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ENVIRONMENTAL EFFECTS OF GAS CONVERSION

Engines of Power Plants

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Tämä opinnäytetyö tehtiin Wärtsilän Project Management -osastolle. Tämän työn tarkoitus oli tutkia, kuinka paljon on mahdollista vähentää päästöjä kaasukonversiolla, kun polttoaine vaihtuu raskaasta polttoöljystä maakaasuun. Kaasukonversio tarkoittaa sitä, että moottori muutetaan joko pelkästään kaasulla tai sekä kaasulla että nestemäisellä polttoaineella toimivaksi.

Polttoprosessi tuottaa aina erilaisia pakokaasupäästöjä. Tässä työssä keskityttiin hiilidioksidi-, rikkidioksidi-, typen oksidi-, partikkeli- ja hiilimonoksidipäästöihin. Etenkin hiilidioksidi voimistaa ilmastonmuutosta ja rikkidioksidi- ja typpioksidipäästöt aiheuttavat happamoitumista. Päästölaskelmat on tehty PerfPro -laskentatyökalun avulla. Perfpro -laskentatyökalu antaa päästötietoja eri moottoreille.

Saadut tulokset on koottu pylväsdiagrammeihin ja päästömäärän vähenemä on ilmoitettu prosenttilukuna, koska tarkat päästötiedot ovat luottamuksellisia. On mahdollista tehdä selkeitä johtopäätöksiä siitä, että kaasukonversio vaikuttaa positiivisesti päästöjen määriin. Maakaasu on puhdas polttoaine ja tulokset ovatkin suhteellisen ilmiselviä. Ainoastaan hiilimonoksidin määrä nousee joissakin tapauksissa, kun käytetään polttoaineena maakaasua. Korkeammat hiilimonoksidipäästöt johtuvat luultavasti polttoprosessista.

Avainsanat	Kaasukonversio, moottori, pakokaasupäästöt, maakaasu, raskas polttoöljy

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ABSTRACT

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This thesis was made for Wärtsilä Finland's Project Management team. The purpose of this study was to research how much it is possible to reduce emissions by gas conversion when the heavy fuel oil is replaced by the natural gas. The gas conversion means that the engine is converted to use either only gaseous fuel, or both gaseous and liquid fuels.

The combustion process produces different kinds of emissions. The carbon dioxide, sulphur dioxide, nitrogen oxides, particles and carbon monoxide are focused on in this study. Especially carbon dioxide contributes to the climate change and the sulphur dioxide and nitrogen oxides cause acidification. The emission calculation was made using the PerfPro calculation tool. The PerfPro calculation tool gives emission data for different types of engines.

The results were gathered into the column charts and the amounts of reductions have been given as percentages, because the exact emission levels are confidential. It is possible to make clear conclusions that the gas conversion causes positive effects on the emission levels. The natural gas is a pure fuel and the results are quite obvious. Only the amounts of carbon monoxide increased in some cases when using natural gas as a fuel. The higher carbon monoxide emissions are probably due to the combustion process.

Keywords	Gas Conversion, engine, exhaust gas emissions, natural gas, heavy fuel oil

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1 INTRODUCTION

This thesis was made for Wärtsilä Finland Oy Services' Project Management Team. The Project Management Team has executed gas conversion projects about 12 years around the world and the main purpose of this work was to research how much the gas conversion reduces emissions. The aim was also to search what kind of emissions a combustion process produces and how they affect the environment.

This subject is very topical because the awareness of pollution and other harmful effects of emissions have increased. Pollution has been a huge issue for several years and it is just not only a local problem, it is a global issue and we really need to think the consequences of our actions. The awareness of the harmful effects of the use of the fossil fuels has increased. Especially the air emissions such as sulphur dioxide, nitrogen oxides, carbon dioxide, other greenhouse gases and particles were focused on in this study. Fossil fuels such as heavy fuel oil, natural gas and coal are the main producers of these emissions mentioned above /1/.

