HYDROGEN-FIRED GAS TURBINE FOR POWER GENERATION WITH EXHAUST GAS RECIRCULATION

Emission and economic evaluation of pure hydrogen compare to natural gas

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HAMSE HASSAN
ABSTRACT

The member states of European Union aim to promote the reduction of harmful emissions. Emissions from combustion processes cause effects on human health and pose environmental issues, for example by increasing greenhouse effect. There are two ways to reduce emissions; one is to promote renewable energy sources and the other to utilize more effectively the available fossil fuels until a long-term solution is available. Hence, it is necessary to strive for CO2 mitigation technologies applied to fossil fuels. Low natural gas prices together with high energy efficiency have made gas turbines popular in the energy market. But, gas turbine fired with natural gas come along with emissions of CO2, NOx and CO. However, these disadvantages can be eliminated by using gas turbine with pre-combustion CO2 capture, separating carbon from the fuel by using fuel reforming process and feeding pure hydrogen as a fuel. Hydrogen fired gas turbines are used in two applications such as a gas turbine with pre-combustion CO2 capture and for renewable power plants where hydrogen is stored in case as a backup plan. Although the CO2 emissions are reduced in a hydrogen fired gas turbine with a pre-combustion CO2 capture, there are still several challenges such as high flame temperatures resulting in production of thermal NOx.

This project suggests a method for application of hydrogen fired gas turbine, using exhaust gas recirculation to reduce flame temperature and thus reducing thermal NOx. A NOx emission model for a hydrogen-fired gas turbine was built from literature data and used to select the best operating conditions for the plant. In addition, the economic benefits of switching from natural gas to pure hydrogen are reported. For the techno-economic analysis, investment costs and operating costs were taken from the literature, and an economic model was developed. To provide sensitivity analysis for the techno-economic calculation, three cases were studied. Literature review was carried out on several journal articles and websites to gain understanding on hydrogen and natural gas fired gas turbines.

Results showed that, in the current state, pure hydrogen has high delivery cost both in the US and Europe. While it’s easy to access natural gas at low cost, therefore in the current state gas turbine fired with natural gas are more profitable than hydrogen fired gas turbine. But, if targeted hydrogen prices are reached while fuel reforming process technology are developed in the coming future the hydrogen fired gas turbine will compete seriously with natural gas.

Keywords:
harmful emission, natural gas, fuel reforming process, hydrogen fired gas turbine, exhaust gas recirculation, techno-economic analysis
PREFACE

This thesis work is done at Mälardalens University, the topic is proposed by prof. Konstantinos Kyprianidis. The project presents a method to achieve low NOx emission from general gas turbine operating with pure hydrogen. The method exhaust gas recirculation is proposed to reduce flame temperature and thus the produced NOx. Main objective of this thesis is to compare pure hydrogen fired gas turbine with exhaust gas recirculation with traditional natural gas fired gas turbine, to highlight differences in economic feasibility and environmental impacts. The focus was to compare how emissions, operating cost and overall investment costs will differentiate. At the end to make verdict whether hydrogen fired gas turbine could challenge natural gas in the coming future. We would like to thank our mentor Valentina Zaccaria, thanks for the motivation and the help you gave us. We would also like to thank our examiner Eva Th.

Västerås in May 2018

Nemir Gibrael, Hamse Hassan
SUMMARY OF THE REPORT

This degree project is about hydrogen-fired gas turbine with exhaust gas recirculation. Increased world's population along with urbanization resulting in increased energy demand. Therefore, long term solutions such as renewable energy together short term or backup energy will be necessary in the coming future. The suggestion in the report is to use the pure hydrogen as a fuel for gas turbine instead of traditional natural gas.

The main objective is to compare pure hydrogen gas with natural gas to highlight difference in economic and environmental impact. While presenting a method to achieve low NOx emissions from gas turbine operating with hydrogen as fuel. Proposed method in the report is exhaust gas recirculation (EGR), which gives the option to reduce the oxygen content while reducing the flame temperature, and this is possible by recirculating a part of the exhaust gas. EGR is a process where the exhaust gas is mixed with the inlet air either internally or externally.

In order to compare pure hydrogen with natural gas a wide literature review was conducted, for the economic calculation investment and fuel cost was found among the review papers. Furthermore, the numerical data was analysed using Microsoft Excel. Three cases were studied where the first case includes three gas turbines located in the US with natural gas, delivered hydrogen and fuel reforming process at gas turbine plant. Current and expected market trends for pure hydrogen are highlighted and used for a sensitivity analysis. The second case include the same gas turbines mentioned above but located in Europe with average electricity prices taken from Sweden and Germany. Finally, the third case include exhaust gas recirculation (EGR) introduced for 40 MW hydrogen fired gas turbine located in US.

In summary, the project is divided into two parts. Where the first part focuses on emissions of the gas turbine cycle operating mainly on pure hydrogen compared to natural gas fired gas turbine. While the second part will include the techno-economic calculations. Regarding the emission model, the results obtained with different equivalence ratios show that highest NOx formation is reached at 0.5 ratio. The higher the ratio becomes the less NOx is created. Increasing the EGR from 0 to 60% is equivalent to increase the equivalence ratio from 0.2 to 0.65, which is the way to ensure NOx<1ppm at the selected turbine inlet temperature (TIT).

For the techno-economy, results for case 1 show that with the current price hydrogen is not competitive with natural gas because of the high fuel costs. The hydrogen fired gas turbine could challenge natural gas in the future when hydrogen price will reduce, but in the current market there is a huge difference in fuel costs. For case 2 a similar comparison as case 1 was done but for the European market. The results show that with the current price hydrogen is much more expensive than natural gas. But, in order to make the hydrogen fired gas turbine more competitive, an alternative of fuel reforming process installation is studied. A comparison between fuel reforming with current available technology and future fuel reforming was made. The results show that it can be economically feasible with current hydrogen production price compared to delivered cost of the hydrogen, but the benefits are still less than natural gas. Comparing long-term goal for hydrogen price with expected future production price, both alternatives have the potential to compete with natural gas, and higher
economic benefits are reached with the future hydrogen price. In all cases, the larger turbine provided a better return. The third case analysed the 40 MW gas turbine located in the US including the EGR, the purpose was to see the difference that EGR would make on the economic calculations shown in case 1. With EGR less fuel was needed compared to case 1, which led to an increase in economic return. 60 and 30% of EGR rates were tested. Results 60% EGR rate showed that required fuel decreases by 23% and the NPV increased by 28%. The highest economic benefits are obtained with future hydrogen price. Thus, we can conclude that the 40 MW plant with TIT=1670K and EGR=60% could be a feasible solution in the future US scenario to integrate hydrogen in the energy market, both from an environmental and economic perspectives.
SAMMANFATTNING OF RAPPORTEN

Detta examensprojekt handlar om väteeldad gasturbin med avgasrening. Ökad världsbefolkning tillsammans med urbanisering resulterar i ökad efterfrågan på energi, vilket resulterar i att det kommer sökas långsiktiga lösningar så som förnybara energikällor men även kortsiktiga lösningar kommer att vara nödvändiga. I denna rapport föreslås det att använda rent väte som ett bränsle för gasturbin istället för traditionell naturgas.

Syftet med denna rapport är att jämföra ren vätgas med naturgas för att betona skillnaden i ekonomisk och miljömässiga påverkan. Samtidigt som man presenterar en metod för att uppnå läga NOx-utsläpp från gasturbin som arbetar med väte som bränsle. Föreslagen metod i rapporten är avgasåtercirkulation (EGR), som ger möjlighet att minska syrehalten och detta är möjligt genom att recirkulera en del av avgasan. EGR är en process där avgasen blandas med inloppsluften antingen intern eller externt.

För att jämföra ren väte med naturgas genomfördes en omfattande litteraturgranskning, Gällande den ekonomiska beräkningar hittades investering och bränslekostnader bland granskningshandlingarna, sedan vidare analyserades de numeriska data med hjälp av Microsoft Excel. Tre fall studerades där det första fallet omfattade tre gasturbiner i USA med naturgas, levererad väte- och bränslereformeringsprocess vid gasturbinanläggning. Aktuella och förväntade marknadsutvecklingar för rent väte framhävs och används för en känslighetsanalys. I den andra fallet som studerades hade man samma gasturbiner som nämndes ovan men i det här fallet låg gasturbinen i Europa och elpriserna var genomsnittliga elpriser tagen från Sverige och Tyskland. Slutligen i tredje fallet ingick det avgasåtercirkulation (EGR) infört för 40 MW väteeldad gasturbin belägen i USA.

Sammanfattningsvis är projektet uppdelat i två delar. Där den första delen fokuserar på utsläpp av gasturbinerna som huvudsakligen arbetar på rent väte jämfört med naturgaseldad. Medan den andra delen kommer att inkludera de teknokonomiska beräkningarna. När det gäller utsläppsmodellen visar resultaten som erhållits med olika ekvivalensförhållanden att högsta NOx-bildningen nås vid förhållandet 0,5. Ju högre förhållandet blir desto mindre NOx skapas. Ökning av EGR från 0 till 60% motsvarar ökad ekvivalensförhållandet från 0,2 till 0,65 vilket kan vara ett sätt att säkerställa NOx <1 ppm vid den valda turbininloppstemperaturen (TIT).

När det gäller teknokonomi resultatet för fall 1 visade att med dagens pris är vätgas inte konkurrenskraftigt med naturgas på grund av de höga bränslekostnaderna. Vätegaseldad gasturbin kan utmana naturgas i framtiden när väte priset har minskat, men i den nuvarande marknaden är det en stor skillnad i bränslekostnaderna. I fall 2 gjordes en liknande jämförelse som i fall 1 men för den europeiska marknaden. Resultaten visade att med dagens pris är vätgasen mycket dyrare än naturgas. Men för att göra väteeldade gasturbinen ännu mer konkurrenskraftig, studeras ett alternativ till att införa bränslereformerings process där vätgas kommer att framställas vid gasturbinanläggningen. En jämförelse mellan bränslereforming med nuvarande tillgänglig teknik och det förväntade utvecklingen i närmaste åren gjordes. Resultaten visade att det kan vara ekonomiskt genomförbar med nuvarande väteproduktionspris jämfört med leveranskostnaden för vätgas, men fördelarna är fortfarande mindre än naturgas. Jämförelsen mellan långsiktigt mål för väte och förväntade
framtidaproduktionspris visade sig att båda alternativen har möjlighet att konkurrera med naturgas samtidigt som ekonomiska fördelar uppnås med framtida väte priset. I de studerade fallen kunde man dra slutsatsen att den större turbinen har bättre avkastning. Det tredje och sista fallet som analyserades var 40 MW gasturbinen i USA, med inklusive EGR, där syftet var att se skillnaden som EGR skulle göra på de ekonomiska beräkningarna som visades i fall 1. Resultat visade att med EGR var bränslebehovet mindre jämfört med fall 1, vilket resulterar i en ökning av den ekonomiska avkastningen. 60 och 30% av EGR-hastigheterna testades. Resultatet av 60% EGR-hastighet visade att det önskade bränslet minskar med 23% och medans investeringslönsamheten ökade med 28%. De högsta ekonomiska fördelarna erhålls med framtida väte priset. Således kan vi dra slutsatsen att 40 MW-anläggningen med TIT = 1670K och EGR = 60% kan vara en genomförbar lösning i det framtida amerikanska scenariot för att integrera vätgas på energimarknaden, både ur miljö- och ekonomiska perspektiv.
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DESIGNATIONS

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<th>Description</th>
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<tr>
<td>T</td>
<td>Temperature</td>
<td>K</td>
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<tr>
<td>P</td>
<td>Pressure</td>
<td>kPa</td>
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ABBREVIATIONS

<table>
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<th>Description</th>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
</tr>
<tr>
<td>CC</td>
<td>Combined cycle</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid oxide fuel cell</td>
</tr>
<tr>
<td>GT</td>
<td>Gas Turbine</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
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<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
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<td>SESMR</td>
<td>Sorption Enhanced Steam Methane Reforming</td>
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<td>Abbreviation</td>
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<tr>
<td>SMR</td>
<td>Steam Methane Reforming</td>
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<td>SCR</td>
<td>Selective Catalytic Reduction</td>
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<tr>
<td>DLN</td>
<td>Dry Low NOₓ</td>
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<tr>
<td>RCCP</td>
<td>The European Climate Change Program</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>HPT</td>
<td>High pressure turbine</td>
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<tr>
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<td>Low pressure turbine</td>
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<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
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1 INTRODUCTION

In the recent years, the concern about carbon dioxide (CO2) emissions has increased due to global warming. The Member States of the European Union are aiming to reduce the greenhouse effect and find renewable energy to replace fossil fuels. One of the options is to focus on using the renewable energy sources available in order to reduce utilization of fossil fuel. However, statistics show that currently, 60% of the world overall energy use is produced by fossil fuels (ekonomifakta, 2017). This suggest that renewable energy is not ready to cover the world’s energy demand yet, due to fossil fuels availability at reasonable costs. This leads to the short-term goals to focus on utilizing the fossil fuels in a better way, hence it’s necessary to strive for CO2 mitigation technologies applied to fossil fuels.

