Technological and economical assessment on hydrogen energy conversion systems based in gas turbines

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

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I dedicate this work to my sister Laura, who is my biggest inspiration.

Abstract

In order to contribute to the ongoing development of hydrogen technology, this study investigates the possibilities of hydrogen combustion and current status for hydrogen gas turbine technology. The study includes the model of combustion chamber developed in order to simulate the formation of emissions during combustion of selected fuels and fuel mixture of $CH_4 - H_2$. Such parameters as adiabatic flame temperature, laminar flame velocity and concentration of emission has been investigated, with regard to the equivalence ratio ranging between 0.5 and 3.5. The study addresses NO_x emission as a main limitation for the hydrogen gas turbines development and indicates the need and possible solutions to mitigate high emissions during hydrogen combustion. Moreover, the study addresses the environmental impact of water resulting from the implementation of hydrogen technology. The study contains a techno-economic study of hydrogen and gas turbine technology including estimation of costs connected with the implementation of large scale heavy duty gas turbine and brief analysis of the expenses connected with the micro-scale gas turbine installation. Moreover the cost of green hydrogen production has been assessed together with sensitivity analysis being conducted. The sensitivity analysis of green hydrogen costs indicates the importance of oxygen revenues and its sales in order to obtain low green hydrogen prices. Moreover the impact of electrolyzer cost and its efficiency has been studied with respect to the price of renewable hydrogen and the utilization factor of the electrolyzer, however the impact of aforementioned parameters is much lower with comparison to the impact on green hydrogen price related to revenues coming from selling oxygen.

Keywords

hydrogen, gas turbine technology, emissions, low-NO_x combustion

Resumo

A fim de contribuir para o desenvolvimento contínuo da tecnologia do hidrogénio, este estudo investiga as possibilidades de combustão do hidrogénio e o estado actual da tecnologia das turbinas a gás de hidrogénio. O estudo considerou o modelo de câmara de combustão a fim de simular a formação de emissões durante a combustão de combustíveis seleccionados e mistura de combustíveis de $CH_4 - H_2$. Foram investigados parâmetros como a temperatura adiabática da chama, a velocidade da chama laminar e a concentração da emissão, no que respeita à relação de equivalência que varia entre 0.5 e 3.5. O estudo aborda a emissão de NOx como uma limitação principal para o desenvolvimento de turbinas a gás de hidrogénio e indica a necessidade e possíveis soluções para mitigar emissões elevadas durante a combustão de hidrogénio. Além disso, o estudo aborda o impacto ambiental da água resultante da implementação da tecnologia do hidrogénio. O estudo contém um estudo técnico-económico da tecnologia de turbinas a gás e hidrogénio, incluindo uma estimativa dos custos relacionados com a implementação de turbinas a gás em grande escala e uma breve análise das despesas relacionadas com a instalação de turbinas a gás em micro-escala. Além disso, o custo da produção de hidrogénio verde foi avaliado em conjunto com a análise de sensibilidade que está a ser realizada. A análise de sensibilidade dos custos do hidrogénio verde indica a importância das receitas do oxigénio e das suas vendas, a fim de obter preços baixos do hidrogénio verde. Além disso, o impacto do custo do electrolisador e a sua eficiência foi estudado em relação ao preço do hidrogénio renovável e ao factor de utilização do electrolisador, contudo o impacto dos parâmetros acima mencionados é muito menor em comparação com o impacto no preço do hidrogénio verde relacionado com as receitas provenientes da venda de oxigénio.

Palavras-chave

hidrogénio, tecnologia de turbinas a gás, emissões, baixo NOx combustão

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List of Abbreviations

AFT	Adiabatic Flame Temperature
Btu	British thermal unit
CAGR	Compound annual growth rate
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CF	Cash Flow
$C_{o\&m}$	Operational and maintenance costs
DLN	Dry-Low NOx
DPP	Discounted Payback Period
EC	European Commission
eff	Efficiency
EGR	Exhaust Gas Recirculation
EI	Emission Index
EU	European Union
electr. Cost	The price of renewable electricity
ETN	European Turbine Network
FCEV	Fuel Cell Electric Vehicle
FCHJU	Fuel Cell Hydrogen Joint Undertaking
GE	General Electrics
GT	Gas Turbine
ha	Utilization factor
HHV	Higher heating value
hPa	Hectopascal
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
I_t	Total Investment
J	Joul
ka	Discount factor
kWh	Kilowatt hour
LCOE	Levelized Cost of Energy
LDI	Lean Direct Injection
LHV	Lower Heating Value
LNG	Liquefied natural gas
LPG	Liquefied Petroleum Gas
LSC	Low Swirl Concept

LSB	Low Swirl Burner
MHI	Mitsubishi Heavy Industries
MMX	Micromix
MWh	Megawatt hour
ng	Nanogram
NG	Natural Gas
NH_3	Ammonia
NO	Nitric oxide
NOx	Nitrogen Oxides
NO_2	Nitrogen dioxide
N_2O	Nitrous Oxide
NPV	Net Present Value
P	Pressure
PFR	Plug Flow Reactor
PM	Particulate Matter
Ppm	Parts per million
Ppmv	Parts per million volume
R	Revenues
RES	Renewable Energy Sources
Rpm	Revolutions per minute
RQL	Rich burn, Quick-mix, Lean-burn combustion technique
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SPP	Simple Payback Period
T	Temperature
t	Lifetime of an electrolyzer
TIT	Turbine Inlet Temperature
UHC	Unburned Hydrocarbon
UK	United Kingdom
WI	Wobbe Index
WSR	Well-Stirred Reactor
OECD	Organization for Economic Co-operation and Development

List of Symbols

α	Moles of CH_4
β	Moles of H_2
Φ	Equivalence ratio
€	Euro
$	US dollar
˚C	Degrees Celsius
K	Kelvin
$\dot{Q}_f$	Fuel volumetric flow rate
$(HV)_{vol}$	Heating value of the fuel per unit volume
ρ_{fuel}	Fuel density
Δp	Pressure drop

List of Software

Python	Python is an interpreted, object-oriented, high-level programming language.
Cantera	Cantera is an open-source chemical kinetics software used for solving chemically reacting laminar flows
GE Calculator	Hydrogen and CO_2 calculator for gas turbines

Chapter 1

Introduction

This chapter provides the insight into the energy context and main motivation of this study. Additionally this chapter addresses the importance of the technology considered within this study and its possible future contribution and development. At the end of the chapter, the final objective and document structure is provided.

1.1 Energy context outlook

Connected with constant development and increasing energy demands, there is a strong need to curb emissions and keep preventing environmental changes. Even tough Renewable Energy Sources (RES) shares are growing, their percentage in total energy production is still significantly lower than these of fossil fuels. The state for 2019 indicates that fossil fuels cover up to 71% [1] of the gross available energy in the European Union (UE), consisting of 27 Member States, and up to 84% [2] of World energy comes from fossil fuels. Where, gross available energy is the amount of energy necessary to meet the energy demand of a region under investigation. Although, the share of fossil fuels in the general energy production has dropped significantly over last decades, due to climate actions and in favour to increased RES shares, a further fossil fuel use reduction is required in order to prevent progressing climate changes. As given by the European Commission (EC), the share of fossil fuels dropped by 10,9 percentage point [1], compared to 1990 data. As International Energy Agency (IEA) gives, in 2021 RES shares in global energy generation reached 28% [3], at the cost of natural gas and coal shares. Nevertheless, those two fossil fuel feedstocks remain leading in energy production and cover nearly 60% of energy demand. As presented in the Figure 1 the global energy-related carbon dioxide (CO_2) emissions reached the peak value around year 2019 and being at the level of approximately 34 Gt CO_2. The contribution of energy-related CO_2 emissions accounts for about two-thirds of global greenhouse gas emissions. An interesting phenomena, related to COVID-19 pandemics, can be observed in the following years. It can be seen that the emissions started to drop by the end of 2019. This represents the response to the limited system operability and highly limited human actions and transportation during the initial phase of global pandemics. Nevertheless, data shows the significant increase in relatively short timeframe compared with data from 1990 and equal to 20 Gt CO_2 .

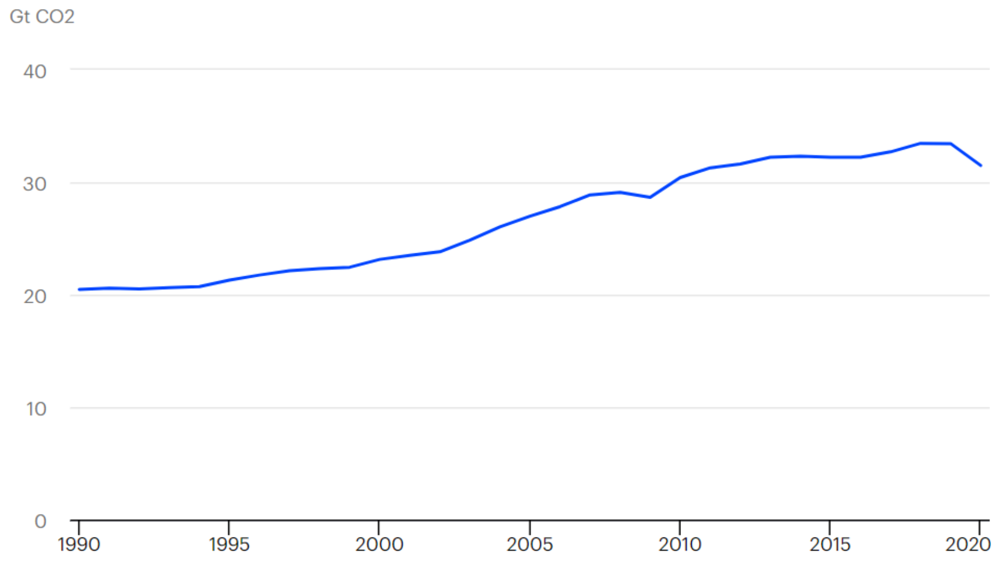

Figure 1 Global energy-related CO_2 emissions, 1990-2020 [3]

As indicated by the EC, the greenhouse gas emissions between 1990 and 2018 has been reduced by 23%. Nevertheless, the goal for 2050 is ambitious and assumes greenhouse gas emission reductions of 60% by 2050, according to the policies set in the Green Deal energy roadmap [4] . This objective will require fundamental changes in many sectors and it will require significant investments and efforts to direct the change towards Net-Zero climate change predicted for 2050.

Presented in the Figure 2, World energy consumption shows the current and predicted levels of energy consumption by sector and with division to Organization for Economic Co-operation and Development (OECD) and non-OECD countries, expressed in quadrillion British thermal units (Btu). The significant growth in each sector can be observed. This results from the predictions of global population growth, which, according to United Nations will reach 9.7 billion worldwide by 2050 [6]. It can be seen that industrial sector covers the highest shares of energy consumption. It is predicted for the energy consumption by industrial sector to increase by more than 30% between 2018 and 2050, due to increasing consumption of goods. By the year 2050, the global industrial sector energy consumption is expected to reach around 315 quadrillion Btu. Transportation accounts for the second most energy-intensive sector. It shows the increase of 40% between 2018 and 2050. It should be addressed, that non-OECD countries play significant role in the transport sector, as the energy consumption in this case increases by 80% between 2018 and 2050, which shows much more rapid shares increase compared to OECD countries. The energy consumption for building sector in general, including residential and commercial units shows the increase of 65% by the 2050, corresponding to 193 quadrillion Btu.

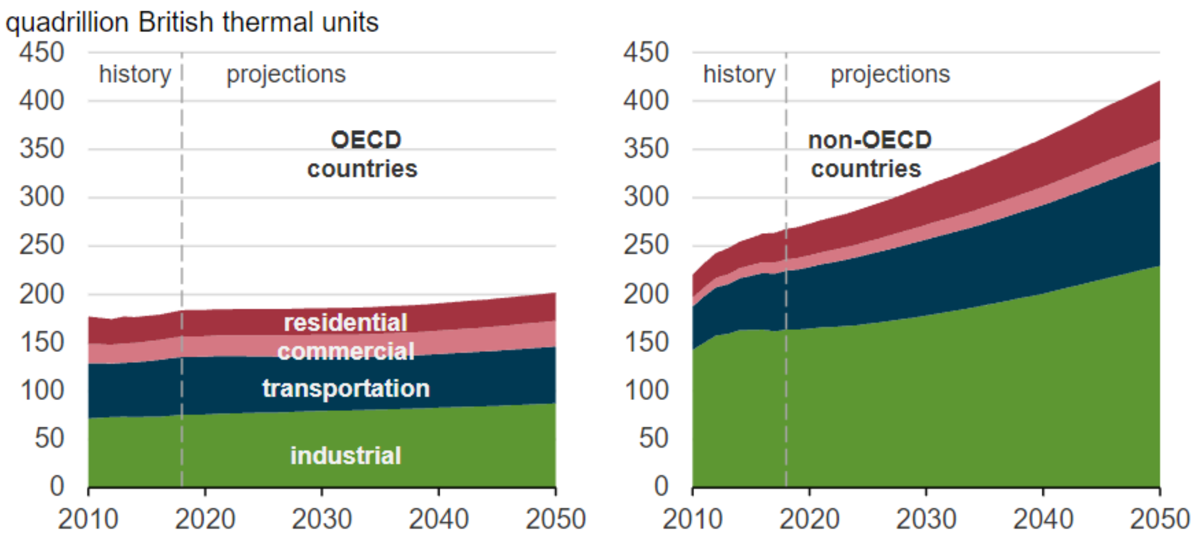

Figure 2 World energy consumption by sector for OECD and non-OECD countries [7]

Shifting towards green energy, not only means getting closer to the clean environment, but also savings of non-renewable energy sources, which each year become more scarce. Moreover, resigning from fossil fuels such as coal or natural gas translates to energetical independence and safety for many countries, together with carbon footprint reduction contributing to clean environment. In fact those are three main objectives for almost all countries all over the world. First goal is to be energetically independent, which means to be able to produce own electricity from the local feedstock. Secondly, to reduce the carbon footprint and greenhouse gases emission which is an essential step towards reduction of average global temperature increase below 2˚C above pre-industrial levels as a reference point [8]. It is worth mentioning that in some regions, as the temperature increase over the globe is not uniform, the rise of 1.5˚C already have been experienced resulting in dramatic climate changes affecting various flora and fauna, as well as human population [9]. Additionally, the need of carbon footprint reduction, on the other hand, is influenced by the need to meet the standards introduced by corresponding organs of each country. And last but not least, the objective for each country is for the energy to come from stable source at competitive prices. Figure 3 demonstrates the changes in Levelized Cost Of Energy (LCOE), which estimates the average cost per unit of energy generated across the lifetime of a power plant. It is expressed in US$ per kilowatt-hour. It shows costs of different alternative energy sources with comparison to fossil fuel range of prices. From the chart it can be noted that the two most competitive energy sources for fossil fuels in 2019 is considered to be hydropower and onshore wind energy – where, in case of the second technology, a significant price drop can be seen over the years of technology development.

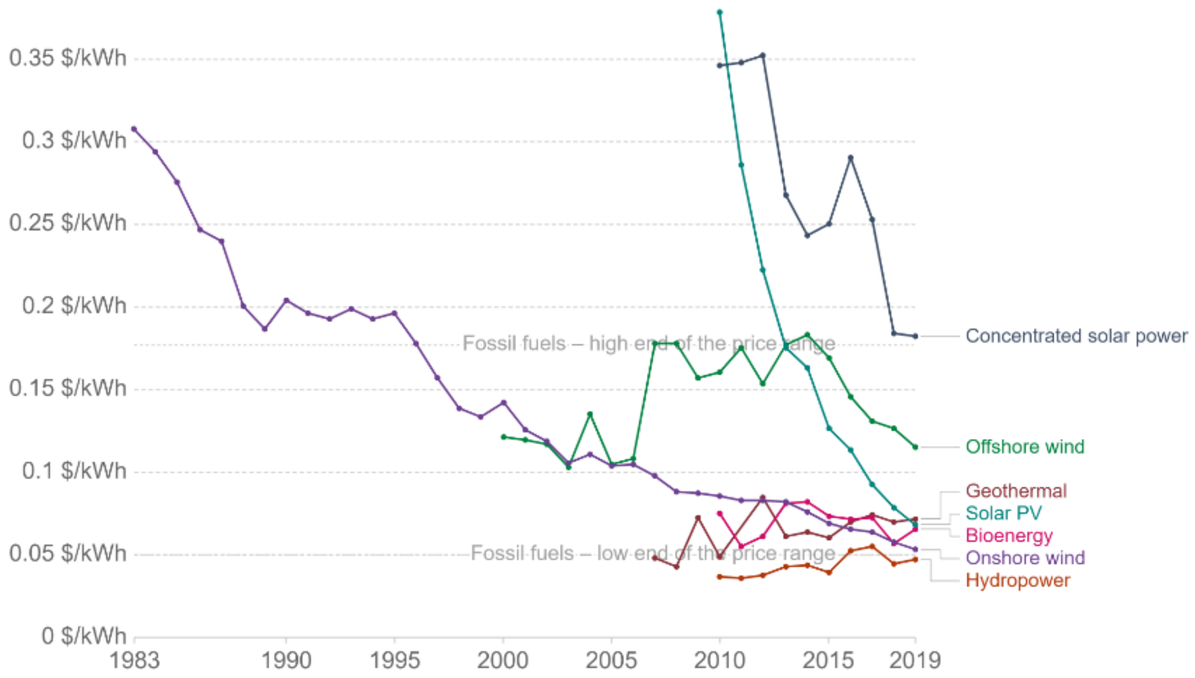

Figure 3 Levelized cost of energy by technology, World 2019 [10]

On the other hand, while comparing various energy sources and energy conversion devices, the capital and operational costs should be included in order to compare two different technologies using various energy feedstocks. For instance, according to 2015 data [11] the price of gas turbine installation, assuming the USD to € exchange rate of 0,86, varies between 430-600 € per kilowatt, while price of renewable technology and nuclear power plant respectively are around 1300 and 4300 € per kilowatt. However, once the renewable energy production unit is installed and connected to the grid the fuel is free of charge, as it comes from natural sources, which do not deplete when used, however their operation is unstable. It is worth recalling the definition of renewable energy which states that the source depletes at lower rates than is exploited, or in other words renews faster than it is exploited [12][11]. On the contrary, in case of gas turbine installation, the fuel cost component at current natural gas prices anywhere ranges between two-thirds up to 80%. While the general costs for gas turbine installation, including fuel, at first glance are higher, this solution provides stable operation in a contrary to renewable energy sources. Based on this comparison, it is therefore indisputable that energy transition is nowadays of major importance and needs to be well balanced and tailored to meet all previously mentioned requirements and energy challenges. Gas turbines together with hydrogen might play an important role and lead to paradigm shift regarding the current energy system. Those two technologies combined might be a missing link between conventional energy system and the renewable energy strategy, providing a smooth energy transition and supporting the pillars of sustainability including economy, environment and social aspect.

1.2 Importance of hydrogen and gas turbines in energy transition

Although each year contribution of green energy in the overall energy system is growing, the renewable energy production still needs fundamental improvements and further development to overcome current energy system malfunctions. Currently the objective is to reach the shares of renewables in the energy sector of 85% by 2050 [13]. As it can be seen the renewable energy sector will be subjected to a significant power increase in the upcoming decades. Main problems connected with introduction of RES into existing energy system is the instability and the changing nature of renewable technology. Energy production utilizing renewable sources strongly depends on atmospheric conditions such as irradiation necessary for solar power production and wind indispensable for energy production within aerogenerators. This intermittent nature of renewable systems is a principal defect preventing those to fully substitute the conventional energy sources, which by far, appear to perform with higher stability. Therefore, in order to compensate seasonal imbalances and changing nature of renewable energy a large-scale energy storage is needed. Additionally this is also an important stage in order to store and save temporary excessive power produced by renewable energy sources in case of more favourable atmospheric conditions.

Since energy storage technology still requires further research and development, it is a great challenge to balance production and demand for energy relying exclusively on RES. By far energy storage still suffers such issues as relatively poor efficiency, durability or high costs preventing the technology to be introduced on higher scale. Additionally, the task of introducing RES into current energy system and coupling them with conventional technology of energy production based on fossil fuels is ineffective without the intermediate stage of energy storage. For better insight into the problem, the start-up of a conventional coal-fired thermal power plant, depending on the power can vary from 1h to even 8h [14]. Therefore frequent shut-downs and start-ups affect negatively the efficiency of such power plants, which operate with highest overall efficiency under constant load. This therefore makes the effective renewable energy surplus allocation impossible, as grid balancing reduces its efficiency and leads to power losses. A way to eliminate the mismatch between load demand and power generation from RES is therefore a proper and efficient accommodation of aforementioned energy surplus.

It can be seen that the word faces two major problems: rising energy demand and the need to cut the emissions leading to global warming and thus negative climate changes such as rising overall temperatures, shrinking glaciers and rising sea levels. Although solar and wind energy sources are promising substitution to non-renewable energy sources, current rising power demand requires a stable energy supply that will not be limited by atmospheric conditions. Therefore, the challenge is to find a solution that would solve both of this issues: providing stable operation, while resigning from use of non-renewable energy sources with a favour to green energy and storage. The common element linking all together is hydrogen, which, by using energy excess produced by RES, works as an energy storage to later power gas turbines to produce power or being directly combusted as a domestic heating source or with the use fuel cells providing electric power without wasting precious renewable energy. This can be done as hydrogen can be produced via electrolysis utilizing the renewable energy to run the process. Those are only some of proposed solutions for hydrogen utilization in the energy transition, as there are many ways of accommodating hydrogen in existing energy system including transport sector, household applications or direct energy production. Moreover, hydrogen could be a good solution for the countries with less favourable conditions for development of renewable energy on desired scale allowing to meet the environmental regulations. It would allow those countries to benefit from renewable energy as hydrogen might enable large renewable energy to be channelled to the regions, or even countries, where the decarbonization is more challenging or even impossible. In this way hydrogen would contribute to achieving at least three positive outcomes, namely the resignation from fossil fuels, integration of renewable energy together with its development on a global scale and, last but not least, making renewable energy delivery possible thanks to hydrogen transportation.

