of a fuel cell: electrodes, electrolyte, oxidizing and reducing agents, anions and cations were discovered through experiments in 1893 by Friedrich Wilhelm Ostwald[13].

In the late nineteenth and early twentieth century the Swiss scientist Emil Baur and William W. Jacques were seen as the leading researchers in the field of fuel cells. They started a decades-long period of innovative research on fuel cells using a variety of liquid and solid electrolytes. The first MCFC was built in 1921 by Baur, while Jacques was the first to build high power systems. One high power system consisted of a 1.5kW fuel cell with a stack of 100 tubular units, while another system consisted of a fuel cell of 30 kW[46].

Thomas Francis Bacon used this discovery and developed it into the first fuel cell with practical use made of oxygen and hydrogen in 1933. After working on the device for three decades, he developed an effective working model, called the "Bacon cell". The fuel cell converted air and hydrogen directly into electricity through electrochemical processes. Different versions of the "Bacon cell" became benchmarks for the fuel cell technology[46].

The following two decades produced important advances for the technology. The first SOFC came in 1937, while an improved MCFC was produced in 1946. The first AFC followed in 1954, while the PEMFC was produced a few years later, in 1958[46].

One of the first practical application of fuel cells was when the United States Navy used fuel cells in their Electrolytic Oxygen generator systems. These systems provided breathing oxygen for the crew of its newly developed class of nuclear submarines in 1956[46]. Several other applications followed in the subsequent years. A 20-horsepower AFC-powered tractor was demonstrated in 1959, while a developed version of the bacon cell was used in a fuel cell power plant for the Apollo Command and Service Module. The firs fuel cell powered car was developed in 1970. The fuel cell was installed in the trunk of the car while the hydrogen tanks were put on the roof, leaving room for four passengers[46].

The expansion of fuel cells was rapid in the 1990s. The first commercial fuel cell power plant was manufactured by UTC power in 1991, consisting of a 200 kW PAFC system. The launch of the first fuel cell powered bus came in Canada in 1993, while a couple of car companies launched the first prototype fuel cell-powered passenger car in 1994. The first fuel cell car approved for commercial use came in 2002, while the first manned airplane powered by fuel cells was demonstrated in 2008 by the Boeing Research & Technology Europe[46].

The development of fuel cells since 1970 has been characterized by aspects such as suppression of diffusion limitations in the electrodes to obtain a greater area of action, suppression of the costs of the catalysts, an increased performance, and a longer lifetime. There has also been a widespread use of petroleum fuels, using the corresponding fuel-reforming unit[13]. Hence the efficiency of the different fuel cell technologies has increased. The efficiency of the PAFC may reach 45%, the SOFC 50%, while the MCFCs may have an efficiency as high as 60%. The high efficiency combined with the low emission of harmful greenhouse gasses make fuel cells strong candidates for a revolution in the field of electric power generation[13].

4.2 Prevalence and Use Today

Many manufactures are working on the application of the fuel cell technology, where the most widespread use is in aircrafts, buses, cars, home power generation, and large power generation.

For the fuel cell industry to keep growing an even more robust infrastructure has to be established. The vehicles using fuel cells for power generation have to be able to refill hydrogen whenever needed, raising the need for more hydrogen refuelling stations(HRS)[47]. One of the projects working on the improvement is The National Innovation Program (NIP II) for Hydrogen and Fuel Cell Technology in Germany. NIP II has road transport, as well as hydrogen infrastructure, as main focus. The goal of the project is to support deployment of fuel cell and hydrogen technology in large numbers[47].

The fuel cell technology may be utilized in several different applications, such as portable, stationary and transport. Portable fuel cells encompass those which are designed to be moved, including auxiliary power units. Stationary power fuel cells are characterized as units designed to provide power to a fixed location, while fuel cells applied in transportation are used to provide either primary propulsion or range-extending capability for vehicles[47].

Fuel cell cars are in many senses the bellwether of the industry[47]. The technology has to compete with several competitors, such as the ICEs, in order to have the most cost-effective, ubiquitous and reliable transport. Several manufactures used fuel cell vehicle for testing and research development in the beginning, however, in 2007 Honda presented the first fuel cell vehicle platform – exclusive in the world manufactured in series[13]. The application of fuel cell for transportation has been increasingly widespread, and Hyundai first small-series production vehicles became available in 2013. Honda followed with their Clarity Fuel Cell in 2016, while Daimler has announced its GLC SUV for next year[47]. The GLC SUV is not only a fuel cell but also a plug-in hybrid. Meaning that the car can rely on the all-electric range and recharge at existing sockets, while for long trips only a limited hydrogen infrastructure is required[47].

Nissan announced the most unexpected fuel cell car. They announced a Ceres Power bioethanol SOFC system in a so-called e-Bio vehicle for testing in Brazil, allegedly to overcome infrastructure problems related to hydrogen while moving towards sustainable mobility[47]. Several other announcements came on many other cars during the year, indicating that fuel cell cars will be launched by several different manufactures in the coming years.

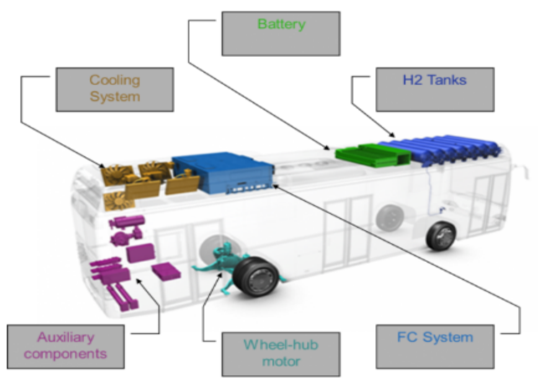
Use of fuel cell cars have been more relevant after the realization of the Paris agreement, and both local and national government have had a growing interest for clean technology solutions. An example is the fleet of hydrogen fuel cell taxis in Paris. The fleet started up with five Hyundai taxis in 2015, and another 60 will arrive in the coming months. The Sociètè du Taxi Electrique Parisien intends to expand the fleet to several hundred vehicles over the next five years[47].

Fuel cells have long been considered suitable for buses, especially those operating in environmentally sensitive urban areas. Local air quality is a major problem in big cities, and diesel buses are definitely a part of the problem. One of the advantages with fuel cell buses are their possibility for zero emission as well as their ability to be highly efficient and assist in reducing noise containment in cities[47]. It is predicted that the bus fleet will change dramatically from now on to 2030. The prediction states that conventional diesel buses will most likely not be allowed in countries and cities with progressive environmental policies[47]. If the prediction is correct, existing buses have to be modified.

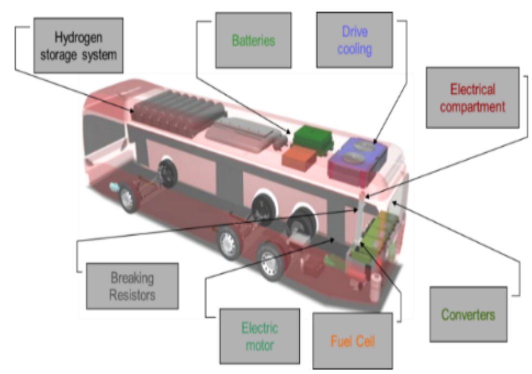
The biggest fleet has been announced in China, which seems considerably more serious about fuel cells than they did a few years ago. Both national and local government support for buses, vans and refueling stations has increased dramatically. They have announced a major government support scheme for New Energy Vehicles, with strong support for fuel cell buses in particular. The national government also want to convince the local bus makers into making fuel cell buses. Thus, hundreds of buses are scheduled to be coming into service starting from 2016[47].

European countries are also investigating in the fuel cell technology. The Clean Hydrogen in European Cities (CHIC) project is a major European project deploying a fleet of fuel cell electric buses (FCEB) and associated HRSs in cities across Europe, and at one site in Canada[48]. The project is funded through the Fuel cells and Hydrogen Joint Undertaking (FCH JU), and has been a six-year flagship project from 2010 to late December 2015[49]. CHIC managed to co-found a total of 26 fuel cell buses in Europe, with five in Switzerland, eight in Italy, eight in London, and five in Norway. Whistler in Canada deployed 20 fuel cell buses. The buses had a power output fluctuating between 75 kW and 150 kW. In addition to the deployment of 56 fuel cell buses nine HRS were installed. The aim of the CHIC project was to further enhance fuel cell bus technology and to offer a functional solution for European cities to decarbonize their fleet[49].

Two different arrangements in a FCEB is illustrated in Figure 4.1a and 4.1b. The fuel cell stack may either be placed on the roof of the bus or in the front. In addition to a fuel cell system, a hydrogen storage tank and a battery is necessary[48].



(a) Possible arrangement in FCEB[48]



(b) Another arrangement in FCEB[48]

Figure 4.1: Illustration of two different FCEBs

Battery electric vehicles (BEV) are getting increasingly more common and are suitable for many types of journeys. The major problem is the required battery capacity, the bigger the vessel the larger battery capacity needed and the harder it gets to deliver against expectations. Satisfying the required battery capacity for buses are hard, and even harder for trucks. Despite this, the Co-op chain of supermarkets in Switzerland has launched the world's first 34t fuel cell truck. The truck consists of a 100kW stack, while the electric motor provides for 250kW. Tanks of 700 bar are stacked behind the cab, giving the truck 32 kg of usable hydrogen and a range of approximately 400km[47].

Fuel cells are also being demonstrated in light rail applications and locomotives. The French company Alstom are testing fuel cell systems in light trains in Germany, and the test will continue through 2017. Alstom expects firm order for 40-70 trains in the coming months[47]. The fuel cell train sets have the same shape and drive equipment as the conventional diesel trains. The two units will directly replace the two diesel units to provide a real-world comparison of performance. The hydrogen tanks, as well as the fuel cells, will be mounted on the roofs. The tanks will be able to carry 94 kg hydrogen each, giving the train a reach of 700 km[50]. However, the most successful fuel cell vehicle up to date is the forklifts. More than 10 000 forklifts are currently in daily use[47]. The fuel cell technology is well suited for forklifts due to their continuous supply of power, which is a major advantage for machines or vehicles with constant stops and starts[13].

Fuel cells are also applied in other types of vehicles, such as motorcycles, electrical conveyor machinery, and some air crafts. The main reason is their ability to reduce the emission and fuel consumption, while increasing the energy efficiency. They also ensure a continuous supply of power. Use of fuel cells is possible in portable applications due to their ability to provide electrical power in places where the grid connection is not available and at the same time reduce emission and noise[13].

Fuel cells are also used in small- and micro applications, such as telecommunication, Internet, mobile phones, and laptops. Fuel cells used in laptops and mobile phones give a higher battery life, and increases the recharging of the equipment[51]. Fuel cell system designed for military use are designed to provide benefits in terms of weight, flexibility, power, lower noise, and heat signatures compared to batteries and generators[47].

However, fuel cells can be applied in larger scale such as in homes, hospitals, police stations, and banks. The fuel cell system is connected to the grid to provide additional electrical power to the plant, or as an independent system of the grid to generate electricity in remote or isolated areas[13].

One of the most, if not, successful fuel cell commercialization program in the world is Japan's ENE-FARM. The project has supported the deployment of more than 120 000 residential fuel cell units[52]. New models which were smaller, more efficient, cheaper, and more easily installed came into the market in 2015. The models have been developed for apartment buildings and homes. The new units are able to operate independently if the power grid fails. Several companies have participated in this project, but the main participants today are Panasonic and Toshiba, offering PEMFC units, while Aisin Seiki offers SOFC units. The

PEMFC units applied are durable, achieving greater than 60 000 hours while cycling daily. The power output from the fuel cells fluctuate between 0.3 kW to 1 kW[53].

Germany had a similar project as the ENE-FARM in Japan, namely the Callux project. This project was a demonstration project used to demonstrate fuel cell heating appliances for home use. The project resulted in installation of almost 500 systems in single - family homes between 2008 and 2011[54]. The project utilizes SOFCs and PEMFCs with a power output between 0.25 - 5 kW. The project has been successfully completed, and will end with the commercial introduction of the innovative systems[55].

The Gyeonggi Green Energy Facility, located in Hwasung city, South Korea is the world's largest fuel cell park. The park consists of 21 2.8MW hydrogen fuel cells, generating a total of 59MW. The fuel cells run on natural gas converted to hydrogen. The fuel cells also provide heat to the local district heating system. The construction of the park began in late 2012 and was completed early in 2014[56].

Seoul City continues to adapt new and renewable power generations in order to reduce their dependence on nuclear power. The Godeok Rolling Stock Management Office fuel cell park was operational by the end of 2014. The park consists of seven fuel cell power plants, each providing 2.8MW of power. The power output is sufficient to power approximately 45 000 households in South Korea[57]. This facility is the first of several fuel cell projects planned to embrace a total of 230MW fuel cell CHP capacity over the next three years in the Seoul area[56]. The plans include 29 fuel cell parks and 102 commercial building installations. The installations include a total of 70MW at 11 locations to support the operation of the subway, 70MW across 10 water treatment and pump facilities, as well as 50 MW at eight resource collection facilities. The building installations will include 10MW at data centers and hospitals, as well as 30MW at high-rise residential developments[58].

Another ongoing pilot project on use of fuel cell technology is The Maritime Hydrogen Fuel Cell Project. The project is based on an analysis performed by Sandia and The Department of Energy in the US, which indicated that utilization of hydrogen fuel cells is more efficient than a diesel engine due to fluctuating loads in maritime auxiliary power applications since fuel cells follow the load and only supply power when needed. The pilot project is a demonstration of this analysis in a commercial port setting and takes place in the Honolulu Harbor in Hawaii, with field trials which started in the late of August 2015 with a duration of six months. The pilot hydrogen fuel cell was used to replace a diesel generator used to provide power for refrigerated containers on land and on transport barges. Major commercial ports can produce emission equal to half a million cars in one day, and implementation of hydrogen fuel cells can reduce the overall amount of diesel or other maritime fuels[59].

The development and application of the fuel cell technology continues and an increasing number of countries participate in this development. Both local and national governments in several countries support the development by funding and introduction of hydrogen road maps, such as in India and UK[47].

The number of various applications of fuel cells, both already existing solutions and new ways to utilize the technology, indicate that the use of fuel cells are extensive. New applications of fuel cells and future projects will be discussed in Section 4.3.

4.3 Future Applications

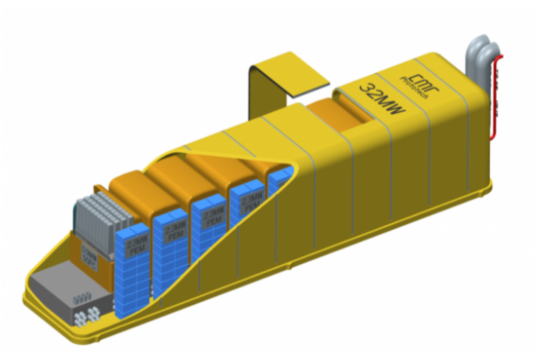
As mentioned in Chapter 2, the requirement for reduction of emission worldwide is increasing. The emission from the offshore oil and gas production have to be reduced since this sector alone stand for approximately a fourth of the Norwegian emission[2]. A possible solution may be to use fuel cell systems in power production offshore. The system will contribute to increased energy efficiency and reduce the need for long power cables at sea. A key factor is to develop compact fuel cell modules which do not require additional reinforcements of the platform structure[2].