A promising approach to reduce CO2 emissions is to capture the CO2 before it gets out to the atmosphere. This technique could be used for power plants, by transporting captured CO2 to an injection site and sequestrate it for a long-term storage (Li, Duan, Luebke, & Morreale, 2013). Considering how to effectively mitigate CO2 emissions, there are three well-proven technological pathways, namely post combustion sequestration, pre-combustion sequestration, and oxy-fuel combustion that can in principle be applied for coal-derived power generation.

A highly competitive technology in coal-derived power generation is combined cycle gas turbine (CCGT) plants. This technology has been used in many decades to produce electricity. Low natural gas prices together with high energy efficiency has made gas turbines popular in the energy market (Colpier & Cornland, 2002). Like other power generation technologies, gas turbines have disadvantages such as emissions of CO2, NOx and increased dependence on fossil fuels, therefore they can be considered as a handbrake for the growth of renewable energy sources.

However, CO2 emissions from gas turbines could be eliminated by pre-combustion carbon capture while using pure hydrogen as a fuel. Research on hydrogen fired gas turbines commonly focuses on two applications such as a gas turbine with pre-combustion CO2 capture and for renewable power plants where hydrogen is produced and stored from excess energy (M. Ditaranto, Li, & Hu, 2014). Although the CO2 emissions are eliminated in hydrogen fired gas turbine, there are still several challenges such as high flame temperatures resulting in high production of thermal NOx.

This project will be focusing on assessing the economic feasibility of gas turbine operating with hydrogen, particularly addressing the challenge of NOx emissions, while comparing the economic benefits of changing from natural gas to pure hydrogen.
1.1 Background

The world is highly dependent on energy for electricity, heat, and transportation; in a short span, energy has become indispensable part of modern-day life. Error! Reference source not found. below shows world overall energy production, where more than 80% of the energy used is from fossil fuels.

![Energy production chart]

Figure 1: World's overall energy used divided into different energy sources (ekonomifakta, 2017)

The high utilization of fossil fuels is increasing the greenhouse effect, because of the emissions produced. The problems that exist now are ozone depletion, acid rain and increased temperature between 0.6 to 0.9 °C until 2017 and are expected to increase in the future. Because of above mentioned problems, EU started a project called European climate change program (ECCP), which focuses on the climate change by reducing the carbon dioxide emissions (ekonomifakta, 2017).

The objective is to reduce 20% of greenhouse gas (GHG) emissions by 2020 compared to 1990; it is even possible to increase the percentage to 30% for those countries with high potential of reducing the carbon dioxide. Another solution is to reduce energy used by 20% until 2020, while increasing the renewable energy share to 20% by the end of 2020. Error! Reference source not found. below shows the emissions from 1990 to 2015. As shown in Figure 2, the emissions have been reduced by 12% between 1990 and 2015 (ekonomifakta, 2017).
Although countries are striving to increase the renewable share, there are still several energy conversion processes that dominates the energy market such as nuclear power, coal plants and gas turbines. Gas turbines have been used for many decades to produce electricity because of the compact size, low weight and fuel flexibility. Fuels such as coal, natural gas, diesel fuel, and Naphtha, methane and biomass gases can be used. Combined cycles are often preferred because of the higher efficiency that could be achieved compared to a single gas turbine. A common combination is a gas turbine with water/steam cycle (Kehlhofer, 2009).

1.2 Gas Turbine

Namely, gas turbines use air as working fluid together with fuel and convert chemical energy into mechanical energy. The energy from the mixed working fluid is converted to rotational energy in the engine to drive the compressor and produce electrical power. At the inlet, the air enters the compressor at ambient condition. The compressor increases the pressure of the air, thus increases the temperature at the same time (Cohen.H, 2008).

Then the flow goes to the next stage, which is the combustor. The combustor mixes the air with the injected fuel, while using excess air to increase the amount of oxygen to ensure complete combustion. Mixed flow leaves the combustor and enters the turbine, which turns the mixed fuel to work. There are two steps in the turbine, the first one takes place in the nozzle of the turbine by expanding the flow and turn thermal energy into kinetic energy. The kinetic energy is transferred to the rotating part of the turbine, thus produces electricity using a generator (Cohen.H, 2008).

Gas turbines often have very high excess air to increase the combustion efficiency, which decreases the concentration of the CO₂ in the exhaust gas. This makes post-combustion CO₂ capture difficult and opens interest for pre-combustion CO₂ capture. Pre-combustion capture involves removing CO₂ after converting a fuel such as natural gas, coal and biomass into mixture of carbon monoxide (CO) and hydrogen (H₂) to form synthesis gas. Formed CO₂ is removed while using the hydrogen as a fuel in the engine (Cohen.H, 2008).
1.3 Previous research

In order to find a solution for CO2 capture, research has been widely focused in the field, such as Kvamsdal et al. who introduced comparison of gas turbine cycles with CO2 capture (Kvamsdal et al., 2007). Kvamsdal et al. investigated CO2 capture in different power plant models and highlighted the importance of having CO2 capture. Important parameter to keep track when it comes to combustion with high temperatures is NOx formation. Shih et al. (1996) presented how the incomplete fuel-air mixing could affect the NOx emissions. They drew the conclusion that instability of fuel-air mixing could lead to increased emissions and the significance to balance the mix of fuel-air to avoid the instability (Shih, Lee, & Santavicca, 1996).

Ditaranto et al. have conducted a research related to this project (M. Ditaranto et al., 2014). The research focused on a hydrogen fired gas turbine with pre-combustion CO2 capture and exhaust gas recirculation, comparing an actual solution to mitigate the challenges with the suggested concept. The actual solution was to lower the emissions to acceptable level by diluting the fuel with nitrogen. While the suggested solution concept was to recirculate a part of the exhaust gas to produce lower temperature combustion with undiluted fuel, outlining the conclusion that exhaust gas recirculation could be used to mitigate the challenges of hydrogen as a fuel without using fuel dilution. This would lower overall cost of the cycle (M. Ditaranto et al., 2014).

Additionally, Jin (2000) conducted a study to compare a simple H2/O2 gas turbine cycle with chemical-looping hydrogen fired gas turbine. As a result, the chemical-looping gas turbine gave high thermal efficiency without any generation of NOx (Jin, 2000).

Regarding techno-economic studies of gas turbine plants with CO2 capture, various research has been conducted. Peeters et al. (2007) described a detailed analysis and costs of post-combustion CO2 absorption in combination with a natural gas combined cycle (NGCC). They concluded that with the natural gas price at the time of that work (2007), there was potential of decreased electricity price for the plant, decreased efficiency penalty and avoidance cost of CO2 (Peeters, Faaij, & Turkenburg, 2007). Furthermore, Hu et al. (2012) carried out a study concerning economic evaluation of evaporative gas turbine with two different CO2 capture options. The reference case of gas turbine without CO2 capture was compared with chemical absorption capture and oxy-fuel combustion capture. Promising results were obtained showing highest avoidance of CO2 in chemical absorbing capture (Hu, Li, & Yan, 2012). However, in the reviewed literature, not sufficient studies on economic benefits of hydrogen gas turbine were found.

1.4 Description of the research

Using hydrogen as fuel results in challenges such as high flame temperatures and consequent production of thermal NOx. A solution to achieve low flame temperature is by reducing oxygen content of the combustion air, which can be achieved by recirculating a part of the
exhaust gas. The task is to compare gas turbine using hydrogen fuel with natural gas and later introduce EGR for the hydrogen fired gas turbine to see the difference it could make both economically and environmentally. The hydrogen fired gas turbine concept used in this project is shown in Figure 3.

Figure 3 Hydrogen fired Gas Turbine

Once a working strategy for the gas turbine above is found, the focus will be to evaluate the economic feasibility of the cycle with and without EGR compared to traditional natural gas fired gas turbine. Emissions and environmental impacts of the cycles will be conducted.

1.5 Purpose

The main objective of this thesis is to compare pure hydrogen fired gas turbine that uses exhaust gas recirculation with traditional natural gas fired gas turbine, to highlight differences in economic feasibility and environmental impact. The core is to introduce EGR system for the hydrogen fired gas turbine to achieve low emission while making the cycle economically feasible. The main focus will be to compare how emissions, operating cost and overall investment costs will differentiate with respect to gas turbines operating with natural gas. Operating parameters will be selected for a hydrogen fired gas turbine with EGR from an emissions perspective. Finally, it will be assessed whether a hydrogen fired gas turbine with exhaust gas recirculation would be economically profitable compared to the traditional natural fired gas turbine.
1.6 Research questions

- How will EGR affect emission and fuel consumption for hydrogen fired gas turbine?
- What is the optimal operating turbine inlet temperature for hydrogen fired gas turbine?
- How profitable is it to use hydrogen fired gas turbine compared to natural gas fired from an economic perspective?

1.7 Scope and limitations

The core of the project is to find solution to mitigate the challenges in operating a gas turbine with hydrogen, particularly flame stability and thermal NOx formation, while comparing economic and emission benefits in changing from natural gas to pure hydrogen. A proposed method to reduce the flame temperature by reducing oxygen content is to recirculate a part of the exhaust gas (with exhaust gas recirculation – EGR), which is a well-established concept for gas turbine plants. Therefore, the effect of EGR on NOx emissions is investigated in this report to suggest an operating strategy for hydrogen fired gas turbines. For the economic analysis, the initial aim was to investigate the economic benefit of using hydrogen gas turbines for electricity production in Sweden. But, since Sweden has low electricity price and a well-stabilized energy mix, it would not be profitable to introduce gas turbines in the grid. Therefore, case studies focused on an international perspective. Investment costs were collected for the USA scenario and assumed to be the same for the European market. Average electricity and fuel prices of Sweden and Germany are used in the European case.
2 METHOD

To compare the economic feasibility and environmental impact of gas turbines operating with hydrogen in comparison with natural gas, a wide literature review was conducted. Several journals, articles and websites were referred to have a thorough understanding on the available technology to operate gas turbines with natural gas and pure hydrogen. A literature review was carried out and most of the literature reviewed was found on databases such as Google Scholar, Primo article library or Science Direct. These databases publish mostly highly rated research work from universities all over the world.

A literature survey was conducted to determine emissions of both hydrogen and natural gas fired gas turbines, partially for combustor technologies used in the gas turbine field and the difference of the natural gas and hydrogen fired gas turbine in terms of released emissions after combustion. To compare emissions of pure hydrogen fired gas turbine with natural gas fired gas turbine, it’s essential to introduce commonly used equations in the literature. For the natural gas case, since it has been used in the last decade data for the emissions were easily found. But, for the hydrogen case sufficient data weren’t available. Therefore, it was chosen to follow an empirical method: few researchers provided data from combustion of hydrogen, mainly thermal NOx, so this data was analysed in excel. Using curve fitting method in excel together with trend line a model for NOx emissions of hydrogen fired gas turbine was developed. The emission model was then used in combination with a performance model previously developed by (Giulio, 2018) to determine the best operating condition for the hydrogen gas turbine plant. The performance model is a Matlab code based on mass and energy conservation equations and fluid property tables, which is presented in the Appendix.

For the economic calculations, relevant literature was studied to get better insight of how gas turbines relate to the energy market. Investment cost for different gas turbines operating with different fuels was gathered to understand real investment cost of a gas turbine. The purpose is to see whether hydrogen fired gas turbine is more economical feasible than a natural gas fired gas turbine. For the techno-economic calculation, three cases were studied where the first case include three gas turbines located in the US with natural gas, delivered hydrogen and fuel reforming process at gas turbine plant. Current and expected market trends for pure hydrogen are highlighted and used for a sensitivity analysis. The second case include the same gas turbines mentioned above but located in Europe with average electricity prices taken from Sweden and Germany. Finally, the third case include exhaust gas recirculation (EGR) introduced for 40 MW hydrogen fired gas turbine located in US.