Many power plants run on heavy fuel oil, but a change has taken place during the past ten years and the number of gas conversions has increased. The reduction of emissions and lower fuel consumption are the main points when planning to order a gas conversion project from Wärtsilä. Gas conversion also causes positive effects on the lifecycle of an engine and prolongs the time period between maintenances.

In this study the PerfPro (2016.1 version) calculation tool has been used as a help when making comparison between the amounts of emissions of heavy fuel oil and natural gas. The PerfPro gives detailed information of emissions also in form g/kWh.

2 INTRODUCTION OF WÄRTSILÄ

Wärtsilä is a global company which offers advanced energy solutions for energy and marine markets. Wärtsilä is focused on sustainable innovations and its target is to improve efficiency, environmental and economic performance of power plants and vessels. Wärtsilä has operations all over the world in about 70 countries. Wärtsilä had about 18 800 employees around the world in 2015. /2/

2.1 Energy Solutions

Wärtsilä Energy Solutions is a supplier of flexible power plants. It offers competitive and reliable innovations for baseload, peaking, reserve- and load following power generations. Energy Solutions has also solutions for oil and gas industry. /2/

Energy Solutions has designed and built power plants for several years. Wärtsilä has supplied over 4700 plants around the world by the year 2015. Nowadays Wärtsilä is a leading provider of Smart Power Generation power plants which are based on multiple internal combustion engines. The possibility to use these engines on liquid or gaseous fuel offers operational flexibility. /2; 3/

2.2 Marine Solutions

Marine Solutions focuses particularly on sea vessels and provides environmentally friendly, effective and economic solutions for marine markets. Marine Solutions has applications in cruise vessels and ferries, they are powering for example navies and coast guards and special vessels such as dredgers and research vessels. Marine Solutions also provides solutions for offshore facilities. /4/

It is important to reduce emissions and develop methods to avoid polluting discharges to ensure that the customer is able to continue to operate in areas which demand high environmental requirements. That is why Wärtsilä designs products which have immediate environmental benefit. Customers’ needs and the environmental requirements are the encouraging factors when developing gas technology and environmental solutions. /5/

2.3 Services

Wärtsilä Services is the largest unit of these three mentioned above (Marine, Energy, Services). About 56 % of Wärtsilä personnel work in Services unit. Services' net sales was a slightly over 40 % of all net sales of Wärtsilä in the year 2015, so Services is an important service provider around the world. /2/

The main tasks of Wärtsilä Services are to provide service and maintenance for customers' existing installations. Services is able to provide very wide and comprehensive services around the world. Services provides solutions and maintenance for all the products which occur in catalogue including engines, propulsion systems, electrical and automation systems and service agreements, also training services are part of the catalogue /6/. Wärtsilä is also capable to provide service for other than Wärtsilä engines. /2/

2.4 Project Centre Finland

Project Centre Finland belongs under the Services unit. Project Management team executes projects which can be for example plant efficiency improvements, upgrades or modifications or fuel conversions of existing installations on power plant as well as on marine side. /7/ Project Centre Finland has grown a lot in past few years and the number of projects has increased.

Gas conversion projects for 4-stroke engines are mainly executed by the Project Centre Finland. By the end of 2012 there were 20 gas conversion projects done in the project centre. /7/ The number of executed gas conversions is about 30 today.

3 GAS CONVERSION PROJECTS

In this chapter the basic information of gas conversions is given. A gas conversion requires a lot of work and many engine parts need to be changed but in this study is not focused on them in detail. In this chapter the conversion types are mentioned and how they differ from each other in general.

3.1 Purpose of the Gas Conversion

Project centre Finland has executed gas conversion projects about 12 years. The number of finished or ongoing gas conversion projects is about 32 around the world. Basically gas conversion means that an engine which runs on liquid fuel (e.g. HFO or LFO) is converted to run either on gas or on gas and liquid fuel. It is possible to convert for example all the engines of power plant or just a few or just one of them. The largest conversion project ongoing right now is gas conversion of eight engines.