The Research Council of Norway is financing a project regarding fuel cells through the PETROMAKS2 - program where Statoil AS and Shell, Norwegian department, are stakeholders from the industry. The project is named Clean, Highly Efficient Offshore Power (CHEOP), and includes the two different fuel cell technologies SOFC and HT PEMFC. The CHEOP project is working on developing a hybrid system which combines the two technologies mentioned above, regarding a set of criteria[2]:

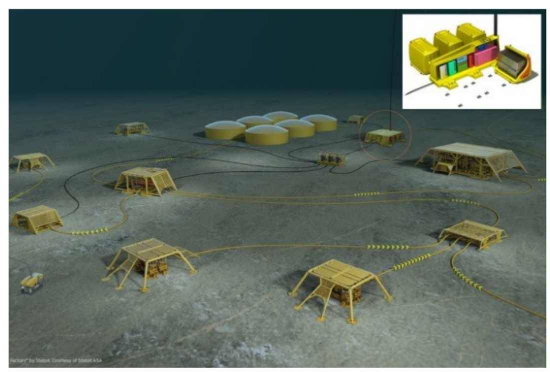
- Access to natural gas.
- Electrical efficiency above 60%.
- Ability to deliver process heat.
- Possibility for expansion with O_2-SOFC for CO_2 separation.

The aim of the project is to develop a compact fuel cell with a output of 3MW, with a size and weight equal to $\frac{1}{10}$ of a 30MW turbine. One full sized gas turbine may be replaced with 10 CHEOP modules, increasing the efficiency from 35% to 60%, resulting in a 40% reduction of the CO_2 emission. Figure 4.2a illustrates 10 CHEOP modules combined. One module consists of one 0.9MW SOFC and one 2.3MW PEMFC[60]. The time schedule for the project is eight years, from 2015 to 2023, where the first phase is supposed to be completed in 2017. The aim of the future work is to be able to mass-produce 25MW fuel cell systems for employment offshore[2].

A pre-project has been performed, proving that fuel cells can be placed subsea in order to produce the power necessary for an increasing number of subsea factories on site. Local natural gas resources will be used as fuel, while air will be drawn from the surface through a flowline. Application of subsea fuel cells may remove the need for additional power from land cables and from floating platforms in subsea factories[60]. A illustration of fuel cells applied subsea is presented in Figure 4.2b.



(a) Possible CHEOP fuel cell[60]



(b) Utilization of fuel cells subsea[60]

Figure 4.2: Illustration of 10 CHEOP modules and fuel cells applied subsea

Another ongoing project is the Pathway to a Competitive European FC mCHP market (PACE) project, founded by the FCH JU. The aim of the project is to ensure that the European residential (μ-CHP) sector makes the next move towards mass market commercialization. A total of 2560 new fuel cell μ-CHP units will be deployed with real customers, and the units will be monitored for an extended period. The project utilizes SOFCs and PEMFCs. The PACE project has a duration of 57 months, from June 2016 to February 2021. By 2018, a capacity for production of over 1000 units per year will be installed. These production lines will test the manufacturing techniques, allowing mass market scale-up leading to a reduction in unit cost. If the project succeeds, the monitoring of fuel cell units will contribute to a upscale of the fuel cell μ-CHP production using new series techniques and increasing automation[61].

Fuel cells are considered for marine applications in the future. The technology has been considered as one of several alternative propulsion systems for the vessels of the future. The potential for high efficiency is of special interest since a higher efficiency may result in a lower fuel consumption, hence, cost savings. The efficiency is relatively constant over a broad range of power settings and fuel cells may therefore be efficiently employed in vessels that frequently vary power demand, such as ferries and offshore supply vessels. Fuel cells could, in addition to the potential for providing main propulsion, supply auxiliary power and other needs. The modular design of the fuel cells enables flexibility in the arrangement of plant components and may result in a more cost-efficient layout of cargo and power space, and basic ship structure[62].

The Swedish company Powercell has retrieved orders for two fuel cell stacks, which are supposed to be integrated into a solar-powered ship. The Royal Caribbean Cruises Ltd. (RCL) is moving towards use of fuel cells on its LNG powered cruise liners[47]. From the beginning of 2017, RCL will begin testing fuel cells as a supplemental energy source on already existing ships, in addition to run progressively larger fuel cell projects on new vessels being built in the coming years. This pilot-project is a preparation for use in the Project Icon vessels. These vessels are to be delivered in the second quarter of 2022 and 2024[63].

There already exist several projects regarding application of fuel cells in buses. However, several of these projects only include a limited number of units. In 2016, Toyota announced its ambition to have 100 or more FCEBs on the roads in time for the Tokyo Olympic and Paralympics in 2020. Deliveries of the FCEB are starting in 2017. The buses will include two 114kW stacks and a 235kWh hybrid battery[47]. Other countries, such as Korea, are also working on expanding their fleet of fuel cell buses. Hyundai and the Korean Government announced their intended plan of replacing 26 000 CNG fueled public transport buses with FCEB. This will lead to environmental benefits and potential economic benefits. However, this would require considerable policy and regulatory underpinning, as well as some form of financial support. During the planning process of these replacement, FCEBs are planned to run during Korea's Pyeong Chang Winter Olympics in 2018[47].

As presented in Section 4.2 and 4.3, several large projects regarding application of fuel cells for transportation and stationary applications exist. The largest transportation projects are compared regarding location, power output, and fuel cell technology in Table 4.1. The same comparison, as well as whether or not it is commercialized, is done with projects utilizing fuel cells for stationary applications in Table 4.2.

Table 4.1: Transportation fuel cell projects around the world

Project	**Country**	**Power output**	**Fuel cell technology applied**
Alstom train project	Germany	NA	Hydrogen fuel cell
Fuel cell trucks	Switzerland	One 100kW fuel cell stack and a electrical motor providing 250 kW	PEMFC
Bus project	Tokyo	Two 114 kW stacks and a 235 kWh hybrid battery	NA
Forklifts	All over the world	Large variations, between 1.5 kW to 30 kW	PEMFC and some DMFC
CHIC	Europe	75 kW - 150 kW	NA

As seen in this chapter, the fuel cell technology goes way back. The technology has a large range of application and the number of projects dealing with fuel cells are growing. As briefly mentioned earlier, the fuel cell technology possees major strengths and opportunities but also some weaknesses and threats, which will be further discussed in Chapter 6.

Table 4.2: Stationary fuel cell projects around the world

Project	**Country**	**Power output**	**Fuel cell technology applied**	**Consumer type**	**Commercial application**
ENE-FARM	Japan	0.3kW to 1kW	SOFC and PEMFC	Households	Yes
Callux	Germany	0.25 - 5kW	PEMFC and SOFC	Heating appliances for home use	Project successfully completed, will end with the commercial introduction of the innovative systems
The Gyeonggi Green Energy fuel cell park	Hwasung City, South Korea.	21 2.8MW fuel cells generating a total of 59MW	Hydrogen fuel cells	Local district heating systems	Yes
The Godok Rolling Stock fuel cell park	South Korea, Seoul City	Seven fuel cell power plants, each providing 2.8MW of power	NA	Households	Yes
The fuel cell project in Seoul City	South Korea, Seoul City	230MW	NA	Households	Planned finished in 2017
CHEOP	Norway	10 0.9MW SOFC, 10 2.3MW HT PEMFC, total output of 32MW	SOFC and HT PEMFC	Offshore	Not yet
PACE	Europe	Around 1kW	PEMFC(both HT and LT) and SOFC	Domestic heating	Duration until February 2021

Chapter 5

Electrical Demand on Offshore Installations

5.1 Ohm's Law

Ohm's law is an idealized model describing the behavior of some materials, however, it is not a general description of all matter[64]. It will be assumed that Ohm's law is valid in the following discussion.

Ohm's law describes the mathematical relationship between electric current, resistance and voltage, as presented in Equation 5.1. The law states that the electrical current passing through a conductor between two points is directly proportional to the voltage across the two points, given that the temperature remains constant. The constant of proportionality is the resistance of the conductor[33].

$$I = \frac{V}{R} \tag{5.1}$$

where I is the current through the conductor, V is the voltage measured across the conductor and R represents the resistance of the conductor. I is given in the units of ampere, V in volts and R in ohm[64].

Two types of current exist, AC and DC. The differences and areas of applications will be further explained in Section 5.2 and 5.3.

5.2 Alternating Current

AC is a flow of electric charge where the movement of the charge changes direction periodically. As a result, the voltage level reverses along with the current. AC is the form in which electric power is delivered to houses and office buildings, among others. It is also the form of electric energy which consumers apply when they plug an electrical device into a wall socket[65].

AC can be generated in gas turbines and steam turbines. It can also be produced using a device called an alternator, an electrical generator used to convert mechanical energy into electrical energy in the form of AC. Electrical energy is often distributed as AC since AC voltage can be decreased and increased by utilization of a transformer, and it is easier to step voltage levels up and down than with DC[64]. The transformation allows the power to be transmitted effectively for long distances through power lines at high voltage and at as small currents as possible, reducing the energy losses, such as copper losses and iron losses. These types of losses will be further explained in Section 5.4.5. Utilization of a higher voltage results in a more efficient transmission of power[65]. The high AC voltage and currents may then be reduced to a lower, safer and usable voltage level for use, such as to supply electrical equipment in homes and at workplaces[6].

5.3 Direct Current

DC, on the other hand, is a flow of electric charge where the movement of the charge is constant and only in one direction. The flow of electric charge may have fluctuating current intensity, and are then called pulsating DC. Even though the DC is constant across a time period, the current may vary with time. The DC may be produced by fuel cells, batteries, rectifiers, or generators with commutators[66].

DC can be obtained from AC supply by use of a rectifier usually containing electronic elements or electromechanical elements allowing the current to flow in only one direction. Small systems may utilize DC, but it has to be converted to AC if it is transported over distances farther away than 100-150 km or for utilization in larger systems. The DC may be converted into AC by use of an inverter or a motor-generator set, which will be further explained in Section 5.4.4[66].

5.4 From Direct Current to Alternating Current

As mentioned in Section 3.1, fuel cells have the ability to convert chemical energy from a fuel into electricity. DC is produced when the electrons move through an external circuit. This is an advantage for small systems which can utilize DC, but when the current is applied for larger systems, such as in CHP systems, the DC must be converted to AC since the fuel cell will need to connect to the AC main grids in these types of systems[3]. The conversion from DC to AC is done by use of an DC/AC inverter, which will be further explained in section 5.4.4. The different components in the inverter, such as electronic switches and diodes will be explained in the following. The electricity will either be converted to a single AC voltage or three-phase AC. The single AC voltage is normally applied for small domestic systems, while the three-phase AC is applied for large industrial systems. When the DC is converted to AC, the electricity has to be transformed in order to be utilized at large installations. The process of converting DC to AC is illustrated in Figure 5.1.

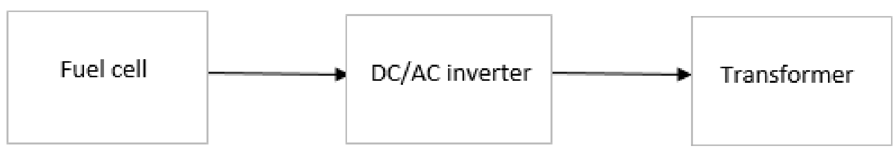


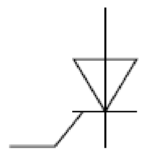
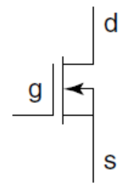
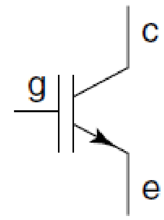
Figure 5.1: The process of converting DC to AC for use in larger systems.

5.4.1 Electronic Switchers and Switching Regulators

The voltage from all sources of electrical power varies with time, temperature, and current. Fuel cells are especially badly regulated and, as presented in figure 3.6a and 3.6b in Section 3.4, the cell voltage rapidly falls with rising current density. Most electronic and electrical equipment require a relatively constant voltage, which can be achieved by dropping the voltage down to a fixed value below the operating range of the fuel cell or by boosting it up to a fixed value. This is achieved by using so called "switching" or "chopping" circuit[3].

An electronic switcher is an electronic component used to switch an electrical circuit, interrupting the current or diverting it from one conductor to another. Type of switch applied does not matter greatly, but the main types with their characteristics and key data are described in Table 5.1[3].

Table 5.1: Key data for the main types of electronic switches used in power electronic equipment[3]

Type	**Thyristor**	**MOSFET**	**IGBT**
Symbol			
Max. voltage (V)	4500	1000	1700
Max. current (A)	4000	50	600
Switching time (μs)	10-25	0.3 - 0.5	1 - 4

A switching regulator, also called chopper, may also be used. An electronic switch with an associated drive circuit, a diode, and an inductor are the main components in a switching regulator, as illustrated in Figure 5.2. When the switch is on, as in Figure 5.2, the current flows through the inductor and the load. The inductor produces a back EMF, resulting in a gradually rise in the current. The switch is then turned off, and the stored energy in the inductor makes the current keep flowing through the load using the diode. The working principle of a diode will be further discussed and explained in the following section[3].

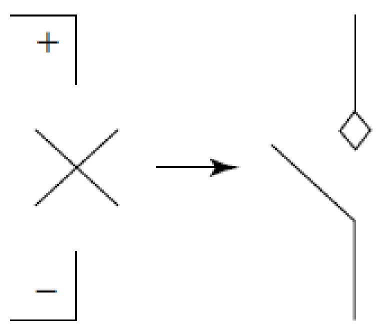


Figure 5.2: Symbol used for an electronically operated switch[3]

5.4.2 Diode

A diode consists of two terminals which both are polarized, making them distinctly different. The positive end of the diode is the anode, while the negative one is the cathode. The current can move from the anode to the cathode, but not the opposite way. This direction is called the conduction direction, while the other one is called the reverse direction. A current in the reverse direction will not result in an electric current through the diode, and it can be said that the diode is blocking the electric current[5]. The circuit symbol of a standard diode is presented in Figure 5.3.