In summary, the project is divided into two parts. Where the first part focuses on emissions of the gas turbine cycle operating mainly on pure hydrogen compared to natural gas fired gas turbine. While the second part will include the techno-economic calculations.
3 LITERATURE STUDY

In this section, the main relevant literature used are highlighted. For the emission model the most critical component of gas turbine is the combustor, therefore a survey was conducted on the combustor and the emissions produced by the combustion. The main emissions highlighted for natural gas plants are NOx, CO and CO2. Furthermore, the choice of a suitable flame temperature and fuel/air ratio are underlined to reduce the emissions. Issues with renewable energy system are mentioned, which lead to the short-term goal of using available options such as hydrogen fuels. Pure hydrogen fuel can’t be naturally found on earth and usually requires primary energy to be produced. Therefore, several hydrogen production methods are highlighted while mentioning future improvement of current used techniques. Finally, economical evaluation of gas turbines is conducted including fuel cost, heat and electricity prices. Case studies will be made for the economic evaluation, and therefore electricity and district heating prices for US, Sweden and Germany are investigated.

3.1 Combustor

Two types of combustor systems were used from the beginning, namely constant pressure and constant volume. Theoretically, the constant volume combustor efficiency is higher, but it was difficult to obtain constant volume. The mechanical part was hard to build since heat was required to be added in constant volume while the valves and combustor were isolated from the compressor and turbine. This method was used in early stages during 1908-1930 in Germany. Constant pressure combustor was easier to use since it doesn’t need isolation of the valve and the combustor. Also, the mass flow could be increased in the constant pressure which results in increased power production. The combustor has been developed during the years, the pressure increased from 5 to 50 atm (atmospheres). The inlet temperature increased from 450 to 900 K. also, the outlet temperature increased from 1100 to 1850 K. There are two types of combustors available today: tubular and annular (Lefebvre, 2010).

3.1.1 Combustion emissions

Emissions from combustion processes contain dangerous substances that may cause healthy and environmental damage. According to the author, they have received huge public concern last decade thus several researcher has focused to find regulations for controlling gas turbine emissions (Lefebvre, 2010). The exhaust gases from the turbine often contain pollutants such as carbon monoxide (CO), carbon dioxide (CO2), water vapor (H2O), unburned hydrocarbons and nitrogen oxides (NOx). These pollutants can be reduced by either burning less fuel or by improving the thermal efficiency of the engine (Lefebvre, 2010).

The hazardous emissions exhausted from the gas turbine causes healthy and environmental damage such as (Lefebvre, 2010):
• Released CO reduces the ability of blood to absorb oxygen and in high concentrations causes asphyxiation and even death.
• Unburned hydrocarbons are highly toxic and could combine with NOx to form photochemical smog and create problems of exhaust visibility of the atmosphere.
• NOx or nitrogen oxides are formed by NO + NO2, they contribute to the production of photochemical smog at ground level and also cause damage such as acid rain.
• CO2 contributes to the global warming.

These pollutants cause healthy and environmental damage, while affecting thermal efficiency of the gas turbine and the operation costs. Therefore, the following subheadings focuses on these emissions (Lefebvre, 2010).

3.1.1.1. CO2
Recently the focus has increased on carbon capture, because the captured carbon can be reused as a fuel. The main focus has been on the power plants, because almost 40% of CO2 emitted is produced from the electrical fossil fuel power plants (Cuéllar-Franca & Azapagic, 2015). Lately the research has focused on how to effectively capture the CO2 from the flue gas with high accuracy.

Kvamsdal et al (2007) highlighted quantitative comparison of gas turbine cycles with CO2 capture. Various pathways to capture CO2 in power productions were presented such as (Kvamsdal et al., 2007):

1. Oxy-fuel CC
2. The water cycles
3. The Graz cycles
4. The advanced zero emission power plant (AZEP)
5. The SOFC+GT cycle
6. The chemical looping combustion cycle
7. Pre-combustion with an auto-thermal reformer
8. Pre-combustion with a hydrogen membrane reactor
9. Post-combustion with amine absorption

The oxy-fuel CC is a concept of using combustion with oxygen instead of air near to stoichiometric combustion. The reason is to remove nitrogen from the combustion, so the outcome will be H2O and CO2. The water will be separated from the carbon dioxide by condensation and further utilized for cooling purpose. The water cycle is almost like the Rankine power cycle. The combination of Oxy-fuel and Rankine-type cycle is called Graz cycle. The AZEP model is based on the combined cycle. In this model the combustor is replaced with a mixed conductive membrane. The objective of the mixed conductive membrane is to separate the oxygen from the air to achieve combustion of fuel with near-to-stoichiometric combustion and heat exchange. The SOFC+GT cycle is close to AZEP, it works by separating the oxygen from the air. The difference in this system compared to other systems is that the fuel is not completely converted, which make afterburner necessary to capture the carbon dioxide (Kvamsdal et al., 2007).
In chemical looping combustion, the cycle doesn’t have direct connection between the air and the fuel. The process is separated into two steps, first step is oxidation and the second one is reduction reaction. For the pre-combustion with an auto-thermal reformer case, the design is mainly the combined cycle. The process contains de-carbonization of the natural gas prior to the combustion (Kvamsdal et al., 2007).

3.1.1.2. NOx
Combustion of fuels with nitrogen and oxygen together with high temperatures leads to formation of NOx. NOx is considered as harmful emission causing lung irritation and low resistance to respiratory infections. The term NOx represents both NO (Nitric oxide) and NO2 (Nitrogen dioxide). The formation of NOx emissions in the combustor are mainly developed by three different reaction mechanisms which are the following (Lefebvre, 2010):

- Fuel NO formation
- Thermal NO formation
- Prompt NO formation

The percentage of organically bond nitrogen depends on the fuel characteristics, which are divided into light or heavy fuels. The light fuels contain 0.06% of organic bond nitrogen while the heavy fuels contain 1.8%. During combustion process some of the nitrogen in the fuel reacts and forms NOx.

As highlighted in the combustion book, when the temperature reaches close to 1900 K in the combustor, the outcome of NOx formation will be about 60% thermal, 10% N2O and 30% prompt. But, when the temperature is lower, specifically at 1500 K, the outcome will be around 5% thermal, N2O 30% and prompt 65%. The oxidation of Nitrogen in high temperature can produce thermal NOx, the process is endothermic (absorbing energy from the surrounding) (Lefebvre, 2010). The reaction scheme will be as shown in Figure 4 (Lefebvre, 2010).

![Figure 4 Reaction of nitrogen and oxygen at high temperature](image)

The Figure 4 shows how NO forms by absorbing the available oxygen in the combustor. NO formation can disturb the combustion of the fuel in the combustor by consuming a lot of oxygen. The NO formation is proportional to the temperature, increased temperature leads to high production of NO. The prompt NOx chemical reaction can be written as in (Lefebvre, 2010):
The prompt NO balance depends on the HCN molecule and N atom, because the HCN can oxidize to NO. In the process HCN can change to CN, when the oxygen is added in the combustor can CN change to NCO which leads to NO. The nitrogen atom reacts to the second Zelodoyich reaction (nitrogen formed in the exhaust gas). It is important to know the pressure because the prompt NO depend on the pressure. Also, nitrogen oxide can damage the ozone by reacting with oxygen as shown in the Figure 5 below (Lefebvre, 2010).

![Figure 5 Reaction between Nitrogen dioxide and ozone](image)

3.1.1.3. CO

In combustion process, the aim is to reach stoichiometric or theoretical combustion which is the ideal combustion where the fuel is burned completely. Low temperature in the combustor leads to unburned fuel and increased carbon monoxide (CO). Carbon monoxide is considered very harmful for human, it affects the cardiovascular system especially in people with heart diseases. CO is formed when burning carbon rich fuels, and often caused by lack of sufficient oxygen to complete CO2 formation in the burner. In theory, formed CO could be reduced in primary combustion to a very low level by accessing additional air. Main factors influencing CO emissions are combustor inlet temperature, combustion pressure and primary-zone equivalence ratio (Lefebvre, 2010).

3.1.1.4. Controlling emissions

One of the most important aspects in controlling the system is to achieve low NOx and CO emissions. A way to reach this goal is by tracking the temperature in the combustor. As Figure 6 below shows, when the flame temperature is lower than 1700 K the CO production starts to increase in the combustor and when the temperature is higher than 1900 K the NOx formation increases. In this case the temperature should be kept in the range 1700 K - 1900 K to achieve low emissions. Therefore controlling the combustor temperature is crucial (Liu et al., 2017).
3.2 Barriers to exploitation of renewable energy technologies

Striving after CO2 free solution for energy utilization has been the main target; a short-term solution is combustion of hydrogen and/or carbon sequestration, while a long-term strategy is to use renewable energy sources. Renewable energy sources involve disadvantages that limit their full exploitation; however, production and storage of hydrogen can be seen as a potential solution.

Energy sources such as oil, coal, and natural gas have been used for decades and are influencing the energy market. But, at the same time causing damage to the environment and to human health (Union of Concerned Scientists [UCS], 2017). Therefore, renewable energy technologies are effective answer to meet future energy demand while replacing fossil fuels. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal often provides sustainability and availability. These sources have shown great potential to replace fossil fuels. However, despite that they have shown great potential, barriers are still present especially in the exploitation of solar and wind. In addition, intermittent production of electricity is also a limitation of these sources.

Share of power from wind energy and solar PV is increasing continuously, which leads to more research to be done on how to produce electricity in a more reliable and cost-efficient manner. Average cost in 2017 to install solar systems was approximately around $2,000 per kilowatt for large-scale systems to almost $3,700 for residential systems in the US. While new natural gas plant costs around $1,000/kW and wind comes in between $1,200 to $1,700/kW (UCS, 2017). Since wind and solar power are of intermittent nature, yearly and daily variations of sun radiation makes the solar energy unsecure, while the wind varies with season and weather conditions (Östergård, 2012). Furthermore, power system stability, reliability and power quality must be addressed. These issues can be addressed either by upgrading current grid to smart grid, or by integrating more storage systems. The energy

Figure 6 Emissions control by measuring CO and NOx levels at different combustion temperature
storage technologies will provide an opportunity to meet power equality and more reliability for the intermittent energy.

The leading and most commonly used energy storage systems are the following (Östergård, 2012):

- Battery storage
- Pumped hydro storage
- Thermal energy storage
- Compressed air energy storage
- Energy storage using flow batteries
- Flywheel energy storage
- Superconducting magnetic energy storage
- Super-capacitors

Optimal use of the batteries and together with control strategy is needed to make the solar and wind energy more competitive in nowadays energy market. However, despite great potential in storage system, it is still expensive solution. Jensen et al. (2007) investigated to use the surplus electricity produced by solar and wind to in a solid electrolyze cell to form various types of synthesis gas as well as pure hydrogen. Results show great potential to produce hydrogen by using solar and wind (Jensen et al., 2007). Dufo-López et al. (2007) presented a novel optimization strategy to control hybrid renewable electric system using hydrogen storage. Obtained results showed that this could be a future solution. In summary, battery storage shows great potential but expensive while forming synthesis gas using the surplus energy has been shown to be promising (Dufo-López et al., 2007). Hence, it is necessary to improve systems that can convert hydrogen into electricity to fully enable the use of renewable sources.

### 3.3 Hydrogen fired gas turbines

A way to reduce CO2 emission in power production is by combustion of hydrogen, because it offers CO2 free combustion (Mario Ditaranto, Li, & Løvås, 2015). Hydrogen as a fuel is becoming an option to reduce the emissions from the gas turbine, since the energy converted by gas turbine is highly depending on fossil fuels. Emissions such as CO, CO2 and NOx are spread in the atmosphere from power production. Hydrogen fuel is considered as carbon dioxide free and has the potential to become one of the most used fuels in the coming future. Figure 7 below shows emission comparison between natural gas and hydrogen fuel after combustion:
The common fuel used for gas turbine is natural gas (NG). NG consist different type of gases such as methane, ethane and propane. The reason why the NG has been dominant is because of easy availability and low costs compared to other type of fossil fuel such as diesel (Akansu, 2004).

3.4 Combustion of hydrogen

There has been a lot of research on utilizing hydrogen as a fuel for gas turbines. Some of the researches focused on using a mixture of hydrogen and NG. The mixture of these two gives better efficiency and lower emissions than using NG alone. Hydrogen is considered as secondary fuel, unlike the primary fuel such as fossil fuels. To produce pure hydrogen, fuel reforming process is needed. In fact, all primary fuel resources contain hydrogen which provides various alternative to produce pure hydrogen (Holladay, Hu, King, & Wang, 2009).