Hydrogen-based energy system can be a resilient competition for conventional fossil fuel-based power plants resulting from the possibility of hydrogen utilization as direct fuel in form of pure H_2 or fuel blends, but also possibility of conversion to other liquid or gas fuels. Proposed in this study gas turbines are important for power generation and it is most likely that their contribution will grow as well in upcoming decades. One of the main reasons of powering gas turbines with hydrogen is the possibility of CO_2 emission reduction, as hydrogen is a carbon-free fuel. Together with hydrogen this solution might play in fact a key role in decarbonization strategy and reduction of non-renewable feedstock depletion. Additionally, Chiesa and Lozza (2005) in a study on hydrogen used in gas turbines already have addressed the possibility of hydrogen combustion in a large-scale, heavy duty gas turbines originally designed to run on natural gas as a short-term intermediate solution to reduce the greenhouse emissions in the power industry sector [15]. On the other hand, presented in the study by Bohn et al. (2005), there has been described the potential and possibilities of employing micro-gas turbines powered by hydrogen and coupled with electrolysers for small and domestic applications supplying the decentralization of energy system and providing electricity, heat and cooling [16].

Although, hydrogen technology becomes an object of great interest recently, there are still some issues to be addressed before considering it an efficient and effective worldwide, commercialized solution. Those issues are further analysed and described in the following chapters presented in this study. Nevertheless, it is undeniable that hydrogen creates strong link between renewable energy resources and will be the key to transition of energy supply, transportation and industry. Previously mentioned so called "power to gas" process of producing gaseous hydrogen fuel with the use of renewable energy excess will be of great importance as it will help to achieve efficient energy conversion and allocation of renewable energy surplus via converting electricity into hydrogen in the process of electrolysis.

Additionally according to The Fuel Cells and Hydrogen Joint Undertaking (FCHJU) [17] some studies have proven that right now gas grids and networks can accommodate shares of up to 20% hydrogen in natural gas (by volume) without introducing any major upgrades of the existing system. The challenges connected with hydrogen and its application are later on described in details in the section 2.1.1 devoted to hydrogen specification and it's properties. In continuation, demonstrative project have already started in some countries such as Germany, France and UK. The vision is to convert the gas grid into 100% hydrogen network. This will be of great significance regarding the gas turbine industry and fuel cells, for power production. Both of these technologies together with improving and growing hydrogen economy are showing a great potential towards reduced emissions.

To sum up, the challenge of limiting the global warming below 2˚C, compared to industrial revolution level is ambitious. It is estimated that the CO_2 emissions should be reduced by approximately 25% by 2030, from 2010 levels and by 2070 the carbon footprint should be reduced enough to achieve the net zero emissions, according to Intergovernmental Panel on Climate Change (IPCC) statement [9]. This is with no doubts the main driver for the hydrogen economy in the process of energy transition. Together with reliable technology such as gas turbines and fuel cells, this solution might contribute to high extend to breaking the link between the economic growth and increased CO_2 emissions.

1.3 Development of hydrogen and gas turbine market

Although at the moment hydrogen technology has not been yet fully competitive, it shows great potential. The forecast provided by IRENA in forms of Renewable Energy road map [18] shows that by 2050 hydrogen share of total energy consumption will reach 6%. However, 2017 Hydrogen Council prediction indicates hydrogen reaching even 18% of global final energy shares by 2050. Although, hydrogen is expected to play an important role in energy system, a significant reduction in the costs of production and distribution is required for the technology to reach the status of economically competitive alternative for other sustainable technologies and conventional solutions. The production in 2019 was estimated to reach around 120 million tons annually. This translates to around 4% of global final energy according to International Energy Agency (IEA) statistics.

On the other hand the European gas turbine market is expected to experience a compound annual growth rate (CAGR) of approximately 3% only by 2025 [19], whereas the US gas turbine market is expected to grow by 6.8% by 2028. This rise up will be the response to reduction of coal shares in energy production and shifting to gas-based power infrastructure and renewables. Consequently, the demand for gas turbines will follow the scenario, contributing to energy transition and decarbonization strategy. Nevertheless, due to great pressure being put on increasing RES shares, the development and contribution of gas turbines in the energy sector will be limited. However, it is undeniable that gas-based power generation will be subjected to general transformation, as a result of EU transition to low-carbon economy. Just by 2030 Europe plans include shutting down 50% of coal power plants [20]. This results not only from the challenges defined in the European Energy Roadmap for 2050, but also by rising prices of CO_2 emissions and decreasing cost of emerging renewable technologies. The current prices for tone of CO_2 emitted, by 2021 reached record value of 50 € per ton and this price is expected to increase even more in upcoming years [21]. This is just one of many actions to be undertaken for energy transition to be possible. It is estimated, that this price of tone of CO_2 emitted should be high enough to make hydrogen obtained from renewable sources prices competitive with the ones for hydrogen produced from fossil fuels. This means rise-up up to even 90 € per ton of CO_2 emitted [22]. As presented in the Figure 4, adopted from [20], in recent years, there could be observed increase in gas power contribution in the energy production. It results from the shift from coal to gas which transfers to growing gas turbine market.

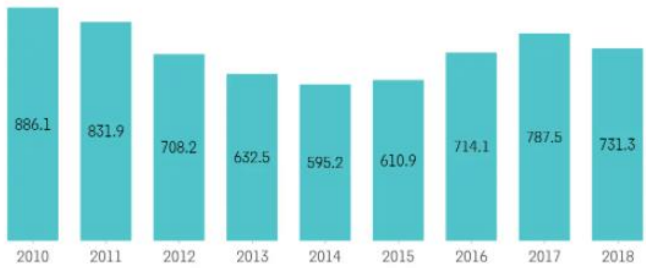

Figure 4 Gas-Based Electrical Power Generation (TW), Europe 2010-2018

Moreover, EC report shows that over Covid-19 pandemic the structure of the energy mix has changed in the year 2020, resulting in dropping coal and lignite generation [23]. However, it should be mentioned that gas generation was affected to smaller extend, thanks to its favourable price. This again proves the stability and importance of gas technology is energy structure. This phenomena additionally supported a power-to-gas transition, resulting in decreasing consumption of fossil fuels such as coal and lignite. Adding to this, it has been noted that, in 2020 the shares of electricity generated from RES in the energy mix in Europe reached 39% at the same time exceeding the shares of fossil fuel, which achieved 36% [24]. In this scenario gas turbines and hydrogen are the missing link connecting growing RES shares in the energy production together with the need of providing grid stability and reliable, uninterrupted power generation, generating large power amounts to balance effectively supply demand curve. This could be done by introducing pure hydrogen or hydrogen blends to the gas grid or directly feed gas turbines with modified fuel. By now, some modern gas turbines are already able to operate with higher H_2 concentrations (see section 3.3). Due to constant improvements of this technology, gas turbines could provide the grid security and at the same time contribute to carbon dioxide emissions reduction. Additionally, hydrogen due to its favourable properties, which from thermodynamical point of view makes it very attractive fuel, is getting more and more attention nowadays. The urge of decarbonization and resignation from fossil fuels contributed to the growing interest in hydrogen economy.

To sum up gas turbines can be the solution to allocate the energy produced with renewable energy, which due to its variable nature suffer the lack of dispatchability. The main advantage of gas turbines is that they are able to operate on hydrogen without introducing the significant changes into system such as changing the combustion system or compressor-turbine section, which allows for a smooth energy transition without major capital costs for the innovatory hydrogen technology. This allows the implementation of existing units as well as newly constructed gas turbines designed for operating on higher hydrogen contents. The great advantage of this solution comes from the fact that utilizing hydrogen as a fuel for energy production within gas turbines significantly reduces the CO_2 emissions and in the future might lead to its complete elimination. Although, gas turbines together with hydrogen can be used in place of energy storage and preventing the power grid strains resulting from growing RE, this technology still rises many questions regarding its long-term use and commercialization.

1.4 Objective

The aim of this study is to provide detailed insight on hydrogen gas turbines development and available hydrogen gas turbine combustion technology. Moreover, this work depicts the challenges that aforementioned technology has to overcome to meet environmental and economical requirements and become commercial solution available on the market. Additionally, this research demonstrates the possible room for improvement for the hydrogen gas turbine technology and the upcoming trends. For this purpose, a broad literature review has been made. When speaking of energy transition it is crucial to emphasize the importance of gas turbine technology in order to make that process as smooth as possible, keeping in mind environmental protection, energy security and stable economy. This solution especially should be addressed in times of growing interest for electric cars, fuel cells and batteries that have a great potential to revolutionize future industry and energy market. Even though the sales of gas turbines experienced significant drop in recent years, the technology is making a constant progress that translates to favourable forecast in upcoming decades. By far the data for hydrogen technology for gas turbines is very limited and requires further research, as the technology is still on in the phase of development, introduction of first pilot units and slowly entering the market still with many limitations. This study covers wide range of aspects regarding hydrogen gas turbine technology, environmental safety and techno-economic analysis. Additionally, the simulation of a combustor model has been provided in order to estimate such parameters as adiabatic flame temperature, laminar flame speed and the concentration of various species being produced during the combustion of hydrogen-rich fuels and other selected fuels. The simulation allowed for comparison of various fuels and observation of potential limitations and possibilities associated with implementation of various fuels including hydrogen and ammonia. The main motivation of this study was to present the potential and limitation of the technology and to address the main challenges and the possibilities of hydrogen gas turbines technology together with the simulation of emission formation.

1.5 Document Structure

The present Master Thesis structure is composed of the following chapters: Introduction, Hydrogen Technology, Gas Turbines and Combustion Technology, Emissions, Reactor Simulation, Techno-economic analysis and Conclusions. A brief outline of each chapter is presented below:

Chapter 1: Introduction

The introductory chapter is subdivided in sub-chapters, where at first the energy context outlook is provided indicating the energy situation together with insight into environmental ambitions. In this chapter also possible solutions and key actions have been indicated. Furthermore, the importance of both hydrogen and gas turbine technology has been highlighted. Last part covers the definition of the main objective and scope of this study and the structure of this document.

Chapter 2: Hydrogen Technology

The objective of this chapter is to provide the background of hydrogen, covering briefly the history of hydrogen, its main characteristics and properties as well as its benefits and potential as an alternative fuels. Moreover this chapter provides the overview of the different pathways for hydrogen production.

Chapter 3: Gas Turbine and Combustion Technology

Third chapter is devoted to hydrogen technology, including the state-of-the-art gas turbine technology for hydrogen combustion, the possibilities and future plans, referring to leading gas turbines manufacturers. Moreover in this chapter the main principles of combustion and combustion regimes has been covered together with combustor role and different types of combustors. Last part of this section depicts the challenges, especially during hydrogen combustion indicating the combustion instabilities and their cause.

Chapter 4: Emissions

In a reference to hydrogen combustion properties and stability issues this chapter is devoted to the formation of emission which impact the combustion of hydrogen. This chapter also provides the insight into the emission standards for gas turbines. A special attention in this section has been put to water pollution which may be of great importance and should not be disregarded when shifting towards hydrogen economy and hydrogen-fuelled gas turbines for stationary and aircraft applications. Furthermore, the most common emission control systems has been described and the methods to mitigate the high emissions and improve the combustion performance in gas turbines.

Chapter 5: Reactor simulation

To better understand better and illustrate the formation of emission in the combustion chamber the simplified model of rector has been prepared and described in this chapter. There has been proposed two approaches to model the combustion inside a reactor namely: Well-Stirred Reactor and Plug flow Reactor. The simulation has been performed for various fuels such as hydrogen, methane, ammonia and methane blend with 50% of hydrogen. Additionally the impact of equivalence ratio has been investigated in this chapter and the possible advantages resulting from using different fuels as well as hydrogen combustion.

Chapter 6: Techno-economic analysis

In this chapter the technological and economic analysis has been performed in order to provide insight into the approximate consumption of large-scale industrial gas turbine using the hydrogen gas turbine calculator proposed by GE. This analysis additionally allows for environmental impact estimation such as assessing of the amount of water necessary to produce enough hydrogen to run the power plant and the amount of emissions avoided and thus the savings. Moreover economic analysis of micro-gas turbine and electrolyzer has been provided together with sensitivity analysis for green hydrogen cost. The importance of electrolyzer capital costs, its efficiency and the revenues coming from the sale of oxygen has been presented in this section.

Chapter 7: Conclusions

The conclusions that have been drawn from this study has been gathered and presented in this section. Additionally possible future work and issues to be further investigated has been indicated in the last part indicating the areas of future development for hydrogen gas turbine technology.

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Chapter 2

Hydrogen Technology

This chapter provides general information about hydrogen and its properties. Additionally, this chapter covers the possible pathways of hydrogen production and the shares of those methods in the general hydrogen production. Furthermore the main combustion characteristics are indicated with comparison to other fuels together with main advantages and limitations that should be overcome.

2.1 Hydrogen

2.1.1 Characteristics and general information

The history of hydrogen reaches Middle Ages as a result of existence of mineral acids, in presence which this flammable gas could have been obtained. However, Henry Cavendish is known as a father of hydrogen, due to his immense and very specific investigation of this gas which was published in 1766 and titled "Three papers containing experiments On Factitious Airs" [25]. Although hydrogen has a deep historical background, its potential is still being discovered. Also hydrogen combustion is a mature technology, however it keeps developing as it needs improvements on many levels and research to meet todays' environmental and economical requirements. In order to recognize and describe its physical and chemical properties hydrogen has been combusted much earlier. The first attempts to utilize hydrogen as gas turbine fuel dates for 1937, when it was applied as jet engine fuel [26]. Therefore, it leaves no doubt, that due to its properties, hydrogen was recognized as a valuable fuel much earlier and nowadays it is getting a second chance, as the technology developed significantly together with scientific progress that has been made. Hydrogen is considered to be an attractive solution for energy production sector, as it is relatively non-polluting, CO_2 emission-free element. Undergoing oxidation hydrogen results only in H_2O being produced. Burning hydrogen itself does not result in production of CO, CO_2 nor SO_2 in the exhaust gases, which is an important aspect towards the zero emission policy, placing the hydrogen higher in the general classification of alternative fuels. However, resulting from using air as an oxidizer for hydrogen combustion process, the emissions eventually occur to be non-zero and in fact are a reason of concern. Resulting from the combustion of hydrogen nitrous oxides (NO_x) are present in the combustion products. As those emissions are of high importance its nature and the formation mechanisms will be more specifically described in the Chapter 4. Another issue that is worth mentioning, is the fact that the emissions often are being estimated in the local scale of hydrogen combustion or electricity production from fuel cell, while in fact when analysing whole life cycle from the point of view of hydrogen and equipment production, the emission will occur to be higher. This study, however will not cover the scope of whole life cycle, but will be limited to the local emissions caused by hydrogen combustions using gas turbines (see section 5 – reactor simulation). Hydrogen is considered to be a fuel rather difficult to handle considering many aspects from production, storage, transport and its direct use. This results from it specific features. Hydrogen is an odourless, invisible and colourless element. In case of fuels such as propane or methane, which are also odourless, some odorants are used for safety reasons in order to enable early detection in case of leakages. So far, there are no odorants suitable for hydrogen applications, due to different dispersion rate and extremely low density compared with air, resulting from very small molecular weight of hydrogen [27]. These issues are to a high extend connected with hydrogen's low molecular weight equal to 1. Hydrogen is also non-corrosive, however in some cases can embrittle metals. Regarding its physical and chemical properties, as an energy carrier is it considered to be the best selection for combustion engines and power plants [28]. However, unlike some typical fossil fuels, hydrogen has to be manufactured, as it does not exist freely due to its extremely high charge density, that causes hydrogen bond immediately with other elements and form compounds. Therefore, hydrogen is not a source of primary energy, but an energy vector. This means, it needs an energy input in order to be produced from other sources and at the same time it has the capability of storing energy and utilizing it when needed. Nevertheless, there are known many methods of obtaining hydrogen further described in the section 2.1.2. As mentioned previously hydrogen, regarding its exceptional properties it is a valuable fuel to be combusted with the use of gas turbines applied in various sectors and for different end users. From the point of view of thermodynamics hydrogen is the best fuel to be burned using gas turbines, as combustion dimensions for gas turbines can be reduced, due to the fact that the speed of burning hydrogen is much higher than for other fuels such as methane or propane. The comparison of laminar flame speed for different fuels used in gas turbines is shown in Figure 5.

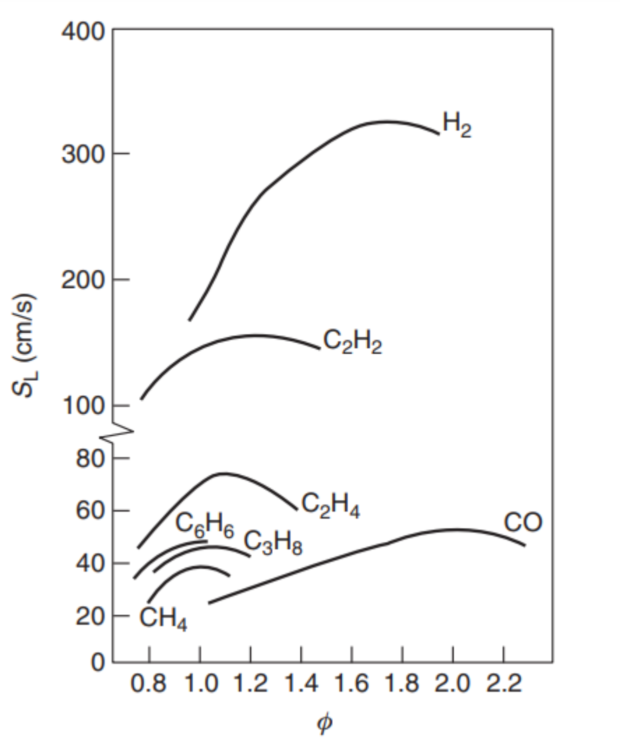


Figure 5 General variation in laminar flame speeds with equivalence ratio φ for various fuel–air systems at P 1 atm and T0 298 K [29].

As it can be seen, the laminar flame speed of hydrogen is around ten times higher than in case of natural gas, which induces certain changes in the existing gas turbine combustion system. Another reason for using hydrogen is that the combustion temperature reaches around 2300 K [30], which is much higher than for conventional fuels. This implies much less reduction of energy rate in burning hydrogen. Presented in Table 1 [31][32][33] comparison of heating values between hydrogen and methane depicts the significant difference in terms of weight basis, as hydrogen's heating value is around three times higher than the one of methane. However, in terms of volume the situation is just the opposite. Hydrogen compared to methane has three times lower heating value on volumetric basis, which also later on induces major changes to the combustion system. This is a consequence of a need to maintain the same power output when changing the fuel from natural gas to hydrogen-rich fuels such as syngas, pure hydrogen or hydrogen-methane blends.

Table 1 Calorific values and Wobbe Indices for hydrogen and methane.

	unit	H_2	CH_4
LHV, weigh basis	$\frac{MJ}{kg}$	120	49
HHV, weigh basis	$\frac{MJ}{kg}$	141,8	54,3
LHV, volume basis at 1 atm	$\frac{MJ}{m^3}$	11	35,8
HHV, volume basis at 1 atm	$\frac{MJ}{m^3}$	13	39,8
Wobbe Index	$\frac{MJ}{Nm^3}$	48,2	53,5

It is necessary to maintain subsequent increase in fuel volumetric flowrate and therefore the air flowrate to keep the mixture lean and provide low NO_x operation. When looking at Wobbe Index the scenario is just the opposite. Wobbe Index (WI) is an important indicator essential in the gaseous fuels classification. Its primarily applied due to variety of natural gas feedstocks coming from different sources with varying composition. Wobbe Index therefore is a key reference standard for the gas industry. WI is defined as the ratio of higher heating value of the gas to the square root of its relative density [34][35]. It is a common indicator of fuel characteristics and interchangeability, allowing the fuel adjustment for the given burner design. In order to maintain the same power output, which is the function of burner's pressure drop, volumetric heating value and density, therefore two fuel mixtures need to have similar heating values per square root of density as presented in the equation (1) presented below.

$$P_{input} = \dot{Q}_f \cdot (HHV)_{vol} \propto \sqrt{\frac{\Delta p}{\rho_{fuel}}} \cdot HHV_{vol} \propto \sqrt{\Delta p} \cdot \mathrm{WI} \qquad (1)$$

Where,

$\dot{Q}_f$ - fuel volumetric flow rate

$(HHV)_{vol}$ – higher heating value of the fuel per unit volume

ρ_{fuel} – fuel density

Δp – pressure drop

WI – Wobbe Index

As indicated by Taamallach [34], the Wobbe Indices of hydrogen and methane are similar. It results from hydrogen's lower volumetric heating value being compensated by its low density. Moreover, as reported in the same study, it is possible for hydrogen to be mixed with methane without major modifications of gas turbine system, providing that the Wobbe Index is maintained within the range of 30-50 $\frac{MJ}{Nm^3}$ approximately .