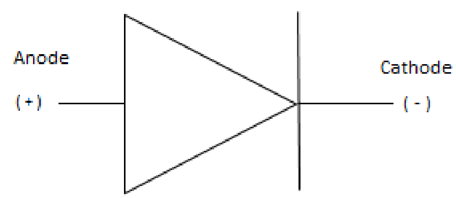


Figure 5.3: The circuit symbol of a standard diode[5]

5.4.3 Load

Load is the generic term for something in the circuit that will draw power, meaning that the load will affects the performance of circuits with respect to output voltage or current. The highest load which the electrical component, e.g. a motor in an electrical circuit, is able of handling without stopping is called breakdown torque. Load is the contrary to a power source, such as a fuel cell, which will produce power. All components in the circuit utilizing electricity to do work will draw current. However, the amount of current drawn depends mainly upon two factors; the devices' resistance to current flow and the amount of voltage applied to it[67].

The electrical load in Figure 5.4 is represented by a resistor and an inductor through which the AC is to be driven[3]. If it was said that a heavy load was connected to the fuel cell in Figure 5.4, or that the fuel cell was supplying a heavy load, it would mean that the load connected across the fuel cell's terminals was drawing a lot of current. Contrary, if it was said that it was a light load, it would mean that only a small amount of current was drawn from the fuel cell[67].

5.4.4 Inverters

An inverter are utilized to convert DC to AC. A single phase inverter, with its key components, is presented in Figure 5.4. The four electronic switchers, labelled A, B, C, D in the figure, is connected in a so-called H-bridge. The term H-bridge is derived from the graphical representation of the circuit and the electronic circuit enables a voltage to be applied across a load in either direction. Across each switch is a diode through which the AC is driven[3].

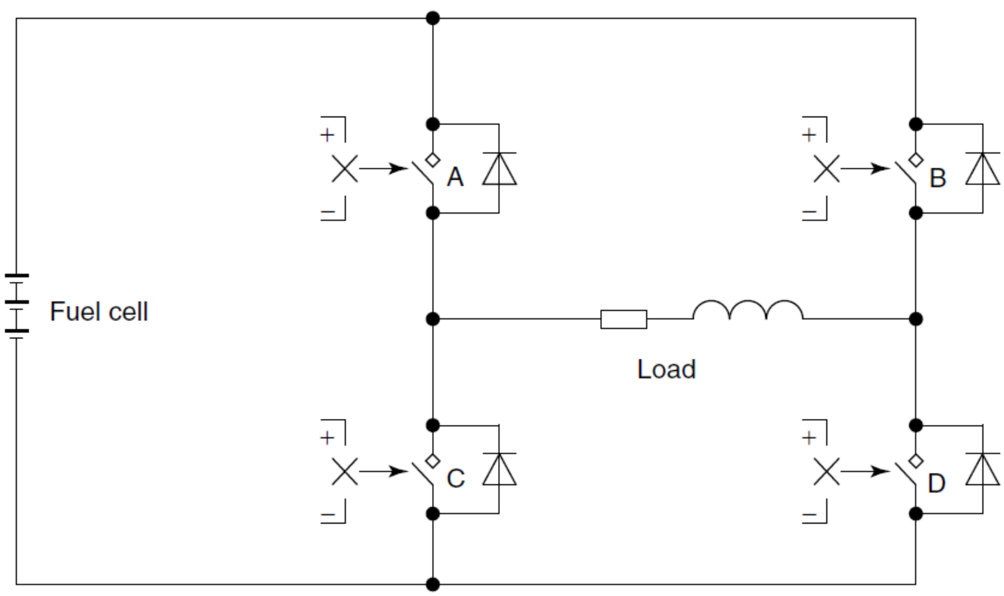


Figure 5.4: H-bridge inverter circuit for producing single-phase AC[3]

The operation of the inverter is as follows: The switches A and D are turned on, and a current starts to flow to the right through the load. The A and D switches are then turned off, and the current will not be able to stop immediately since the load has some inductance, and will therefore continue to flow in the same direction through the diodes across switches B and C before it flows back into the supply. The switches B and C are then turned on, making the current to flow in the opposite direction, to the left. When these switches are turned off, the current flows through the diodes across switches A and D[3].

The three-phase AC is merely a bit more complicated than the single-phase AC explained above. This inverter circuit consists of six switchers with associated diodes connected to the three-phase transformer on the right in Figure 5.5. The way these six switchers are used to generate three similar but out-of-phase voltages is also presented in Figure 5.5[3].

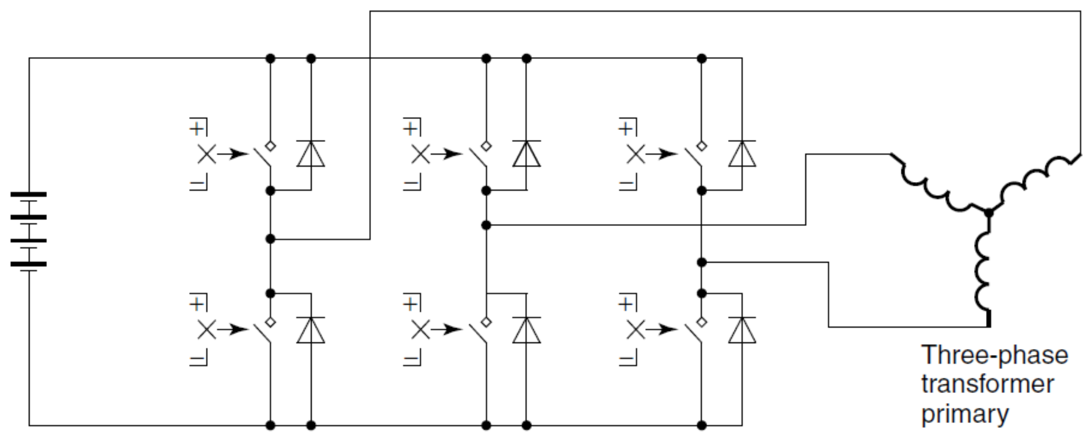


Figure 5.5: Illustration of a three-phase inverter circuit[3]

5.4.5 Transformers

A single fuel cell deliver a low voltage, around 1.0 V as mentioned in Section 3.3.2. A transformation of the current is therefore necessary after the conversion from DC to AC, and this is done by use of transformers. The key components of the transformer are two coils or windings, which are electrically insulated from each other but wound on the same core[64]. They operate on Faraday's principal of "mutual induction", meaning that "the induced EMF in a closed loop equals the negative of the time rate of change of magnetic flux through the loop"[64]. Faraday's law of induction is presented with symbols in Equation 5.2, where the ε represents the induction and the Φ_B the flux. The AC source causes an AC in the input winding, also called the primary winding, which results in a alternating flux in the core. This flux induces an EMF in each winding, in agreement with the Faraday's law explained above. The induced EMF also gives rise to an AC in the output winding, also called the secondary winding. The induced EMF results in a delivery of energy to the device in which the output winding is connected to. Both the currents and the EMFs have the same frequency as the AC source[64].

$$\varepsilon = -\frac{d\Phi_B}{dt} \tag{5.2}$$

An illustration of a transformer is presented in Figure 5.6, where the V_P is the primary voltage and V_S is the secondary voltage. The N_P represents the number of primary windings, while N_S is the secondary number of windings. I_P and I_S represent respectively the primary and secondary current, while the Φ_B is the flux[6].

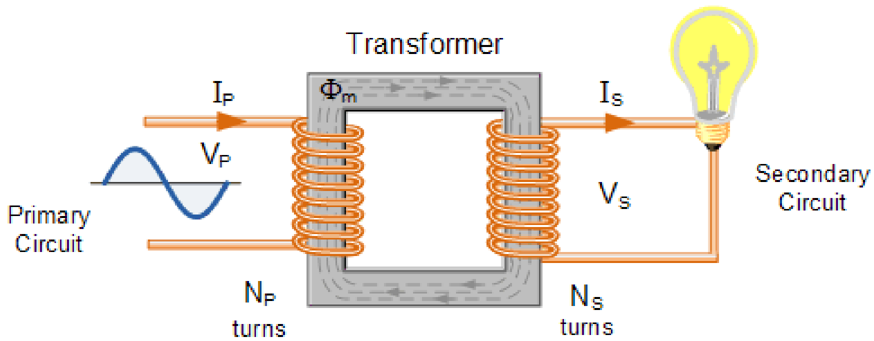


Figure 5.6: Illustartion of a single phase voltage transformer[6]

The voltage across the output winding can be made larger or smaller in amplitude than the voltage across the input winding, depending on the requirements from the end user of the electric current. If the N_S from Figure 5.6 is larger than N_P, then V_S is larger than V_P and the transformer is called a step-up transformer indicating that the transformer increases the voltage. On the other hand, if N_S is smaller than N_P such that V_S is smaller than V_P, the transformer is a step-down transformer. This type of transformer decreases the voltage from the input winding to the output winding. The last type of transformers is the type where both the input and output winding have the same number of windings, meaning that the voltage and currents are the same for both windings. This type of transformer is called an isolation transformer[64]. In situations where fuel cell systems are utilized to produce electric current, the step-up transformer are applied since the consumers of the current require a higher voltage than the one delivered from a single fuel cell[64].

Since the transformer do not require any moving part to transfer energy, no friction or windage losses occurs. However, other types of energy losses, such as copper losses and iron losses, may occur. Due to the resistance of the windings, some copper losses, also called I^2R losses, can occur. These loses are caused by the electrical power which is lost in heat due to the circulation of the current around the transformers copper windings and are considered the greatest loss in operation of a transformer[6].

Iron losses, also known as hysteresis, is another type and are a result of lagging of magnetic molecules in the core. This lagging condition is a result of the need of power in order to reverse magnetic molecules, and they are not reversed until the flux has obtained enough force to reverse them. The reversal of the molecules results in friction, which again leads to a production of heat in the core, resulting in power loss[6].

It is desirable to achieve the highest possible efficiency in a transformer. The efficiency depends on the power lost between the input and output windings, as presented in Equation 5.3[6].

$$Efficiency, \eta = \frac{Output\ \ power}{Input\ \ power} * 100\% \tag{5.3}$$

Real transformers, unlike ideal transformers, are not a 100% efficient. The efficiency of a transformer with full load is between 94% and 96%, which is quite good. The efficiency may be as good as 98% if the transformer is operating with a constant voltage and frequency with a high capacity[6].

5.5 Electrification

An alternative way of meeting the energy demand offshore is electrification of offshore installations. Electrification is an effective climate initiative to reduce the emissions from the petroleum industry. The idea is that electrical power generated from gas turbines offshore should be partially or completely replaced with power from shore. Some of the main advantages with electrification are reduction of emission, improved safety, inferior operation, and maintenance costs, as well as higher energy efficiency. A power-from-shore solution is also cost efficient and has the advantage of saving space and weight on the installation. For a field with several platforms, the converter stations can be located on one of them, or on its own platform, and power can be distributed to the others through AC cables, or DC power can be distributed to several platforms in a multiterminal arrangement[68]. In the last case, each platform need their own converter station.

The forecast for the CO_2 emission from the petroleum production and an estimate for CO_2 operational savings from both accomplished and approved electrification projects are presented in Figure 5.7. The shaded area represents the accomplished and planned CO_2 emission by utilization of electrification, while the all-covering area represents the forecast for CO_2 emission[69].

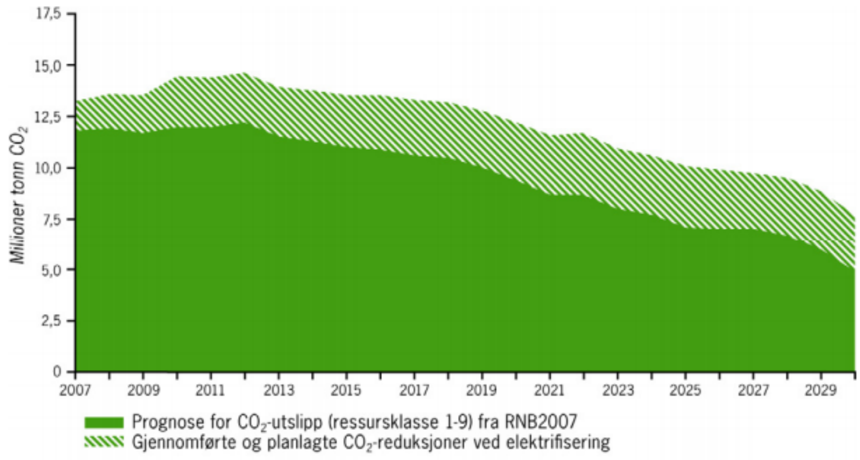


Figure 5.7: Forecast for the CO_2 emission from the petroleum production and an estimate for CO_2 operational savings from both accomplished and approved electrification projects[7]

The Norwegian power system consist of a power station and a power grid to transfer electrical energy to the consumers. Distribution of the electrical power takes place through a network of open-wire lines and cables with different capacity and size[70].

The power grid can be divided into three voltage levels: the central grid, the regional grid, and the distribution grid. The central grid constitutes the main part of the power lines grid. This power grid has the highest voltages, either 420, 300 or 132 kV, and are used to distribute electric current from province to province and across borders. The regional grid are used to distribute electric current for larger areas, such as parts of one or several counties. This grid is the connection between the central grid and the distribution grid with a voltage level of 132 kV and 66 kV[70]. The distribution grid, on the other hand, are used to distribute power directly to the local community and housing estates. This grid transforms the voltages down from 22 kV to 230 V which is the voltages utilized in outlets in households[34].

Two types of electrification exist; partly electrification and complete electrification. When a installation is partly electrified, a part of the electricity is generated from gas turbines while the rest is transported from shore in order to meet the field's electrical demand. Gas turbines are energy intensive and the emission of CO_2 would be reduced if the equipment driven directly by these received their power from shore. All the electricity is transported from shore when the installation is completely electrified[69].

Several factors affect the decision related to electrification. Such factors may be the different facilities fluctuating frequencies (50 or 60 Hz), price and capacity associated with DC- and AC installations, restrictions related to weight and space on the installation, distance to shore, energy, and efficiency requirements, as well as possibilities for construction and positioning of a juncture utilized for power distribution at sea[7].

5.5.1 Electricity Delivered as Direct current

There are several large ongoing electrification projects on the NCS, such as Troll A, Gjøa, Valhall, Goliat, as well as the four planned oil fields at Utsirahøyden. Some of them are completely electrified, while others are only partly electrified[69]. The installations receive their power supply from the land grid, from the gasworks at Mognstad, or from other installations[2].

The transportation of the electricity from shore are performed by utilization of high voltage direct current (HVDC) power systems. The system consists of two converter stations, one onshore and one offshore, submarine cables and high voltage engines. The engines are placed on the offshore installation in order to drive the compressors, which purpose is to maintain the production as the pressure in the reservoir drops. The electrical power from shore is converted into DC in a converter station, then transported through the submarine cables before it is converted back to AC in the converter station at the installation[69].

The order of magnitude of the converter station may vary with efficiency and number of disconnecting switchers, but it normally has a length between 9-15 meters, a width of 8-10 meter and a height between 8-9 meters[7]. Several disadvantages associated with application of converter stations offshore are stated in a study performed by Nexas, Vattenfall and HVDC Tech. Their vulnerability for defects due to rough climate and sensitive components are a problem, as well as the possibility for a long awaiting-repair time. These converter stations are also expensive and time consuming to build, and the risk for problems are high[71].