One of the suggestions is to use sorption enhanced steam methane reforming (SESMR) to produce hydrogen. Hydrogen can be produced by using water and methane or by using carbon monoxide with water (H2O) leading to following chemical reaction (Shokrollahi Yancheshmeh, Radfarnia, & Iliuta, 2016)

\[
CH_4 + H_2O = 3H_2 + CO
\]

\[
CO + H_2O = H_2 + CO_2
\]

The first reaction produce carbon monoxide (CO) and hydrogen. Formed CO can be used to produce more hydrogen by reacting with the steam as shown in the second chemical equation. The final step will be to separate the CO2 from the hydrogen by using pressure swing adsorption. The advantage of SESMR is high production of hydrogen while producing less CO and CO2 (Shokrollahi Yancheshmeh et al., 2016). Another promising method is steam methane reforming (SMR), which is widely used producing more than 80% of hydrogen fuels in the market. The rest is produced by gasification and water electrolysis, the latter is considered the cleanest method (Boyano, Blanco-Marigorta, Morosuk, & Tsatsaronis,
It is possible to use hydrogen in hybrid systems, which may include components such as wind turbine or PV-system, batteries, charge regulator, hydro turbine and AC generator. It can be any type of generator, battery charger (AC/DC), inverter (DC/AC), fuel cell, H2 tank and electrolyser. Hydrogen tank can be filled externally or by using electrolyzed water. The stored hydrogen in the tank can be used when the wind or PV-system reach their limits.

Modern gas turbines avoid the NOx formation by using dry low NOx (DLN) burner, but the DLN is difficult to handle since it needs a specific air degree which make the combustor less stable. Another option to achieve low emissions would be by using selective catalytic reduction (SCR) but it is complicated to use since the combustion of the hydrogen is wide flammability and high temperature reaction in the combustor. Cam et al (2017) investigated numerical behaviour of combustion and emission of hydrogen air mixture in a micro cylindrical combustor model (Cam et al., 2017). The characteristics of the combustion and emission was studied by dividing the combustor model into small species while varying the ratio of hydrogen/air between 0.5 – 1.2. Concluding that decreased ratio leads to displaced chemical reaction in the combustor while the temperature decreases. Suitable temperature distribution is reached between the ratios 0.8 – 1.0, while achieving maximum NOx formation at the ratio 0.9 (Cam et al., 2017).

Furthermore, Lin et al. (2012) studied the characteristic of turbulent combustion and NOx emission for high hydrogen content fuels. Especially the correlation between pressure and NOx formation. The results showed generally a consistent level of NOx formation, drawing the conclusion that the pressure doesn’t have significant effect on the NOx formation (Lin et al., 2012). Additionally, Colorado (2013) has conducted a study to predict NOx emissions from premixed natural gas and hydrogen enriched fuels. The conclusion was that pure hydrogen has high flame temperature producing three times more NOx formation than natural gas (Colarado, 2013).

Finally, the biggest issue with combustion of hydrogen is the high flame temperatures and thus high production of thermal NOx. To avoid it, an option is to reduce the oxygen content while reducing the flame temperature, and this is possible by recirculating a part of the exhaust gas. This method is called exhaust gas recirculation (EGR). EGR is a process where the exhaust gas is mixed with the inlet air either internally or externally. It’s a well-known method which has been used to increase the CO2 in the flue gases and thus increased efficiency of post combustion. But, it can also be used to reduce NOx emission by decreasing oxygen concentration and therefore decrease the production of thermal NOx (Lipardi, Berghorson, & Bourque, 2015).

Study regarding hydrogen fired gas turbine with EGR was conducted by Giulio as a master thesis in University of Genoa (Giulio, 2018). The study focused on how efficiency, power and combustion temperature are affected by EGR. The model developed in that study was employed here to find a trade-off between efficiency and NOx emissions and select the optimal operating parameters for the gas turbine.
3.5 Economy evaluation of gas turbine

Growing industrialization together with growing electricity demand will drive the global gas turbine market in the future. Generally, when investing in a power system the investor sets a target return on the investment. Similarly to every investment, the expected return depends on several factors, for the energy power case the following factors are crucial to consider (Kehlhofer, 2009):

- Market price of the electricity
- Production cost of the electricity
- Interest and amortizing costs
- Fuel costs
- Operation and maintenance costs

The most important parameter is the electricity price, because in the current market the electricity prices tend to fluctuate widely. So, crucial thing is to find electricity off-takers who would buy the electricity at fixed rate under long term sale contracts. Another important issue is the risk with the plant itself such as costs, efficiencies and reliability. Power plant projects are normally exposed to the market, which leads to high risk profiles. Therefore, it’s highly important to do market analysis and develop a solid market scenario by doing sensitivity analyses and including worst case scenarios (Kehlhofer, 2009).

Fuel cost per unit of electricity is directly dependent on the specific price of the fuel and the average electrical efficiency of the installation. Normally operation and maintenance costs are fixed costs of operation, maintenance and administration such as insurance, cost of repair, spare parts etc. The cost of electricity is calculated by adding the capital costs with fuel cost, maintenance and operation costs (Kehlhofer, 2009).

When comparing different types of power plants economics, net present value (NPV) is used as a general basis. Costs of the power stations are sustained at different times, but the financial calculation are corrected to present time reference. It’s important to consider that the electricity price varies up and down, therefore this needs to be accounted for. To avoid it, the cost of the electricity should be calculated with referenced equation including both fixed and variable costs. This will make it easier to decide whether to shut down the power plant if the sale price of the electricity is lower than the variable costs (Kehlhofer, 2009).

There are several factors affecting the specific prices such as market conditions, type of cooling, emission limits, commercial risks and legal regulations. The gas turbine gained high attention during 2009, because it’s wide-spread acceptance together with simplicity and short start-up time to full load (Kehlhofer, 2009).

Pilavachi et al. (2009) evaluated nine types of electric energy generation options which uses natural gas or hydrogen as fuel. Evaluated options was hydrogen combustion turbine, hydrogen internal combustion engine, hydrogen fuelled phosphoric acid fuel cell, hydrogen fuelled solid oxide fuel cell, natural gas fuelled phosphoric acid fuel cell, natural gas fuelled solid oxide fuel cell, natural gas turbine, natural gas combined cycle and the natural gas internal combustion engine. Evaluated criteria for the selected options were efficiency, CO2
emissions, NOx emissions, capital cost, operation and maintenance costs, electricity cost and service life. The results show that the preferable electricity generation technology proved to be the hydrogen fired gas turbine. Despite high price of hydrogen at that time (2009) the hydrogen fired gas turbine offered clean and low-cost power generation. However, the hydrogen fired gas turbine is still under development and the actual performance which is assumed in this case could be different (Pilavachi et al., 2009). Yet, the economic benefit of hydrogen fired gas turbine with exhausted gas recirculation as a concept still needs to be evaluated.

3.5.1 Investment cost of gas turbine

Investment cost of hydrogen fired gas turbine is difficult to calculate, since pure hydrogen fired gas turbine isn’t available in the market yet. Therefore, to facilitate the economic calculations literature study on investment costs of general gas turbines has been made. Kang et al studied economic feasibility of a small combined heat and power (CHP) and combined cycle (CC) using 5 MW gas turbine fired with biogas. Total cost of 8.9 M$ are shown including gas turbine investment cost and several highlighted costs such as consulting, installation and inspection costs (Kang et al., 2014).

Additionally, the National Renewable Energy Laboratory (NREL) hired the company Black & Veatch to provide a report describing power generation costs and performance estimations for various power production technologies. For the gas turbine case, typical industrial heavy-duty gas turbine with dry low NOx combustion system were highlighted. Total investment cost of 1195 $/kW was given (Black& Veatch, 2012).

Finally, U.S. Department of energy provided power technology Fact sheet including capital costs for six representative gas turbine CHP system used in typical applications. Highlighting installed costs of $3,320/kW - $1,276/kW for power system between 3MW – 40MW. In the figures above, the investment costs only include the installation, while fuel and electricity cost, EGR investment costs (case 3) and heat generation costs would be added as an additional cost in the coming sections.

3.5.2 Techno-economics of hydrogen fuel pathways

Continued concern of the energy supply security together with increased energy demand has driven the development of hydrogen as energy carrier. Hydrogen as a fuel has a lot of advantages and could be used to complement electricity production, chemicals/synthetic fuels production, and for transport applications. It has the capacity to be stored for a long time without significant losses, while it’s almost emission free. It can be produced from both renewable energy and fossil fuels, but currently the production is dependent on fossil fuels by fuel reforming of coal and natural gas. The long-term goal is to produce hydrogen by renewable electricity and biomass. Hydrogen production at minimum cost and environmentally friendly is essential to make hydrogen fuels economically feasible.
Muellerlanger et al. investigated hydrogen production processes which are expected to dominate economically in EU in the short and long term (up to 2020). Results indicate that for the near future the main production of hydrogen will come from fuel reforming of fossil fuels, therefore carbon capture technologies will be developed. But a big problem will be if the price of natural gas increases (Muellerlanger et al., 2007).

3.5.3 Fuel price

The aim of the project is to determine whether it’s economically feasible to replace traditional natural gas fired gas turbines with hydrogen gas turbines. To make this comparison a literature study of current fuel cost for both natural gas and hydrogen is made. Additionally, the expected market trends for both gases are investigated.

3.5.3.1. Hydrogen

As mentioned previously hydrogen as a fuel has great potential in the future to cover apart of energy that will be needed. It can be produced either by using renewable energy sources such as wind and solar or by fuel reforming of fossil fuels. As Reddi et al (2017) investigated the cost of hydrogen gas is strongly dependent on the production technology used when reforming the gas. The cost of producing hydrogen via steam methane reforming of natural gas is around $2-$3/kg. Current hydrogen refuelling station levelized cost in California for 200 kg/day is around $6-$8/kg when supplied hydrogen in gas form. But, accounting refuelling, packaging and transportation the cost becomes around $13-$15/kg. In current market, the hydrogen gas is expensive compared to other gases, because of the high refuelling cost and material costs such as compressor and cryogenic pumps. However, United States Department of Energy has set a long-term cost target for hydrogen gas. The target is to reach a cost of $2/kg at delivery for hydrogen in 2020 (Reddi et al., 2017).

There is an alternative to install hydrogen production station to lower the total cost of power plant. As mentioned before there are various methods to produce hydrogen. A report was conducted by the Department of Energy (DOE) analysing multiple hydrogen production technologies and the corresponding levelized production cost of hydrogen. Using the H2A hydrogen Analysis Tool developed by the DOE, four different hydrogen production methods was studied such as (James, DeSantis, Saur, National Renewable Energy Lab. (NREL), Golden, CO (United States), & Argonne National Lab. (ANL), Argonne, IL (United States), 2016):

- Proton Exchange Membrane technology (PEM)
- High temperature solid oxide electrolysis cell technology (SOEC)
- Dark fermentation of biomass for H2 production
- H2 production via Monolithic Piston-Type Reactors with rapid swing reforming and regeneration reactions

The report includes projections for capital costs, fuel/feedstock usage, energy usage, indirect capital costs, land usage, and labour requirements. In the current case, an average cost-value
between 2013 – 2016 were used, while the future case reflects on expected costs in 2025. The baseline projections shown in the table below are determined using manufactures supplied fuel together with the balance of the plant costs, while the low and high value include expected spread in uninstalled capital costs and uncertainties. Results are shown in the table below (James et al., 2016).

**Table 1 Hydrogen production costs for different methods with average (Current 2016) and expected (future 2020) cost values (James et al., 2016).**

<table>
<thead>
<tr>
<th>Method</th>
<th>Low value [$/kg H2]</th>
<th>Baseline [$/kg H2]</th>
<th>High value [$/kg H2]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton Exchange Membrane Electrolysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current production cost (2016)</td>
<td>4.80</td>
<td>5.12</td>
<td>5.45</td>
</tr>
<tr>
<td>Future production cost (2020)</td>
<td>4.07</td>
<td>4.20</td>
<td>4.33</td>
</tr>
<tr>
<td><strong>High Temperature Solid Oxide Electrolysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current production cost (2016)</td>
<td>3.73</td>
<td>4.85</td>
<td>5.84</td>
</tr>
<tr>
<td>Future production cost (2020)</td>
<td>2.80</td>
<td>3.83</td>
<td>4.67</td>
</tr>
<tr>
<td><strong>H2 Production via Fermentation of Biomass</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current production cost (2016)</td>
<td>40.88</td>
<td>51.02</td>
<td>75.67</td>
</tr>
<tr>
<td>Future production cost (2020)</td>
<td>3.39</td>
<td>5.65</td>
<td>7.90</td>
</tr>
<tr>
<td><strong>H2 Production from steam reforming of pyrolysis in monolithic piston- type reactors</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current production cost (2016)</td>
<td>2.30</td>
<td>2.58</td>
<td>3.06</td>
</tr>
<tr>
<td>Future production cost (2020)</td>
<td>2.75</td>
<td>3.10</td>
<td>3.59</td>
</tr>
</tbody>
</table>

As the Table 1 shows, the highest production cost is reached when using hydrogen production from biomass, therefore this method would be neglected in this report. Average cost of the current and future price of the other methods would be used in further calculations.