Gas conversion projects are done for 4-stroke 32 and 46 types engines. The numbers 32 and 46 refer to the measurement of cylinder bore, so if the type is 32, the cylinder bore is 32 cm. The number of cylinders and cylinder configuration can vary. Most of the gas conversions are done for W18V46 and W18V32 engines. The letter in the front, W, tells that is Wärtsilä engine. The first number after the letter tells the number of cylinders. The letter in the middle tells is it in-line or V-form engine. One engine example is given in the table below.

Table 1. An example of Wärtsilä engine.

W	18	V	46
Wärtsilä engine	18 Cylinders	V-form	Cylinder bore 460 mm

In case of a converted engine, the letter combination at the end tells the engine type (e.g. W18V50DF = Dual Fuel engine).

There are three possible options to choose gas conversion type: SG (Spark-ignited Gas), DF (Dual Fuel) and GD (Gas Diesel). The difference between these three types is based on their operation type because the ignition of fuel depends on gas conversion type. /8/ One remarkable change in gas conversion from a technical point of view is that the cylinder bore widens. The reason for that is to ensure to be possible to get at least nearly the same or even the same output (kW) after the conversion than before it. If a W18V46 engine is converted, it will become W18V50 DF or SG depending on which conversion type has been executed. After the conversion the W18V32 engine will become W18V34 DF or SG. One possibility is to execute a DFc conversion, which means that the engine is converted but the size of cylinder bore does not change. “DFc conversion is a “light” version of DF conversion” /8/.

3.2 Types of Gas Conversions

As mentioned earlier, there are three different possibilities to choose a good gas conversion option. The properties of gas conversion types varies so it is very important to know the ambient conditions and requirements of power plants before deciding which gas conversion type would be the best choice.

3.2.1 DF Conversion

The most executed conversion type is DF or Dual Fuel conversion. The advantages of DF engines are their ability to run on gas (otto- process) or on liquid fuel (diesel- process). This provides operational flexibility and it is also possible to switch between gas and diesel modes. The DF conversion is the best choice when it cannot be guaranteed that the gas supply is stable. In a DF engine and on gas mode the fuel is ignited with pilot fuel which is usually LFO. /8/

3.2.2 SG Conversion

Other gas conversion type is SG- conversion or Spark- ignition gas conversion. An SG engine requires a stable gas supply because it is able to run only on gas (it is not possible to use HFO or LFO after the conversion). An SG engine operates with otto- process in which the air and gas mixture is ignited with a spark plug. /8/

3.2.3 GD Conversion

The third conversion option is GD-conversion or Gas Diesel conversion. A GD engine is designed to run on either liquid fuel (HFO, LFO, crude oil) or on various gas or diesels mixtures. The GD engine operates always with the diesel- process despite of what fuel type is used. The major advantage of a GD engine is that it is able to tolerate also the worse fuel qualities. The cylinder bore stays the same before and after the GD conversion. /9/

3.3 Gas Conversion Benefits

It is possible to reach several benefits with gas conversions. The most remarkable benefits from an environmental point of view are the lower nitrogen oxides, sulphur dioxide, particles and carbon dioxide emissions /8/. In Chapter 6 more detailed comparisons of emission levels are made before and after the conversion.