The losses in a converter station depend on several parameters, such as the facilities power factor. The amount of converter station losses depend on the location, offshore or onshore. A converter station applied onshore are normally designed for transferring large effects, around 500MW, and has around 1% losses. Those optimized for application offshore have a relatively low effect, are compact, has a low weight and a direct start of engines. This type of design results in a relatively low current, increased margin in regulation of voltage and reactive effect support, leading to higher losses[72].

The submarine cables are normally designed to transport the required amount of DC on the installation, normally between 25MW - 150MW. Around 10% of the current is lost during transportation when the cable runs at full power. These losses include the losses in the AC/DC and DC/AC inverter, and those in the cable itself. The losses in the cable are affected by the thickness of the cable. A thicker cable would result in a reduction of losses, but an increase of costs. On the other hand, a reduction of the thickness would result in higher losses but a lower cost. It is therefore said that the losses in the cable are reduced with the square of the power[72].

5.5.2 Electricity Delivered as Alternating Current

Currently, all the electrification projects on the NCS make use of HVDC power systems in order to transport electrical current from shore. There do not exist any suitable techniques for transportation of AC from shore to offshore installations, provided that the distance is further than 100-150km. Transportation of AC over long distances results in some disturbance in the AC waves which results in a poorer quality of the electrical current delivered and different types of losses, such as ohmic losses[73].

However, several studies are evaluating the possibility for transportation of electric current from shore to installations as AC despite a distance farther away than 150 km. The Norwegian cable company Nexans has together with the Swedish company Vattenfall and the British company HVDC Tech developed a study considering the possibility for utilization of low-frequent AC instead of DC when transporting 1200 MW from a wind farm 200 km from shore. There still exists several problems associated with application of the technology, but a further development would result in large economical savings since the need for DC/AC inverters would disappear[71].

The losses arising from transportation of AC over long distances may be reduced by lowering the frequency from 50Hz to e.g. $16\frac{2}{3}$Hz, in addition to reduction of the ohmic losses as well as a reduction of the reactive effect[71].

A possible obstacle with a lower frequency is the expanding size of the transformation stations, and thereby an increased weight, since the efficiency of the transformation stations depends on the frequency of the current. The volume of the magnetic core has to be increased in order to maintain the magnetic flux which is required from the voltage transformer. A commutator transformer is also necessary in order to increase the frequency up to 50 or 60 Hz, depending on the wiring on the installation[71].

5.6 Electrical Integration of Fuel Cells

5.6.1 Inrush Current

Inrush current, also called starting current, input surge current or switch-on surge, is the maximum immediate input current drawn by an electrical device when first turned on. This large current flow exceeds the steady-state current value. The maximum instantaneous input current drawn by an electrical device during the initial power up determines the size of the inrush current. A high input current results in a high inrush current, and vice versa, a lower input current results in a lower inrush current. AC electric motors and transformers are devices which may draw several times their normal full-load current when first energized. Inrush current is essential in order to be able to start up components in an electrical circuit, and inrush current and load are therefore closely related[8].

The current waveform when a device is powered up is presented in Figure 5.8. Current begins to flow when the power is turned on and the initial current flow reaches the peak current value which is larger than the steady-state current value. Shortly afterwards, the current value gradually decreases until it stabilizes at the steady-state current. Therefore, inrush current is the part during which a large current flows before reaching the steady-state current. The size of the inrush current is determined by the magnitude of the inrush current, the range between the peak current and the steady-state current value in Figure 5.8, and the length of its duration, named pulse width in the figure. If the size of the inrush current exceeds the allowable value, the parts used in the circuit may overheat, causing the electrical device to malfunction or break down[8].

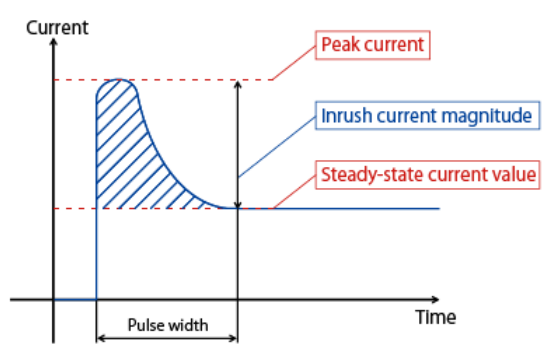


Figure 5.8: Current waveform when the device is powered up[8]

The inrush current may affect electrical components in different ways, such as tripping, circuit breakers and fuses. Momentary contact bouncing in switches or relays during start-up can result in arcing between the contact points, which can cause the contacts to become pitted. Serious damage, such as welding switch contacts together, may also be caused by this surge in current. In order to prevent the inrush current from becoming too high, a resistance can be coupled in series, also called a start resistor. By regulation of the resistances, the electrical components characteristics at start-up can be affected by increasing the starting torque, plus a reduction of the inrush current and the reactive power. Another way to limit the inrush current is by utilization of a inrush current limiter, a component used to avoid gradual damage to the components in the electrical circuit and to avoid blowing of fuses or tripping circuit breakers[74].

Fuel cells are not able to deliver the required inrush current, and the electrical equipment on the installation are therefore dependent on receiving it from another energy power system. A possible solution may be to get the inrush current from a hybrid system. This system will act as an energy buffer. A hybrid power system is designed for generation, as well as utilization of electrical power. These systems may range in size, from several a few kW to several MW, depending on application area[73].

If the inrush current exceeds the steady-state current value, it may result in challenges related to application of fuses. A typical fuse will blow at the same time as it receives current above its current rating. This means that any momentary surge will make the fuse blow, and the electrical circuit will no longer work. A slow-blow fuse is designed differently and allows for temporary current levels above its current rating, and will not blow immediately if the current levels exceeds the current rating. However, the slow-blow fuse will blow if it is exposed for current levels higher than its current rating over a period of time. Utilization of slow-blow fuses are therefore necessary in electrical circuits where the requirement for inrush current is present[75].

5.6.2 Reactive Power

The active power and the imaginary, reactive power in a electrical circuit is called the complex power. The active power in a electrical circuit is the power which can be utilized, while the reactive power is the amount of power electrical components deduct from the electrical grid in order to produce active power. The power in a circuit is an active power when the current is in phase with the voltage[8].

The reactive power arises when a phase displacement between the current and voltage arise, meaning that some energy are alternating being consumed and then disengaged again. The reactive power for an AC circuit are equal to the product of the effective voltage(V_{eff}), effective current(I_{eff}) and the sinus of the phase displacement between the current and voltage, as presented in Equation 5.4[76].

$$Q = V_{eff} * I_{eff} * sin(\phi) \tag{5.4}$$

The reactive power contributes to erect the magnetic field when the current increase in situations with an electromagnetic force where a coil is winded around a core. The same energy is returned from the coil when the current decreases, and it can therefore be said that the reactive power is not "consumed". Thus, the reactive power only oscillates between the source of voltage and the load and cannot be converted into work. However, it is required that the source of voltage is large enough to satisfy the reactive power needed. The reactive power results in a voltage loss and the efficiency of the conductor are reduced[77].

5.6.3 Losses Due to Reactive Power

Active power is the real power utilized to drive electrical equipment, such as pumps, in an electrical circuit, while the reactive power is power stored in reactive components, such as inductance and capacitance. As mentioned in Section 5.6.2, the reactive power are not utilized to perform work, it only moves backwards and forwards in the circuit. Due to resistance in the conductor, the reactive power results in so-called ohmic losses in the circuit. Two other types of losses exist, inductive losses and capacitive losses. These types of losses are due to inductive and capacitive loads[78]. The difference between the two types of losses are related to the phase displacement of the current and voltage. The losses are inductive if the current and voltage have a phase displacement of 90° with the current 90° ahead of the voltage, and inverted when the losses are capacitive. The losses due to inductive load are presented in Figure 5.9. The phase angle is presented on the x-axis, while the fluctuations are presented on the y-axis. The voltage is represented by the blue graph and the current by the red one[9].

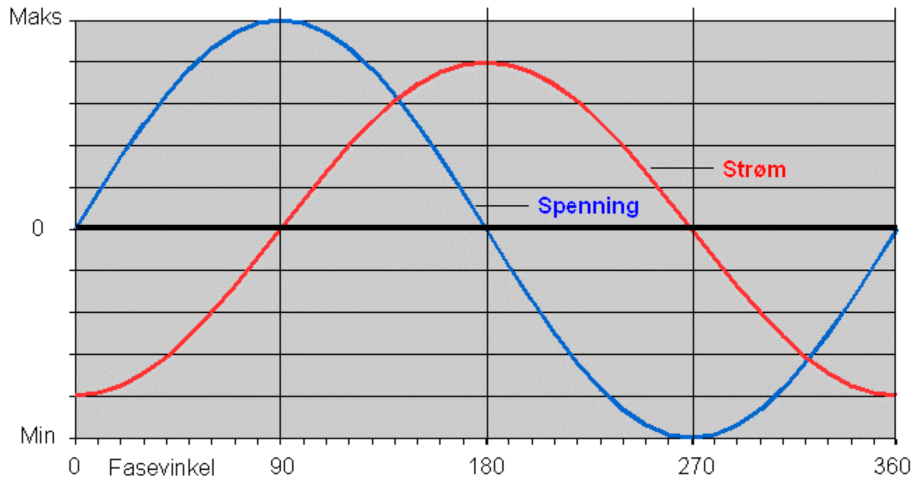


Figure 5.9: Phase displacement between current and voltage at inductive load[9]

The reactive power is zero when the current and voltage is moving in phase, since $\sin(0) = 0$, and losses due to the reactive power are avoided. Different types of phase compensations are therefore applied. Phase compensation will be further discussed in the next section, Section 5.6.4.

5.6.4 Reactive Power Compensation

Phase compensation are used to compensate for the reactive power in electrical circuits and components. The load components in an electric circuit include a reactive power component, corresponding to the reactive power, whereby an increase in the electrical current in the circuit which is higher than it would have been if only active power was present. A higher amperage results in a greater loss and a voltage drop. It is therefore desirable to eliminate, completely or partly, the reactive power component by use of phase compensation. The reactive power is zero when $\sin(0) = 0$, i.e. the phase displacement is zero, as mentioned in Section 5.6.2[79].

Most of the loads are of inductive character, such as motors, and the phase compensation may be executed by connecting a condenser in the electrical circuit together with the electrical component which are the source of the inductive load. A coil may be connected in the analogous way if the load is of capacitive character. By connecting a suitable sized capacitive- or inductive load more or less of the phase displacement would be canceled, minimizing the resulting current. Ideally, a power factor close to one is desirable[79].

5.7 Energy Demand Offshore

As well as being a major producer of energy, the oil and gas industry itself is a major consumer of energy. The energy is, among other, used to extract resources from the ground and to process, transport and deliver these resources to the end-users[80]. Around 30 MW is required for everyday use in order to keep the production going, however, the demand may fluctuate depending on type of operations executed[73].

To put the amount of electrical energy consumed each year by the oil and gas industry into perspective, the consumption at a typical installation may be compared to the one in a single household. In accordance to Central Bureau of Statistics in Norway, a single household consumes around 20 000kWh each year while the consumers on a typical offshore installation consume 600 000 - 700 000MWh, depending on the size of the installation. This means that the amount of energy produced at a typical offshore installation during a year is enough to meet the energy demand for 30 000 - 35 000 single households[81].

Oil refining is one of the most energy-intensive activities, counting for about half of all energy consumed by the oil and gas industry as a whole. The demand for increased processing, place an upward pressure on the overall energy intensity for refining. The pressure is affected by several different factors, such as more stringent oil standards, increasing demand for lighter products, and heavier crude oil slates[80].

The oil and gas production also requires a huge amount of energy to extract oil and gas. The energy used in the petroleum extraction covers a range of activities, such as driving pumps to extract hydrocarbons and to re-inject water, heating the output stream to allow separation of the oil, gas, and water, to production of stream, and re-injection of gas for enhanced oil recovery, and last but not least it is used to drive the export compressors on the platform. These compressors are the main consumers of the energy, in fact, around 50% of the produced power are used by these. Some of the compressors on the installation is driven directly by gas turbines. The amount of energy needed at an offshore installation vary widely according to local circumstances and operational conditions[80].

Gas turbines are generating the electricity needed for on-site operations, and are widely used for a variety of purposes with a power requirements ranging up to several hundred megawatts. There are two main types of gas turbines, respectively industrial and aero-derivative. The aero- derivative gas turbine offers higher efficiency and faster start-up, particularly for larger engines. These turbines offer an advantage in use offshore where mass and space is limited[82].

5.7.1 Energy Flow on Offshore Installations

As mentioned in Section 5.7, several components on an installation require energy. Such components may be AV pumps, heating agent pumps and components for gas re-compression. Several offshore installations therefore have their own gasworks in order to provide the required energy. These gasworks are often driven by fuel gas[73].

Huge amounts of energy are processed each year, and an energy flow diagram for a typical offshore installation is presented in Figure 5.10. The diagram shows the different ways the fuel gas may be processed. Some of the fuel gas is utilized for flaring, while the rest of the fuel gas is processed by the GT generators. Power, emission, and heat are generated. Some of the power is used to operate components on site the installation, while a large amount is used for re-compression of gas from the separators. The gas has to be re-compressed in order to be exported to receiver terminals. A huge amount of the burned fuel becomes emission. Heat exchangers are used to generate heat from the emissions, which again is utilized by several components. The consumers of the power and the waste heat is presented at the far right of the diagram. The biggest consumers of the waste heat are the stabilizers reboiler and the component for the Amine regeneration. The components for gas re-compression and the AV pumps are the biggest consumers of the power[73].

Between 125 and 145TWh of the generated power, depending on the size of the installation, is applied as electrical power while the rest is utilized for other applications. The power consumption on an installation is far higher than the electrical consumption[73].

5.7.2 A Combination of Fuel Cells and Gas Turbines

A possible way to meet the energy demand can be by use of bottoming cycles. The term refers to the utilization of waste heat from fuel cell exhaust gasses to drive heat engines. This is typically performed in two ways: either by utilization of the waste heat in a boiler to raise steam to drive a steam turbine, or by pressurizing the whole system, including the fuel cell, where the exhaust gasses from the fuel cell are used to power a gas turbine. A third way, which has not yet been built, is to combine a fuel cell with both a steam turbine and a gas turbine into a triple cycle[3].