When it comes to hydrogen price in EU current price is around 9.9 euro/kg and the target is to reach 5.5 euro/kg in 2025 (Rebecca, 2013). For the hydrogen production case in EU the rules are very strict for using non-renewable sources, it would be unnecessary to build hydrogen fuel reforming station using fossil fuels. The literature research was limited to production and installation of water electrolyzers for hydrogen production, which is renewable hydrogen production method. Using wind or solar energy the total hydrogen production costs in 2015 was in the range 2.7 – 4.0 $/kg while the expected cost in 2020 is in the range 1.3 – 2.7 $/kg (Jon Andre, 2017).

### 3.5.3.2. Natural gas

Natural gas is a fossil fuel commonly used for energy purposes such as heating, cooking, and electricity generation. The gas was created by the biomass that existed on earth thousands of years ago, which were rich in lighter hydrocarbons and methane. To use the natural gas, it is condensed as liquid which is energy consuming process. Then the gas is transported using trucks, ships or giant pipelines. Natural gas was introduced in Sweden in 1985 and transported through a pipeline from Denmark which continues along the Swedish west coast (SWEDEGAS, 2012).
The price of natural gas in the EU depends on several things including demand conditions, energy mix, network costs and environmental protection. The average natural gas price in EU presented by EU statistical database is around 0.3 euro/kWh. In the US, the price has been high at beginning of the year with almost 3.7 $/MMBtu (1 Btu=1.055 kJ), but it has fallen sharply and is currently 2.8 $/MMBtu.

### 3.5.4 Electricity and heat price

Electricity is traded under market rules using spot and derivative contracts. It’s economically non-storable which means power system stability requires constant balance between production and consumption. Total electricity price is divided into electricity price, electricity network fee and taxes. The electricity price is the real price which electricity is sold for. In some countries, a fee is paid for the electricity grid owners which is called electricity network fee, while taxes are paid to government. The taxes and network fee are constant values, which means only the electricity price is affecting the total electricity price.

A central link when setting the electricity price for Sweden is the Nordic electricity exchange Nord Pool in Oslo. There are two markets at Nord Pool, the spot market where the variable and fixed electricity costs are set. And secondly the financial market where contracts for defined period are sold. Normally the electricity price is seasonally dependent, which means in Sweden less electricity is needed in the summer while the demand is high in the cold winter months. The electricity price in Sweden is currently low, therefore a case study of Germany is made to compare. The figure below shows electricity prices for households in Germany from 2010 to 2017. To make the techno economic calculation more reliable a case study of Europe and the US are made. The Figure 8 below shows electricity price for Sweden, Germany and US.

![Electrical Price](image)

*Figure 8 Electricity price in Europe and US (Statista, 2018)*

It can be seen from the figure that Germany has highest electricity prices, while Sweden has lowest. Average value of Sweden and Germany electricity prices will be used for the Europe
case. The electricity price changes from year to year which means sensitive analyse will be needed in the economy evaluation.

When using gas turbine, the exhaust gas from the turbine could be used for a heat generator to produce heat. Produced heat could be sold for district heating purpose. Figure 9 show the price development for district heating in Sweden.

![DH Sweden Price](image)

*Figure 9 district heating price in Sweden*

District heating is a common production and distribution solution for a smaller or larger number of properties. A central boiler provides many subscribers with heat through an expanded management system. It is the most common heating method for multi-family houses and premises in Sweden. 80 percent of residential heating in Sweden comes from district heating. District heating production is a pervasive activity in which the effect of new investments is delaying, in many cases, several years. The district heating prices vary between different locations because it’s often based on local conditions. Fuel prices are the factor that has the greatest impact on pricing, but even the network affects the price. Smaller networks and networks with large distances between houses generally have higher prices (Rydegran, 2017).

Considering district heating in EU, Germany together with Poland remains biggest market for district heating system in terms of total figures. The market share of district heating of Germany’s residential heat sector is 13.8%. Almost half of the heat demand in Germany is given by natural gas. As the district heating demand increases in Germany, the price for delivered heat increases as well. The prices for district heating in both Germany and Sweden will be converted to same unit and average value of both prices will be used for the Europe case. The

![DH Germany Price](image)

*Figure 10 district heating price development in Germany (Statista, 2018).*
For the district heating case in US limited data were available, therefore only season prices are shown in the Table 2 below (Energiforsk, 2016).

Table 2 district heating price in US

<table>
<thead>
<tr>
<th>Period</th>
<th>Price [dollar cents/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>6.4</td>
</tr>
<tr>
<td>spring</td>
<td>6.2</td>
</tr>
<tr>
<td>summer</td>
<td>3.8</td>
</tr>
</tbody>
</table>
4 CURRENT STUDY

In this section, the focus is to introduce all the equations and data used to obtain results. The current study is divided into two parts. First part shows equations used to calculate emissions from the gas turbine using both pure hydrogen and natural gas. Equations to calculate emissions from natural fired gas turbine are taken from the literature, while the equations for pure hydrogen emission calculation are developed by gathering data from literature and extrapolating a model using a curve fitting method in Excel. The second part shows all the data used for the techno-economic evaluation. It’s divided into several cases, beginning with the description of the case and showing the data used for the case. Only data and equations are shown in this section, the results are introduced in the next section.

4.1 Emissions calculations

The typical emissions from gas turbine are NOx, CO2, CO and unburned carbon depending on utilized fuel. Since the comparison is between pure hydrogen and natural gas, the focus will be NOx because it’s the only emission emitted when burning pure hydrogen. But, when burning natural gas emission such as CO2 is created which leads to additional costs due to carbon taxation. Therefore, for the techno-economic analysis it’s important that CO2 costs are included.

Data on NOx emission for natural gas are available in the literature and were gathered for a comparison with hydrogen. For CO2 case, as mentioned above its only significant when it comes to natural gas. CO2 emission factor for natural gas is 0.572 kg/kWh (Wingas, 2011). Once total electricity produced by the gas turbine per year is known, CO2 factor times the total electricity per year gives amount of CO2 produced per year.

One purpose of this work was to develop an emission model for hydrogen combustion as function of gas turbine operating parameters such as pressure ratio, turbine inlet temperature, and combustion equivalence ratio. The emission model can then be integrated to the hydrogen gas turbine performance model to select the optimal operating conditions. Lin et al. (2012) observed that pressure didn’t influence NOx generation for hydrogen and hydrogen-rich fuels (Lin et al., 2012). Therefore, this parameter was taken out of the equation. While Daniele et al. (2008) investigated NOx emissions of hydrogen with relation to temperature (Daniele et al., 2008). Provided NOx data by Daniele et al. together with similar data provided by Lin et al was used to study temperature dependence. Table 3 shows collected data:
### Table 3 NOx formation by hydrogen combustion

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>NOx [ppm] (Daniele et al., 2008)</th>
<th>NOx [ppm] (Lin et al., 2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>0,3</td>
<td>0,25</td>
</tr>
<tr>
<td>1500</td>
<td>0,6</td>
<td>0,7</td>
</tr>
<tr>
<td>1600</td>
<td>1</td>
<td>1,1</td>
</tr>
<tr>
<td>1700</td>
<td>1,5</td>
<td>1,8</td>
</tr>
<tr>
<td>1800</td>
<td>2,5</td>
<td>2,0</td>
</tr>
<tr>
<td>1900</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2200</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

Once the data were collected, a trendline shown in the Figure 11 was developed to generate an equation to use for the emissions model. The blue dots are data provided by (Daniele et al., 2008) while the orange dots shows data taken from (Lin et al., 2012). It could be seen in the figure that gathered data have great agreement. Next step was to find a trendline, where suitable trendline was reached with exponential trendline which is shown in the figure.

The following trend line equation was noted:

$$\beta = 8 \times 10^{-5} \times e^{0.058T}$$

*Equation 1* trend line for NOx formation at exhaust temperature

So far, the relation between temperature and NOx formation are known. To further improve the emission model the double dependence of temperature and equivalence ratio will be covered. The equivalence ratio is defined as the ratio between actual fuel/air ratio to the ideal stoichiometric fuel/air ratio. Cam et al. (2017) showed the influence of equivalence ratio
when burning hydrogen and hydrogen rich fuels (Cam et al., 2017). The initial tested equivalence ratio was from 0.5 to 1.2. The data at 0.5 was less reliable because the temperature range was very limited, and the values was discarded since it is not recommendable to work at such low equivalence ratio. In this report, the ratio will be limited to the range 0.6 - 1.0 to avoid using high amount of fuel. Figure 12 shows results highlighted study made by (Cam et al., 2017) for chosen equivalence ratios.

![Figure 12 NOx dependence of equivalence ratio (Cam et al., 2017).](image)

The end points in the figure above are the emission at the exit of the combustor. Table 4 shows useful data points collected from Figure 12.

Table 4 NOx values provided by (Cam et al., 2017).

<table>
<thead>
<tr>
<th>Fuel/air ratio</th>
<th>NOX [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.033</td>
</tr>
<tr>
<td>0.7</td>
<td>0.083</td>
</tr>
<tr>
<td>0.8</td>
<td>0.217</td>
</tr>
<tr>
<td>0.9</td>
<td>0.383</td>
</tr>
<tr>
<td>1</td>
<td>0.250</td>
</tr>
</tbody>
</table>

To improve the emission model, the NOx dependence of temperature and equivalence ratio were fitted into one main equation. Collected NOx data in Table 4 were fitted to Equation 1 assuming that the trendline with respect to temperature is kept exponential, and a coefficient was found as function of the equivalence ratio. The coefficient could be taken out from the equation, so it becomes:

\[ C_{\text{new}} = \beta e^{0.0058 \cdot T} \]
Where this time $\beta$ are the NOx data which are dependent on equivalence ratio and shown in Table 4. The temperature is in the range 1100 – 1900 K. Using a similar method, a suitable trendline was found which are shown in the Figure 13.

The following trend line equation was noted:

$$C_{new} = 6 \times 10^{-5} \times ratio^{-1.501}$$

Equation 3 coefficient equation

So far two main equations are noted, where Equation 1 shows NOx dependence on temperature and Equation 3 shows dependence on equivalence ratio. Putting equations 1&3 together, a new equation is obtained which shows double dependence on temperature and equivalence ratio. So, the main final equation for the emission model is expressed as the following:

$$NOx \ [ppm] = C_{new} \times e^{0.0058 \times T}$$

$$NOx \ [ppm] = 6 \times 10^{-5} \times ratio^{-1.501} \times e^{0.0058 \times T}$$

Equation 4 final equation for the NOx model

Equation 4 is used to provide a complete NOx model considering double dependence of temperature and equivalence ratio. Results of the model are shown in the next chapter.
4.2 Economic calculation

The investment may be considered a cost paid in the beginning of the project. A practical approach if the costs of different options are compared on basis of net present values. Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is used in capital budgeting to analyse the profitability of a projected investment or a project itself. The flowing formula is used:

\[ NPV = PV(benefits) - PV(costs) \]

\[ NPV = \sum_{i=1}^{Y} \frac{C_i}{(1 + r)^i} - C_0 \]

*Equation 5 Net present value (NPV)*

Where: \(C_i\) cash flow every year, \(C_0\) initial investment, \(I=\)interest rate and \(Y\) are year.

Determining a value of a project is challenging because there are different ways to measure the value of future cash flows. Because of the time value of money, money in the present is worth more than the same amount in the future. This is both because of earnings that could potentially be made using the money during the intervening time and because of inflation. In other words, a dollar earned in the future won’t be worth as much as one earned in the present. The discount rate element of the NPV formula is a way to account for this. Companies may often have different ways of identifying the discount rate. Common methods for determining the discount rate include using the expected return of other investment choices with a similar level of risk (rates of return investors will expect), or the costs associated with borrowing money needed to finance the project.