Other unique properties that make hydrogen an attractive fuel alternative are, its wide flammability range – hydrogen combusts through a wide range of fuel-air mixtures. Compared to other fuels, at ambient conditions hydrogen's flammability limits are between 4-74% in air by volume, while for methane this value places between 5 to 15%, 2-9.5% for propane, 15-28% in case of ammonia and 1.2-7.1% for gasoline [36]. It is suitable to run on lean mixtures, which means that the amount of fuel is not stoichiometric – that is less than the amount needed for complete combustion with a corresponding amount of air. Therefore, the mixture is more diluted and in the combustion products there will be present also the excess of the air added to the combustion. This feature contributes to better fuel economy and lower combustion temperature protecting the turbine from thermal damage. Moreover, it reduces the NO_x concentration in the exhaust gases. Another feature is hydrogen's high auto-ignition temperature – this characteristic property of hydrogen enables high compression ratios, which then result in greater thermal efficiency, or in other words, lower pressure drop while running the combustion process. Due to very low density and low viscosity, hydrogen is prone to leakage. It can be especially dangerous if the leakage occurs in confined spaces resulting in hydrogen accumulation, that may lead to flammable concentrations. And as stated before due to its wide flammability range, hydrogen which is hard to detect might undergone ignition in this situation, which is of great concern when being utilized as a fuel. On the other hand, thanks to this property, it might facilitate mitigation of the risk due to uncontrolled fire or explosion, as in case of any irregularity during operation, provided the event occurs in the open space, the hydrogen tank could be emptied withing the seconds by opening the safety valve [36]. Regarding this explosive nature of hydrogen and its unique properties, a proper ventilation and detection system is crucial in order to reduce hazards and meet safety requirements. Additionally, resulting from aforementioned hydrogen properties there is a risk of flashback and blowoff – phenomena which are of great concern for gas turbine combustion, described with more details in the section 3.4.4.

To sum up, hydrogen offers wide range of possibilities and applications. Nowadays, hydrogen already is being used in many sectors like industry in the processes of refining, treating or food processing, but also in transport, especially aerospace in such companies as NASA. The future of hydrogen as an energy carries will cover such applications as transportation, also on the commercial scale, heating and power generation thanks to its high efficiency and low pollution combustion. However, having a great potential, it still raises many concerns and issues that need to be resolved before hydrogen technology is fully commercialized.

2.1.2 Production of hydrogen

Although it is the most abundant element on earth, as mentioned previously hydrogen does not exist as an individual element. In fact, the greatest part of it can be found in form of water – H_2O. Besides water, which is covering around 70% of the earth, hydrogen is a component of organic compound such as coal, methane, petroleum. Hydrogen is considered a renewable source of energy as once derived from water, later it the process of oxidation it returns to water closing the cycle. Although hydrogen does not occur in ready-to-use form, there are various pathways of its production. Some examples of most common ways to obtain hydrogen is by fossil fuels reforming and water splitting in the process of electrolysis. Hydrogen production methods can be divided into groups depending on the process used, mechanism of formation and the source of energy supplied for the reactions to occur. Among those processes, we can distinguish four main groups, which include: thermal processes, electrocatalytic processes, photocatalytic processes and metal-based hydrolysis [37]. Besides this classification, it is very common to group hydrogen produced with various methods and assigning corresponding colours to those processes with regard to the origin of energy supplied needed to run the process. We distinguish green hydrogen coming from renewable energy sources, more specifically the hydrogen obtained in the process of electrolysis, with electrolyzer being supplied with the energy produced by renewable technology. Then the grey hydrogen which is being produced most typically by natural gas reformation, so the one derived from fossil fuels and finally blue hydrogen, which in fact includes the same process as grey hydrogen production, with the difference that CO_2 produced in this case is not being emitted to the atmosphere, as additional units are being applied in form of carbon capture and storage technology (CCS). Hydrogen therefore, can be obtained by the use of renewable energy sources or fossil fuels, which in the latter case includes its direct conversion into hydrogen as presented in the Figure 6 adopted from [38].

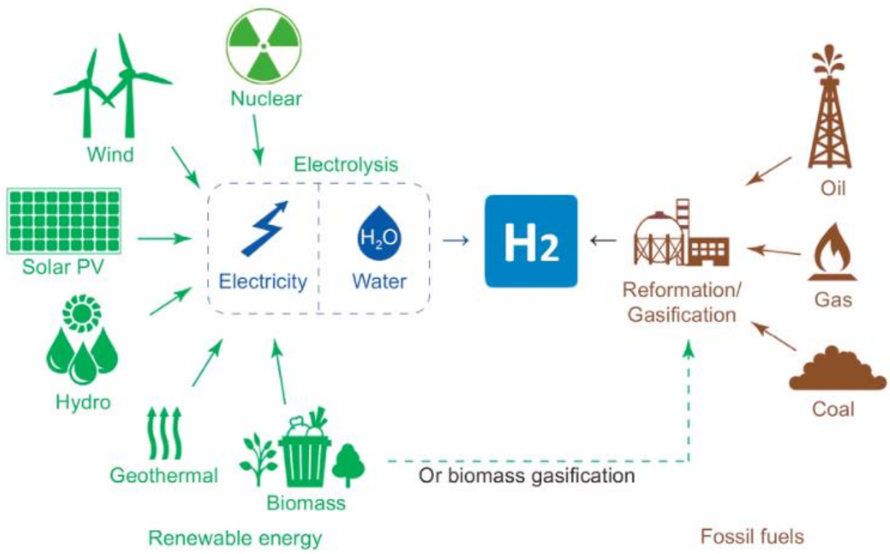


Figure 6 Renewable and non-renewable hydrogen sources.

It can be seen that there are various feedstocks and routes of hydrogen obtention. Moreover, the variety of hydrogen obtention ways by renewable resources shows the great potential of the green energy and possibility of energy transition towards sustainable energy and hydrogen storage in the future. However, currently hydrogen obtained with the supply of renewable energy states only for 10% of the overall hydrogen production. By far hydrogen is manufactured mainly by steam reforming of natural gas, coal gasification and some part of renewable being obtained in the process of electrolysis. Nevertheless, 48% of hydrogen comes from steam reforming of natural gas, 30% is obtained from petroleum fraction, 18% is assigned to coal gasification and only 4% so far comes from electrolysis. It should be also stressed out that those 4% is not exclusively covered by energy coming from renewable resources [36]. Being most common by today, the conventional technology of hydrogen production involves fossil fuels being processed by methods including hydrocarbons reforming, pyrolysis and gasification. Moreover, we can distinguish such processes as steam reforming, partial oxidation and autothermal steam reforming. In general, the hydrocarbon reforming assumes the hydrocarbon fuel conversion into hydrogen fuel. This process occurs in the presence of other reactants such as either steam (steam reforming process) or oxygen - referred to as a partial oxidation, where the steam reforming is the exothermic reaction, whereas the oxidation on the contrary is an endothermic process. Hydrogen obtained from fossil fuels, and most specifically natural gas is currently one of the most economic ways of hydrogen production [36]. The comparison of hydrogen generation costs by various means has been presented in the Table 2.

Table 2 Approximate costs of various hydrogen production pathways. Adopted from [36]

Process	**Approximate cost $/kg of H_2**
Natural gas reforming	0.9 -3.2
Natural gas reforming with Carbon Capture and Storage Technology (CCS)	1.5 -2.9
Coal gasification	1.2-2.2
Electrolysis with renewable energy input	3.0 -7.5

Natural gas reforming is a mature technology, adopted on a world-wide scale, especially applied in the petrochemical sector. The great advantage of methane is its high hydrogenation content as the compound of methane, is build up from four atoms of hydrogen. Using thermal processes such as steam reformation, allows for hydrogen production from natural gas which is composed of methane in around 70 – 90% . In the process of natural gas, steam-reforming we can distinguish three fundamental stages, namely the production of syngas, followed by two stage gas shift reaction and last but not least the hydrogen purification [39]. The general division and classification of the hydrogen production pathways is presented in the Figure 7.

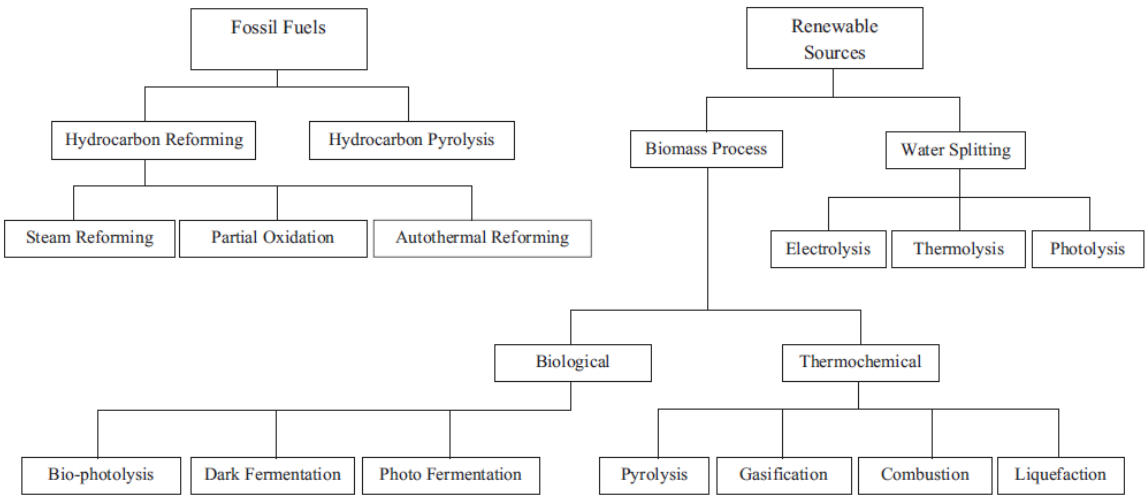


Figure 7 Classification of hydrogen production methods. Adopted from [40]

The second pathway of hydrogen obtention using the RES can be divided into two main feedstocks: water and biomass. Water splitting includes such processes as electrolysis, thermolysis and photolysis, where in case of photolysis the technology is still under the development phase [36]. Biomass conversion technology further can be subdivided into two groups of processes considering thermochemical and biological processes.

Nowadays, there are many options to obtained hydrogen, depending on the available resources and technology. Hydrogen production is the sector that has a great importance on further applications. It not only influences the final cost of technology selected, but also it plays a major role when speaking of environmental safety. Described in [41] eight different hydrogen production pathways and the study based on cost-benefit analysis shows that in general the fossil fuel-based processes are most cost-cost effective, however are showing greater negative environmental impact. On the contrary hydrogen derived with the use of renewable energy source, although showing much lesser environmental impacts, appears to be more expensive and therefore less cost-effective. This results from still relatively high price of electrolysers and renewable energy, with capital costs decreasing each year, however being still high in comparison to, conventional technologies utilizing fossil fuels, which low price results from relatively low natural gas and methane price. However it should be mentioned that until late 50s, electrolysis was the main way of hydrogen production since around 1920s, but the situation changed significantly with the dropping price of methane and natural gas later on [42]. Nevertheless, renewable energy for hydrogen production has a great potential and as mentioned in the study by Posso and Zambrano (2014) [43], technologies such as water splitting using the chemical looping, are a promising ways of hydrogen obtention from renewable energy feedstock. Therefore, it leaves no doubts that, hydrogen, even though can be produced in various ways, creates as many opportunities as challenges in terms of cost-efficient, environmental friendly production and effective storage to allocate energy surplus on the other hand.

Chapter 3

Gas Turbine and Combustion Technology

In this chapter the gas turbine technology has been described, including general information about gas turbines. Furthermore this section provides the classification and state-of-the-art technology for gas turbine hydrogen combustion. Additionally this section comprises the principle of operation and role of the combustor including most typical combustor designs. Last but not least this section provides the insight into main combustion regimes and depicts main combustion instabilities and their origin.

3.1 Gas turbines – general information

Gas turbines are advanced and mature technology. Their development contributed to high extend to the industrial revolution and gave the impact to the development of industry and energy production on a worldwide scale. Nowadays, gas turbines are considered to be the most versatile turbomachinery equipment. They found application in many sectors and show wide range of rated powers from micro turbines of nominal power of the order of single digit kilowatts up to industrial gas turbine capable of providing hundreds of megawatts of power. Gas turbines found its application in such sectors as transportation for aviation and marine transport, they play an important role in energy production. They are being used in critical industries like oil and gas industry, process plant, but also they are very often used in domestic application and small industries.

The term "gas turbine" refers both to the power plant as a whole, as well as to one of the components of the unit, namely the turbine from which that terminology derives. The power plant unit is composed of a compressor which function is the increment of the intake air's pressure which results in its reduced volume in order to allocate higher mass flow, which is then directed to the combustion chamber, thus providing higher power. At the combustion chamber after the fuel is injected into the burner, the process of oxidation occurs and the heat is being released. The exhaust gases are being delivered to the turbine stage where the gas expands, driving the turbine unit. The turbine and compressor are placed usually on the common shaft, therefore when turbine's shaft rotates it also drives a compressor. In other words, gas turbines is a turbomachinery which's principle of operation is based on conversion of energy of the flowing fluid into mechanical energy thanks to the rotor mechanisms. This mean that gas turbines are capable of converting either kinetic energy of the fluid or thermal energy into work to drive compressor, auxiliary equipment such as fans or fuel pumps or electrical generators when speaking of shaft-based engines [44][45]. The representation of a gas turbine unit with its main components has been presented in the Figure 8.

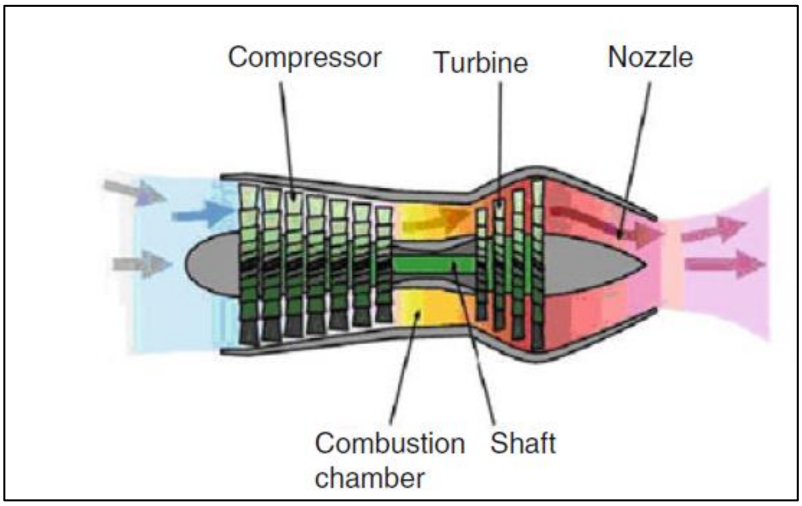


Figure 8 Scheme of gas turbine engine with axial compressor. Adopted from [45].

Power plants based on gas turbines in simple cycle reach full load operation in only 10 to 15 minutes [46]. Thanks to these characteristics, turbine technology is especially attractive solution that reduced the start-up times and allows quick and flexible operation of power plant. In case of combined cycle that time can be double, but still it is much less than in case of conventional coal-based power plants. This is a very important aspect for electric system balancing and providing grid reliability. Gas turbines provide flexible operation and fast response which is so important while coupling unstable energy with grid. Gas turbines' great advantage is their relatively low operational cost compared to other low-carbon alternative energy sources, which automatically places gas turbines higher in the ranking of available solutions. Gas turbine concept is a mature technology suitable for energy production for any scale starting from microturbines generating power of the order of tens of kilowatts up to big heavy-duty turbines covering the demand of hundreds megawatts. Another strong argument for gas turbines is their compact design and as previously mentioned the possibility or providing large amounts of power, maintaining lightweight construction. It is also worth mentioning that the other advantages of gas turbines are their longevity and low maintenance costs. They can operate on wide range of fuels from heavy oils and low-quality process fuels up to high quality pure fuels providing high efficiency of operation. Moreover, no additional coolant is required using the gas turbines as the air which is usually the working fluid can be effectively utilized for cooling of the gas power plant. Over years gas turbines significantly improved their efficiency. Starting from around 18% [44] reached by Swiss gas turbine set build in 1939, nowadays gas turbines are capable of reaching around 43% efficiency in simple cycle and 64% in combined cycle being the records hold by GE 7HA model [48][49].

3.2 Gas turbines – classification

Gas turbines can be first divided into aeroderivative and heavy duty units. The principle of operation for both types is the same but regarding different application the main features of both types may vary depending on its application. Aeroderivative gas turbines are as the name indicates are turbines derived from the aviation sector. Those turbines are much lighter and more compact due to limited space. Moreover, the propulsion system must withstand extreme conditions and provide reliable operation on high altitudes. To provide fast and efficient performance for the aircraft this type of gas turbines have been specially adjusted for this purpose. They are lightweight version of the units for industrial applications. Aeroderivative gas turbines mostly operate on liquid high quality fuels. Aeroderivative gas turbines as the name suggests are based on the existing aircraft engines. They usually have faster response to load changes and lower start-up/shut down time and their weight is lower. This type of turbines also finds application in marine and offshore industry due to its light-weight construction, which is their main advantage. On the contrary industrial gas turbines characterize of much heavier construction, as the weight was not of paramount importance. These units tend to be more bulky, but at the same time industrial turbines can withstand high operational temperatures due to sophisticated metallurgical technology and materials implemented in this type of gas turbines. Moreover, industrial turbines do not require fuel of such high purity as in case of aeroderivative gas turbines or aircraft engines operating in extreme conditions and high altitudes. Usually in the turbomachinery terminology the classification by highest turbine inlet temperature (TIT) can be met. GE proposed the division using the alphabet letter corresponding to the temperature ceilings and therefore implying higher powers of the unit [44]. In the Table 3 , the most typical division and gas turbine classification regarding its application and power output has been presented.

Table 3 Gas turbine classes of efficiency [50],[51],[52],[53]

Classes	Rated power	Characteristics
Micro gas turbines	30 kW to over 200 kW	High shaft speed (up to 100 000 rpm). A heat recuperator is usually fitted to reduce fuel consumption and achieve efficiencies of up 30%.
Small-size gas turbines	200 kW – 25 MW	Usually incorporates single stage radial compressor. Can operate with LPG, coke oven gas, landfill or digester gas. Low TIT. Higher emissions.
Medium-size gas turbines	25 MW -100 MW	High electrical efficiency for modern units. At rated load of medium-power plants reach 43-44%. Relatively low exhaust gas temperature.
D and E	75 MW - 100 MW	Designed for application where superb reliable workforce is not required. Can operate on cheap or low-quality fuel. Relatively low emissions, reliable power with average efficiency
F	150 MW - 230 MW	Most often come in combined cycle configuration. Optimized design of hot gas flow path, more efficient and therefore more complex combustion system. Mostly for NG and fuels of higher quality.
G,H,J	>250 MW	Superb efficiency of more than 62 % in combined cycle. These units employ state-of-the-art solution. Employ materials and technologies for very efficient and clean gas power. Very low emissions.

3.3 State-of-the-art Gas Turbine Technology

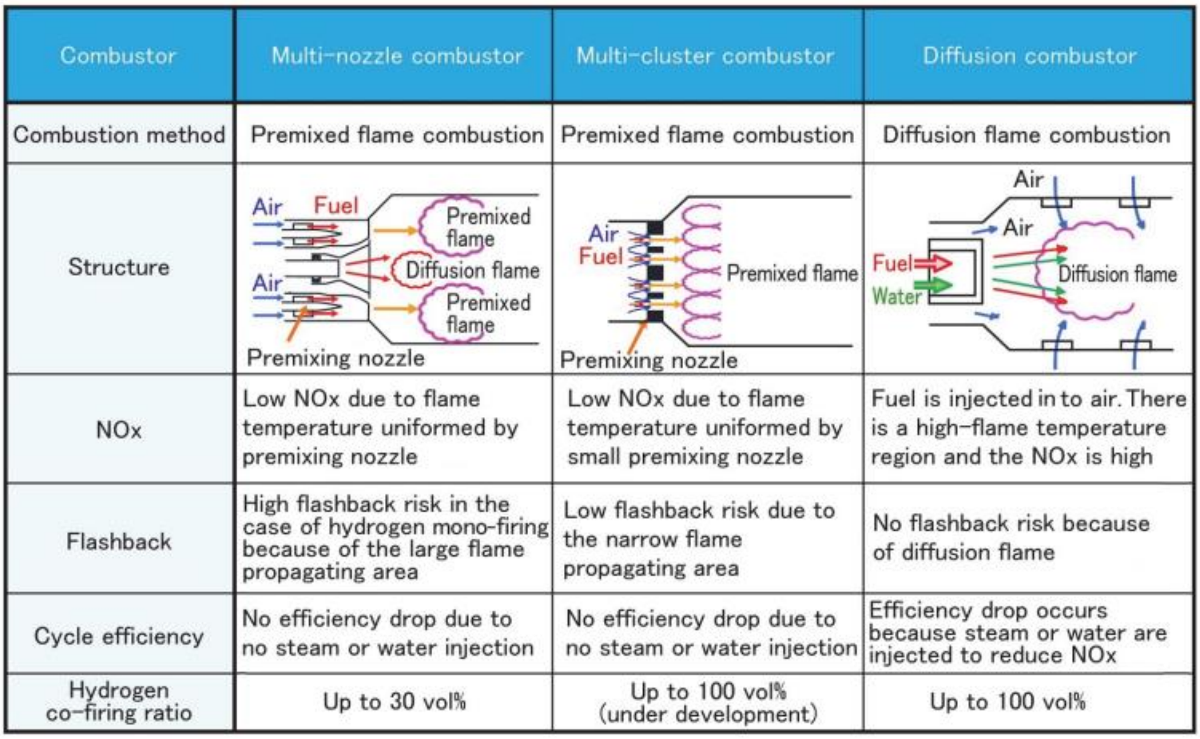
There are already some manufacturers that developed a technology for stable hydrogen-fuelled operation. This concept is not yet fully commercialized due to the lack of hydrogen infrastructure, regulation connected with the hydrogen economy and some technological issues. However, this technology has been proved to be feasible and showing a great potential toward sustainable hydrogen energy development. By 2021 the gas turbine industry has already proposed some successful hydrogen combustion technologies.