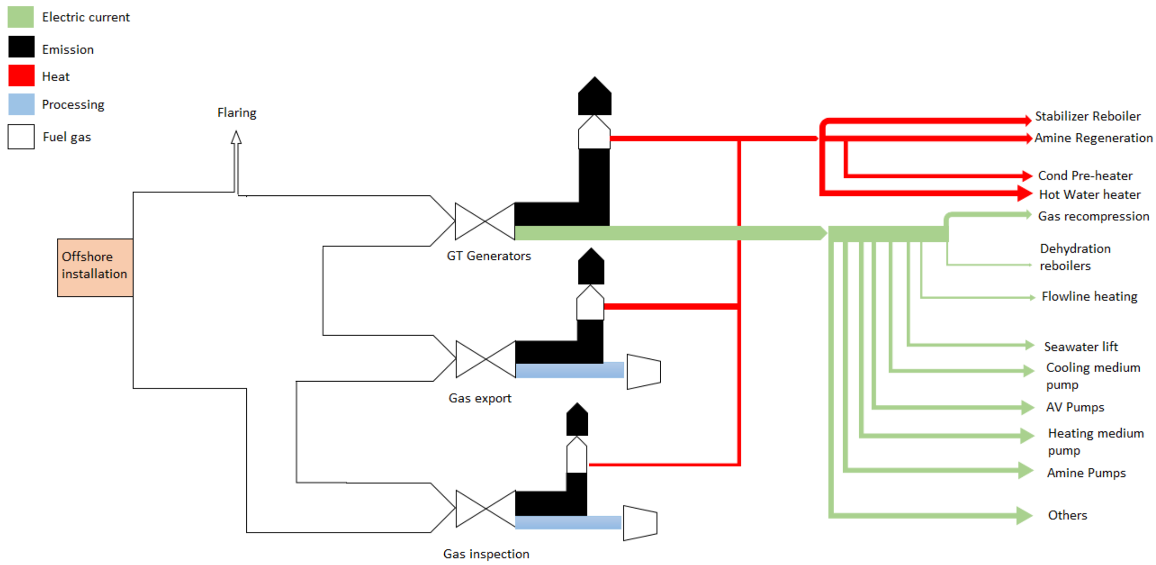


Figure 5.10: Energy flow on a typical offshore installation[3]

A combination of fuel cells and gas turbines will achieve a higher efficiency than a fuel cell or a gas turbine on its own, as presented in Figure 5.11. However, the level of emission will not be as low as when fuel cells operate on their own. The graph of the efficiency limits of a fuel cell and heat engine on their own, as well as the efficiency limit for a combined cycle fuel cell and heat engine is sketched graphically in Figure 5.11[3]. It can be seen that the efficiency for the combined cycle is stable with temperature, while the efficiency for the hydrogen fuel cell and the heat engine varies with temperature.

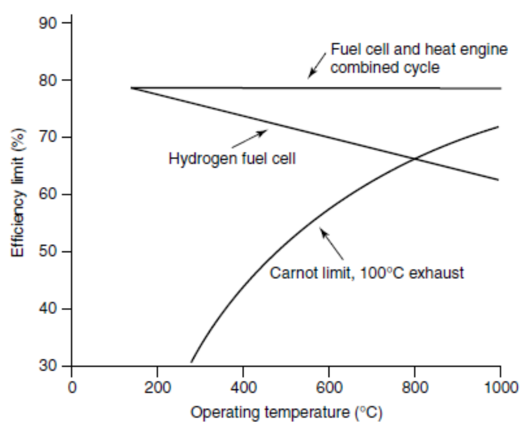


Figure 5.11: Efficiency limits for a hydrogen fuel cell, a heat engine and a fuel cell/gas turbine combined cycle[3].

Chapter 6

SWOT Analysis

6.1 Method Description

SWOT is an acronym for strengths, weaknesses, opportunities and threats, and a SWOT analysis is a useful tool for understanding and decision-making. The method is used to analyze a company's, a product's or a technology's strengths, weaknesses, opportunities and threats, which may affect the company, product, or technology on a small scale or as a whole. The objective are specified and internal and external factors that are favorable or unfavorable to achieve the objective are identified. Strength and weaknesses are considered internal factors, while opportunities and threats are considered external factors[83].

The internal factors deal with the internal environment, with other words the situation inside the company, organization or the technology itself. Such factors can be costs, performance, adaptability, infrastructure, etc. The external factors, on the other hand, deal with the external environment and look into how the situation outside the company, organization or technology will be influential. External factors may therefore be factors related to competition, economics, environment, etc[83].

A SWOT analysis is often framed as a 2x2 matrix, where the internal factors and the external factors are listed. An example of a template for a SWOT analysis is presented in Figure 6.1a. The analysis may also be a bit more complex by developing an "action-based" 2x2 SWOT matrix, as the one presented in Figure 6.1b. The internal factors are compared with the external factors, meaning that the analysis automatically suggest actions for issues identified in the SWOT analysis. The strengths are compared both with threats and opportunities, and the same goes for the weaknesses[83].

STRENGTHS Positive internal factors within your control on which you could capitalise	**WEAKNESSES** Negative internal factors within your control that should be limited or improved upon
OPPORTUNITIES Positive external factors outside of your control on which you could capitalise	**THREATS** Negative external factors outside of your control whose effects you should seek to lessen

(a) Template for a SWOT analysis[83]

	Opportunities (external, positive)	**Threats** (external, negative)
Strengths (internal, positive)	**Strength-Opportunity strategies** Which of the company's strengths can be used to maximize the opportunities you identified?	**Strength-Threats strategies** How can you use the company's strengths to minimize the threats you identified?
Weaknesses (internal, negative)	**Weakness-Opportunity strategies** What action(s) can you take to minimize the company's weaknesses using the opportunities you identified?	**Weakness-Threats strategies** How can you minimize the company's weaknesses to avoid the threats you identified?

(b) Template for an action-based SWOT analysis[83]

Figure 6.1: Illustration of two different templates for the SWOT analysis, the 2x2 matrix and the action-based 2x2 matrix

6.2 Performance of the Analysis

A SWOT analysis is performed for the fuel cell and gas turbine technology in the following sections. The analysis is performed in order to examine if fuel cells can be a suitable replacement for gas turbines on offshore installations in the future. The strengths, weaknesses, opportunities, and threats for the two different technologies will be highlighted and discussed in Section 6.3, 6.4, 6.5 and 6.6. This is done to examine if fuel cells are able to perform equally, or better, than gas turbines as power generating system offshore. The analysis is an attempt to highlight the different technical requirements the fuel cell technology has to meet in order to be suitable for offshore application, and these requirements are especially emphasized when the strengths and weaknesses are highlighted. The result from the SWOT analysis will be discussed in Section 6.7, and the strengths, weaknesses, opportunities and threats the most relevant for application offshore are emphasized the most.

6.2.1 Limitations

Since this thesis examines the opportunity to replace gas turbines offshore with fuel cells in the future, some limitations for the SWOT analysis have been established. This means that factors and requirements especially important for offshore power generation are highlighted above others. This is done to limit the extent of the analysis, as well as making the analysis the most relevant. However, this limitation may cause the SWOT analysis to be less current for other industries since the requirement for the different power generating systems can fluctuate.

The fuel cell technology is evaluated as a whole during the analysis, meaning that common factors for the different types are emphasized the most. Such factors may be emission and OCV from a single cell. This is done in order to create a general picture of the characteristics for the technology since these are the most interesting ones since the technology is not yet applied offshore. If it turns out that the fuel cell technology is suited for application offshore another SWOT analysis examining the internal and external factors for the six different types may be conducted.

6.3 Strengths

Strengths are the fuel cells and gas turbines positive characteristics. These characteristics are internal, and only consider the fuel cell or gas turbine itself. They do not take the environment or circumstances into consideration. The strengths of the fuel cell technology and gas turbines are listed in Table 6.1. Each of the listed strengths will be further explained in the following subsections.

Table 6.1: Strengths of gas turbines and fuel cells

Fuel Cells	**Gas Turbines**
High availability and reliability	High availability and reliability
Low maintenance requirement	Low Downtime
Low downtime	May achieve a high power output
Relatively high efficiency	Fuel flexibility
Silent operation	Alternating current
No need for recharging	High power density
	High power-to-weight ratio

6.3.1 Downtime, Availability, Maintenance, and Silent Operation - Fuel Cells

Most fuel cell technologies have a simple design and a reliable operation, with no or few moving parts. The only moving parts in a fuel cell are involved with the ancillary systems, such as water, heat, and air management. Due to none or a few moving parts in the power generating stack, the requirement for maintenance is kept at a minimum. Hence the fuel cell systems achieve a high availability, and thereby a high reliability. A high availability and reliability results in a high uptime, which is desirable in order to maintain a stable and efficient power generation. Routine maintenance may be completed at scheduled intervals, typically quarterly or annually. Fuel cells are installed as modules, simplifying the maintenance tasks since one module can be replaced with a spare one when maintenance is required and thereby reducing the downtime.

Another advantage with a power generating system having no or few moving parts, is that the cell operates with less noise pollution. This is advantageous when fuel cells are used in portable applications, such as buses or cars, and for local power generation in CHP systems.

6.3.2 Relatively High Efficiency - Fuel Cells

It is desirable with a high efficiency since this will result in a better utilization of the fuel, which will lead to fuel savings.

The characteristics of a fuel cell is its ability to convert chemical energy from a fuel into electrical energy without combustion and emission of greenhouse gasses. The reaction occurs directly, providing the cell with a much higher conversion efficiency than any other conventional thermo-mechanical system. Fuel cell systems perform with the highest efficiency compared to conventional distributed energy systems, as presented in Table 6.2. This is the result of its ability to deliver maximum efficiency at low power levels. An additional feature of the high efficiency is that small systems can be just as efficient as larger ones. It can be seen from Table 3.1 that there is a clear connection between the maximum EMF for a fuel cell and its maximum efficiency, the higher the EMF the higher efficiency.

The fuel cells efficiency vary with operating temperatures, and the efficiency will be lower than the one for heat engines at operating temperatures above 800 °C, as presented in Figure

3.5. However, the high efficiency is one of the fuel cell technologies main advantages compared with other power generating systems.

Table 6.2: Comparison of fuel cell with other power generating systems[10]

	Reciprocating engine: diesel	**Turbine generator**	**Photovoltaic**	**Wind turbine**	**Fuel cells**
Capacity range	500kW-50MW	500kW-5MW	1kW-1MW	10kW-1MW	200kW-2MW
Efficiency	35%	29 - 42%	6 - 19%	25%	40 - 85%

6.3.3 No Need for Recharging - Fuel Cells

A huge advantage related to utilization of fuel cells is their non-existing requirement for electrical recharging. A fuel cell operates much like a battery, but the main difference is that a battery stores all its chemical energy inside before converting it into electricity. When these chemicals run out, the battery dies. Fuel cells, on the other hand, have the ability to produce electricity as long as fuel is supplied. Thus, it does not run down or require recharging, meaning that they are able to generate power almost indefinitely.

This characteristic is a huge advantage when fuel cells are utilized, especially when applied for transportation, as power generating systems for relatively small applications, such as forklifts. The fuel cell technology is well suited for forklifts due to their continuous supply of power, which is a major advantage for machines or vehicles with constant stops and starts.

6.3.4 Reliability, Availability, and Downtime - Gas Turbines

The most important aspect of a plant is high availability and reliability. In some cases, even more significant than efficiency. Both the availability and reliability have a major impact on the economy, since a high value of both will result in a low downtime and thereby a stable power generation. The availability factor for gas turbines fluctuate depending on size. Gas turbines with a power generation below 100MW have an availability factor between 94% - 97%, while gas turbines with a power production above 100MW have an availability between 85% - 89%[84]. The reliability of gas turbines is lower than the availability, around 92%[85].

A low reliability gives rise to high maintenance costs, and are often a greater economic factor than the high maintenance costs[84].

Several components influence the gas turbines availability and reliability, and thereby their downtime. The major components are combustor cans, first stage nozzles and first stage blades. Components such as controls, bearings, and couplings also influence the downtime[84].

6.3.5 High Power output, Power Density, and Power-to-Weight Ratio - Gas Turbines

Gas turbines have a fluctuating power output depending on application. The General Electric GE LM2500+DLE is one of the most common gas turbine installed at the NCS after year 2000, standing for approximately 80% of the total installed capacity at the Norwegian shelf. This type of turbine is able to deliver the required amount of power for daily use, as well as for operations, on oil and gas installations[2]. They are capable of delivering a power output of approximately 32MW[86].

Gas turbines also have a relatively high power density, which is their ability to deliver power. A high power density minimizes weight and size, hence provide a highly enhanced mobility. In addition, these gas turbines have a relatively high power-to-weight ratio, which is especially desirable when applied offshore where space is limited and weight requirements are strict. The power-to-weight ratio is used as a measurement of actual performance of any engine or power source, and is calculated by dividing the amount of generated power with the weight of the system[87].

6.3.6 Fuel Flexibility - Gas Turbines

Fuel flexibility is defined as the components or system's ability to burn a variety of fuels and immediately switch fuel during operation without reducing load or sacrificing power plant availability. One major advantage associated with fuel flexibility is that power plants may have a reliable operation on a variety of gaseous or liquid fuels, providing energy security in the event of fuel supply disruptions[88].

One major advantage with gas turbines are their fuel flexibility. Both commercial fuels, such as petrol, natural gas, propane, diesel, and kerosene, as well as renewable fuels, such as biodiesel and biogas, may be utilized in order to generate power[89].

Fuel flexibility results in less need for fuel reforming, hence, limiting the need for reforming equipment. Due to fuel flexibility, the risk for CO and CO_2 poisoning is removed. This is important since poisoning result in a decrease of efficiency, and thereby an increase in fuel consumption, hence higher operation costs.

6.3.7 Alternating Current - Gas Turbines

Electrical power generated in gas turbines are AC, a major advantage when the current is applied for larger systems, such as CHP systems and at oil and gas installations. This eliminates the need for an inverter, since the current already has the preferred condition. The only equipment needed is a transformer to scale the current up or down. The transformation allows the power to be transmitted effectively for long distances through power lines at high voltage and at as small currents as possible, reducing the energy losses, such as copper losses and iron losses[65]. The almost non-existing need for transformation equipment results in weight, space, and cost savings. It also results in less losses, since some losses arises when the current is converted.

6.4 Weaknesses

Weaknesses are the fuel cells and gas turbines negative characteristics. These characteristics are internal, and only consider the fuel cell or gas turbine itself. They do not take the environment and circumstances into consideration. The weaknesses of the fuel cell technology and gas turbines are listed in Table 6.3 below. Each of the listed weaknesses will be further explained in the following subsections.

Table 6.3: Weaknesses of gas turbines and fuel cells

Fuel Cells	Gas Turbines
Little fuel flexibility	Efficiency
Direct current	Maintenance requirements
Low open circuit voltage in a single fuel cell	Noisy
Inrush current	
Relatively low power output	
Possibility for CO poisoning	
Fuel cross-over	
Life span	

6.4.1 Open Circuit Voltage in a Single Fuel Cell, Direct Current, and Inrush Current - Fuel Cells

The theoretical OCV value for a single fuel cell differs depending on the operating temperature. A single fuel cell operating at low temperatures will have a theoretical OCV value around 1.2V while it would be lower, around 0.98V, for a fuel cell operating at high temperatures. However, it is found that the output voltage for fuel cells is around 0.7 when put to use. This is a low voltage output, meaning that a single fuel cell is unsuitable for application alone. Several fuel cell units are therefore required to achieve a usable current flow rate. This problem becomes even bigger when fuel cells are applied in large power generating systems, where the required number of fuel cells will be extensive.