Another method used to compliment the NPV is to calculate Internal rate of return (IRR) using the formula by setting NPV equal to zero and solving for the discount rate \(r\), which is here the IRR. Because of the nature of the formula, IRR cannot be calculated analytically. Therefore, it must be calculated either through trial-and-error or using software programmed to calculate IRR such as EXCEL. As mentioned previously, the intention of the economic model is to evaluate the economic feasibility of using hydrogen instead of natural gas. Table 5 below shows the energy content of the fuels, which shows that hydrogen has almost twice as much energy content as natural gas. This means that less fuel is needed in the hydrogen case to obtain the desired power output; nevertheless, the total fuel cost will depend on the fuel price per kg for both fuels, which will be determined first.

*Table 5 Energy content of the fuel used*

<table>
<thead>
<tr>
<th>Type of Fuel</th>
<th>Energy content [MJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>120</td>
</tr>
<tr>
<td>Natural gas</td>
<td>44</td>
</tr>
</tbody>
</table>

To evaluate the economic feasibility of a project, the investment cost, annual income and annual expenses need to be determined. The investment cost of the gas turbine is highlighted in the literature study and it’s highly dependent on desired power. Once the desired power
output of the gas turbine is decided, the investment cost and produced power, both electricity and heat, are calculated. The annual income comes from selling the electricity together with the heat produced for the district heating. Once the power output is decided, the fuel consumption is calculated. The annual expenses include fuel costs, operation and maintenance cost.

Apart from the turbine characteristics, everything else is dependent on where in the world the gas turbine is installed. Therefore, to assess the feasibility of the hydrogen power plant, few cases including different countries will be studied. This will make it easier to draw the conclusion on economic feasibility. The studied cases are described in the following sections and the results are shown in the result section.

4.2.1 Case 1 US gas turbine with heat generation

The investment costs include costs of components such as gas turbine and heat generation system, balance of the plant, construction, installation and equipment costs, emission control, permits and inspection costs. The annual income and expenses would be different from country to country, therefore this report includes comparison between US and Europe.

The electricity price, fuel costs and district heating cost are highlighted and compared. The first case compares two gas turbine plants of respectively 3 and 40 MW, situated somewhere in the US. Chosen gas turbines operate at 38% efficiency, which is achievable in the hydrogen fired case with a TIT of 1670K and a pressure ratio of 30. This choice will be motivated in the next chapter. For a fair comparison, the same efficiency was assumed for the natural gas case, assuming that higher TIT values are achievable since the NOx generation is lower with natural gas. Table 6 below shows yearly operation time, total electric output and the amount of fuel needed with 38% efficiency of the gas turbine. For the 3.3 MW gas turbine operation time of 8000 h per year are assumed, while for the 40 MW gas turbine seasonal load are considered since the gas turbine will only operate full load between November – February leading to 5000 h per year.

Table 6 characteristics of 3 and 40 MW gas turbine

<table>
<thead>
<tr>
<th>Capacity [MW]</th>
<th>3.30</th>
<th>40.49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hour [h]</td>
<td>8000</td>
<td>5000</td>
</tr>
<tr>
<td>Power [kWh]</td>
<td>26 432 000</td>
<td>323 880 000</td>
</tr>
<tr>
<td>Natural Gas [kWh/kg]</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Hydrogen [kWh/kg]</td>
<td>33</td>
<td>33</td>
</tr>
</tbody>
</table>

As described in the literature study, the electricity price and district heating prices vary with the season. Average yearly prices are shown in the Table 7 below. Current hydrogen and natural gas prices are shown in the table as well. As mentioned before the hydrogen gas could be produced by various fuel reforming methods and the price is dependent on which fuel reforming method is used. In the first part of the calculation current average price of the hydrogen are used, and it could be seen that the current price is very high. Therefore, expected future price are used in the second part of the analysis.
The third part of the analysis includes the investment cost of a fuel reforming system. The price of producing a certain kg/day is shown in the table below. It’s expected in the future that more research would be done in the hydrogen reforming process to lower the production costs. The expected production cost in the future is shown in Table 8 as well. The current and future hydrogen production would be compared.

Table 8 hydrogen production cost in US for current (2016) and future (2020)

<table>
<thead>
<tr>
<th>Hydrogen production</th>
<th>Current price</th>
<th>Future price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,73 $/kg</td>
<td>2,8 $/kg</td>
</tr>
</tbody>
</table>

4.2.2 Case 2 Europa gas turbine with heat generation

Using the same gas turbines and investment costs as the case 1, this case includes current and expected prices for Europe. Average value of prices in Sweden and Germany will be used as Europe prices. Both electricity and district heating costs are higher in Germany than Sweden. Table 9 below shows electricity and district heating prices in Sweden, Germany and average value used for the European scenario.

Table 9 Electricity and district heating price in EU

<table>
<thead>
<tr>
<th></th>
<th>Electricity price [$/kWh]</th>
<th>District heating price [$/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>0,1</td>
<td>44,6</td>
</tr>
<tr>
<td>Germany</td>
<td>0,2</td>
<td>73,1</td>
</tr>
<tr>
<td>EU average price</td>
<td>0,1</td>
<td>58,8</td>
</tr>
</tbody>
</table>

For the fuel prices in EU compared to US, it can be seen that the current and future hydrogen prices shown in the Table 10 below are much higher in Europe than in the American case. Natural gas price, because of easy availability, is almost the same in EU and in the US.

Table 10 fuel price in EU

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>EU Price [$/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen price 2018</td>
<td>12,28</td>
</tr>
<tr>
<td>hydrogen price 2020</td>
<td>6,82</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0,3</td>
</tr>
</tbody>
</table>

As mentioned in the first case, current and future cost of the hydrogen will be compared to hydrogen production cost from a fuel reforming process built near the gas turbine plant. The production costs are shown in Table 11 below and the investment costs will be included directly to the total investment costs. These data are compiled data using Table 1 together with wind and solar hydrogen production costs.
## Table 1: Hydrogen production cost in EU with current price and expected price in the near future

<table>
<thead>
<tr>
<th>Hydrogen Production Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current production cost (2016) [$/kg]</td>
<td>3</td>
</tr>
<tr>
<td>Future production cost (2020) [$/kg]</td>
<td>1</td>
</tr>
</tbody>
</table>

### 4.2.3 Case 3 US gas turbine with heat generation and EGR

The third case investigates a 40 MW gas turbine plant with EGR located in the US. The same costs and incomes are used as case 1, the only difference here is the addition of EGR. Investment costs for EGR are accounted in the total investment costs. As Figure 14 shows, the higher EGR rate used the less fuel will be needed. This will lower the fuel consumption, but the EGR represents an additional investment cost. A trade-off between additional investment cost and reduced fuel consumption is expected.

![Fuel Consumption vs EGR](image)

**Figure 14 Decreased Fuel consumption when EGR are used, less fuel is needed because of the recirculated gas**

The equivalence ratio is the ratio between the actual fuel to air ratio and the stoichiometric ratio. Once the fuel to air ratio of the gas turbine was calculated at different EGR ratio Figure 15 was obtained. The figure shows how EGR affects the equivalence ratio.
Figure 15 relation between equivalence ratio and EGR
5 RESULTS

In this section results with tables and figures together with brief explanation will be introduced. The discussion and conclusion are included in the sections below. Following the same procedure as the current study, the results are divided into two different sections. The first part shows results from the emission calculation, while the second part shows the techno-economic results.

5.1 Hydrogen NOx Emissions

One of the main purposes of this work was to develop an emission model for hydrogen combustion which to find optimal TIT. Results from this model is shown in this section. Equation 4 was used to plot Figure 16, which shows NOx dependence on temperature and equivalence ratio.

![NOx emissions dependence on temperature & equivalence ratio](image)

Figure 16 results of NOx model

As expected higher temperature gives higher NOx, which means lower TIT is beneficial to lower the NOx formation. But, to find optimal TIT the overall efficiency needs to be checked.

Figure 17 shows overall efficiency and NOx formation as a function of temperature.
Figure 17 increased temperature leads to increased NOx emission and higher overall efficiency.

It can be seen from Figure 17 that higher temperature leads to increased overall efficiency but also the emissions, therefore the choice of TIT depends on both efficiency and emission. The efficiency increases linearly with the temperature, while the emission increases exponentially. To justify an operation range for TIT, it’s important to have emissions at stable condition. Liu et al. (2017) concluded that the temperature should be kept in the range 1700 – 1800 K. In this case, optimal TIT is selected at 1670 k giving efficiency of around 38%. Table 12 shows proposed operation parameters for the gas turbine.

Table 12 proposed operation parameters for gas turbine

<table>
<thead>
<tr>
<th>Power</th>
<th>40 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>37.9%</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>30</td>
</tr>
<tr>
<td>TIT</td>
<td>1670</td>
</tr>
</tbody>
</table>
5.2 Techno-economic results

5.2.1 Case 1 US gas turbine with heat generation

As mentioned in the current study, the first case analyses a 3.3 MW gas turbine with heat generation in the US. As the table below shows, several alternatives were compared. The first alternative is if the gas turbine operates with natural gas, while the second and third alternatives compare use of hydrogen and buying the gas from the open market. The price of the hydrogen is currently very high but is expected to go down, therefore the second and third alternatives compare hydrogen current and future price. In the fourth and fifth alternatives, a fuel reforming process is introduced. Currently hydrogen can be produced through various methods, but the production cost is expected to decrease since the technologies develop each year. Thus, the difference of the fourth and fifth alternatives is in accounting decrease of production cost of the gas. Hydrogen is expected to be highly produced by renewable in the future, but price in this latter case was not considered in this work.

Table 13 case 1 results of techno-economic study comparing delivery and produced hydrogen, for 3.3 MW gas turbine

<table>
<thead>
<tr>
<th>USA</th>
<th>Natural gas</th>
<th>Hydrogen current price</th>
<th>Hydrogen Future price</th>
<th>Hyrogen produced Current Price</th>
<th>Hyrogen produced Future Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment [$]</td>
<td>10 969 280</td>
<td>-</td>
<td>10 969 280</td>
<td>-</td>
<td>11 313 370</td>
</tr>
<tr>
<td>Fuel Price/ Production cost [$/kg]</td>
<td>0.2</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>1 944</td>
<td>794</td>
<td>794</td>
<td>794</td>
<td>794</td>
</tr>
<tr>
<td>Bying fuel cost / production cost [$]</td>
<td>388 706</td>
<td>5 556 276</td>
<td>1 587 508</td>
<td>2 995 190</td>
<td>2 248 400</td>
</tr>
<tr>
<td>O&amp;M [$]</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
</tr>
<tr>
<td>Electrical income per year [$]</td>
<td>2 764 787</td>
<td>2 764 787</td>
<td>2 764 787</td>
<td>2 764 787</td>
<td>2 764 787</td>
</tr>
<tr>
<td>Heat income per year [$]</td>
<td>1 442 306</td>
<td>1 442 306</td>
<td>1 442 306</td>
<td>1 442 306</td>
<td>1 442 306</td>
</tr>
<tr>
<td>Net income [first year]</td>
<td>2 560 718</td>
<td>-</td>
<td>1 870 509</td>
<td>2 117 872</td>
<td>710 189</td>
</tr>
<tr>
<td>Payback Time [year]</td>
<td>4</td>
<td>-</td>
<td>5</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 13 shows the results of the techno-economic analysis of the 3.3 MW gas turbine. The investment cost of the cases 1-3 is same, but for the alternative 4 and 5 fuel reforming investment cost is added to the initial investment cost. Fuel price is accounted for the first three cases, while production costs is used in the last two cases, since in the first cases delivery fuel is used while the two last cases fuel reforming are used to produce fuel.

Since, hydrogen has almost twice as much energy content as natural gas, the required fuel is much higher for the natural gas fired gas turbine. But, this is cancelled out by high cost of hydrogen compared with low cost of natural gas in the current energy market. The highest net income in the first year is reached with the natural gas fired gas turbine.
Figure 18 shows the net present value (NPV) of the gas turbines highlighted in the previous table. With discount rate of 2% and operation time of 20 years, the natural fired gas turbine shows great economic benefit compare to hydrogen. The hydrogen fired gas turbine could challenge the natural gas in long term, but in the current market there is a big difference. The current hydrogen price of 7 $/kg doesn’t provide any economic benefit. To make the hydrogen fired gas turbine more competitive an alternative of fuel reforming process installation is studied. Figure 19 shows NPV results of hydrogen fired gas turbine with fuel reforming process.