Launched in May 2020 HYFLEXPOWER - a demonstrative project by Siemens which purpose is to prove the possibility of green hydrogen production, storage and utilization in the gas turbines up to 100% hydrogen volumes [54]. The predictions show that this would result in reduced CO_2 emission by 65.000 tons annually for a gas turbine model SGT-400 operating at baseload. Tests performed in years 2018, 2019 on the SGT-600 model with 60% hydrogen co-firing has been successfully completed, showing the power plant stability. Moreover, Siemens signed a commitment to increase the gas turbines hydrogen capability up to 20% by 2020 and up to 100% until 2030. As indicated by Siemens company for now the only limitation is the hydrogen availability as hydrogen production is still not enough to provide a power generation for high industrial and worldwide scale [55][56].

GE also declared the readiness to already run the gas turbines on 100% hydrogen volumes and the commercialization of this solution in power plants over the next decade [57]. The GE 7HA.02 model of today is capable of running on up to 15-20% hydrogen volumes initially with the capability to run on 100% hydrogen over time. While performing the test GE was already capable of introducing 95% hydrogen volume into combustion. However, the producent also indicated the necessary changes done to the system in order to reach the stable combustion under such a high hydrogen fuel content. The system used has been changed to non-premixed in order to provide stable combustion, however GE stated that partially-premixed combustion is also allowed. The company introduced so called Multi Nozzle Quiet Combustion System which employs the diffusive combustion regime in order to avoid the autoignition of the fuel or such phenomena as flashback and other dynamic instabilities described in more details in further sections of this chapter 3.4.4. GE also indicated that burning pure hydrogen requires changes in turbomachinery, especially compressor unit due to low volumetric heating value per volume. Moreover combustion of hydrogen would require an increased air flow in order to maintain lean, hence low NO_x operation, that on the other hand would reduce the surge margin, so the modification of the compressor design would be required in order to avoid damage of the components. Moreover, the hydrogen combustion required the firing temperature reduction, in order to prevent combustor and gas turbine unit damages, which could occur due to hydrogen high adiabatic flame temperature. Also the fuel injector might require major adjustments due to increased fuel flow being a consequence of low fuel heating value per volume unit [34]. Moreover, the company indicated the impact of implementing hydrogen fuel in the gas turbine power plants. Where not only the changes done to the turbomachinery can be required but also other adjustment at the level of auxiliary equipment such as bottoming cycle components, fuel accessories and safety systems of a power plant. Additionally, the manufacturer once stressed out, that despite the fuel flexibility of gas turbines and their ability to run on hydrogen the modifications and scope of adjustments that has to be made to the gas turbine unit depends on the initial configuration of the gas turbine, the hydrogen content being introduced into the combustor as well as overall balance of the plant.

Another example is the technology employed by Mitsubishi Heavy Industries. The company declared the successful operation of a large-scale gas turbine running on 30% hydrogen-natural gas blends.

MHI also stated that the system reaches the CO_2 reduction of around 10% with comparison to conventional natural gas-fired gas turbine. Presented in the Figure 9, adopted from [55], the table shows various combustor designs and configurations utilized in hydrogen gas turbine technology and the characteristic features of each system with the capability of varying hydrogen content conversion. MHI mentions here such solutions as multi-nozzle combustor, multi-cluster and diffusion combustor where each of these technologies employs differing combustion method and structure. It can be seen that diffusion combustion allows for gas turbine operation with 100% volume of hydrogen. However, this solution results in the highest NO_x emissions together with efficiency drop resulting from the necessity of water injection for emission control. Multi-nozzle and multi-cluster combustors show better performance regarding the NO_x emission, however their solution is still under development and not enough to provide yet stable operation on pure hydrogen fuel.



Combustor	Multi-nozzle combustor	Multi-cluster combustor	Diffusion combustor
Combustion method	Premixed flame combustion	Premixed flame combustion	Diffusion flame combustion
Structure	Air, Fuel, Premixed flame, Diffusion flame, Air, Premixed flame, Premixing nozzle	Air, Fuel, Premixed flame, Premixing nozzle	Air, Air, Fuel, Water, Diffusion flame
NOx	Low NOx due to flame temperature uniformed by premixing nozzle	Low NOx due to flame temperature uniformed by small premixing nozzle	Fuel is injected in to air. There is a high-flame temperature region and the NOx is high
Flashback	High flashback risk in the case of hydrogen mono-firing because of the large flame propagating area	Low flashback risk due to the narrow flame propagating area	No flashback risk because of diffusion flame
Cycle efficiency	No efficiency drop due to no steam or water injection	No efficiency drop due to no steam or water injection	Efficiency drop occurs because steam or water are injected to reduce NOx
Hydrogen co-firing ratio	Up to 30 vol%	Up to 100 vol% (under development)	Up to 100 vol%

Figure 9 Mitsubishi Heavy Industries combustors for hydrogen gas turbines. Adopted from [55].

In 2021 Kawasaki Heavy Industries launched a demonstrative project which at the same time was technology verification test in Kobe City's Port Island [58][54]. The company for the first time worldwide, run successfully a 100% hydrogen-powered gas turbine with Dry Low NO_x combustion technology. This achievement has been possible by using the micro-mix combustion principle. This technology thanks to the low NO_x operation and no necessity of water injection results in improved overall system efficiency when compared to conventional power plants. The demonstrative project carried out in Kobe City involved the hydrogen cogeneration system making possible for the first time in history the delivery of heat and electricity coming from 100% hydrogen cogeneration power plant at urban area of Kobe City.

3.4 Combustor

3.4.1 Combustor role

Combustion chamber is considered the most complex part of gas turbine power plant. The main role of combustor is energy release by heat addition and conversion of fuels' chemical energy into mechanical energy in the turbine section followed by generator, in case of industrial gas turbines. This process occurs by raise of temperature of the high-pressure gas coming from the compressor. In the liner section the thermal energy of a flowing gas is increased as a result of exothermic chemical reaction between fuel and oxidizer in the system. In case of aircraft application, the combustion chamber's principle of operation is exactly the same but from the definition it serves to produce high velocity exhaust gas, which is known as propulsive force or thrust [59]. Combustion chambers must provide stable operation, regardless changing atmospheric conditions both for industrial and aircraft applications. They must be carefully designed to maintain efficient and safe fuel combustion within the limited space available. Combustor can be considered as the most sophisticated part of the system, as it connects both the compressor and the turbine. Moreover, combustor must meet such criteria as high efficiency, low emissions and nowadays it is crucial for the burner to be fuel-flexible. The most important functions and features of the combustor are complete combustion, minimized pressure drop, combustion stability, proper and uniform temperature distribution, wide operating range and satisfactory emission limits [45]. Currently with improving materials and thermal coating technologies the goal is also to develop a design capable of withstanding high combustion temperatures with use of advanced materials and cooling designs [60].

3.4.2 Combustor components and classification

Today there can be distinguished three main combustor configurations. However, there may occur some variations of the basic configurations, regarding the specific application of the power plant. Moreover, the combustion chambers can be classified into main burner or afterburner unit – in case of aircraft application. The further division is done regarding the speed of airflow within the burners and can be divided into subsonic or supersonic types. Also, within the burner types there can be distinguished the direct or reverse-flow direction burners [45]. In the Figure 10, presented below, the main components and three main combustion zones of a typical burner has been presented.

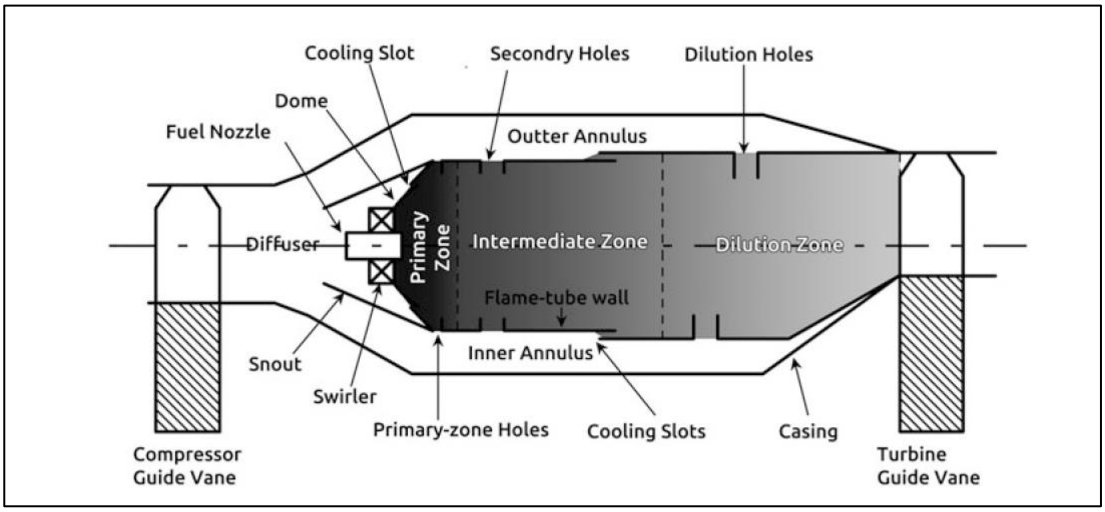


Figure 10 Combustion chamber schematic identifying main components of a conventional combustor and various combustion zones [45].

As shown in the Figure 10 the combustion chamber is divided in the three main sections namely the primary zone also knows as combustion zone where the fuel ignition and combustion occurs, followed by two dilution zones also described as secondary and tertiary zone. The dilution zones main purpose is to lower the gas temperature, below admitting it to the turbine stage, by introducing the increasing amount of cooling air through secondary and dilution holes. In the primary zone the main combustion process takes place. Fuel mixed with adequate amount of air is being burned and later the combustion propagates and the heat release occurs. The unburned combustion products are being mixed in the dilution zones to lower the mixture's temperature before its being admitted by the first stage of turbine in order to protect the turbine blades from degradation.

Entering the combustion chamber sector the compressed air is at first delivered to the diffuser which main task is to reduce the velocity of high speed high pressure air and slow it down to the velocity optimal for the combustion process and low enough for the flame not to blow off.

The combustor liner is the main section where the combustion occurs. This component can be divided into inner-liner, which has direct contact with hot combustion gases, and outer liner. Liners, in order to withstand very high combustion temperatures are usually made from super alloy such as Hastelloy X and some of the liners additionally use thermal barrier coatings. Additionally, air film cooling or transpiration cooling is used, in order to protect the liner and lower the temperature.

The dome and swirler play an important role of turbulence generation within air entering the combustion chamber. This allows for rapid and efficient mixing of entering air with the fuel injected into the chamber. Moreover, swirler establishes low-pressure zones, which forces some of the combustion products to recirculate and thus creating higher turbulent flow. The dome and the swirler must be both carefully designed as higher turbulence corresponds to higher pressure drop and thus lower overall efficiency of the combustion process.

For different gas turbine application there can be distinguish three main types of combustors: tubular or can-type combustor, annular and cannular or tubo-annular burner. The silo type combustor is a variation of can-type combustor that has found its application especially in industry, where compact design and lightweight construction are not of paramount importance.

Can-type also known as tubular combustor was one of the first types of burners and at the same time is characterized by the simple design. This type of combustion chamber layout consists of individual single or multiple combustion chambers. The air that enters the combustor is divided into separate air ducts and is being delivered to each liner. The main disadvantage of this combustor is its increased weight. This results from the separate chambers where each liner additionally consists of two cylindrical tubes. On the other hand, this kind of design allows for easier maintenance and replacement as in case of any damages it is enough to replace only single unit instead of whole combustor. This also allows for running test within just one tube. Tubular burners are characterized also by high robustness, but on the other hand this type of burners suffers relatively high pressure drop and contributes to higher drag in aircraft application due to increased frontal area. Silo-type combustor as previously indicated is a variant of tubular combustor. This class of burners is specially utilized for industrial application where space or weight reduction are of minor importance. Moreover, silo combustors are suitable to burn fuels of lower quality often utilized in industry, unlike the aircraft burners as fuel for aviation, due to extreme conditions of operation, has to be of very high purity and quality. Silo combustors are mounted outside of the gas turbine main frame, which as a consequence results in easier and therefore cheaper maintenance, however resulting in more bulky construction.

On the other hand, the annular type combustor is especially used in aviation thanks to its lightweight construction. Unlike in tubular combustor, instead of separate tubular liners, in annular combustors the air is deliver to single annular liner, which in some designs can be placed around the turbine. In comparison to other burner types, the wall area of a comparable annular chamber is much lower. Consequently, the amount of cooling air required to prevent the burning of the flame tube wall is much less. This reduction in cooling air raises the combustion efficiency, which then eliminates the unburned fuel reducing at the same time the emissions. The greatest advantage of annular combustion chamber therefore is its compact design which significantly reduces the weight and space needed for combustor assembly.

The last type – tubo-annular combustor also known to as cannular, combines the advantages of both tubular and annular burners. This type of combustor has common air duct and it consist of a series of cylindrical burners arranged within common annulus. The cannular combustor consists from annular part which is the outer shell and the inner section consisted of cans placed around the engine axis. The flame is distributed by crossover tubes to all the liners, but ignition occurs only in some of the cans.

3.4.3 Combustion: diffusion and premixed flame.

Combustion stands for the process in which a fuel is oxidized which results in the release of large amount of energy. The oxidizer usually is an atmospheric air, due to its availability and abundance. In some special cases a pure oxygen is used, then this process is so called oxy-combustion, however this leads to higher costs as well as much higher combustion temperatures reaching 3000 K in case of hydrogen combustion (see section 5 – reactor simulation). An atmospheric air is composed in 21 percent of oxygen and 7 percent of nitrogen leaving approximately 1% for such components as argon and scarce amounts of carbon dioxide, helium, neon and hydrogen, when considering mole or volume basis of dry air. Resulting from this for each mole of oxygen in the combustion reaction corresponds a 3.76 mol of nitrogen assuming 79 percent of nitrogen in the air mix as the remaining gases are usually neglected and treated as nitrogen. In the combustion process nitrogen does not react with other gases showing the inter gas properties, however it tends to form small amounts of nitric oxides. Nevertheless, since nitrogen introduced into combustion chamber with atmospheric air comes in great quantities it can affect the combustion process. Combustion air enters at low temperatures or around 300 K after the compression stage and leaves the burner at much higher temperatures, which results in large part of the chemical energy being absorbed by nitrogen [62].

There can be distinguished two main combustion regimes namely the premixed combustion and diffusion flame combustion. The diffusion flame combustion is the type of process in which the reactants: fuel and oxidizer, most typically air, are not mixed prior to injection into combustion chamber. Both of those reactants are being injected separately into the combustor to later diffuse together at the boundaries. The characteristic for this process is yellow, sooty flame that can be encountered for example in all types of furnaces, diesel engines, standard combustors or in daily application – for example in form of a candle flame. The main disadvantage of this combustion regime is that the combustion process occurs under stoichiometric conditions which results in regions of very high temperature. This leads to NO_x concentration of about 70 - 100 ppm for gas and liquid fuels respectively. However, this combustion method provides robust and stable flame, as well as wide fuel flexibility. Therefore, the characteristic feature of the diffusive combustion is usually a very robust, stable flame. This combustion is typically operable over 1100 ˚C temperature rise range, however if no diluent is used, the NO_x emissions are very high, which is main disadvantage of the diffusion flame combustion. On the other hand the CO emissions are significantly lower in case of dilution flame, however usually water or steam is used in this process which results in many negative side effects.

On the contrary in case of premixed combustion the characteristic feature is a blue flame. In this situation the reactants are being uniformly mixed upstream of the flame, prior to injection and combustion in the chamber. The flame occurs downstream the premixing. This type of flame can be found in spark-ignition engines, oxy-acetylene welding torches or Dry Low NO_x burners. The other solution namely which is premixed flame used in Dry Low NO_x burners as the name itself suggest is known for very low NO_x content in the exhaust gasses, however just the opposite phenomena can be observed regarding CO emissions which usually are significantly higher in case of this combustion system. Opposite to the diffusion combustion the DLN technology has very narrow range of operation which corresponds to temperature of 110-165˚C of temperature rise range [63]. Very problematic for this type of combustion method is the flame instability. Especially when using hydrogen as a fuel the premixed flame combustion is prone to flashbacks and flame blow off described in details in the following section.

3.4.4 Combustion instabilities: Flashback and Blow off

In general the term "combustion instabilities" refers to the dynamic instability, which is in fact an oscillation caused by the fluctuations during the heat release in the combustion process. This phenomena leads to combustor wear and limited durability of the components even leading to complete destruction of component and then following damages even in the turbine section.

The phenomena of flashback occurs resulting in the flame travelling upstream the burner back to the mixing zone. This can result due to various conditions such as boundary layer propagation or vortex breakdown. Flashback, as previously mentioned is a typical combustion instability occurring in the premixed combustion system. It occurs when the gas velocity, therefore the velocity of incoming reactants appears to be lower than the turbulent burning flame velocity, which results in the flame propagating upstream the pre-mixer or burner tube, often leading to damage of these components, as they cannot withstand those extreme temperatures. Hydrogen combustion is the premixed combustion systems additionally tends to undergo flashback resulting from the hydrogen's high laminar flame speed mentioned in previous chapters. Moreover, for hydrogen fuels and hydrogen-natural gas blends the flashback is a special problem, resulting from aforementioned flame speed, and thus often new design or completely modified combustors are required, especially for fuel blends above 40% of hydrogen content by volume, which results from different requirements of the two various fuels.

The second most common phenomenon during combustion is known as blow off. This phenomena occurs in combustors being an effect of various causes, inter alia using a very lean mixtures. It can also result from strong combustion instabilities and oscillation which may lead to complete flame extinction. This occurrence again applies to low NO_x burners due to the fact of utilizing lean mixtures and therefore operating close to the blowoff limits. The greatest problems following the blowoff may be the re-ignition of the mixture especially in the difficult conditions like low temperatures and pressures, for example at high altitudes.

Both of those phenomena being a result of combustion instabilities can be avoided with the implementation of swirling and other systems improving the combustion stability and performance further described in the section 4.1.3. Especially the swirling method mitigates the risk of blowoff and flashback, improving the stability and extending the blowoff limits. As previously mentioned, swirling flow with adequate level of turbulence stabilizes the flame by inducing the recirculation of hot products that results in constant re-ignition in the air including the additional fuel entering a burner. The higher the swirl number the higher the recirculation. As indicated by Syred et al. (2012), the flows with high-intensity turbulence result in swirl number ranging between 0.6-2.5 [64].

Chapter 4

Emissions

In this chapter the main mechanism of emission formation within gas turbines has been described. Additionally the potential issues connected with water pollution has been presented in this section. The last part is devoted to the possible emission control techniques and methods of combustion performance improvement.

4.1 Emissions – introduction and regulations

The energy sector together with transport are the two most demanding sectors, which needs by far are mostly covered through combustion of fossil fuels, and therefore it is of great importance in terms of environmental pollution and emissions. The main contribution results from the combustion of fossil fuels which generates key pollutants such as: nitrogen oxides, carbon monoxide, sulphur oxides, unburned hydrocarbons and particulate matter. Resulting from the rapid growth of aviation sector, as well as development of industrial stationary gas turbines, the emission control system has been exposed to significant changes and regulations. The consumption of fuel by civil aviation has increased significantly, making at the same time the air transport world's fastest growing energy-use sector. Simultaneously the industrial gas turbines keep experiencing dynamic development and acquiring new ranges of efficiencies in various applications and cycle combinations. As emissions are of great concern due to their impact on health and environment, there is a lot of pressure being put on the construction of new gas turbine combustors and adjustment of the previous models and retrofitting. The development of new technologies and continuous improvement sets the bar even higher, thus leading to increasingly stringent emission requirements. This performance has been reached by some manufacturers, for instance GE, which equipment is capable of operating at 9 ppm of NO_x – single digit levels and is likely to reach even better performance in the future [65]. In the exhaust from combustion system can be distinguished pollutants in form of combustion products such as CO, CO_2, water vapor H_2O, unburned hydrocarbons (UHC) - resulting from incomplete combustion, particulate matter, NO_x, as well as excessive oxygen and nitrogen coming from atmospheric air, being typically the oxidizer in the combustion processes. Special attention should be given to CO_2 and H_2O as those species are usually disregarded, as they are natural consequence of hydrocarbon combustion. Moreover, the importance of water vapor pollution should be indicated, due to hydrogen solutions being developed nowadays and implemented worldwide in many sectors.