Fuel cells are not able to deliver the required inrush current, which is a problem since the other electrical components in the electrical circuit require inrush current in order to be able to start. The electrical equipment on the installation therefore have to receive it from another energy power system. The requirement for extra equipment in the electrical circuit is not desirable, and will result in a higher cost as well as an increased weight and size of the construction.

DC is produced by the fuel cell stack, which rarely is suitable for direct connection to an electrical load. If the fuel cell is used to power equipment requiring AC, the DC will have to be converted to AC. This conversion process requires different components, such as an DC/AC inverter and a transformer, which will increase the costs and weigh of the fuel cell system. A small amount of the current will also be lost during the conversion and transformation.

6.4.2 Clean Fuel, Poisoning, and Fuel Cross-over - Fuel Cells

One weakness with some types of fuels cells, is the possibility for CO poisoning. Hydrogen-rich fuel utilized by fuel cells are either pure hydrogen or reformed fuel. CO is produced around the electrodes during the reforming process, as explained in section 3.6.2, and trace amounts of CO remain present in the flow fed to the electrodes. This is a problem for low operating fuel cells using platinum as catalyst, such as PAFC and PEMFC. CO has an affinity for platinum thus poisoning the catalysts when binding tightly to the catalyst, and by this lowering the overall performance of the fuel cell when hydrogen is blocked from reaching the catalysts. Further fuel processing with complete removal of CO is critical for these types of fuel cells, but the additional processes require design modifications of the systems, which again translates into higher overall costs[29]. By increasing the anode tolerance temperature, the CO absorption is reduced. At high temperatures, the CO is desorbed in reversed electro-catalyst reaction at the cathode[10].

Another type of poisoning is the one occurring in the AFC. This fuel cell technology utilizes an alkaline electrolyte consisting of potassium hydroxide(KOH) in a water based solution, where the hydroxyl ions(OH^-) travel across the electrolyte. The water based alkaline solution can absorb CO_2, which means that the fuel cell can be poisoned through the conversion of KOH to potassium carbonate (K_2CO_3). This will reduce the efficiency of the fuel cell[10].

Fuel cross-over is also a weakness associated with different fuel cell technologies. The phenomenon describes a situation when fuel flows from the anode to the cathode without reacting, causing the voltage to drop. Fuel cross-over results in a direct combustion of the fuel and oxygen and thereby a lowering of the efficiency. Additionally, fuel cross-over reduces the cells performance and durability and results in a shorter lifetime[90].

6.4.3 Relatively low Power Output - Fuel Cells

The different fuel cell technologies power output fluctuates between 1W to 10MW. Higher power outputs may be achieved by operation at higher temperatures, utilization of catalysts or by increasing the surface area of the electrodes. However, only two of the six fuel cell technologies are categorized as high operating temperature, thus the low operating temperature fuel cells may have problems achieving a high-power output.

The problem arises when fuel cell systems are applied for power generation for large applications, such as oil and gas installations, where the power demand is large. It can bee seen from Figure 6.2 that the output power is higher for the fuel cell technologies operating at higher temperatures, such as the PAFC, MCFC, and SOFC. The orange graph represents the fuel cells highest operating temperature, while the blue columns represents their maximum output.

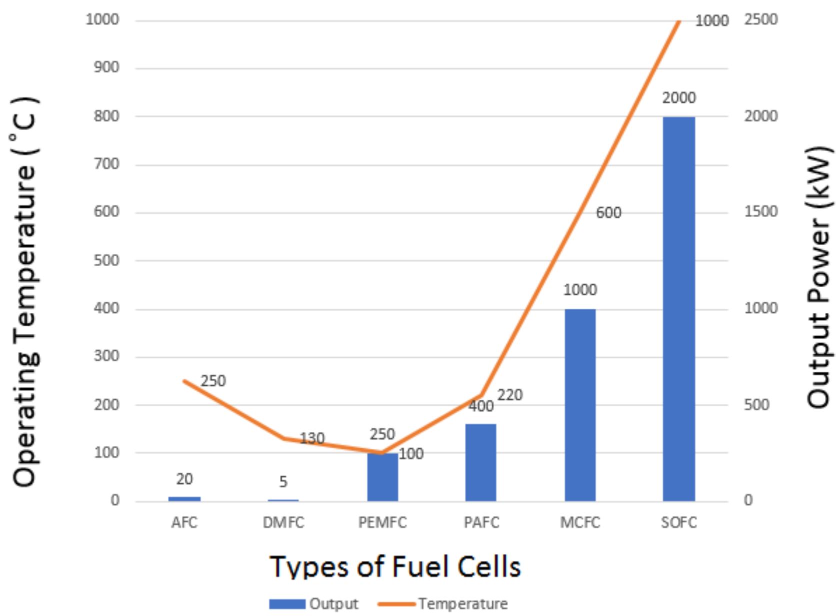


Figure 6.2: Comparison of maximum operating temperature and power output for the six different types of fuel cells[10]

6.4.4 Life span - Fuel Cells

The life span of a fuel cell is shortened by pulse demands, impurities of gas stream and fuel cross-over. It is rather difficult to specify the lifetime of a fuel cell and standard engineering measures such as MTBF do not really apply well. This is explained by the fact that a fuel cell's performance gradually deteriorates, meaning that their power drops steadily with time as the electrodes and electrolyte ages. Formally, the life of a fuel cell is over when it is no longer able to deliver the rated power[3].

When it comes to the lifetime of a fuel cell, two main operation alternatives are considered: continuous operation and cyclical operation. A fuel cell has a continuous operation when applied in stationary applications, such as CHP systems. A cyclic operation consists of frequent start and stop cycles, e.g. forklifts. The cyclic operation is considered more damaging than the continuous operation, due to differences in the voltage. The cycling operation has a more fluctuating voltage than the continuous operation, hence in theory a shorter lifetime[91].

6.4.5 Maintenance and Noise - Gas Turbines

A gas turbine consists of a compressor, a combustor, and a power turbine. Power is generated when compressed air is mixed with fuel and burned under constant pressure conditions. The hot gas then expands through a turbine, producing a shaft work output. The shaft work is used to drive the compressor and other devices coupled to the shaft. The upstream rotating compressor is coupled to a downstream turbine, with a combustion chamber in between[89]. The combustion process involves several moving parts which contributes to the need for maintenance.

Routine maintenance may be completed at scheduled intervals, typically quarterly or annually. The turbines require periodic inspection, repair, and replacement of components in order to achieve a high availability and reliability. A maintenance task related to moving parts are for instance oil change which are supposed to be performed every 150 hours[92]. The whole gas turbine has to be disconnected from the electrical circuit when parts of the turbine require maintenance, which may result in a less stable power production.

Maintenance performed on a gas turbine are normally maintenance inspection, operational maintenance tasks, and scheduled maintenance tasks. Maintenance inspection may be classified as standby, running, or disassembling inspections. The standby inspection is performed when the unit is not operating, including routine service of accessory systems and calibration of device. The running inspection is performed through observation of key operating parameters while the turbine is running. During a disassembling inspection, the turbine is opened for internal inspection of components. Operational maintenance tasks are typically performed on a daily, weekly, or monthly basis, while scheduled maintenance task can be carried out in calendar intervals. Major maintenance on the aero-derivative and industrial turbines are performed differently. Major maintenance on aero-derivative and smaller industrial gas turbines is normally performed off-site, while major maintenance on industrial gas turbines are usually on-site[82].

Gas turbines emit extreme levels of noise due to the high horsepower output and several moving parts, such as the high-speed rotating blades. The major contributors to the noise are intake, exhaust, and casing. The inlet and exhaust sound power levels range from 120 dB and up to 155 dB[93]. The extreme levels of noise make the gas turbines unsuitable for application inside, which limits its area of application. The noise pollution also results in a requirement for hearing protection.

6.4.6 Efficiency - Gas Turbines

The Brayton cycle is the thermodynamic process used in gas turbines. Two of the most significant performance parameters are the pressure ratio and the operating temperature. The efficiency can be optimized by increasing the ratio between the inlet air pressure and the compressor discharge pressure. Gas turbines designed for power generation can either be industrial or aero derivative. The differences between the two designs are application and pressure ratios. Industrial gas turbines have a typical pressure ratio up to 18:1, while the pressure ratio for the aero derivative gas turbines are up to 30:1. Hence the aero derivative gas turbines have a higher efficiency[94].

Another significant performance factor is operating temperature, where higher temperatures lead to higher efficiency. However, the inlet temperature is limited by thermal conditions which can be tolerated by the turbine blade metal alloy[94].

Due to the power requirement to drive the compressor, a simple cycle gas turbine normally has an efficiency around 30%. The relatively low efficiency results in a high fuel consumption, resulting in high operation costs. It is therefore desirable to increase the efficiency for a simple cycle gas turbine[94].

6.5 Opportunities

Opportunities are the fuel cells and gas turbines positive characteristics. These characteristics are external, meaning that they take the environment and circumstances into consideration. The opportunities for the fuel cell technology and gas turbines are listed in Table 6.4. Each of the listed opportunities will be further explained in the following subsections.

Table 6.4: Opportunities for gas turbines and fuel cells

Fuel Cells	**Gas Turbines**
Environmental friendly	Cost competitive
Large area of application	Well established and tested technology
Increasing demand for greener technology	CHP systems
CHP systems	Combined cycles
Market opportunities	Combined with carbon-saving technology
If successfully commercialized, may result in cost savings	
Can reduce economic dependence	
Stacking arrangements	

6.5.1 Market Opportunities, Cost Savings, and Economic Independence - Fuel Cells

Access to secure, reliable, and affordable energy is essential for economic growth, which means that the energy industry plays a key role in making global development and economic growth possible. The availability of cheap oil is declining as the most accessible resources are extracted, hence, further research on alternative energy is necessary or global energy security might be compromised. Such alternative energy can be fuel cells, which may help reduce the dependence of oil since the technology utilize hydrogen or natural gas as fuel[2]. The fuel cell technology can lead to increased energy security by reducing the oil consumption, cut oil imports, and by increasing the amount of the available electricity supply for a country[12].

Fuel cell systems are serving a variety of industries, including transportation, stationary and portable applications. The technology provides a wide range of benefits, such as low-to-zero emissions, high efficiency, reliable and resilient power, energy security, durability, and quiet operation. Market opportunities for the fuel cell technology will mainly depend upon the different technologies individual operating characteristics. The commercial and industrial sector, as well as the electric utility sector represent a large potential market for the technology. Integration with coal gasifiers and bottoming cycles for applications for base load central station is important in the long-range market for the technology in the electric utility sector[95].

Further development of the technology can result in cost savings due to its reduction of emission and high efficiency. A higher efficiency results in lower fuel consumption, which will lead to cost savings. A reduction of CO_2 will also result in cost savings, due to the CO_2 tax implemented by the Norwegian government.

6.5.2 Environmental Friendly and Greener Technology - Fuel Cells

A CO_2 tax was introduced by the Norwegian government in 1991 in an attempt to reduce emission from the petroleum sector. The CO_2 tax gave the petroleum industry a financial incentive to seek technological solutions to cut carbon emissions, reduce flaring, increase electrification, and look for more efficient solutions for power supply on offshore installations[17]. The demand for green technology are therefore increasing, and fuel cells may be a good alternative.

One of the main advantages with fuel cells are their minimum impact on the environment during operation. Since there are no combustion, fuel cells do not produce any of the pollutants emitted by boilers and furnaces. If direct hydrogen is used as fuel, the greenhouse gas emission is practically zero and the only by-products are electricity, water, and heat. However, it should be noted that emissions of CO_2 always are involved in the production of the hydrogen needed as fuel[3], as presented in Section 3.6. A small amount of CO_2 is produced if the fuel cell consumes natural gas or other types of hydrocarbons as fuel, but this is far less than from burned fuel[38][29].

6.5.3 Large Area of Application - Fuel Cells

It is clearly stated in Section 3.8 that the fuel cell technology has a wide area of application. The advantages of fuel cells are particularly strong for CHP systems, for mobile power systems, such as vehicles, and for electronic equipment. These areas are the major fields in which fuel cell technology is utilized. A key point for the technology is the wide range of application of fuel cell power, from systems of only a few watts up to systems of megawatts. The technologies range of application far exceeds all other types. Because of this fuel cells are quite unique as energy converters[3].

One main contributor regarding application area is the operating temperature. Low operating temperature fuel cells, such as the PEMFCs and DMFCs, generate small amounts of power and are therefore most suitable in portable electronic equipment. The PEMFC is also a low operating fuel cell, but due to its ability for a larger power generation, the technology is also suitable for transportation, such as cars and forklifts, and in domestic CHP systems. The low temperature operating fuel cells have a limited power production, but they are able to store a high-energy content in a small space. Thus, they are able to produce a small amount of power of energy over a long time period. They are therefore ill-suited for powering large vehicles, but well suited for use in application with modest power requirements. In addition, they have a fast start-up time, and are therefore suitable in equipment with frequent start and stop cycle.

The PAFCs operate at a higher temperature, and are mainly developed for medium-scale power applications, such as larger vehicles or relatively small CHP systems. The MCFCs and SOFCs are operating at high-temperatures and generate a higher amount of electricity, and are designed for large power utilities, such as in large CHP systems, CCP plants and buses.

6.5.4 Stacking Arrangement - Fuel Cells

Due to the low OCV for a single fuel cell, the cells may be connected in different arrangements, depending on application, to achieve a desired output voltage. The concept behind fuel cell stacking is explained in Section 3.5. The anode of one cell is connected to the cathode in the neighbor cell, either by utilization of bipolar plates, the tubular design or by utilization of planar stacking[3]. The stack can be configured in series, parallel or series parallel. The amount of current produced is proportional with the surface area of the membrane and the amount of fuel. Fuel cells are therefore easy to scale; the higher the number of fuel cells connected, the higher the voltage. In addition, the current produced depend on the area. The bigger the area, the more current generated[34].

The possibility for configuration of fuel cells in stacking arrangements makes it possible to increase or decrease the current and voltage delivered by the fuel cell system, increasing the area of application. Thus, the fuel cell system may be applied for power generation of small systems as well as lager ones. This is an important characteristic, making the fuel cell technology suitable for various areas of application.

6.5.5 Fuel Cells in CHP Systems

The net electrical efficiency for the various fuel cell technologies fluctuates between 30% to around 60%. However, when applied in CHP systems, the overall efficiency may be as high as 85% for some fuel cell types since the waste heat is captured and utilized[96]. The different fuel cell technologies with their electric efficiency and their efficiency when applied in CHP systems is presented in Figure 6.3. The blue colour represents the efficiency when the fuel cell is operating alone, while the orange one is when the fuel cell is utilized in a CHP system. It should be mentioned that the DMFC normally is not applied in CHP systems, as seen in the figure.