In Figure 19, the blue line shows results for hydrogen production with current price while the red line shows expected hydrogen production costs. Comparing the current hydrogen production costs with current hydrogen price better economic benefits is reached but still less then natural gas. Comparing current hydrogen price with expected future production price
both alternatives have the potential to compete with natural gas, but higher economic benefits are reached with the future hydrogen price.

A 40 MW gas turbine with the same alternatives was tested to see if the economic analysis shows the same trends. As Table 14 shows, the highest net income of the first year is reached with the natural fired gas turbine.

Table 14 case 1 results of techno-economic study comparing delivery and produced hydrogen, for 40 MW gas turbine

<table>
<thead>
<tr>
<th>USA</th>
<th>Natural gas</th>
<th>Hydrogen current price</th>
<th>Hydrogen Future price</th>
<th>Hydrogen produced Current Price</th>
<th>Hydrogen produced Future Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Price/Production Cost [S/kg]</td>
<td>0.2</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>14 884</td>
<td>6 079</td>
<td>6 079</td>
<td>6 079</td>
<td>6 079</td>
</tr>
<tr>
<td>Buying Fuel cost / production cost [S]</td>
<td>2 976 838</td>
<td>42 551 802</td>
<td>12 157 658</td>
<td>21 173 655</td>
<td>17 020 721</td>
</tr>
<tr>
<td>Electrical income per year [S]</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
</tr>
<tr>
<td>Heat income per year [S]</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
</tr>
<tr>
<td>Net income [first year]</td>
<td>22 951 405</td>
<td>10 834 203</td>
<td>19 559 941</td>
<td>9 043 567</td>
<td>14 696 878</td>
</tr>
<tr>
<td>Payback Time [year]</td>
<td>2</td>
<td>-</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 20 case 1 results of 40 MW gas turbine

As Figure 20 shows, even with bigger gas turbine the most economic benefits are reached with natural fired gas turbine. But, the difference between the natural gas fired gas turbine and the case with hydrogen future price decreased.
Results of 40 MW gas turbine with introduced fuel reforming process are shown in Figure 21. The NPV results shows the same behaviour as the 3.3 MW gas turbine. But, in this case the difference between future and current production of the hydrogen is less than before. Therefore, for the US scenario, a larger plant size is recommended for the hydrogen gas turbine since with future hydrogen prices the economic return could be competitive with natural gas.

5.2.2 Case 2 Europa gas turbine with heat generation

For this case, the same alternatives as case 1 are studied but the difference here is that the gas turbine is located in Europe, which means that fuel costs, production costs and the income would be different.

Table 15 case 2 results of techno-economic study comparing delivery and produced hydrogen, for 3.3 MW gas turbine

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment [$]</td>
<td>-10 969 280</td>
<td>-10 969 280</td>
<td>-10 969 280</td>
<td>-11 313 370</td>
<td>-11 313 370</td>
</tr>
<tr>
<td>Fuel Price/ Production cost [$/kg]</td>
<td>0</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>1 944</td>
<td>794</td>
<td>794</td>
<td>794</td>
<td>794</td>
</tr>
<tr>
<td>Bying Fuel cost / production cost [$]</td>
<td>583 059</td>
<td>5 556 276</td>
<td>1 587 508</td>
<td>2 143 135</td>
<td>1 031 880</td>
</tr>
<tr>
<td>O&amp;M [$]</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
</tr>
<tr>
<td>Electrical income per year [$]</td>
<td>3 568 320</td>
<td>3 568 320</td>
<td>3 568 320</td>
<td>3 568 320</td>
<td>3 568 320</td>
</tr>
<tr>
<td>Heat income per year [$]</td>
<td>1 554 995</td>
<td>1 554 995</td>
<td>1 554 995</td>
<td>1 554 995</td>
<td>1 554 995</td>
</tr>
<tr>
<td>Net income (first year)</td>
<td>2 398 119</td>
<td>-1 870 509</td>
<td>-791 800</td>
<td>2 478 465</td>
<td>3 589 721</td>
</tr>
<tr>
<td>Payback Time[year]</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

As Table 15 shows, both current and expected hydrogen prices are higher than in the previous case. This means that hydrogen would be less competitive in Europe.
Results of the NPV for 3.3 MW gas turbine with 2 % interest rate and 20 years of operation time are shown in Figure 22 above. As expected the only economic benefit is reached with the natural fired gas turbine.

It's more profitable to build fuel reforming process for 3.3 MW gas turbine in Europe than in the US, as the incomes shown in Figure 23 is higher than the values shown in Figure 19. As such, the expected production cost is much lower in Europe.
Table 16 case 2 results of techno-economic study comparing delivery and produced hydrogen, for 40 MW gas turbine

<table>
<thead>
<tr>
<th>EU</th>
<th>Natural gas</th>
<th>Hydrogen current price</th>
<th>Hydrogen Future price</th>
<th>Hyrogen produced Current Price</th>
<th>Hyrogen produced Future Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment [$$]</td>
<td>- 51 658 860</td>
<td>- 51 658 860</td>
<td>- 51 658 860</td>
<td>- 52 002 950</td>
<td>- 52 002 950</td>
</tr>
<tr>
<td>Fuel Price/Production Cost [$$/kg]</td>
<td>0,3</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>14 884</td>
<td>6 079</td>
<td>6 079</td>
<td>6 079</td>
<td>6 079</td>
</tr>
<tr>
<td>Bying Fuel cost / production cost [$$]</td>
<td>4 465 257</td>
<td>74 648 018</td>
<td>41 457 613</td>
<td>16 412 838</td>
<td>7 902 477</td>
</tr>
<tr>
<td>O&amp;M [$$]</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
</tr>
<tr>
<td>Electrical income per year [$$]</td>
<td>27 327 375</td>
<td>27 327 375</td>
<td>27 327 375</td>
<td>27 327 375</td>
<td>27 327 375</td>
</tr>
<tr>
<td>Heat income per year [$$]</td>
<td>11 908 663</td>
<td>11 908 663</td>
<td>11 908 663</td>
<td>11 908 663</td>
<td>11 908 663</td>
</tr>
<tr>
<td>Payback Time[year]</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 16 shows the case of bigger gas turbine built in Europe with the same alternative as before. In this case the highest economic befits is reached with natural gas, but the expected production cost of the hydrogen is very low so that the future expected return becomes almost equal to the natural gas fired gas turbine. Both current and future prices of the hydrogen show negative results which means that, unlike the US case, the 40 MW gas turbine in Europe is not competitive.
Figure 24 shows the results of NPV for 40 MW gas turbine in Europe.

![Graph showing EU NPV of 40.485 for current and future cases.]

Figure 25 shows the results of NPV for 40 MW gas turbine with fuel reforming in Europe. More promising results are obtained. The production costs are very low and are expected to drop further in the coming future. As Figure 25 shows, the hydrogen production case of 40 MW gas is more competitive and could represent a solution for the short-term future.

5.2.3 Case 3 US gas turbine with heat generation and EGR

In this case, the purpose is to see what difference the EGR would make to the economic calculations shown in the previous cases. In this case a 40 MW gas turbine with EGR located in the US is considered, since it represents the most favourable scenario. The EGR circulates a part of the exhaust gas which means less fuel is needed. Two cases of 30% and 60% EGR rates are studied.
The Table 17 shows results of 40 MW hydrogen fired gas turbine fired with EGR. The EGR investment costs are accounted, so the investment costs become higher. But, the required fuel is 4% less. The case with current hydrogen price gives still negative benefit, while the case with expected future price of hydrogen gives the highest economic benefit.

Table 17 case 3 results with 30% EGR rate

<table>
<thead>
<tr>
<th>USA EGR 30 %</th>
<th>Hydrogen current price</th>
<th>Hydrogen Future price</th>
<th>Hydrogen produced Current Price</th>
<th>Hydrogen produced Future Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Price/ Production Cost [$/kg]</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>5 319</td>
<td>5 319</td>
<td>5 319</td>
<td>5 319</td>
</tr>
<tr>
<td>Bying Fuel cost / production cost [$]</td>
<td>37 232 827</td>
<td>10 637 950</td>
<td>19 839 778</td>
<td>14 893 131</td>
</tr>
<tr>
<td>O&amp;M [$]</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
</tr>
<tr>
<td>Electrical income per year [$]</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
</tr>
<tr>
<td>Heat income per year [$]</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
</tr>
<tr>
<td>Net income [first year]</td>
<td>- 5 515 228</td>
<td>21 079 648</td>
<td>11 877 821</td>
<td>16 824 468</td>
</tr>
<tr>
<td>PayBack [year]</td>
<td>- 3</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

The Table 18 presents the result for 40 MW hydrogen fired gas turbine with 60% EGR. The required fuel decreases further with 4%. Overall, the same trends as for 30% EGR are shown. The highest economic benefits are reached for the case with future hydrogen price.

Table 18 case 3 results with 60% EGR rate

<table>
<thead>
<tr>
<th>USA EGR 60 %</th>
<th>Hydrogen current price</th>
<th>Hydrogen Future price</th>
<th>Hydrogen produced Current Price</th>
<th>Hydrogen produced Future Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Price/ Production Cost [$/kg]</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Required fuel Ton</td>
<td>4 635</td>
<td>4 635</td>
<td>4 635</td>
<td>4 635</td>
</tr>
<tr>
<td>Bying Fuel cost / production cost [$]</td>
<td>32 445 749</td>
<td>9 270 214</td>
<td>17 288 949</td>
<td>12 978 300</td>
</tr>
<tr>
<td>O&amp;M [$]</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
<td>501 714</td>
</tr>
<tr>
<td>Electrical income per year [$]</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
<td>21 173 655</td>
</tr>
<tr>
<td>Heat income per year [$]</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
<td>11 045 658</td>
</tr>
<tr>
<td>Net income [first year]</td>
<td>- 728 150</td>
<td>22 447 385</td>
<td>14 428 649</td>
<td>18 739 299</td>
</tr>
<tr>
<td>PayBack [year]</td>
<td>- 2</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
6 DISCUSSION

The aim of the report was to compare pure hydrogen fired gas turbine with and without exhaust gas recirculation with traditional natural gas fired gas turbine, to highlight differences in economic feasibility and environmental impact. The utilization of pure hydrogen in a gas turbine leads to certain challenges such as low flame stability and production of thermal NOx. Pure hydrogen has high reactivity, reacting easily with oxygen leading to concern of flashback and auto ignition for premixed systems.

Pure hydrogen has higher adiabatic flame temperature (approx. 2500 K) that natural gas (approx. 2230 K) at stoichiometric conditions. To achieve 1700 K as adiabatic flame temperature for natural gas mixed with air, the mixture will have higher equivalence ratio than hydrogen mixture. Once the NOx emissions are corrected to the reference conditions, the hydrogen rich mixture will be shifted to the left showing higher emissions for given temperature compared to values for natural gas. From the emissions model, a TIT of 1670 K was chosen as it allows to achieve an efficiency around 38% and at the same time the NOx emissions are below 1 ppm with an equivalence ratio >0.6. Lowering the temperature could lower NOx but paying in efficiency. Therefore, the economic analysis could be also conducted for different values of TIT, but a lower economic return would be obtained with lower TIT. Since from the economic analysis it was shown that hydrogen isn’t, yet a feasible solution compared to natural gas in terms of economic return, it is not possible in the near future to lower the TIT and reduce NOx formation in hydrogen plants. On the other hand, since pressure was not shown in the literature to affect emissions significantly, the pressure ratio can be chosen as high as possible to achieve better efficiency.

Proposed solution to mitigate high flame stability and production of thermal NOx is to use exhaust gas recirculation (EGR). In general, EGR leads to low oxygen concentrations. It’s a well-known method which has been used to reduce NOx emission by decreasing oxygen concentration and therefore decrease the production of thermal NOx. Varying fuel to air ratio is the same principle as using EGR. Higher equivalence ratio means a rich mixture, where less oxygen is available for reactions and hence less NOx can be produced. Introducing EGR has the same effect as increasing the equivalence ratio as the gas entering the combustion chamber contains a mix of oxygen, nitrogen, and steam. The results obtained with different equivalence ratios show that highest NOx formation is reached at 0.5 (which means double air content as the stoichiometric condition). As such, in this condition a lot of excess air is present to form NOx. The higher the ratio becomes the less NOx is created. Increasing the EGR from 0 to 60% is equivalent to increase the equivalence ratio from 0.2 to 0.65, which is the way to ensure NOx<1ppm at the selected TIT.