Currently still under development, Mitsubishi Hitachi Power System gas turbines capable of operating on blends of 30% hydrogen and 70% natural gas are planned to be released for commercial use already by 2025 [66]. This transition, also expected to be done by other gas turbine producers, is going to be another step towards carbon-free society but at the same time will have a strong impact on the environment and emissions. Recalling once more, when considering combustion and gas turbine operation, emissions of CO and NO_x are of major concern. In fact, the nitrogen oxides are the main pollutant that arise from GT combustion and hydrogen-rich fuels usage. Usually, the nitric oxides produced during the combustion process oxidize in further process to NO_2. For this reason, often those two species are associated together as one group of NO_x. That group involves nitric monoxide (NO), nitric dioxide (NO_2) and nitrous oxide (N_2O). Nitrogen dioxide is an irritant gas. In case of high concentrations, it causes negative organism reaction, inter alia inflammation of the airways. Nitric oxide on the contrary is not considered as hazardous at typical ambient concentration [67]. Nitrogen present in the exhaust gases reacts with oxygen forming NO. The reaction propagates and leads to formation of NO_2. Characteristic for hydrogen combustion is the fact that once the NO is formed there is no further possibility for it to be reduced as in pure hydrogen fuels there are no hydrocarbon species responsible for NO reburning mechanism [68].

In general, the origin of these gases might result from natural resources, combustion engine vehicles and other fuel burning processes. Both of these gases nitric oxide - NO, as well as nitrogen dioxide - NO_2 are colourless, with the difference, that NO_2 has a specific odour, unlike nitrous oxide which is odourless. NO_2 is an acidic gas with highly corrosive properties having negative impact on environment and affecting human health. The public health might suffer problems resulting from long-term exposure to increased NO_x levels in the atmosphere. The major effects caused by higher nitrogen oxides level involve increased risk of respiratory conditions and increased sensitivity to allergens [67]. Moreover, it contributes to formation of photochemical smog resulting in yellowish-brown smog and formation of particulate matter (PM) or ground level ozone [69]. All those pollutants are associated with severe adverse health effect. Unlike during the Industrial Revolution, nowadays those compounds are submitted to a strong regulation which are the indicator and guidelines for the further gas turbine and fuel industry development. According to Standards 40 from Code of Federal Regulations the emissions regulations depend on the engine's input energy and its application. The summary of NO_x and SO_2 emissions regulations with respect to output power and fuel type is presented in Table 4 adopted from [70].

Table 4 Standards 40 CRF – depending on the engine's input energy and application. Emission regulation of different species for different output powers.

	NOx				SO2	
Input Energy	Electricity-producing turbines firing NG	Electricity-producing turbines firing fuels other than NG	New mechanical drive turbines firing NG < 3.5 MW	New mechanical drive turbines firing NG < 3.5 MW	Continental areas	Non-continental areas
< 3MW	42 ppmv	96 ppmv	100 ppmv	150 ppmv	100 ng/J	780 ng/J
3-110 MW	25 ppmv	74 ppmv				
> 100 MW	15 ppmv	42 ppmv				

However also indicated in the Table 4, SO_2 emissions are being mentioned, however in fact those are generally not considered in case of natural gas, hydrogen the combustion of the blends of both those fuels as the amount of fuel-bound sulphur is either negligible or zero, therefore the SO_2contribution in the general emission is also negligible. According to European Turbine Network (ETN) using hydrogen fuel leads to many challenges which as ETN states might require some flexibility on NO_x limits in order to enable decarbonization [71] This indicates that current technology is still not advanced enough to meet the environmental requirements, however at the same time this indicates somehow controversial exchange. It has been a longstanding industry challenge to cope with all the requirements to satisfy the society demand and at the same time protect the environment from negative side effects. In order to reach energy transition and resign from coal dependency, it would be necessary to expose the environment to NO_x above the acceptable limit levels and thus greater pollution. Consequently, all this exchange comes down to reducing one negative factor at the expense of increasing shares of the other one. In aircraft context the formulation of these regulations differs slightly. As the output power of the aircraft engine varies strongly during different flight phases, the emission limit is calculated as a function of pressure ratio and rated thrust of the engine. This equation is changing for different types of aircraft and depending on the flight phase from take-off through cruise and descend of the aircraft [72]. The following exemplary equation (1) is valid for engines with a pressure ratio in the range between 30 and 104.7:

$$\text{g/kN rated output} = -9.88 + (2.0 \cdot \text{engine pressure ratio}) \tag{2}$$

Below the equation (2) presents the exemplary calculation of NO_x emissions for Pratt and Whitney engine which found its application inter alia in Airbus A220 with engine model PW8000 developing thrust of 89 kN and with pressure ratio of 40:1

$$\begin{aligned} \text{g/kN rated output} &= -9.88 + (2.0 \cdot \text{engine pressure ratio}) = \\ &= -9.88 + (2.0 \cdot 40) = \\ &= 70.12\ \text{g} / 89\ \text{kN} = 0.787\ \text{g/kN} \end{aligned} \tag{3}$$

Usually, to measure the aviation climate impact, the CO_2 emission are being measured. Approximately aircraft engine emits 3.15 kilograms of CO_2 for each kilogram of jet fuel burned [73]. This CO_2 might be present in the upper atmosphere even up to 100 years. Unlike CO_2, the remaining emissions in form of NO_x, soot, water vapor emitted by aircraft are present in the atmosphere for approximately few weeks, yet those still contribute to ozone formation having negative climate impact. This aspect is critical as NO and NO_2 when released in the atmosphere react photochemically with organic compounds to release O atoms, which in further process combine with oxygen and form ozone. Thus, NO_x are primary air pollutant that contributes to the formation of photochemical smog, acid rain phenomena, tropospheric ozone, ozone layer depletion and finally global warming [74][73].

4.1.1 Water emissions

When considering various sources of environmental pollution and emissions, special attention should be put to one of the main products of combustion and fuel cell chemical reaction product which is water. Although carbon dioxide is nowadays a greenhouse gas that is of mayor concern due to emissions from industry and transport sector, water vapor is responsible for 60% of the global warming effect [75] . Moreover, it is very hard to control the overall water content in the Earth's system. The water cycle is dependent on many factors and it is very hard task to measure it as all the processes of the water cycle undergo on different levels, conditions and timeframes. Water vapor present in the atmosphere is strongly dependent on the temperature which means that the mechanism is reversed and it does not control the temperature unlike the other greenhouse gases.

When considering aircraft water emissions and radiative impact it has to be taken into account that it depends on many factors. Water vapor present in the atmosphere strongly depends on the type of aircraft being considered and the flight altitude. The values will be different for subsonic and supersonic aircrafts. For example, the water vapor emitted by subsonic aircraft in conditions below 400 hPa can remain in the atmosphere for around 5 days. This mainly depends on the flight altitude and therefore corresponding surroundings conditions. When discharged in the atmosphere the lifetime of water vapor is different for various Earth's atmosphere layers. For lower altitudes the water will condensate with temperature drop and will precipitate in form of rain to the surface while in upper tropopause and stratosphere this water vapor emission will build up contributing to increased radiation. Radiation phenomena also is considered as a function of season along the year. As suggested in [76] the highest radiative forcing is observed in April while the lowest can be observed in October for both kerosene-fuelled aircrafts as well as hydrogen powered fleet. Moreover, contrails and cirrus formation are caused by the emission of water vapor, which combined with soot from conventional combustion and particles in the atmosphere contributes at the same time to environmental degradation and air pollution.

Not only considering the aircraft water pollution, but also water emissions coming from various hydrogen-powered applications such as fuel cells for power generation or fuel cell electric vehicles (FCEV), which are being introduced on a worldwide scale and undergoing a rapid growth. For each 1 kWh of electricity generated with fuel cells a 0.5 L of water is produced, or assuming the water density of 1000 kg per cubic meter it corresponds to 0.5 kg of water being expelled to atmosphere [77]. Considering the growth of fuel cell and hydrogen-powered fuel-cell vehicles that by 2050 might reach the shares of 20 percent of total vehicle fleet corresponding to 400 million cars, not counting trucks and buses, the water emissions are of paramount importance [78]. For a comparison, the plans for aircraft sector are not any less ambitious assuming creating a fleet of aircraft powered by fuel cells by 2030 and assuming future plans of aircraft units powered by hydrogen engines [79]. This proves that regardless of the hydrogen application either for energy production with the use of fuel cells or combustion engines, the water emissions should be taken into account as it is the main product of oxidation processed undergoing by using those previously mentioned technologies. Even tough hydrogen when burned does not result in carbon dioxide emissions, however a plane with a propulsive system utilizing hydrogen would produce around 2.6 times as much water vapor the same aircraft unit flying on kerosene.

Performing a simple calculation for the case of Portuguese fleet in 2019, a simple estimation of annual water emissions are presented assuming the scenario that the same fleet would run on hydrogen fuel. The estimation together with assumptions for the calculation can be found in the equation (3) presented below [76][80][81]:

$$\text{Annual } H_2O \text{ emissions} = 1412578000 \, \frac{\text{kg fuel}}{\text{annually}} \cdot 1230 \, \frac{\text{gH2O}}{\text{kg fuel}} \cdot 2.55 = 4.43 \cdot 10^{12} \text{ g}H_2O$$

$$= 4.43 \text{ Tg of } H_2O = 4.43 \text{ million t of } H_2O \text{ annually} \qquad (4)$$

where,

annual fuel consumption in Portugal in 2019 = 1 412 578 000 kg Jet fuel A [80]

Emission Index (EI) for Jet fuel A = 1230 $\frac{\text{gH2O}}{\text{kg fuel}}$

Emission index (EI) for hydrogen = 2.55 · E.I Jet fuel A

Number of aircrafts of Portuguese fleet in 2019 = 105 [81]

Resulting from this rough approximation, a fleet of just 150 units would generate 4.43 million tons of H_2O per year. Therefore, resulting from transport sector rapid growth which will result in great amount of water being additionally introduced into the system will have an impact on the environment and definitely should be taken into account for the future plans of hydrogen economy development.

To sum up, potentially harmless exhaust gas product, water in fact has a great impact on the environment and contributed to global warming to high extend. Additionally, atmospheric deposition is the pollution of water which is caused by air pollution, forms a weak acid as water particles mix with carbon dioxide, nitrogen oxides or sulphur dioxide. As a consequence, when condensed, the water polluted with those gases precipitates in form of so called acid rain. Those acid rains have a negative effects on human health, wildlife, agriculture and also lead to degradation of buildings. Moreover, the acid rains pollute marine habitats such as rivers and lakes, harming the aquatic life. This proves that water present in the exhaust gas products resulting from hydrogen combustion as well as chemical reaction of hydrogen fuel cells is of paramount importance and its impact ought to be studies in details, together with its possible negative environmental impacts.

4.1.2 NOx and CO formation mechanisms

To better understand the emissions associated with gas turbine operation, what then translates to more effective system of control, this section focuses on main mechanism of NO_x formation, as this group of exhaust components is of special concern in combustion power plants.

Although hydrogen as a fuel does not contain nitrogen component, some studies show that combustion of hydrogen in air or hydrogen-rich fuels, such as blends of hydrogen and natural gas (NG) can lead to even around nine times higher NO_x emission, in case of pure hydrogen combustion, than when burning only methane or natural gas. Additionally, the study presented in Cellek et al. (2018) showed that by far emissions observed from the combustion of hydrogen compared to combustion of natural gas or methane can be as much as even six times higher. The research is based on Eddy Dissipation combustion model showing that combustion of pure hydrogen in low swirl industrial burner results in increased NO_x emission by 659.30% compared to pure natural gas. On the other hand the author indicated that implementation of hydrogen helps to reduce the fuel consumption, which in turn could also result in decreased emissions and better fuel economy. More specifically, based on the aforementioned study the fuel savings could reach around 60% when compared to natural gas [82]. Nevertheless, this study proves that NO_x contribution in hydrogen gas turbines is significantly higher and therefore a special attention should be paid to the phenomena of NO_x formation.

The formation of nitrogen oxides (NO_x) is a result of different mechanisms which occur at different conditions and thus they vary by pathways of formation. There are four main mechanisms of NO_x formation, namely: thermal NO_x, NNH, fuel NO_x and Prompt NO_x.

The first and main mechanism observed in hydrogen gas turbines is Thermal NOx. Although there are many ways of NO_x formation Thermal also known as Zel'dovich mechanism is seen to be most significant for gas combustion due to the high temperatures existing during the combustion process being the main driver of that mechanism. Thermal NOx mechanism is a result of the thermal dissociation and further nitrogen reaction with oxygen. This mechanism refers to NO_x being formed at high temperatures above 1850K. Significant part of thermal NOx is formed in high temperature stoichiometric flame regions downstream of the fuel injectors. In those regions fuel mixed with air reaches peak temperatures. Moreover the Zel'dovich is a significant mechanism in lean fuels $\Phi < 0.8$ and as stated in the same study by Lefevbre et al. - nitrogen oxides peaks can be observed in fuel-lean mixture combustion [70]. The thermal NO_x reaction usually propagates according to the extended Zel'dovich reaction mechanism as presented below:

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH = \rightarrow NO + H$$

This mechanism especially plays a major role in the high-hydrogen content fuels combustion due to, previously mention very high combustion temperatures reached in this process. The sensitivity of thermal NO_x formation to temperature changes shows exponential behaviour, meaning a small increase in the higher range of temperature results in an exponential increase of NO_x. Moreover, the increased thermal NO_x levels during the hydrogen combustion are a result of the higher flame speed which increases the flame temperature locally [83]. The main factors influencing the thermal NO_x mechanism are temperature, especially in the reaction zone, the equivalence ratio also known as air-fuel ratio, which results from the N_2 high activation energy equal to 941 kJ/mol necessary to dissociate the N_2 molecule. Resulting from the observation the NOx emission drops with decrease in the air-fuel ratio. Additionally, the time of reaction and retention time of the reacting gases is of great importance. The shorter the reaction time, the lower the emissions.

Another formation pathway of nitrogen oxides is recently discovered NNH Mechanism. This mechanism plays especially significant role in the hydrogen combustion process, as well as hydrocarbon fuels with large carbon to hydrogen ratios. The reaction propagates following the two reactions presented below:

$$N_2 + H \rightarrow NNH$$

$$NNH + O \rightarrow NO + NH$$

From the research by Purohit et al [84] the general conclusions about the NNH mechanism can be drawn inter alia that, this pathways contributes to high extend to NOx formation especially in hydrogen rich fuel combustion at low temperatures. Moreover, this pathways is a dominant mechanism in the early flame region in lean combustion. It is also a leading mechanism in the regions where the H radical concentration is high.

The Fuel NOx formation pathway is a result of reaction of fuel-bound nitrogen with oxygen. In case of pure hydrogen combustion this mechanism will not occur, however it plays significant role when speaking about ammonia combustion which is considered as an alternative to pure hydrogen combustion or substitute for methane-hydrogen blends. In the situation when fuel contains nitrogen, it essentially all converts into NO_x. In case of lean mixtures about two thirds of fuel bound nitrogen is being converted into NO and the remaining part reacts to molecular nitrogen form. On the other hand in rich mixtures less NO is being formed with a favour to more ammonia NH_3 and hydrogen cyanide HCN being formed according to the reaction proposed by Fenimore presented below:

$$CH+N2 \leftrightarrow HCN+N$$

$$C+N2 \leftrightarrow CN+N$$

Those two compounds when released to atmosphere undergo decomposition to finally form NO. In case of rich mixtures the oxygen is being in first line consumed by the fuel, preventing at the same time nitrogen to oxidize into NOx. Moreover, in rich-fuel mixtures the peak occurs due to the higher temperatures. In case of lean mixtures the phenomena is connected with the competition between fuel and nitrogen for the available oxygen.

The following mechanism is Prompt NO_x. Prompt NO_x arises during the combustion process from the early reaction of nitrogen molecules in the air and hydrocarbon radicals coming from the combusted fuel. The amount of Prompt NO_x is usually negligible comparing to thermal and fuel NO_x. This mechanism is observed when thermal and fuel NOx are eliminated. In general, this formation pathways involves the atmospheric nitrogen undergoing reaction with combustion radicals in the early stages of combustion. Unlike in Zel'dovich mechanism, Prompt NO_x is not significantly temperature dependent. Therefore, this mechanism becomes more significant when other formation pathways have undergone reaction. Due to extremely small lengths scales of Prompt NO_x, there are no feasible ways to stop the process and therefore a higher pressure is being put to reduce the other NO_x formation mechanism and prevent them [85]. Nevertheless, from all those mechanisms described in this study, thermal NO_x is the predominant NO_x formation regime and the one from which major design and material challenges arise.

Usually, the decreasing NO_x levels result in rising emission of CO. Investigating gas turbine combustion it can be seen that the presence of CO and NO_x formation occur in different temperature regimes. CO due to lower reaction rate is present at lower temperatures and has lesser tendency to oxidate forming carbon dioxide CO_2. It can be seen that the temperature range where both of those compounds are minimized is very narrow as presented below in Figure 11.

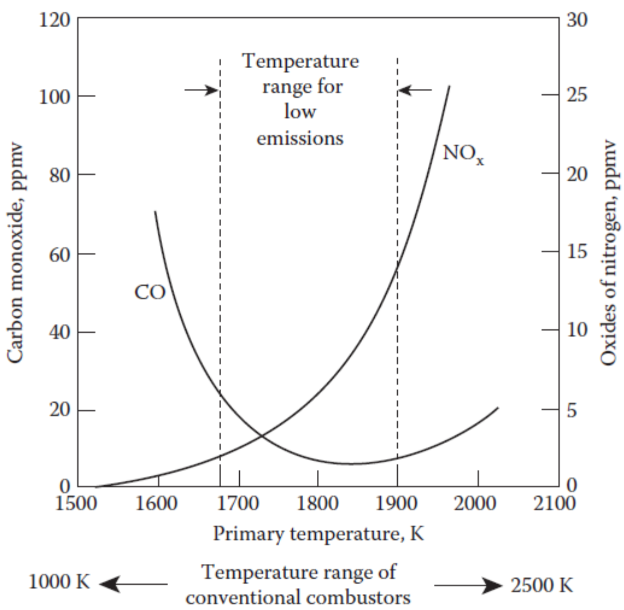


Figure 11 Influence of primary-zone temperature on CO and NO_x emissions. Adopted from [69].

Carbon monoxide (CO) is a significant compound in the process of hydrocarbon oxidation. Over the combustion process the fuel will at first break down into CO before being oxidized to CO_2. The kinetics of CO oxidation is a slow process [85]. Hydrogen-containing species and compounds such as water might speed up the process, however the principal method of CO emission reduction is the control of equivalence ratio. In case of fuel rich mixtures, the steady increase of CO concentration can be observed with the increment in equivalence ratio, while for fuel-lean mixtures the overall CO concentration is lower and less prone to equivalence ratio changes, except when the combustion process is incomplete. Resulting from high combustion temperatures occurring in near-stoichiometric combustion there might be observed significant CO concentrations coming from the CO_2 dissociation. Concluding, the CO emission level decreases rapidly with the drop of temperature, providing that the CO has enough time to react and oxidize to form CO2 [87]. It can be seen therefore, that there is strong link between the NOx and CO concentration, which both depend on temperature changes and variable of equivalence ratio. In the further section of the study there are presented and described various methods of emission control in the gas turbine system.

4.1.3 Gas Turbine emission control and improved combustion performance systems

Resulting from the specific hydrogen properties, the gas turbine design is a great challenge. The goal il to improve the power plant efficiency while maintaining the emission on the low level. However, those two objective most often collide with each other. The means to improve the efficiency involve higher fluid temperature, which on the other hand promote the NO_x formation. Moreover, combustion in reduced oxygen environment leads to reduced NO_x level, however it promotes the CO rise and unburned hydrocarbons as a result of incomplete combustion. Additionally, rising the temperature is a great challenge for the materials as its durability is being reduced together with temperature increase and the longevity of components is limited.

There are several techniques of the emission control in gas turbines, especially NO_x. As previously mentioned, it is not an easy task to maintain the NO_x levels in the limits together with providing high combustion efficiency. This results from the trade-off between NO_x production and CO species together with unburned hydrocarbons UHC, where the dependency is inverse and strongly linked to the temperature and equivalence ratio as previously stated.

NO_x emission reduction techniques involve combustion controls or flue gas treatment. These reductions can be achieved by water or steam injection or implementation of Dry Low-NOx (DLN) combustor designs which are the most common combustion control techniques available. The post-combustion treatment of flue gas involves Selective Catalytic Reduction (SCR), which in fact is the only feasible and commercial method of post-combustion emission control compatible with gas turbines. The other methods are selective non-catalytic reduction (SNCR), however the temperature this method employs are much higher than gas turbine exhaust gas temperatures. Additionally, the residence time of the exhaust gases in the high enough temperature is longer than available in case of gas turbines. Another alternative is SCONOx™, which is a catalytic absorption system, however this solution has limited application and commercial use. The SCR system are capable of NOx reduction in the gas turbines by 75% to 90% or more. Although there are new emerging technologies for emission reductions, most recent and new turbine installation use the SCR emission control together with DLN combustor technology.

More of the NO_x emission control methods have been described and listed by Rokke et al. (2003) [88] involving such technologies as water or steam injection, Lean Prevaporized Premixing (liquid fuels), Lean Premixed combustion, Lean Direct Injection, Staged combustion, with two or more steps of fuel injection or air introduced in parallel or serial manner, Variable Geometry – constant equivalence ratio, Rich-Quench-Lean-Burn combustion and Catalytic combustion. The Table 5 below presents some of the previously mentioned technologies and the levels of emissions achievable by employment of the aforementioned methods.