CHP systems are systems where power generation is combined with recovery and use of the waste heat. Exhaust gas including water condensation, stack cooling, anode-off gas combustion and reformer heat are the four primary potential sources of usable waste heat from a fuel cell system. The waste heat available from fuel cell systems generally represents 20% to 50% of the inlet fuel energy. The waste heat is, among other, used for domestic hot water applications and space heating. The hot exhaust gas from the fuel cells are also used, primary in recuperative heat exchange with the inlet processes gasses but can also be used directly for process drying. The high efficiency of fuel cell systems intends that the waste heat is only a small fraction of the inlet fuel's heating value[96].

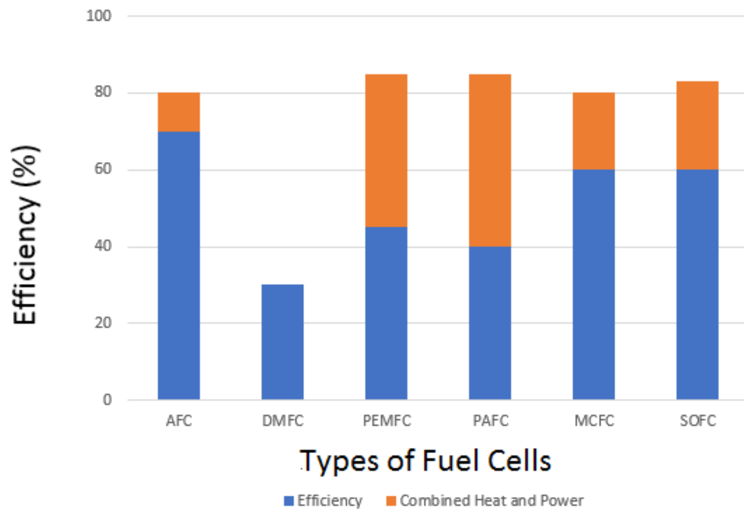


Figure 6.3: Efficiency of different fuel cell technologies when operating alone and in CHP systems[10]

6.5.6 Combined with Carbon-Saving Technology - Gas Turbines

The gas turbine technology can be combined with emission saving technologies, such as CCS, in order to reduce the CO_2 emission. The CCS technology is one of the most important technologies in the long-term work with reduction of the world's greenhouse gas emission from offshore activities. The technology separates the CO_2 from the emission before it is stored to avoid it from reaching the atmosphere. CCS is considered a cost-effective technology in order to achieve the world's climate goal, and is the only technology able to contribute to significant reduction of CO_2 emission[2].

The ability to combine gas turbines with emission saving technologies cause the gas turbine technology to be equally relevant even if the world is moving towards a greener shift and constantly requires greener technology.

6.5.7 Cost Competitive, Well Established, and Tested Technology - Gas Turbines

Gas turbines have had an increasing application during the past 40 years in the power industry, both among utilities and merchant plants, as well as in the petrochemical industry and utilities throughout the world. It is a natural power plant for offshore application due to its compactness, low weight, and multiple fuel application. There has been a large growth in the gas turbine technology in the last 20 years, caused by the growth of material technology, new coatings and cooling schemes which have resulted in an increased compressor pressure ration leading to a higher efficiency. The improved material technology also resulted in a higher operating temperature, hence a higher efficiency[84]

Multiple years of experience in design, analysis and testing of gas turbines, mainly related to the fields of thermodynamic, fluid dynamic and heat transfer, have resulted in a well-established and tested technology. The development within the technology has resulted in a cost competitive technology, where gas turbines, especially those applied for stationary applications, have the ability to generate electricity at a lower price than other power generating systems. In addition, the cost related to installation of gas turbine based facilities are among the lowest in fossil generation. Hence, gas turbines will, most likely, continue to play an important role in the power generating industry in the following years[84].

6.5.8 Combined Cycles and CHP Systems - Gas Turbines

Gas turbines may be configured in a simple cycle or as a combined cycle. The main difference between these two are the number of power cycles. The simple cycle consists of only one power cycle, while the combined cycle has several power cycles. This means that no provision for waste heat recovery in the single cycle exist, while it does for the combined cycle. The gas turbines can also be combined in an open or closed cycle. The main difference is the circulation of the working fluid. In the closed cycle is the working fluid circulated repeatedly within the turbine, while it in the open cycle is replaced again and again when flowing through the gas turbine[82].

Gas turbines may be used in a variety of configurations, such as in simple cycle operation, CHP operation, or combined cycle operation. In the single cycle operation is one or more gas turbines producing power alone, while in a CHP operation is a heat recovering heat exchanger used to recover the heat from the turbine exhaust and converting it into useful thermal energy, usually in the form of steam or hot water. If the waste heat is used to produce more useful work in a CHP cycle, the efficiency may reach 55% to 60%[94]. In the combined cycle operation is high pressure and high temperature steam generated from recovered exhaust heat and used to create additional power by utilization of a steam turbine[87]. The main advantage with these types of systems are their ability to provide both electric power and heat from a single fuel source. This results in an increased efficiency and thereby a lower fuel consumption.

6.6 Threats

Threats are the fuel cells and gas turbines negative characteristics. These characteristics are external, meaning that they take the environment and circumstances into consideration. The threats for the fuel cell technology and gas turbines are listed in Table 6.5. Each of the listed threats will be further explained in the following subsections.

Table 6.5: Threats for gas turbines and fuel cells

Fuel Cells	**Gas Turbines**
Not cost competitive	Not environmental friendly
Commercial competitors	Small area of application
Lack of front-runners	Increased CO_2 taxes
Lack of initiative-takers	Paris climate agreement
Dependence of government support	Desire for greener technology
Hydrogen production, storage, and transportation	
Lack of hydrogen infrastructure	
Fuel safety	
Lots of remaining work	
Only a few of the technologies are commercial	

6.6.1 Commercial Competitors and Cost - Fuel Cells

Cost is the biggest deterrent for the fuel cell technology and developers and manufactures are focusing on limiting the cost of both materials and manufacturing of their system. Investments costs for most fuel cells are around €10 000/kW, which is far more than for competitive power systems. The competitive cost targets of the market is around €700-1,500/kW for large stationary applications, and €3,000-4,000/kW for small stationary applications[97]. Hence, fuel cells cannot compare economically with more traditional energy technologies although rapid technical advancement is taking place. The reason is that despite all the advantages associated with application of fuel cell systems most fuel cell systems have commercial competitors[98]. In addition, most of the competing technologies are in the mature markets. An example is the stationary power market where the large generators based on gas or steam turbine technology are able to produce electricity at a lower cost than most fuel cell systems[3].

Another example is the ICE in the transportation sector. The ICE is a highly engineered and evolved technology, with a relatively low cost compared to fuel cell systems. Such competing technology sets the cost targets which fuel cell systems will have to meet in order for the technology to become commercially viable[3].

6.6.2 Dependence of Government Support - Fuel Cells

There is a continuous growth in the fuel cell industry, however, the industry remains small, fragile, and almost entirely driven by government support. Several countries in Asia, such as Japan, Korea, and China, have invested in fuel cells. Japan maintains its resolution on application of fuel cells, and continuous to draw in private corporations, while Korea tries to accomplish something similar. China too seems eager to step up the support for development of the fuel cell technology with a dramatic increase in fuel cell deployment side by side with ongoing support for science and technology. However, it is no surprise that Asia leads in development given the large investment and support by the government, as well as major private sector corporations[47].

The situation is different in Europe and North America where the situation continues at its typical pace. Enough support is provided to keep most of the participants alive, but not enough to contribute to commercial growth or to prove that the technology is not competitive[47]. Thus, the situation in Asia, Europe, and North America is that the fuel cell technology is dependent of government support to fund market development activities in addition to research and development in order to be able to compete with other power generating technologies.

6.6.3 Lack of Initiative-Takers and Front-Runners - Fuel Cells

One challenge associated with the fuel cell technology is the lack of a "halo" product such as Tesla's cars have been for the BEVs. Neither do fuel cells have the same strengths of advocacy and momentum[47]. The technology needs a typical front runner leading the way in order to make the technology more well-known so several participants want to contribute with more research and development. This is a requirement to make the technology competitive to other power generating systems.

Even though the overall growth in shipment and units continues to signal a positive growth in the fuel cell market, fuel cell companies continue to struggle towards profitability. The signing of the Paris agreement, and thereby the shift towards greener technology, is a positive sign for all technologies with carbon reduction meaning that all options for improvements ought to be pursued. However, the fuel cell technology lacks an initiative taker to turn intentions into action[47].

6.6.4 Hydrogen Infrastructure, Production, Storage, and Transportation - Fuel Cells

Leaving aside practical issues, such as manufacturing and material costs, at least two fundamental technical problems remain. One of them is distribution, transportation, and storage of hydrogen[99]. Hydrogen is a secondary energy source and has to be generated from fossil fuels. Several methods may be applied, all with one common disadvantage: CO and CO_2 as by-products.

Handling of hydrogen, like other flammable fuels, entails a number of hazards. Hydrogen is characterized by high volatility, high specific energy, and flammability in addition to low density, meaning that it disperses extremely rapidly and the ignition and detonation levels are not easily reached[29]. These properties contribute to difficulties associated with storage of a large mass of hydrogen in small spaces. They also make it difficult to liquify hydrogen[3]. However, hydrogen may be stored in several ways, both as hydrogen and by use of chemical hydrogen carriers.

The transportation methods may be the same as for natural gas, either through pipelines or by use of tankers, depending on the quantity and distance. One of the most conventional transportation methods for hydrogen is pipelines. However, the pipeline delivery infrastructure for hydrogen is relatively poor. Transportation of gaseous hydrogen by use of existing pipelines is a low-cost option for delivering large amounts of hydrogen. However, the high initial cost of new pipeline constructions represents a major barrier for expansion of the pipeline infrastructure able to deliver hydrogen.

Hydrogen is extremely flammable, particularly hydrogen gas fuel and liquid hydrogen, when mixed with even small amounts of air. Leakage is therefore a huge challenge associated with distribution, storage, and transport of hydrogen[39]. In order to proceed the growth in the fuel cell industry an even more robust hydrogen infrastructure has to be established[47].

6.6.5 Fuel Safety - Fuel Cells

There exist concerns related to both types of fuels utilized by fuel cells, however, more concerns are related to utilization of hydrogen than natural gas.

Hydrogen has both unique physical and chemical properties, resulting in benefits and challenges related to its widespread adoption as a fuel. It has the lowest molecular weight of any gas, and is therefore 14 times lighter than air and rises at a speed of almost 20 m/s, six times faster than natural gas[100]. In addition, it has the highest thermal conductivity, and the lowest viscosity and density of all gases. These properties result in a fast leak rate. Actually, hydrogen possesses a leaking ratio which is 2.8 times faster than methane and 3.3 times faster than air[3]. A hydrogen leakage is difficult to detect by human senses since hydrogen is odorless, colorless and tasteless[100].

Hydrogen is also a highly volatile and flammable gas, and a mixture of air and gas may detonate. It burns very quickly, and under optimal combustion requirements the energy required to initiate hydrogen is significantly lower than for other types of fuels. Hydrogen flames do have a low radiant heat, thus, a hydrogen fire has less radiant heat than a hydrocarbon fire[100].

Methane has a relatively high energy density, and a leakage of methane is not desirable due to its extreme flammability. When mixed with air it might form an explosive mixture. It also possesses a high global heating potential, which is 25 times higher than that of CO_2, indicating that even small amounts of methane contribute significantly to enhanced greenhouse effect[2].

Key properties related to safety of hydrogen and methane, as well as propane, is presented in Table 6.6. It can be seen that the major problem with hydrogen is related to its minimum ignition energy, which is far less than for methane and propane, indicating that a fire could be started very easily. Another hazard is the rather great range of concentration needed to cause detonation. Altogether, from the point of view of potential danger hydrogen and methane seems much the same as other fuels. Hydrogen even has a comparative advantage from a safety point of view, the low density. This indicates that hydrogen is so light that it rapidly disperses upwards, as mentioned earlier, and thereby making it difficult to achieve the concentration levels necessary for ignition or detonation[3].

Table 6.6: Properties relevant to safety for hydrogen, methane and propane[3].

	Hydrogen	**Methane**	**Propane**
Density, kgm^{-3} at NTP	0.084	0.65	2.01
Ignition limits in air, volume % at NTP	4.0 to 77	4.4 to 16.5	1.7 to 10.9
Ignition temperature, °C	560	540	487
Min. ignition energy in air, MJ	0.02	0.3	0.26
Max. combustion rate in air, ms^{-}	3.46	0.43	0.47
Detonation limits in air, volume %	18 to 59	6.3 to 14	1.1 to 1.3
Stoichiometric ratio in air	29.5	9.5	4.0

Overall, like all other fuels, hydrogen and methane have to be carefully handled. By taking all the factors mentioned above into consideration, hydrogen and methane do not present any greater potential for danger than any other flammable liquids or gases used as fuel today. However, safety consideration must be contemplated when designing fuel cell systems and they need to be designed in such a way that the danger for leakage is minimal[3].

6.6.6 Lots of Remaining Work - Fuel Cells

Lots of work have to be performed in order to make the fuel cell technology competitive with other power generating systems. Several of the currently available fuel cell technologies are still in the prototype stage and not yet validated. Four out of six fuel cell types are commercially available: PAFC, PEMFC, MCFC and SOFC. More research and studies have to be executed, and as mentioned earlier, governmental support and a front-runner are necessary. Cost competitiveness may be the most important aspect in order to make the technology competitive.

However, a lot of work remains for the technology to be applied offshore. There does not exist any suitable fuel cell technology for utilization offshore, and a combination of different technologies has to be developed. Power generating systems applied offshore has to meet different requirements, such as weight, size, efficiency and output, in order to be suitable. Several projects are looking into this problem, however, it may take a while to solve.

6.6.7 Paris Climate Agreement, CO_2 Taxes, and Environment - Gas Turbines

A gas turbine is a type of internal combustion engine where the electricity is generated through a combustion, resulting in emission. As a matter of fact, gas turbines alone represent 81% of all emissions from offshore installations[14]. It is desirable to reduce the amount, and measures to reduce emissions should be directed towards making gas turbines more energy efficient, less carbon intensive and more sustainable[2].

With the signing of the Paris Climate agreement in 2015 and the introduction of the CO_2 tax in 1991, an increasing demand for substantial changes in our energy systems has occurred. Burning of fossil fuels is a significant driver of global climate change and the demand for greener technology has increased since the world economy needs to shift from a carbon dependent economy to a more carbon efficient economy in order to combat climate change[2].