For the economic analysis, since economy and politic policies differ from country to country and it has a huge impact on the economic feasibility of the gas turbine, therefore several case studies were conducted to use as sensitivity analysis. Gas turbines has huge impact on US electricity production, almost 32% coming from natural gas fired gas turbine together with steam turbines. Therefore, the first case includes gas turbine located in the US.

While the second case was initially about Sweden, but it was quickly realized that Sweden has high renewable energy production and it would be difficult to integrate gas turbines.
Additionally, the current Sweden electricity price is very low compare to rest of Europe, therefore the second case evaluated the gas turbine plant in a generic European scenario. Sweden has low electricity prices while a country such as Germany has opposite very high electricity price, hence the average value of these countries is used in the second case. Finally, a third case was evaluated which included exhaust gas recirculation (EGR) for the 40 MW gas turbine located in the US.

For case 1 where two different size of gas turbine operating with hydrogen and natural gas located in the US were compared, the results show that with the current price hydrogen is not competitive with natural gas because of the high fuel costs. The hydrogen fired gas turbine could challenge natural gas in the future when hydrogen price will reduce, but in the current market there is a huge difference in fuel costs. The current hydrogen price of 7 $/kg doesn't give any economic benefit. But, if the proposed cost target of $2/kg at delivery for hydrogen is reached, it could make hydrogen more economically feasible and competitive with existing natural gas plants, although natural gas will remain slightly cheaper even considering taxation for CO2 production.

In order to make the hydrogen fired gas turbine more competitive, an alternative of fuel reforming process installation is studied. A comparison between fuel reforming with current available technology and future fuel reforming was made. The results show that it can be economically feasible with current hydrogen production price compared to delivered cost of the hydrogen, but the benefits are still less than natural gas. Comparing long-term goal for hydrogen price with expected future production price, both alternatives have the potential to compete with natural gas, and higher economic benefits are reached with the future hydrogen price. In all cases, the larger turbine provided a better return.

For case 2 a similar comparison as case 1 was done but for the European market. The results show similar trends, where with current price hydrogen is much more expensive than natural gas. The figures with NPV for both 3.3 & 40 MW gas turbine indicated that with both current and expected future price, hydrogen fired gas turbines are not economically feasible in Europe.

However, it could be more profitable with fuel reforming process for the gas turbine in Europe than in the US. This is because the expected production cost is much lower in Europe. With the 40 MW gas turbine in Europe, promising results were obtained with future expected production cost of hydrogen. Expected future production cost of hydrogen in Europe is 1 $/kg which is very low, leading to potential economic growth.

The third case analysed the 40 MW gas turbine located in the US including the EGR, the purpose was to see the difference that EGR would make on the economic calculations shown in case 1. With EGR less fuel was needed compared to case 1, which led to an increase in economic return. 60 and 30% of EGR rates were tested. Results 60% EGR rate showed that required fuel decreases by 23% and the NPV increased by 28%. The highest economic benefits are obtained with future hydrogen price. Thus, we can conclude that the 40 MW plant with TIT=1670K and EGR=60% could be a feasible solution in the future US scenario to integrate hydrogen in the energy market, both from an environmental and economic perspectives.
In the future, resources such as solar and wind are becoming a larger portion in the energy mix. These renewable sources have natural fluctuations in produced electricity which could be mitigated by producing hydrogen during peak load and converted back to electricity to provide constant power when needed. Therefore, more hydrogen will be produced in the future leading to reduced fuel cost. By accounting this the hydrogen fired gas turbine will have promising future and will be expected to compete with natural gas even sooner.

7 CONCLUSION

Hydrogen fired gas turbine has great potential to increase energy conversion efficiency and reduce CO2 emissions. Hydrogen has high energy content compared to natural gas and doesn’t produce greenhouse gases such as CO2 and CO. The drawback is that it has big issues with high formation of NOx: hydrogen fired gas turbine would release almost three times more NOx than natural gas at a given TIT. EGR helps to reduce the temperature in the combustor while decreasing fuel consumption, which means that lower NOx emissions are achieved.

A NOx emissions model was developed from empirical data taken from the literature and it was used to determine the best operating condition for a hydrogen gas turbine. It was evaluated that with combustor exit temperature below 1700 K, a reasonable NOx level is reached when burning hydrogen at equivalence ratio above 0.6. Therefore, a TIT value of 1670K was selected for the hydrogen plant to maintain an efficiency of 38%, and an EGR ratio of 60% is recommended to achieve the suitable equivalence ratio. The turbine inlet temperature can’t be reduced too much because even if it is beneficial for the emissions, the efficiency is also reduced, and the economic results will suffer. Therefore, a trade-off between performance and emissions is necessary.

With the current hydrogen and natural gas prices, the same trends are shown in both US and Europe cases, where it is concluded that natural gas fired gas turbine is more economical in the current market. If the government target of hydrogen cost is reached in the future, promising results would be obtained. In particular, with future hydrogen price, a large gas turbine plant (40 MW) can be competitive with natural gas in the US scenario. When adding EGR, NOx emissions are maintained below 1 ppm and the hydrogen plant was demonstrated to be both environmentally and economically feasible. Instead, in the European scenario, production of hydrogen in the same plant site was observed to be more economical both now and in near future, while the high cost of delivered hydrogen would limit the feasibility of these plants. In conclusion, hydrogen fired gas turbine can only be profitable in the US with the current estimations, while it seems more beneficial to use fuel reforming process than buying hydrogen gas in EU. Policies to favour hydrogen penetration in the market are essential to increase the feasibility of these plants and strive toward a carbon-free economy.
8 PROPOSAL FOR FUTURE WORK

The obtained results can be used for further studies on hydrogen fired gas turbines. The results are based on general data for both in US and EU. Therefore, this study can be properly used when investing in hydrogen fired gas turbine or interested to know how the gas turbine emissions using hydrogen as fuel can look like. Particularly, how the cost factor varies depending on the location of the landfill and the fuel used.

There were few necessary assumptions made to facilitate the calculation, which could be avoided by validating the emission and economic models with real data. Measuring emissions in real gas turbine to validate the theoretical model provided in this report is critical. The full integration of emissions model, economic model and performance model with a conceptual design of hydrogen-fired gas turbine would be interesting. The performance of the power plant should be estimated across the whole operating range and an optimisation strategy should be applied.

In the future, production of hydrogen from renewable sources will play a key role, which will change significantly the hydrogen price and possibly the available infrastructure. Therefore, in the future a more accurate economic evaluation could be done by considering hydrogen from renewables.
REFERENCES


APPENDIX 1: EQUATIONS AND DATA FOR THE GAS TURBINE MODEL

In this appendix, all the equations and data for the gas turbine model are introduced. The first part gives equations and assumptions made to reach desired power outcome of the gas turbine

Fundamental of gas turbine engine

Basic principle of gas turbine engine is identical to any engine that extract energy from chemical fuel. These following four steps are basic for any internal combustion engine:

- Intake of air
- Compression of the air
- Combustion, where fuel is injected and burned to convert the storage energy
- Expansion and exhaust, where the converted energy is used.

To produce the desired power a large mass of air is taken in to the compressor. The compressor converts mechanical energy from the turbine to gaseous energy in the form of pressure and temperature rise. After the compression, the air enters the combustor, where air and fuel are blended and burned to increase the velocity of the gas. Increasing the velocity of the gas is essential for the turbine rotors to rotate and produce desired power.

The main parameters calculated are the following:

- Pressure
- Temperature
- Enthalpy
- Entropy (Φ)
- Mass flow
- Fuel flow

All the calculations are done assuming the air as an ideal gas. Total temperature, total enthalpy, Fuel to air ratio (FAR), water to air ratio (WAR), entropy (PHI) and mass flow are calculated for each step. They are dependent on each other so if some of them are known, the rest can be calculated or retrieved in tables. Gibbs equation is used to calculate the relation between entropy, pressure ratio and temperature.

Gibbs equation:

\[ \Delta S = \int_{T}^{To} \frac{C_p}{T} \ast dT - Rg \ast \ln \left( \frac{P_o}{P} \right) \]
Equation 6 Gibbs equation
Where Rg is universal gas constant and assumed to be 287.05 and the integral is calculated as:
\[
\int_T^{T_o} \frac{C_p}{T} = \varphi(T_o) - \varphi(T)
\]
Assuming an ideal gas, the equation becomes:
\[
\varphi(T_o) - \varphi(T) = R_g \cdot \ln\left(\frac{P_o}{P}\right)
\]
Equation 7 Gibbs equation for ideal gas

COMPRESSOR

Assuming ideal air to enter the compressor, Gibbs equation for ideal gas could be used to calculate the temperature and entropy since we know the compressor pressure ratio. For the inlet of the compressor all the values are known, but for the outlet these equations are used:
\[
\varphi(out) = \varphi(in) + \frac{R_g \cdot \ln\left(\frac{P_{out}}{P_{in}}\right)}{\eta_{c,\infty}}
\]
Once the outlet entropy is known and FAR is equal to zero for the compressor case, the outlet temperature could be interpolated in the steam tables. In the same way, the inlet and outlet enthalpy could be interpolated in tables using FAR and temperatures. As mentioned previously the compressor need work to increase the pressure and temperature, this work is given by the turbine by using rotation shaft. The compressor work needed is calculated as:
\[
W_c = airflow \cdot (h_{ut} - h_{in})
\]
Equation 8 compressor work

COMBUSTOR

Inlet parameters of combustor are the same as the outlet parameters of the compressor. Assuming the combustor to have pressure loss of 4%, the total pressure could be calculated. In this case FAR changes because of the injection of the fuel. With desired outlet combustion temperature, the outlet enthalpy could be calculated using two different methods.

First method is by chosen combustor with desired outlet temperature of 1500 k and using guessed FAR to interpolate the total outlet enthalpy.
The second method by assuming relative temperature 298.15 K and using FAR to zero, the relative inlet enthalpy could be calculated. Using the relative temperature and guessing FAR the outlet relative enthalpy are calculated. Here is the equation used:

\[ m_{fuel} = m_{air} \times FAR(\text{guessed}) \]

*Equation 9 fuel flow*

Since the inlet enthalpy and heating value of the fuel are known, the flowing equation is used:

\[ h_{out} = h_{\text{relative, out}} + \frac{m_{air} \times (h_{in} - h_{\text{relative, in}}) + (m_{fuel} \times Q_{LHV} \times \eta_{\text{combustor}})}{m_{air} + m_{fuel}} \]

*Equation 10 enthalpy derived from mass balance*

MATLAB is used to iterate the guessed FAR to have same total enthalpy from both methods. Knowing the total enthalpy, FAR and total temperature the rest could easily be calculated.

**TURBINE**

High-pressure turbine (HPT)

Assuming there is no pressure loss and the total pressure is known as its same for the outlet of the combustor. For the turbine rotor inlet of the high-pressure turbine, the total inlet flow is mixed with 60 % of the cooling flow from the compressor. Here are how the mass flows are divided:

\[ m_{\text{combustor}} = 0.8 \times m_{air} \]

*Equation 11 combustor flow*

\[ m_{\text{cooling}} = 0.2 \times m_{air} \]

*Equation 12 total cooling flow*

\[ m_{\text{cooling,HPT}} = 0.6 \times m_{\text{cooling}} \]

*Equation 13 cooling flow for HPT*

Since we have all the mass flows needed, the sum of the energy can be calculated as following:

\[ \text{Sum energy} = (m_{\text{cooling,HPT}} \times h_{HPC,\text{out}}) + (m_{\text{combustor}} \times m_{\text{fuel}}) \times h_{\text{combustor, out}} \]

*Equation 14 total energy produced from the HPT*

Once the sum of the energy is known, the outlet enthalpy can be calculated. To calculate the outlet temperature the same formula mentioned previously could be used, but we need to calculate FAR and since we have mixed flows the FAR is calculated as:

\[ FAR_{\text{HPT}} = \frac{m_{\text{fuel}}}{m_{\text{combustor}} + m_{\text{cooling,HPT}}} \]
**Equation 15 fuel to air ratio for the HPT**

After total enthalpy and FAR are calculated, total temperature and total PHI interpolated using the new FAR. The mass flow raises with portion of the cooling flow.

When calculating the HPT power outlet, the work for high pressure compressor (HPC) and the efficiency of the high-pressure shaft are known. Having in mind that the HPC are rotating the HPT with help of the high-pressure shaft and using given shaft efficiency the HPT work are calculated. The mass flow is constant through the turbine.