Table 5 Achievable Emission Levels with NO_x Control Techniques. Adopted from [89]

Control technique	**NOx Emissions, gas-fires turbines (ppm)**
Uncontrolled Emissions	155
Steam/Water Injection	25
Lean Pre-Mix Design	9
Selective Catalytic Reduction	2-5
Catalytic Combustion	3
SCONOx	1-3

The wet combustion involves the water injection in the vicinity of the fuel injector. This causes the level on NO_x being controlled by the amount of steam in the combustion chamber. The limitation for the amount of steam injected again are the rising CO levels. Additionally, the process of steam purification rises the operational costs and therefore the overall costs of the installation. Due to water consumption and the efficiency reduction this method is rarely applied nowadays.

On the other hand, the post-combustion treatment main principle is the conversion of NO_x or its direct absorption from the flue gas. Compared to water or steam injection those emission technology methods are relatively inexpensive, but also their efficiency does not exceed the low emission potential of modern combustors. The diffusion flame is a selected type of combustion by manufacturers nowadays due to the very stable combustion as the flame front is being stabilized as a result of the stoichiometric combustion. However, the main flaw of this method is high concentration of NO_x in the flue gas due to the high combustion temperature reaching 2000 ˚C. On the contrary as presented in the Figure 12 the operating range for premixed flame is very narrow, however both CO and NO_x values tend to be rather lower than in case of diffusion flame. Although diffusion flame provides more stable combustion, premixed combustion in recent installation is able to reduce the NO_x emissions bellow 10 ppm.

Usually, the most typical reduction method in the case of diffusion burners is the water injection and catalytic converted, however unlike SCR, the water injection in many application is insufficient and does not provide enough NO_x reduction to meet the limits. On the other hand the SCR results in higher complexity of the installation and higher overall costs.

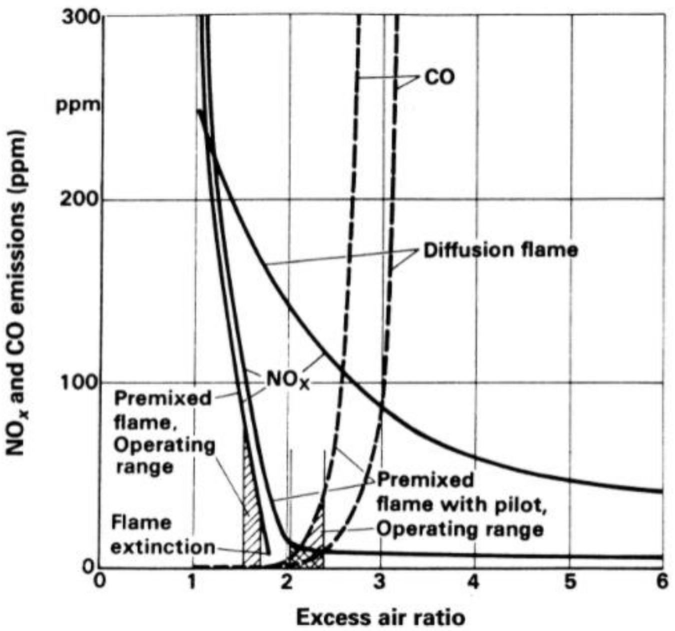


Figure 12 Operating range for premixed and non-premixed flames

Another method in efficient NO_x emission reduction is Lean Direct Injection (LDI) and Rich burn, Quick-mix, Lean-burn combustion technique (RQL). LDI combustion method refers to the combustion in the primary zone following the principles of lean combustion. This specific feature then requires a proper flame stabilization. The second method – RQL provides rich combustion in the primary zone, followed by lean combustion through rapid mixing downstream the combustor with the dilution air.

Both of those methods are focused on non-stoichiometric combustion which allows to avoid high temperature combustion zones and thus minimize the thermal NO_x formation. The main difference in LDI and RQL techniques is the flame stabilization and the combustion in the primary zone. LDI emission control especially has found its application in the aviation sector for the liquid fuels, while RQL combustion is a preferred technique in stationary gas turbines which is gaining more attention nowadays, especially while speaking of fuels with more complex composition.

Flue gas recirculation also known as Exhaust Gas Recirculation (EGR) is another method proposed to mitigate the NOx formation. This technology relies on the flue gases being recirculated and introduced again to the combustion chamber which provides the combustion in air with reduced oxygen content. This therefore leads to reduced temperatures of combustion and as a result, decreased NO_x species in the exhaust. This method is especially attractive in high hydrogen content fuels, however this application is still being developed and have not yet found the commercial applications.

Since high hydrogen content fuels combustion is characterized by high reactive combustion properties, the dilution or other emission control system is inevitable to meet the limitations. The high EGR rate has been studied and applied in the gas turbine unit in order to obtain oxygen air depleted combustion. From the study performed by Ditaranto et al. (2015) results that this is a promising technology for hydrogen gas combustion turbines [68]. The EGR implementation shows efficiency improvement and nitrogen dilution with relatively low efficiency cost of 1.3% in case of wet EGR. However, dry EGR appears to be preferred option, even though higher EGR rate is required.

Another method of NO_x emission reduction is introduction of swirling. The study by et al. proves that changing the swirl angle has an effect on NOx reduction. With decreasing swirl angle the NO_x concentration in the flue gas is also lower especially at temperatures below 1800 K [90]. Low Swirl Concept (LSC) has been commercialized for industrial application and can be readily applied to hydrogen enriched fuels. High Swirl Burner find its application in both premixed and diffusion combustion systems, as this methodology improves the flame stability, while maintaining high combustion intensity and thus the combustor performance. The principle of operation of a swirl burner involves the creation of recirculation zones in the primary combustion zone, which promotes the turbulent mixing of fuel and oxidizer. Moreover, in DLN systems, this technology provides a stable heat source for a continuous ignition of the fresh portions of reactants being introduced into the chamber. High Swirl Burners are therefore characterized by strong toroidal vortices which main aim in to provide stable combustion and continuous re-ignition of the reactants, providing better flame stability. On the other hand the Low Swirl Burners, which are suitable only for premixed combustion systems, are only suitable for the premixed combustors due to the fact that there occurs the combustion in form of propagating self-sustained wave downstream the burner, where diffusion flames do not propagate, as the mixing occurs only on the interface where the fuels mixes with the oxidizer in the reaction zone. Additionally, swirling mitigates the risk of flashback and blowoff which is of great importance for DLN combustors. LSB are an emerging technology of great importance for meeting the emission limits, reliability and stable combustion for next-generation combustors, also the ones which will be able to allocate hydrogen rich fuels [91].

Very efficient for emission control during hydrogen combustion is the Micro-mix (MMX) technology [92]. The principle of operation is based on cross-flow mixing of air and hydrogen, providing low emission gas turbine that has been recognized as an efficient method of emission reduction for the future gas turbine units. This technology stands out due to the fact that combustion takes place in form of hundreds diffusion-type flames of miniature size. In this way the reaction zone has been minimized as the size of the flame is of the order of 5-15 mm length. Moreover, this technology combines the advantages of both premixed and diffusive combustion. The risk of flashback is lower than in case of Lean Premixed Combustors and with improved mixing due to the cross-flow for fuel and oxidizer meaning that the hydrogen is jet is perpendicular to the air inlets. This technology has been already successfully tested and applied in small conventional gas turbine units.

Therefore, this proves that there are many methods of emission control, each of which is more of less effective and can be employed for gas turbines employed depending of type of combustion regime and fuel characteristic and other features of the burner. To sum up, the two preferred solutions for hydrogen rich fuels and pure hydrogen combustion is the MMX technology utilizing multiple micro-flames, providing better heat distribution and therefore preventing the hot spots creation, lowering the formation of NO_x and on the other hand the swirl stabilization in premixed combustion is getting special attention in the state-of-the-art modern combustor models, promoting the high degree of premixing and better flame stabilization which mitigates the flashback and blowoff phenomena [93].

Chapter 5

Reactor simulation

In this chapter the simulation of a combustion chamber has been presented. This analysis allows better understanding of the emission formation in the combustion chamber. The simulation has been performed for various fuels such as hydrogen, methane, ammonia and methane blend with 50% of hydrogen.

This section presents the analysis and a simulation prepared with Python-based Cantera Software. The main goal of the reactor simulation was the analysis of such parameters as adiabatic flame temperature (AFT), laminar flame speed and the concentration of emissions from the combustion of various fuels and the assessment of those parameters against changing equivalence ratio over the range between 0.5 and 3.5. The analysis was performed using the Well Stirred Reactor (WSR) model in order to simulate the combustion using the “GRI mech 3.0” mechanism implemented in the Cantera suite. The mechanism includes 325 reactions and 53 species and it’s an optimized mechanism designed for the gas combustion modelling, together with emission formation [94]. A WSR provides a idealization of primary zone of a gas turbine and allows for the analysis of the combustion and emissions [95]. In this study WSR was implemented in order to evaluate the formation of emission various fuels. Moreover, this study compared the laminar flame speeds of methane and hydrogen and the adiabatic temperatures of those fuels. In further part a Plug Flow Reactor (PFR) model has been implemented in order to simulate the combustion of various fuels, which allowed the observation of the residence time of species during the combustion process and formation of products. The study was performed by the use of Lagrangian particle approach. This analysis demonstrates the behaviour of various fuel in a hypothetical reactor and the possibilities of modelling these types of phenomena within the Cantera environment and GRIMECH 3.0 mechanism. Moreover, the analysis demonstrates the dependency of such parameters as equivalence ratio, adiabatic flame temperature (AFT) and emissions of NOx, CO and H_2O for various fuels and under different conditions. Plug Flow Reactor is the second most simple ideal reactor, similar to the continuous stirred tank reactor. According to S.Lju [96] PFR is an idealized flow in which all the reaction mixture is moving along the direction of the flow at the same speed. PFR is an idealized flow reactor where the contents flow like plugs from inlet to outlet [97]. In PFR all the reaction mixture moves along at the same speed along the direction of flow. In PFR there no mixing and no backflow occurs. The model assumes well mixed mixture, like in case of batch reactor in each plug or on the PFR cross-section plane. These assumptions and idealization allows for the PFR to be treated as one-dimensional flow reactor, thanks to maximal simplification of the PFR analysis. Common practice in more advanced cases is utilizing both of those models combined together with PFR following the WSR representing the primary combustion zone followed by the secondary or dilution zone respectively. The advantages of PFR are connected with possibility of particles sampling in which the axial diffusion species are negligible, resulting from high gas velocity, also the total residence time is spread over the entire lengths and the disturbance due to the sampling probes is minimized as PFR does not suffer the flame stability issues [98] . Moreover, in PFR there occur nearly isothermal conditions [99]. While these two models and approaches provide quick insight into the emission formation and trends, a PFR can be utilized for more complex analysis, such as combustor dimensioning and previously mentioned coupled with WSR in order to model the combustion in the various zones of gas turbine burner.

There have been many similar studies performed on the gas turbines combustors with implementation of various fuels in order to evaluate the combustion performance and the emission formation. In the study presented by Zelina et al. (1996) [95] the implementation of the WSR served in order to analyse the formation of CO, CO_2, NO_x and UHC for various fuels such as ethane, methane and hydrocarbon blends. The study showed that for all three fuels the CO emission were slightly varying however it reached minimum for the equivalence ratio ranging around Φ=0,6. The rapid increase of CO concentration have been observed with the increasing equivalence ratio. NO_x formation has been strongly dependent on the temperature and as Zelina indicated the peak occurred around the Φ=1, resulting in the highest combustion temperatures. Moreover, that study evaluates and confirms the NOx concentration correspondence with the flame temperature.

In the first step the combustion of two independent fuels have been performed. The combustion was performed in atmospheric air at inlet temperature of 1650 ˚C and pressure of 1 atmosphere the equivalence ratio ranging between 0.5 and 3.5. Presented results in the Figure 13 demonstrate the flame velocity for hydrogen and methane. It can be seen that the flame velocity of hydrogen is around 8 times higher than in case of methane and equal to around 300 m/s for equivalence ratio of 1.5, while for the same Φ for methane the velocity reaches around 40 m/s. Moreover, it can be seen that the flame velocity shows dependency on the equivalence ratio and with increasing equivalence ratio there can be observed slight increase in the flame velocity for both fuels. Presented in Figure 13 Flame velocity vs. Equivalence ratio of hydrogen H2 and methane CH4, combustion at T=1650 K, P=1 atm.

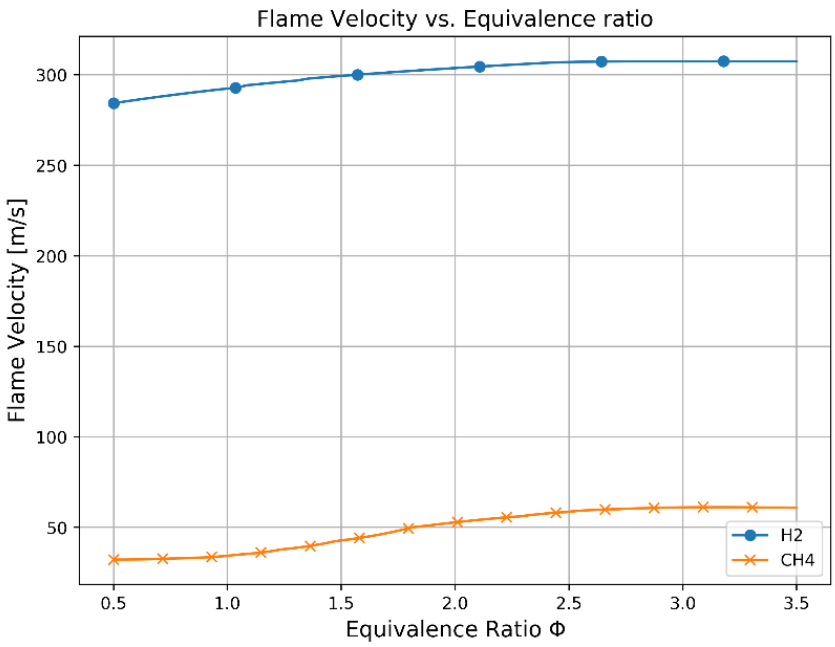


Figure 13 Flame velocity vs. Equivalence ratio of hydrogen H_2 and methane CH_4, combustion at T=1650 K, P=1 atm.

Figure 13 there can be seen that the flame speed of hydrogen is much higher than the flame speed of methane. This specific feature is one of the main limitation in pure hydrogen combustion in gas turbines. The common phenomena for high-hydrogen content fuels are flashback and blow-off. As mentioned in previous chapters flashback occurs when the gas velocity is lower and the flame speed of fuel becomes higher than the gas velocity as the flame propagates within the boundary layers, core flow or as a result to combustion instabilities [63]. Moreover, the higher the burning velocity, the higher the probability for transition from deflagration to detonation. The high flame speed of hydrogen results from its fast chemical kinetics and high diffusivity. Additionally, the hydrogen's flame speed in air at ambient conditions equals to 2.55 m/s and can reach even 11.75 m/s in pure oxygen, which is an important aspect while considering hydrogen oxy-combustion [99][100]. Blending methane and hydrogen could result in obtaining the desired properties of both of this fuels when combusted separately, therefore the hydrogen-rich fuel would provide higher laminar flame speed, which as commented in previous sections also contributes to better flame stabilization and increased combustion performance, but on the other hand the addition of methane would allow for obtaining lower adiabatic flame temperatures, preventing the burner components and turbine unit from damage and wearing out. Moreover, blending of hydrogen and methane could contribute to widening the flammability limits of the fuel [100]. Additionally resulting from many previous studies inter allia by Çeper and Syred (2012) shows that this type of fuel blending decreases a ignition delay in internal combustion engines as the minimum ignition energy for hydrogen equals to 0.02 mJ which is much lower than for hydrocarbon-air mixtures. This kind of blending besides the chemical and physical properties also contributes to better fuel economy and reduces the demand for pure hydrogen, at the same time contributing to smoother and more flexible energy transition [101]. Therefore hydrogen-methane blends are considered a potential alternative to common fuels for internal combustion engines.

The following simulation was performed for the combustion of hydrogen, methane and the mixture of methane with 50% hydrogen. The analysis allowed to evaluate the formation of such species as NO, N_2O and NO_2 forming together the NO_x group. Also the formation of water during the combustion of those three proposed fuels have been modelled against the increasing equivalence ratio over the range Φ=0.3 to Φ=3.5. The combustion parameters were set to the inlet temperature of 300 K and P of 1 atmosphere. The stoichiometry for the hydrogen-methane mixture has been set according to the stoichiometry reaction equation of CH_4 - H_2 blend presented below:

$$(\alpha\, CH_4 + \beta H_2) + (2 \cdot \alpha + \frac{\beta}{2}) \cdot (\, O_2 + 3{,}76 N_2) \quad (5)$$

It can be observed Figure 14 that the highest contribution in the NO_x formation comes from the NO species forming during the combustion, where the contribution of NO_2 and N_2O is very small almost negligible. In case of the NO_x formation including NO, N_2O and NO_2 the peak in the concentration is being observed close to the equivalence ratios of Φ=0.7-1, therefore in the region where the highest adiabatic flame temperature occurs as well. The highest concentration both of NO_x and water can be observed in case of pure hydrogen combustion, while the lowest are observed during the methane combustion. The hydrogen-methane blend allows for significant emission reduction. On the contrary demonstrated in the Figure 15 CO emission show opposite behaviour. There can be seen a very sudden CO concentration increase after reaching the Φ=1 when considering the combustion of methane and the blend of methane-hydrogen. For pure hydrogen that value is zero since hydrogen does not contain any fuel bounded carbon particle. Moreover, it can be seen that the optimum point for both low CO and NO_x is very narrow and could be observed around the equivalence ratio of Φ=0.9-1. Therefore, it proves how challenging is keeping both of those parameters low and maintain high combustion performance as two types of emission depend on different formation mechanisms and reaction rate.

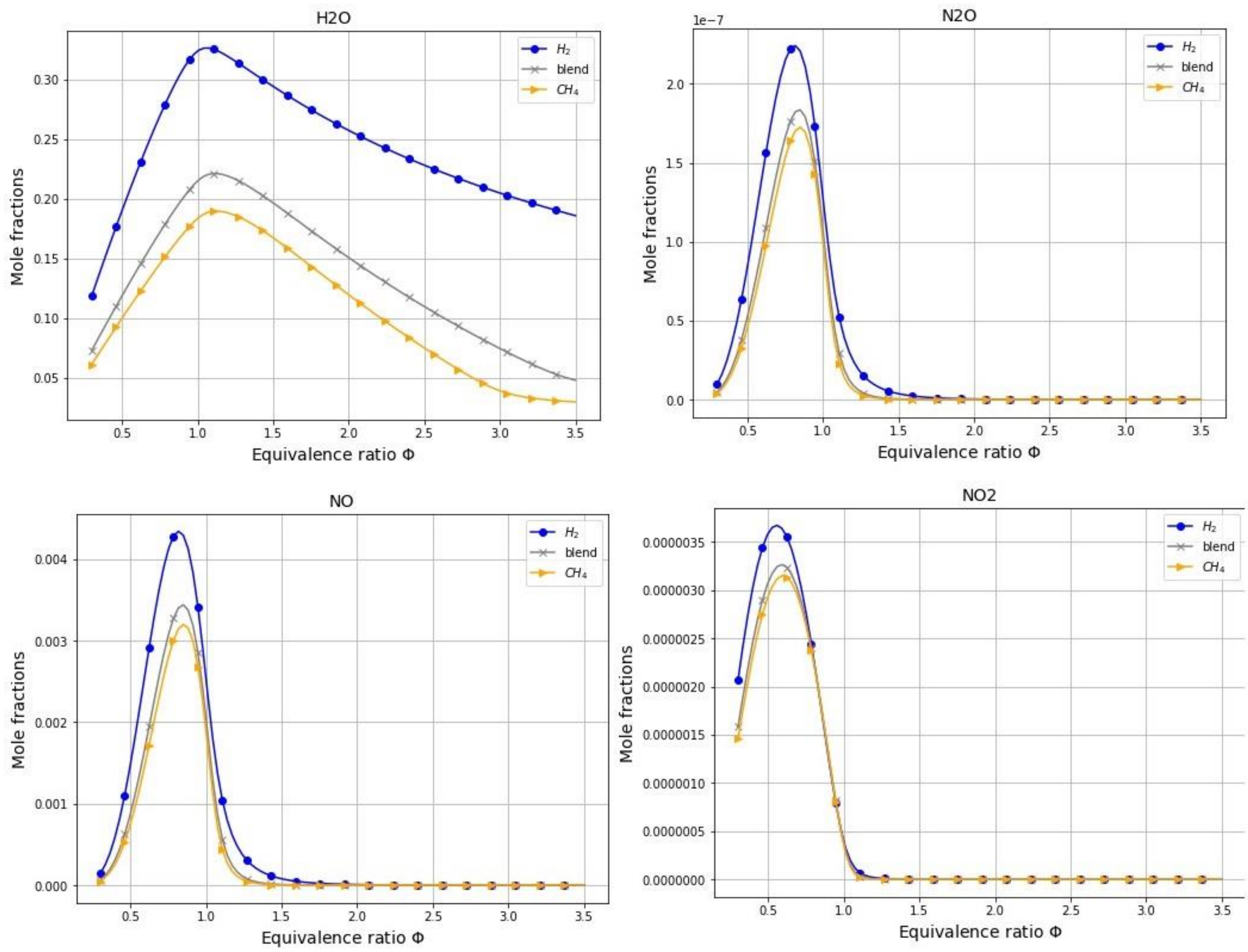


Figure 14 Emission formation, combustion of hydrogen, methane and methane blend with 50% hydrogen at T=300 K and P=1 atm.