According to the Norwegian Environmental Agency, the total emission of CO_2 from the NCS was approximately 11 635 190 tons in 2015. The emission has increased between 2011 and 2015 with approximately 1 180 580 tons CO_2[101]. The total cost of the CO_2 emission between 2011 to 2015 and the associated CO_2 tax is presented in Table 6.7, indicating that the emission costs the industry several billion NOK every year[101].

This green shift may be a threat to existing technologies for power generation and can result in modifications or replacement of these. As emissions from the use of gas turbines is such a significant polluter and reducing greenhouse gasses is desirable, a feasible solution may be to replace gas turbines with fuel cells.

Table 6.7: Total emission from the NCS with associating CO_2-tax between 2011 to 2015

Year	CO_2**-tax [NOK/ton]**	**Emission in 1000 ton**	**Total cost [billions NOK]**
2011	200	10 454,61	2,091
2012	200	10 476,39	2,095
2013	410	10 984,40	4,504
2014	410	11 125,58	4,561
2015	490	11 635,19	5,701

6.6.8 Small Area of Application - Gas Turbines

Gas turbines are mainly applied for aircraft propulsion, power generation and mechanical drive. Gas turbines applied for mechanical drive are widely used to drive pumps and compressors, especially in the oil and gas industry. Those used for power generation are normally utilized for stationary power generation or for power generation in propulsion systems[84].

However, gas turbines applied for power generation in transportation are only used in large systems, not in buses, cars, or forklifts. The main reason for this is their large noise pollution. Overall, gas turbines may be utilized for large transportation applications, as well as in stationary applications. However, they are not commonly used for power generation in portable applications.

6.7 SWOT Analysis - Results and Discussion

The strengths, weaknesses, opportunities and threats associated with gas turbines and fuel cells have been listed and discussed in the previous sections, and the most important ones for fuel cells related to application offshore are listed in Table 6.8. It should be noticed that for every weakness lies an opportunity, and equally, for every strength lies a threat. This section will contain a discussion on whether the fuel cell technology is able to satisfy the most important requirements for offshore power generating systems. The emphasis will be placed upon important requirements the technology has to satisfy in order to be applied offshore. Some of the most important requirements for power generating systems offshore are ability to deliver the required amount of power, efficiency, emissions, maintenance, availability and reliability, downtime, costs, and fuel supply. Hence, the fuel cell technology has to be able to meet these requirements.

Table 6.8: SWOT analysis results

Strength	**Weaknesses**
• High efficiency • High availability and reliability • Low downtime • Low maintenance	• Low OCV in a single fuel cell • Little fuel flexibility • Relatively low power output • Inrush current • DC • Life span
Opportunities	**Threats**
• Environmental friendly • Large area of application • Increased demand for green technology	• Not cost competitive • Commercial competitors • Fuel safety • Dependence of government support • H_2 production, transportation and storage

Power Demand

The power generating system offshore, whether it is gas turbines or fuel cells, need to be able to meet the energy demand offshore. The daily requirement for maintaining production is around 30MW, while it for days where operations, such as drilling, are executed increases[102]. The power output for the different fuel cell technologies fluctuates between 1W to 10MW, which is a problem when applied for large systems. Gas turbines applied for large power generation are able to deliver a power output higher than 100MW, indicating that the fuel cell technology has to improve before it is able to meet the power requirements for large applications.

Another obstacle with the fuel cell technology is its low OCV in a single cell. The output voltage of a single fuel cell is as low as 0.7V, meaning that a single cell is unsuitable for application alone. This becomes an even bigger problem when fuel cells are applied as energy systems on offshore installations, where the energy demand is high. The fuel cell then has to be stacked since the voltage increases with number of cells and the amount of current generated depend on the area. Due to the high power requirements, the number of cells in the stack is extensive, resulting in an increased weight and size.

The number of cells in the fuel cell stack might be a problem since the weight and size requirements for power generating systems offshore are strict. Gas turbines have a relatively high power-to-weight ratio and a high power density, which helps minimize the size and weight.

Fuel cells generate DC, another challenge when applied offshore. The end-users require AC, meaning that a DC/AC inverter is necessary along with a transformer to scale the voltage up or down. The conversion and transformation of the current include losses, indicating a reduced efficiency. The need for more equipment results in increased costs, as well as an increased weight. Gas turbines, on the other hand, generate AC and thereby remove the need for an inverter. Most components in an electrical circuit require inrush current in order to start. Another obstacle with fuel cells, as opposed to gas turbines, is their inability to deliver this. This raises the need for an alternative energy source, hence extra equipment is needed. This is a drawback on offshore installations where space is limited and the weight requirement is strict.

Based on the above remarks, it can be concluded that there exist several challenges related to electrical integration of fuel cells. In addition, several challenges related to the technologies ability to individually meet the energy demand offshore arises, and as of today there do not exist any fuel cell technology able to meet the energy demand offshore and at the same time meet the requirements regarding electrical integration, size, and weight.

Efficiency

It is desirable with as high efficiency as possible since this results in a lower fuel consumption and thereby cost savings. The efficiency for both technologies can be increased by increased operating temperatures. One of the main advantages with fuel cells are their ability to convert the chemical energy in the fuel into electricity without combustion. The direct conversion results in a high efficiency compared to other conventional thermo-mechanical systems. A certain amount of power is required to drive the compressor in the gas turbine, hence the efficiency of gas turbines is lower than the one for fuel cells. The efficiency for the different fuel cell technologies fluctuates between approximately 35-80%, while the efficiency for gas turbines is around 30%.

With this said, it can be concluded that the fuel cell technology is able to achieve the desired efficiency for power generating systems offshore and that they are a suitable competitor to gas turbines in regard to this area. They may even be better than gas turbines since they are able to achieve a higher overall efficiency.

Fuel Supply

Gas turbines have a great fuel flexibility which means that various different fuel types can fuel them. This is an advantage compared to fuel cells, which possess little fuel flexibility since they can only be fuelled by hydrogen or natural gas.

Natural gas is easily accessible on offshore installations extracting natural gas. The gas must be processed before used, which takes place on the installation. Even if natural gas is not extracted on the installation, transportation and storage is usually not problematic.

By contrast, transportation and storage of hydrogen are problematic. Hydrogen is a secondary energy source, and has to be generated from other primary energy sources. The reforming process requires extra equipment, and as the hydrogen infrastructure is limited, several obstacles regarding transportation and storage exist. A further obstacle is the flammability of hydrogen. Hydrogen, and particularly hydrogen gas and liquid hydrogen, is extremely flammable when mixed with even small quantities of air. Leakage is therefore a significant challenge associated with distribution, storage, and transport of hydrogen.

Based on the remarks given above, it may be concluded that production, transportation, and storage of hydrogen on offshore installations are challenging. It is therefore an advantage if the power generating systems offshore possess a certain fuel flexibility. This indicates that gas turbines still have the upper hand in this area. However, it should be mentioned that the development of the hydrogen infrastructure is in progress, and will improve just like the infrastructure of gas has over the last decades.

Emission

One of the main reasons for replacing gas turbines with other power generating systems offshore are their high emission of CO_2 as they represent 81% of the total emission from offshore installations. After the introduction of the CO_2 tax by the Norwegian government in 1991, and the signing of the Paris climate agreement in 2015, an increasing demand for greener technology has occurred. Such a technology can be fuel cells where hydrogen or natural gas is utilized as fuel. The conversion of the chemical energy in the fuel take place without a combustion, resulting in almost zero emission. However, utilization of natural gas as fuel results in small amounts of emission, but these are less than those from gas turbines.

Fuel cells have little, or none, fuel flexibility and it might be worth noticing that production, storage, and transportation of hydrogen results in small amounts of CO_2 emission. Gas turbines are able to utilize several types of fuels, which is an advantage. However, emission due to production, storage, and transportation of hydrogen are small compared to operation of gas turbines. Gas turbines are the largest emitter on offshore installations, hence the fuel cell technology is better than the gas turbine technology regarding emission.

Maintenance, Availability, Reliability and Downtime

One of the most important aspect of a power generating system is availability and reliability. Both have a significant influence on the economy since a high value of both results in a low downtime, and thereby a stable power production. Both technologies have a high availability and reliability, hence, they are relatively equal in that aspect.

However, the need for maintenance differs between the two technologies. Due to few or none moving parts, the requirement for maintenance for fuel cells is low. Gas turbines, on the other hand, have several rotating parts and the requirement for maintenance is higher. Routine maintenance for fuel cells and gas turbines is typically performed quarterly or annually. In addition, gas turbines require extra maintenance due to the moving parts.

Fuel cells are installed as modules, i.e. a 30MW fuel cell systems consist of 10 modules each delivering 3MW. Spare modules are often stored, making it possible to deliver 10-20% more power than required. Maintenance of fuel cells are performed by replacing one of the modules in the stack with a spare one, hence, maintaining a stable power production. Maintenance of gas turbines are executed differently and the whole gas turbine has to be taken out of production if some parts of the gas turbine require maintenance, resulting in a longer downtime[73].

It should also be mentioned that less need for maintenance means less requirement for maintenance personnel, which results in lower maintenance cost. Another advantage with components and systems requiring less maintenance is related to safety. Less need for maintenance crew on the offshore installations means a lower visit frequency, resulting in a risk reduction for personnel related to transportation to and from the installation and a risk reduction related to staying on the installation.

It can be concluded that both fuel cells and gas turbines are able to meet the requirement regarding availability and reliability offshore. However, maintenance of fuel cells and gas turbines is carried out differently resulting in differences in downtime. Maintenance tasks are easier to perform for fuel cells than gas turbines due to the module structure of fuel cell systems. The conclusion may be that fuel cells satisfy the requirement related to maintenance and downtime offshore as good as, or even better, than gas turbines.

Costs

The main obstacle to the fuel cell technology is its high costs. Considering that the technology is relatively "new", a lot of work remains related to cost reductions, such as materials and manufacturing. The investment cost for the technology is tremendous compared to other power generating technologies. In fact, the investment cost for the technology is around €10 000/kW while it for the competitors fluctuate between €700-1500/kW for large stationary applications and €3000-4000/kW for small stationary applications[97]. Gas turbines, on the other hand, are able to deliver power at lower costs than other power generating systems, especially for stationary applications. The technology is also one of the technologies with the lowest installation costs.

This indicates that the fuel cell technology is not cost competitive with other power generating technologies, such as gas turbines, at the present and that the technology do not satisfy the cost requirement for offshore application.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

It is challenging, if not close to impossible, at this point with the existing information to draw a conclusion regarding the feasibility of replacing gas turbines with fuel cells as power generating system on offshore installations in the future. While the fuel cell technology is applied in various applications such as portable, stationary and transportation, it has never been utilized offshore.

Power generating systems on offshore installations have to meet a wide range of existing requirements such as demands regarding power output, efficiency, costs, maintenance, size, weight, and emission. None of the existing fuel cell technologies are yet able to individually satisfy these demands, and the development of a fuel cell stack consisting of two or more of these technologies are therefore necessary.

However, several recommendations regarding application of fuel cells offshore may be presented. A SWOT analysis has been conducted in order to examine the strengths, weaknesses, opportunities, and threats for the technology according to the demands placed on the power generating system offshore. The findings are then discussed, and recommendations are given accordingly.

The SWOT analysis indicates that the fuel cell technology is equally good to, or even better, in some areas than gas turbines while it is insufficient in others. Fuel cells are able to compete with gas turbines in areas such as efficiency and emission due to their ability to convert the chemical energy in the fuel into electricity without combustion. The efficiency for fuel cells is generally higher than for gas turbines, resulting in a lower fuel consumption, hence cost-savings.

Both technologies are close to equal when it comes to reliability and availability, however, fuel cells have an advantage over gas turbines when it comes to maintenance and downtime. This is because fuel cells in a fuel cell system are delivered as modules, which means that maintenance tasks are simplified.

On the other side, fuel cells are not competitive with respect to power output, costs, and fuel supply. Fuel cells are not able to deliver the required power, which is a vital obstacle for the application of the technology. A further obstacle for the technology is the financial costs since the installation costs as well as the operation cost are considerably higher than those for gas turbines. Utilization of hydrogen as fuel is also an obstacle due to a limited hydrogen infrastructure.

A further challenge is the electrical integration of fuel cells. The end-users of the produced power require inrush current in order to be able to start. Fuel cells, however, are not able to deliver this current. Another minor obstacle with the technology is the production of DC since the consumers on offshore installations require AC. Additional equipment used to convert the DC to AC is therefore needed. The final obstacle regarding electrical integration is the low OCV produced by a single fuel cell, making the fuel cell unsuited for application alone. Several cells are required in order to achieve a satisfying voltage and current level. This is particularly a problem when fuel cells are utilized for large applications, such as offshore installations, where multiple cells are required. The extended number of cells in the stack increases the weight and size of the fuel cell system, which is a major problem when the fuel cell system is applied offshore.

Based on the remarks given above, the existing technology and the findings from the SWOT analysis, it can be concluded that further research and development may result in a fuel cell technology that is able to compete with gas turbines as power generating system offshore in the future. However, several obstacles, with output, emission and electrical integration being the most important ones, have to be overcome in order for the technology to be viable option to gas turbines.

However, the technology has future potential. If the technical challenges are successfully addresses so that fuel cells meet the offshore industry's requirements, fuel cells will become a viable competitor to gas turbines. If the environmental benefit is as significant as expected to be, the fuel cell technology could be an important way in which the petroleum industry adjusts to global climate change.

7.2 Recommendations and Further Work

In order for the fuel cell technology to be a true opponent to gas turbines for application offshore further research and development is essential. As of today, none of the existing fuel cell technologies are able to meet the demands placed on power generating systems offshore. Further development of a fuel cell system combining two or more of the already existing technologies are therefore necessary.

A thorough comparative study examining the characteristics of the six major types of fuel cells can be conducted. This can be done in order to decide which of the technologies that are best suited for offshore application.

Another obstacle for the technology is costs. Further development is therefore essential to achieve a cost reduction in order to make the technology cost competitive to other power generating systems. This may be accomplished in several ways such as reduction of cost associated with materials and manufacturing. Several economic studies regarding fuel cell systems have been conducted in the recent years, but these are not enough. A lot of the information related to fuel cell components is concealed, therefore, a detailed study of the economics of these systems is required.

By obtaining a "halo" product, exactly as Tesla is for batteries, the technology may be more familiar to the public and commercialization of all the different fuel cell types may be easier to accomplish. This may result in an increase in demand, hence, a reduction of production costs.

A development of production, storage, and transportation of hydrogen is necessary. All the different segments result in emission of greenhouse gases, and it is desirable to reduce these as much as possible in order to make the fuel cell technology as environmental friendly as possible. This raises the need for an improvement of the hydrogen infrastructure.

The remarks given above are just some of the actions which can be relevant in order to develop a fuel cell system for application offshore. Overall, further development of the fuel cell technology requires additional research as well as an increased economic support from the governments and private corporations.

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