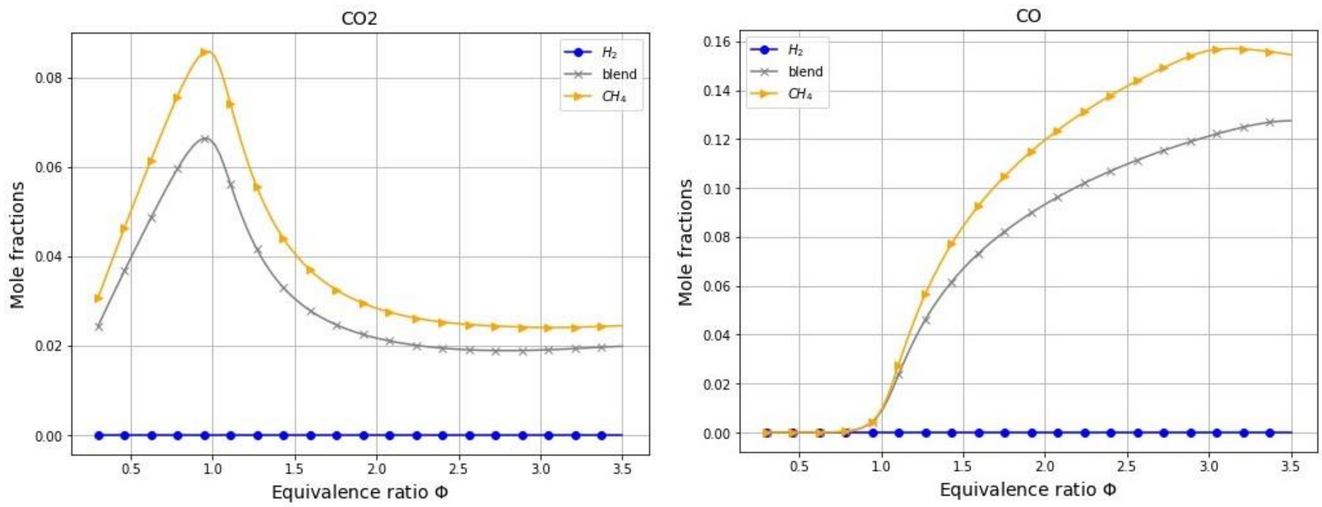


Figure 15 CO and CO_2 formation, combustion of hydrogen, methane and methane blend with 50% hydrogen at T=300 K and P=1 atm.

In the Figure 16 the combustion of hydrogen (blue) and methane (orange) has been presented with respect to the residence time of the particles. In case of hydrogen it can be observed that hydrogen is being combusted almost immediately and the only product of this process is water vapor and trace amounts of NO_x which seem to be zero compared to concentration of remaining species. In case of methane combustion the reactants are being combusted more steadily. The products of methane combustion is water vapor and CO_2 and can be seen in the Figure 16 Hydrogen and methane combustion residence time T=2000 K, P=1 atm. The NO_x species are negligible.

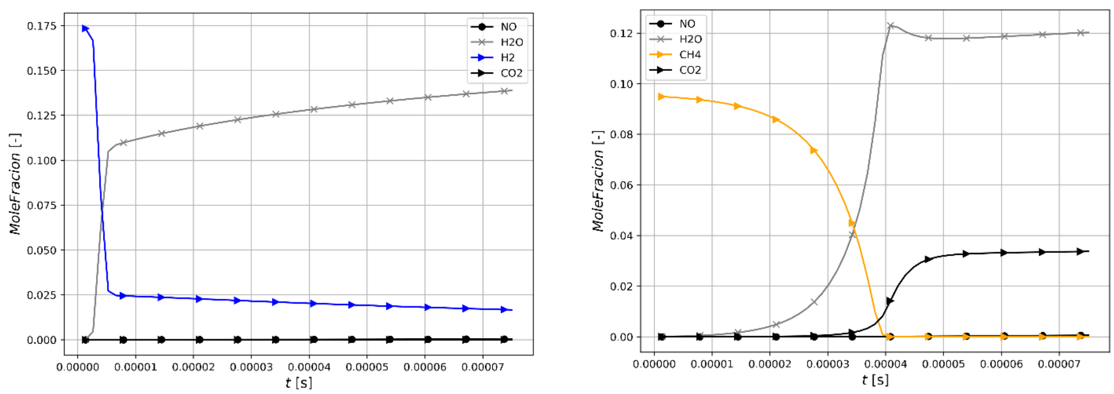


Figure 16 Hydrogen and methane combustion residence time T=2000 K, P=1 atm.

As shown in the Figure 17 the hydrogen combustion in pure oxygen results in much higher temperature compared to combustion in air. The AFT for hydrogen oxy-combustion peaks around equivalence ratio of 1 and reaches values up to around 3100 K. This is a very high temperature that might lead to the burner walls deterioration and damage the turbine unit. As indicated in the study by Aminov et al. (2018) the temperature of hydrogen oxy-combustion can reach values even around 3600K which then would require more sophisticated cooling method. However, this solution might be feasible in order to produce superheated steam which could be later utilized to produce energy at various power plants, and also Aminov indicated the possibility of utilizing this solution as a back-up power in case of power plant black out [102].

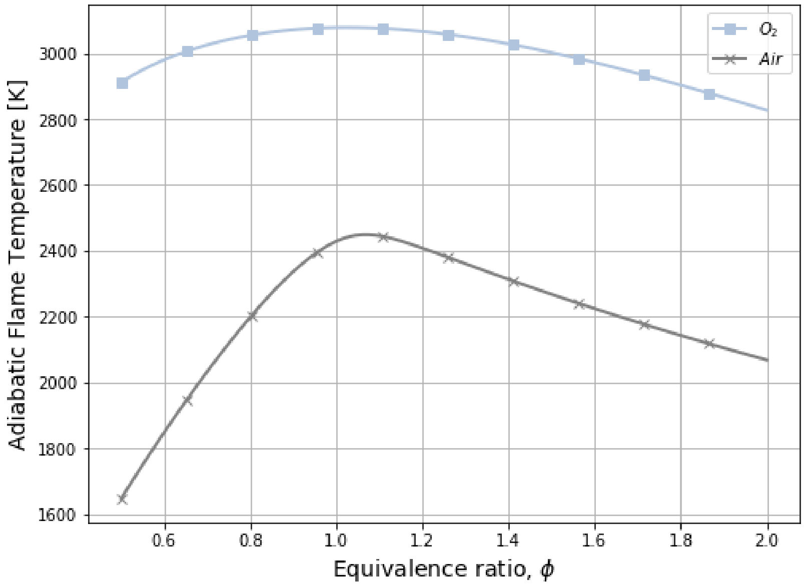


Figure 17 Hydrogen's adiabatic flame temperature against equivalence ratio, combustion in air and pure oxygen combustion at T=300 K, P=1 atm.

For better overview in Figure 18 has been presented comparison of combustion of different fuels namely: hydrogen, ammonia, methane and methane-hydrogen blend, shows that pure hydrogen reaches the highest values of adiabatic flame temperature, where for methane and mixture of hydrogen with methane, that temperature is significantly lower. The complete combustion has been performed for the temperature of 300 K and pressure of 1 atm.

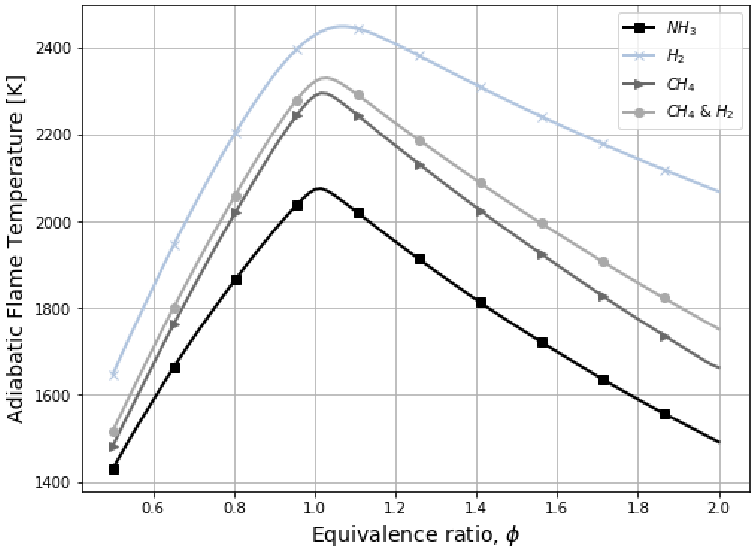


Figure 18 Adiabatic flame temperature for various fuels combustion in air at T=300 K, P=1 atm.

For comparison in case of ammonia NH_3 combustion the flame temperature is about 100-200 K lower compared to methane at corresponding equivalence ratio, which can be also observed in the Figure 18 and it is value corresponding to the results obtained by Kobayashi et al. in the research of "Science and technology of ammonia combustion" [103]. Moreover, as indicated in the study by Ilbas et al. (2019) the hydrogen oxy-combustion would require a burner modification especially done on the inlet to the burner [104][103]. That research states that decreasing the burner inlet section would be necessary in order to prevent the burner walls from overheating and provide better flame stabilization, which therefore would help to avoid the consequences of combustion instabilities in form of flashback and blow-out. Nevertheless, this method of combustion would result in lower NO_x concentration, resulting from the hydrogen combustion, however the material durability and TIT by far result to be of great concern considering the high AFT of hydrogen-rich fuels oxy-combustion.

On the other hand, it can be observed as presented in the Figure 18 that compared to ammonia, the combustion of pure hydrogen results in very high temperature. Adiabatic flame temperature is of great importance while considering the gas turbine combustion. This type of flame temperature is named so as there is no energy exchange with the surroundings, and therefore this temperature influences the radiation heat transfer that is responsible for the thermal loading of the combustor. The walls of the combustor are especially exposed to heat degradation which leads to premature failure of the burner and thus rises the operational costs of power plant. Therefore, ammonia and hydrogen-methane blends might be an attractive substitute, which additionally would protect the walls of the burner from premature deterioration.

Moreover, the potential of ammonia NH_3 as an alternative fuels have been studied and described by Liu [105]. There are in fact many aspects of utilizing ammonia making this fuel an attractive substitute to pure hydrogen. Also in case of blends of ammonia and hydrogen there can be observed an improved velocity of combustion as in the case of methane. The biggest advantage of NH_3 is the significant reduction of the combustion temperature and therefore the NO_x emission and laminar burning velocities. This is a specially important feature for fuel-rich mixtures. Moreover ammonia, regardless the initial concentration in case of blending and for different Φ undergoes complete combustion and is not found later on in the exhaust, as indicated in the research on ammonia combustion by Liu et al. Last but not least, ammonia, despite being hazardous to human health, is much easier in handling and transportation compared to hydrogen. Therefore, ammonia and $NH_3 - H_2$ blends are also a promising solutions increasing the combustion performance and contributing to lower emissions. The study by Hussein et al. shows that the lowest values of unburned ammonia and higher flame temperatures were achieved for the $NH_3 - H_2$ blends between 40-60% reducing at the same time NOx fraction in the exhaust gas. However, the ammonia due to the low laminar flame speed, required partial cracking into hydrogen and nitrogen in order to be considered an efficient fuel for gas turbines which then results in higher system complexity and most typically higher costs [106]. Additionally, presented in the Figure 19 emission formation for ammonia combustion in T=300 K and at atmospheric pressure proves that, NO_x emissions result to be slightly higher. Especially in case of N_2O and NO_2 which comes from the fact that ammonia contains the fuel bound nitrogen which results in the formation of fuel NO_x apart from thermal NO_x mechanism contribution in the total NO_x concentration in the flue gas. However, again as in case of methane-hydrogen blends, mixing ammonia with hydrogen might lead to reduced emissions and better combustion performance, through benefits of both types of fuels. The analysis performed in this section therefore allowed for obtention of results corresponding to the results presented in the literature. It shows the possibilities coming from introduction of various fuels and combustion in the gas turbines. Moreover, it leaves the room for future investigation including more complex combustor models allowing for the burner dimensioning and the study of combustion performance of hydrogen rich fuels within the gas turbine and implementing possible modifications.

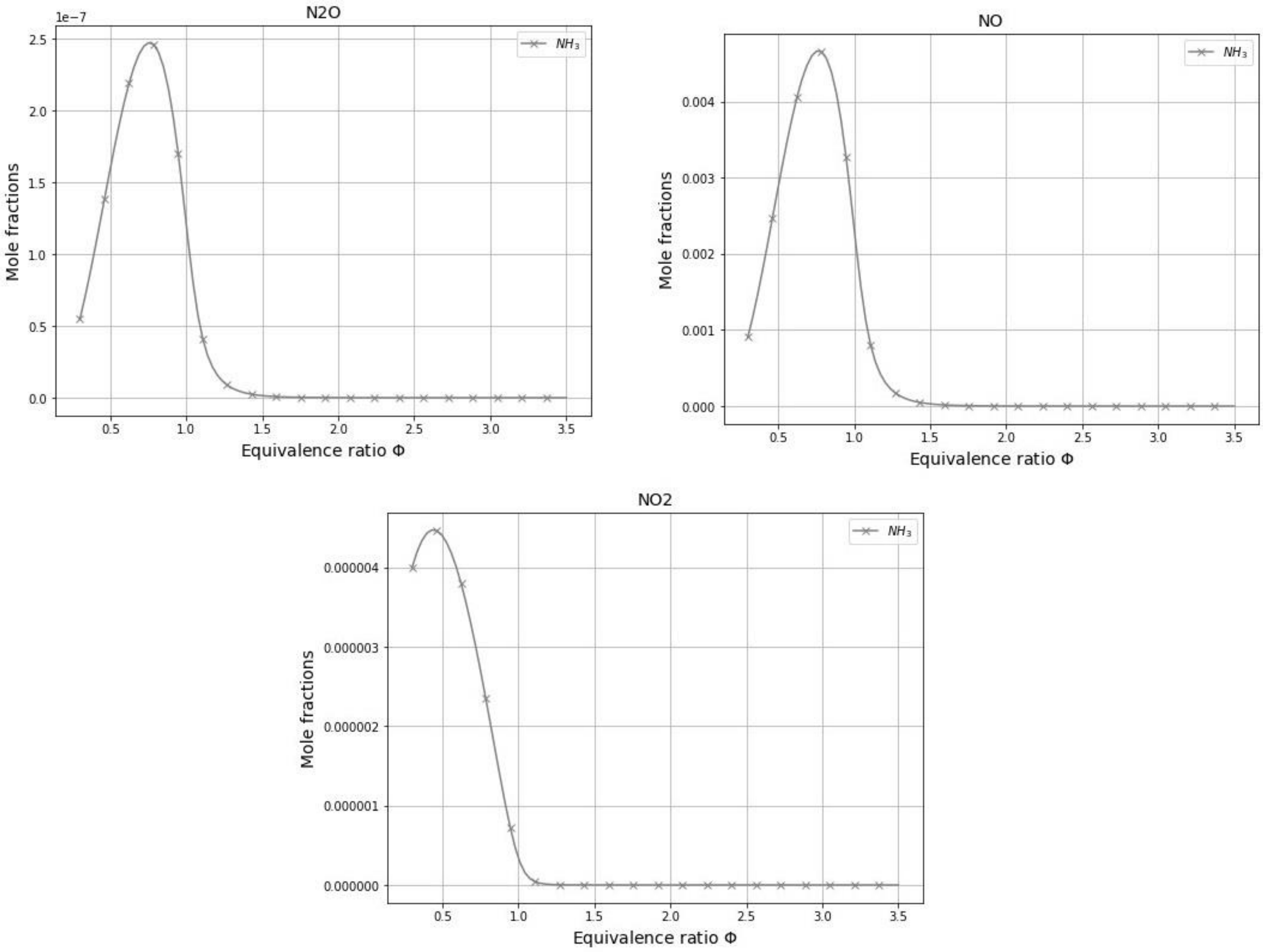


Figure 19 Ammonia combustion in air at T = 300 K and P = 1 atm.

Chapter 5

Techno-economic analysis

In this chapter the technological and economic analysis has been performed in order to provide insight into the approximate consumption and impact of large-scale industrial gas turbine using the hydrogen gas turbine calculator proposed by GE. Moreover, economic analysis of micro-gas turbine and electrolyzer has been provided together with sensitivity analysis for green hydrogen cost. The importance of electrolyzer capital costs, its efficiency and the revenues coming from the sale of oxygen has been presented in this section.

6.1 Technological and economic analysis

Due to the complexity of the analysis and difficulties in obtaining the data necessary to run the calculation, a calculator proposed by GE has been utilized [107]. This tool has been based on the information provided by the manufacturer and serves only for rough estimation of the system. This analysis allowed to estimate the impact of running gas turbine with methane and various hydrogen contents.

The site allows for selection such parameters as model of the gas turbine and its configuration, the hydrogen percentage volume in the fuel mixture, annual operating hours of the unit, as well as the country in order to assign the CO_2 tax rate.

The analysis has been performed for the region of Portugal assigning it the value of 29.48 UDS per ton of CO_2 emitted equivalent to 24,96 $€_{2021}$. However, it should be taken into account that the actual tax for EU reached 56 € per ton of CO_2 emitted as previously mention in the Introduction chapter [23].

The selected gas turbine investigated in this case is 9HA.02 by GE – it a high efficiency turbine model from the H-class, considered to be one of the most efficient gas turbines in combined cycle. The Net output power of this turbine is of 571 MW. The net efficiency of this turbine is equal to 44% is single configuration and 64,1% in a combined cycle.

The Case 1 have been calculated for the gas turbine operating 4000 hours annually and hydrogen content of 30%. The gas turbine was operating in a simple cycle. The hydrogen for the gas turbine has been produced with electrolysis.

In the Case 2 the gas turbine was operating at the same conditions however, the hydrogen needed for the gas turbine operation has been produced in the process of gas reformation.

In the Case 3 the gas turbine in single configuration operating 4000 h per year as in the case 1 and 2. Supplied with hydrogen produced via electrolysis, operating at 100% of hydrogen.

Case 4 considered the gas turbine in single configuration operating 4000 h per year as in the case 1 and 2. Supplied with hydrogen produced via steam reformation, operating at 100% of hydrogen.

The results of the calculation generated by the program proposed by GE has been presented in the Table 6. This rough approximation allows for the better visualisation of the sizes of the hydrogen infrastructure, water consumption and the approximate savings resulting from the avoided CO_2 emission.

The first conclusion that shall be drawn is that the amount of hydrogen required to power gas turbine producing energy on a great, industrial scales is very high. In Case 1 for the 9HA.02 running on the mix of 30% hydrogen, the required hydrogen flow is estimated to be around 106 tons of hydrogen per day and even 445 tons of hydrogen daily in case of operation on 100% hydrogen volume. This creates a first big challenge for the gas turbines industry as the hydrogen production at this stage is the first limitation. There are still not enough units to provide this amount of hydrogen to provide constant operation, even considering only 4000 hours operation annually.

According to the FCH Roadmap for Portugal [108], the ambitious plan assumes the renewable hydrogen generation to reach 2.7 GW by 2030 by the means of electrolysis. Assuming that for the production of 1 kg of hydrogen the input power of about 50 kWh to run the electrolysis according to the SEAS study [36], the produced amount of hydrogen would be about 54 000 ton H_2 per hour. Therefore, this gives the insight into the size of infrastructure required for shifting into 100% hydrogen firing. On the other hand as results from the GE analysis the energy required to power the electrolyzer would is the equivalent of the 179 units of wind turbines each one of 1,5 MW power operating on 50% capacity factor.

Table 6 9HA.02 hydrogen and emissions results for different plant configurations and hydrogen source

CASE	1	2	3	4
Electricity required [MW]	268,1	-	2303,3	-
No. of 150 MW turbines operating at 50% capacity factor, equivalent	179	-	1536	-
Water flow [litres]	956 903	478 332	8 218 505	4 109 251
Olympic-sized pools equivalent	0,38	0,19	3,28	1,64
Hydrogen flow required [mln m3/day]	1,13	1,13	10,6	10,6
Hydrogen flow required kg/day	106 163	106 163	445 554	445 554
Hydrogen flow required kg/hour	4423	4423	38001	38001
Methane required kg/hour	-	8847	-	76000
CO_2 reduction [%]	11,6	11,6	100	100
Potential tax savings [mln €]	3,3	3,3	28,6	28,6

As mentioned previously, the highest contribution in the expenses over the time of the gas turbine system operation are the fuel expenses. Nowadays the big pressure is being put on utilizing green hydrogen in order to avoid additional greenhouse gases emission. The price of 1 kg of hydrogen obtained via electrolysis for the state of 2020 places around 4-6 € per kg. This price however depends on many factors such as the price of energy necessary to run the electrolysis process, the capital costs of electrolyzer (CAPEX) and the system efficiency. The analysis below demonstrates the hydrogen price dependency on those factors. The equation (6) proposed by Rui Pedro da Costa Neto [42] presented below allows for the green hydrogen cost calculation including the revenues coming from the selling of oxygen produced as a by-product of the electrolysis process.

$$Cost\ of\ green\ H_2\left[\frac{€}{kg}\right] = \left(\frac{electr.cost\left[\frac{€}{MWh}\right]}{1000} + \frac{CAPEX\left[\frac{€}{kW}\right]}{t}\cdot\frac{1}{ha}\right)\cdot\frac{H_2\,LHV}{eff} - O_2\ revenue\ \left[\frac{€}{kg}\right]\cdot 8 \qquad (6)$$

Where,

Electr. cost – the price of renewable electricity in €/MWh

1000 – the conversion factor to kWh

CAPEX – Capital cost of electrolyzer

t – lifetime of an electrolyzer

ha – utilization factor of renewable energy source

eff – in this case refers to electrolyzer efficiency

$H_2\,LHV$ – Lover Heating Value of hydrogen equal to 33,33 kWh/kg [110][36]

8 – resulting from the reaction of water electrolysis for each 1 kg of H_2 there are 8kg of O_2 $produced$

In this analysis the price of renewable energy was assumed to be 30 €/MWh and the renewable power plant to be operating with the utilization factor of 4000 h. The efficiency of alkaline electrolyzer is approximately equal to 70% with its continuous operation of 10 years [110].

The first part of the analysis shows the dependency between the hydrogen price with regard to the capital costs of electrolyzer unit ranging between 900-200 €/kWh since the electrolyzer prices are predicted to experience a drop in the upcoming years as indicated by Hydrogen Council [111] [120]. The sensitivity analysis have been performed for four electrolyzer CAPEX cost with respect to the utilization factor of the unit and changing green hydrogen cost per 1kg. It can be seen in the Figure 20 that for the lower utilization factors the electrolyzer CAPEX is of greater importance.

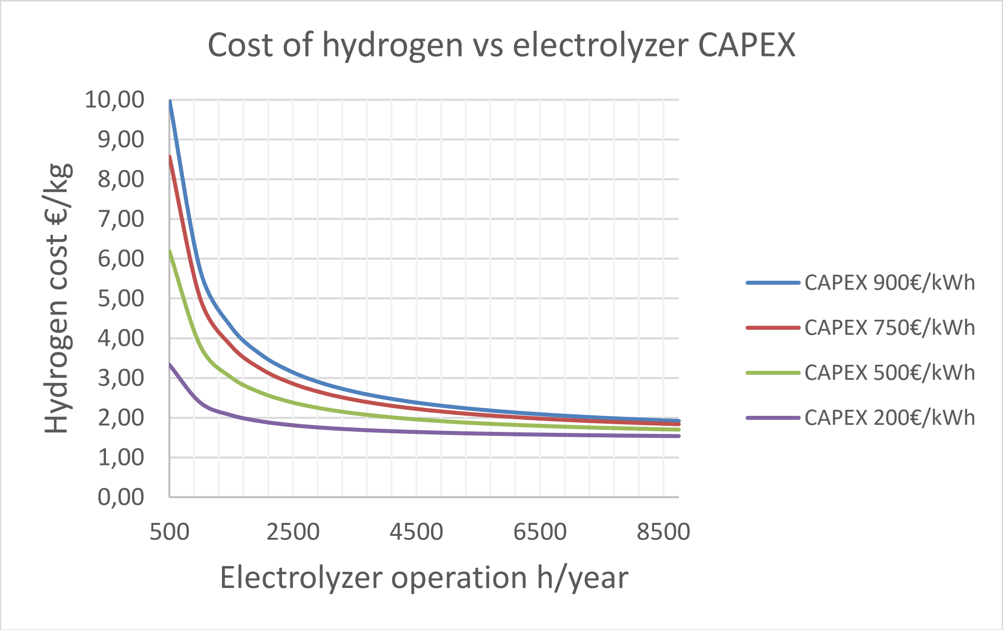


Figure 20 Cost of green hydrogen as a function of electrolyzer capital costs.

With the price of 900 €/kWh, which reflects to high extend the current status of alkaline electrolyzer market nowadays, the price of 4 € per 1 kg of hydrogen requires the electrolyzer unit to operate with utilization factor of around 2000 h annually. The same electrolyzer having the CAPEX cost of 500 €/kWh reaches this price with operation time approximately three times lower. In case of CAPEX price dropping to 200 €/kWh and below the cost of hydrogen production would not even reach the 4 €/kg, not considering any revenues form oxygen. The CAPEX cost of electrolyzer is of lower importance when considering operation close to full year, where the price of hydrogen places between 1-2 €/kWh. In the further part of the analysis the green hydrogen price has been presented as a function of electrolyzer efficiency, presented in the Figure 21. Compared to CAPEX cost factor, the influence of electrolyzer efficiency has lower impact as can be observed on the graph. The greatest change can be observed for the utilization factor between 500h to around 3000h annually. Nowadays the average utilization of electrolyzer is about 41% which corresponds to around 3500 h of operation annually [112].

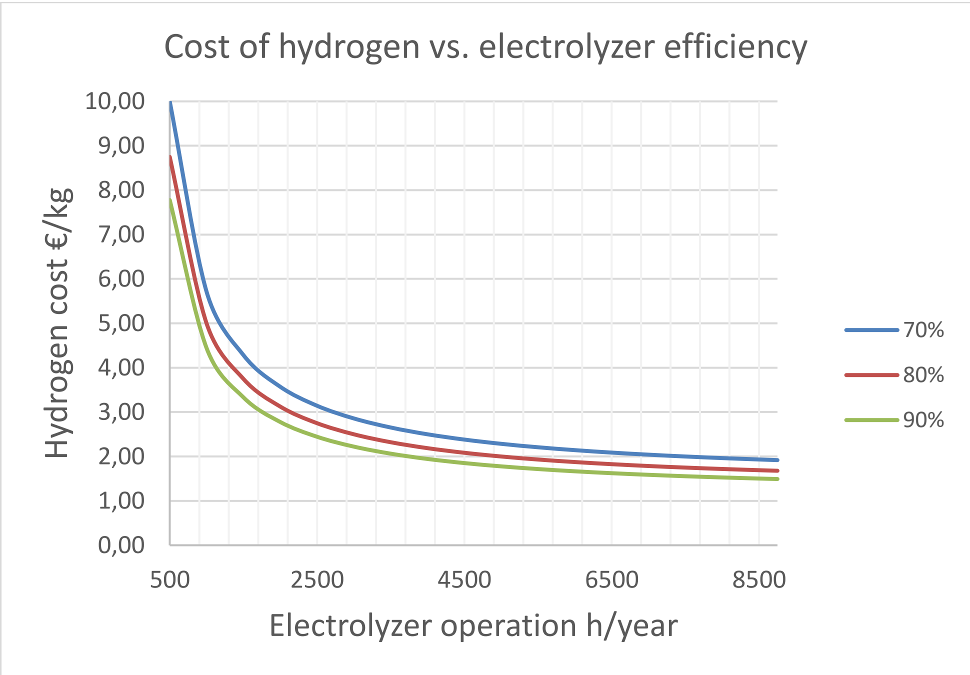


Figure 21 Green hydrogen cost as a function of electrolyzer efficiency.

The last scenario studies and presents the dependency of the green hydrogen production and the income generated from selling oxygen in order to prove the importance of oxygen and its contribution in the revenues, resulting in very low, even negative hydrogen price. The analysis has been done following the primary assumption namely, the electrolyzer efficiency of 70%, the price of renewable energy input of 30 €/MWh and the electrolyzer CAPEX cost of 900 €/kWh. It can be observed that among the three analysed factors the oxygen revenue from its selling has a highest impact on the green hydrogen cost as indicated in Figure 22. It shows the great importance of oxygen production. Moreover, the oxygen produced from the electrolysis is of very high purity.

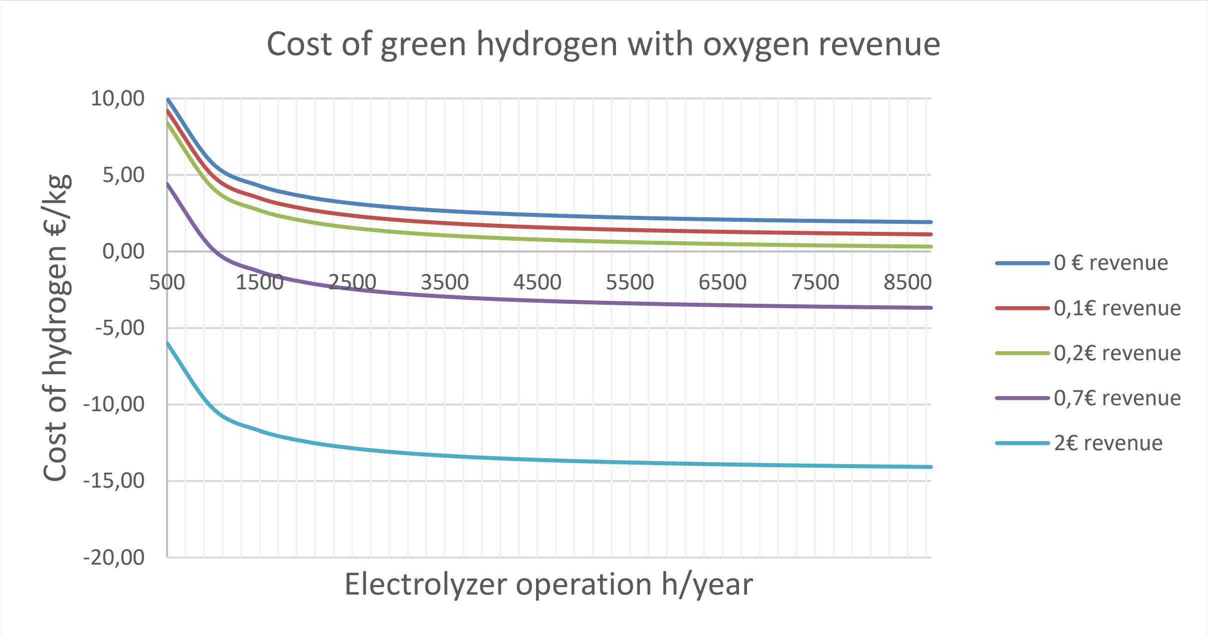


Figure 22 Green hydrogen cost including the revenue coming from selling electrolysis by-product in form of oxygen and different cost scenarios

As indicated in the study by Kato et al. (2005) [114], there is a very high potential for allocating this by-product in form of oxygen as there is a high demand on oxygen by many sectors. From the study by Kato et al. (2005) results that the demand for the oxygen is already 4 times as high as the current oxygen availability, and at the same time great amount of oxygen from electrolysis and not only is being wasted. The production and supply of oxygen from electrolysis has a high potential to contribute for energy saving. The demand for oxygen is growing especially for such applications as energy efficiency and industrial processes, electric power production but also for medical purposes as medical oxygen. In this way the process of electrolysis would bring mutual opportunities and benefits to all the sectors providing both economic and environmental advantages. In the Table 7 there has been presented the approximate current prices of oxygen with respect to the sector and its application.

Table 7 Oxygen price regarding sector and application. [113],[114][115]

Oxygen cost	Application
0,1 €/kg	Glass industry
0,2 €/kg	Waste water treatment
0,7 €/kg	Hospital
2 €/kg	Medical oxygen

In Table 8 the data used for the techno/economic analysis presented in further part of the study has been gathered. The purpose of the following analysis was the assessment of the necessary conditions which have to be fulfilled for the investigated system to be feasible. The aim was to evaluate the possibilities of application of small gas turbine installation coupled with electrolyzer and the economic assessment of the system. The detailed description of the case can be found below.

Table 8 Data for the economic analysis [116][117]

Gas Turbine			Electrolyzer		
Model	Capstone C30	Unit	Model	Teledyne HM-200	Unit
Rated power	30	kW	Rated power	59	kW
Fuel consumption	11	m_3/h	Hydrogen production	24	kg/h
Investment cost	550	€/kW	Investment cost	900	€/kW
Utilization factor	4000	h			
Additional data and assumptions					
Fuel cost	6	€/kg H_2	Energy selling price	0,2	€/kWh
O&M costs	3	%			
Discount rate a	7	%			
Time of operation	10	years			

Formulas used for the techno-economic analysis:

Net Present Value $NPV = (R - C_{o\&m}) \cdot k_a - I_t$

Discount factor $k_a = \sum_{j=1}^{n} \frac{1}{(1+a)^j} = \frac{(1+a)^n - 1}{a(1+a)^n}$ and $i = \frac{1}{k_a} = \frac{a(1+a)^n}{a(1+a)^n - 1}$

Internal Rate of Return $IRR \approx a_1 - (a_2 - a_1) \cdot \frac{NPV_1}{NPV_2 - NPV_1}$

Simple Payback Period $SPP = \frac{I_t}{CF}$

Discounted Payback Period $\mathrm{DPP} = -I_t + \sum_{j=1}^{n} \frac{CF_n}{(1+a)^j}$

Where,

R – revenues

CF – Cash Flow

$C_{o\&m}$ - operation and maintenance costs

I_t – total investment cost

n – year of operation

Selected for the analysis equipment in form of 30 kW micro-gas turbine and the alkaline electrolyzer of the rated power of 59 kW, able to produce around 24 kg of hydrogen daily [36][118], are just a proposed configuration in order to match approximate fuel consumption of the gas turbine with the production capacity of the proposed electrolyzer.

The analysis has been performed neglecting the fuel cost and electrolyzer energy or water consumption. The total investment of the installation including the price of gas turbine unit of 16 500€ and electrolyzer with the price of 53 100 € with the assumption that the actual CAPEX of the alkaline electrolyzer is around 900 €/kW [116][110]. This results in the total investment cost I_t of 69 600 €. The power plant of the installed capacity of 30 kW is assumed to operate with the utilization factor of 4000 h over the period of 10 years according to average lifetime of alkaline electrolyzer [119].

Performing the first part of the economic analysis it results that the project to be feasible, meaning that the net present value of the project equals zero, assuming the discount rate of 7%, and utilization factor of 4000 h during 10 years the selling price of energy should be equal to at least 0,1 €/kWh.

On the other hand with the energy selling price of 0,2 €/kWh observed by the end of 2020 [120][120], the Internal Rate of Return (IRR) equals 19,69% which is the annual IRR that would have discounted all the cash outflows over the project lifetime to a value of initial investment, with the assumption that the power plant is operating 4000 h annually over the period of 10 years. However, is the capacity factor of the power plant would be reduced to 1000 h per year, the IRR would be negative and equal to about -3%, which means that the aggregate amount of cashflows, not including additional fuel, electricity and water costs, caused by the project is less than the amount of the initial investment, meaning that the project is not feasible. The Simple Payback Period calculated simply as the ratio of the initial investment to the cash flow expected over 10 years of system operation with utilization factor of 4000 h and energy selling price of 0,2 €/kWh and the only expenses in form of operation and maintenance costs being equal to 3% of the total investment, not counting the additional costs of fuel and electrolyzer consumption. In this case the Simple Payback Period equals 3,17 years. However, the Discounted Payback Period turned out to be a slightly longer. The Discounted Payback Period is equal to 3,24 years. This difference results from the fact that the calculation on the discounted payback period takes into account the present value of future cash inflows, which based on this assumption is going to take much time before the initial investment is recovered. In reality, this time will be much longer taking into account all the expenses.

Based on this calculation the installation of micro-gas turbine running on hydrogen might be a good solution for small and medium sized applications such as households, residential areas or small industries, however the fuel costs should be taken into account and the fact that green hydrogen price is still rather elevated. Selected for this analysis gas turbine model Capstone C30 is designed to run on different fuel like natural gas, propane and the biogas, therefore is shows some fuel flexibility and potential to accommodate hydrogen [16]. Moreover, in this case it is not compulsory to implement the electrolyzer unit, providing that the gas turbine will be able to operate on gas blends, and that the hydrogen content in the grid will keep rising in the future and will be available to various consumers, to consider that solution feasible and sustainable to some extent. In fact, this solution is a proposition offering the flexibility of assembly and fuel being applied. However, 100% hydrogen gas turbines are not yet fully commercial product, this technology shows great potential making the energy transition possible, together utilizing existing units and infrastructure.

Chapter 6

6.Conclusions

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7.1 Conclusions

To sum up, hydrogen has been recognized as valuable fuel and together with gas turbines will play a significant role in the upcoming Energy Transition. Nevertheless, the technology still suffers some issues that ought to be resolved to enable the broad roll out of hydrogen gas turbine technology. However, the state-of-the-art review shows, that this solutions shows a great potential and that in the upcoming years it will most probably enter the market and the shares of hydrogen will keep growing together with the possibilities offered by hydrogen gas turbine technology.

By far the biggest limitation for green hydrogen production on a global scale and sufficient to cover the energy demand is its high price compared to other hydrogen feedstock and methods of production.

Another principal limitation preventing this solution to be fully introduced into the market are the technical and economic issues connected with utilizing hydrogen as a gas turbine fuel. In order to commercialize this technology and run a gas turbines on 100% hydrogen, there is a strong need in NOx emission reduction along with reduction of green hydrogen costs and technology scale-up in order to provide enough fuel for gas turbine to meet the energy demands and environmental limitations.

Moreover, this study provided the insight in the hydrogen alternative fuels such as ammonia, hydrogen-ammonia mixture and hydrogen-methane blends together with its properties. It can be seen that blending hydrogen with other fuels allows for achieving properties of both of those fuels, which usually improved the performance of combustion at the same time mitigating the risk of components damage due to reduced firing temperatures. Adding hydrogen to other fuels extends its flammability limits and increases laminar flame speed being responsible for better flame anchoring and stabilization. In addition this practice primarily helps to reduce carbon dioxide emissions. Another important aspect, especially considering ammonia as a hydrogen substitute is its ease of transportation and handling which is much easier than in case of hydrogen. Therefore, it can be seen that there are many possibilities in order to allocate hydrogen fuel or hydrogen-rich fuels in the energy system.

Additionally the impact of water emission has been studied and described. It has been shown that introduction of large amounts of water vapour into the system could disrupt the environmental balance leading to negative consequences. Water vapour contributes in 60% to global warming, therefore in this situation its contribution should not be disregarded.

The techno-economic analysis gives the idea about the quantities of fuel and water needed to run one of the GE commercial gas turbines model of a high power - 9HA.02. The program designed by GE for the approximation of the resources needed to run this gas turbines under different hydrogen volumes and operating in various cycles allows for the estimation of emission and cost reduction coming from saved emission and tax that would be paid otherwise. The main conclusion that can be drawn is that switching to full hydrogen operation in gas turbines would require large amounts of water, very large amounts of hydrogen needed to cover the energy demand as well as renewable energy to run the process of electrolysis in order to obtain green hydrogen. With current hydrogen infrastructure and still developing technology it is a great challenge to provide this big hydrogen quantities and it proves the need of technology scale-up.

The further calculation allowed to estimate the payback time and internal rate of return of micro-turbine installation with electrolyzer for hydrogen production without including the fuel costs and electrolyzer demand. It shows that the installation of electrolyzer and 30kW gas turbine consuming around 24 kg of hydrogen per hour would need a bit more than 3 years to be paid back, assuming the power plant operation of 10 years with capacity factor of 4000 h annually, energy cost of 0,2 €/kWh and discount rate of 7%.

The last part shows the dependency of green hydrogen cost with respect to changing factors. It can be seen that the highest impact on the green hydrogen cost results from the revenues or lack of revenues from the oxygen sale. Another cases has been analysed inter alia the electrolyzer CAPEX, which is predicted to drop in the upcoming years to the price of 200 €/kWh. This would have as well a significant, positive impact on the green hydrogen prices drop. The last variant has been studied for electrolyzer efficiency. With improving efficiency of electrolyzer the same price of green hydrogen can be achieved with lower utilization factor. Therefore, it can be seen that improved efficiency, and improved system performance reduces the operation time of the system or allows for achieving lower hydrogen cost at the same utilization factor.

It demonstrates the wide range of configurations and options to be used with the hydrogen gas turbine system. This technology appears to be very versatile and flexible, allowing smooth energy transition, with existing technology and its retrofitting. Moreover, this technology can be applied on various scale from small household application or to cover small energy demands or for big industrial or aircraft applications.

7.2 Future Work

Hydrogen economy and hydrogen gas turbine technology are very dynamically developing areas. The magnitude of possible solutions, combinations and alternatives offered by hydrogen creates many pathways of possible further research and development. The main strategy for hydrogen transition right now, and the crucial steps to be taken involve the scale-up of the technology and development of hydrogen technologies in order to prepare the hydrogen energy sector to broad expansion over upcoming decades. In this situation the study of possible pathways of hydrogen production on a worldwide scale and introduction of hydrogen into the gas network would be of significant importance. Additionally of great importance would be an insightful analysis of combustor optimization and possible adjustments to be done over the whole gas turbine unit. Moreover, resulting from the high combustion temperature, a study of advanced cooling systems for hydrogen units and the study of materials withstanding extreme temperature would be an interesting contribution in the shift to hydrogen fuel. As presented in the study, the great limitation holding the hydrogen gas turbine technology to be fully commercialized are high NO_x emissions. This additionally leaves a room for investigation of possible solutions preventing the NO_x formation and improving the combustion performance. Very challenging aspect of hydrogen gas turbine implementation would involve the aircraft application. The aircraft gas turbines, due to the operation in the extreme conditions must fulfil very strict requirements and provide unfailing operation. Therefore the design of propulsion system in case of aircraft gas turbine units require high precision at the same time being more challenging resulting from the limited space and weight limitations being of paramount importance considering aircraft applications. Last but not least, valuable and study would include the comparative study of hydrogen fuel cells for energy production together with hydrogen gas turbines in order to highlight the importance and possibility of application for both of those technologies. Moreover the Life Cycle Assessment study for both those technologies would allow for calculating the environmental impact and carbon footprint of both solution over their lifecycle including the manufacturing state and post-processing and possibility of components reuse would bring high value to the development of both technologies and the process of energy transition towards sustainable and environmentally friendly alternative energy sources.

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