With gas conversion it is possible to get an engine with the same concept as a new engine from the factory. The newest possible technology is used in the converted engine and the main components of an engine are changed, also the control system and software are latest versions. In general it could be said the converted engine is a new engine and the running hours reset to zero. /8/

The maintenance of an engine is important to ensure that the engine is able to run properly and as long as possible. The gas conversion and specially the use of gas as a fuel are remarkable actions which have effects on the time period between maintenances. The natural gas is quite pure fuel, so it is possible to prolong the period between maintenances and that is a straight way to decrease maintenance costs. The lifetime of engine components is also longer and the time periods between oil changes are prolonged. /8/

Gas conversions, especially DF and GD conversions, provide operational flexibility because it is possible to use both liquid fuel and gas. The DF conversion is a very flexible solution because it is possible to switch over from gas to liquid fuel also in the operation mode or some cases even at full load. /8/

3.4 Diesel and Otto processes

Otto and diesel processes have different igniting methods. The SG engine operates on the lean burn otto process. In otto process the natural gas is mixed with air before the inlet valves. After that the gas is fed into the prechamber. In the prechamber the gas mixture is richer than in the cylinder. When the compression phase is at the last section, the gas/air mixture is ignited with spark plug. DF engines use the same otto process, but there the gas/air mixture is ignited with pilot fuel injection. The peak temperatures are reduced by the leaner combustion. The lower the peak temperatures are, the less NOx emissions are produced. One remarkable thing regarding the NOx emissions is that the gas is mixed with air before combustion. In the lean burn method every gas molecule has the optimum amount of air in their use. /10 /

When the GD engine operates on the gas mode, the air is first compressed and then the gaseous fuel is injected at high pressure into the combustion chamber. The high pressure and high temperature contribute to the ignition in the combustion chamber. The GD engine operates on diesel process despite what fuel is used. /8; 10/

4 FUELS

4.1 Fossil Fuels

Fuels can be divided into renewable fuels and non-renewable fuels. The non-renewable fuels are called fossil fuels. The fossil fuels are formed from organic material over a long time period in anaerobic conditions. Natural gas, crude oil and coal are fossil fuels. Peat is also fossil fuel because it regenerates so slowly (about 1 cm during 100 years). /11, p. 123/

Fossil fuels are currently the most used energy sources in industrial area around the world /12/. Fossil fuels always contain carbon and hydrogen as compounds and sulphur and usually nitrogen /11, p. 124/. Burning the fossil fuels causes harmful exhaust gases to the atmosphere. The most harmful substances of these exhaust gases are carbon dioxide, sulphur dioxide, nitrogen oxides and particles /13/. For example, the sulphur dioxide content of exhaust gases varies and depends on what fuel type has been used. When selecting the fuel type, it is important to know the purpose of the use and what kinds of properties are demanded. For example, the net calorific value (lower calorific value) tells how much thermal energy is released when burning 1 kg solid or 1m^3 gaseous fuel /11, p.125/. The table below (Table 2.) tells the net calorific values for usually used fossil fuels /11, p. 124; 23, p.142 /. Even though coal and oil are the most used fuels around the world, they have lower calorific values than natural gas. If the net calorific value was the only thing under the review, the natural gas would be the best choice because it produces more thermal energy than the other fossil fuels.

Table 2. Net calorific values of fossil fuels.

Fuel	Net Calorific Value
Coal	27 MJ/kg
Light Fuel Oil	43 MJ/kg
Heavy Fuel Oil	41 MJ/kg
Natural Gas	49,2 MJ/kg

4.2 Crude Oil

Crude oil is one of the fossil fuels and it is pumped out of the ground. The oil resources exist around the world on different continents. Over half of the existing oil deposits have been found from the Middle East. Significant oil deposits are located also in Central and South America. Remarkable deposits of oil sand have been found in Canada. /14/

It is important to realize how much oil we have and how long it will take before our reserves are empty. It has been estimated that the existing oil reserves would suffice over 40 years, if the consumption stayed at the present level and new oil deposits were not found. There have also been found non-conventional oil reserves, such as sand oil and oil shale and if these are included in the whole oil reserve, it has been estimated that oil reserves will suffice over 200 years. The oil searching methods and technologies have been developed so new oil deposits are still found. /14/ Nowadays the crude oil is produced about 89 million barrels per day (one barrel is about 159 dm^3) /15/.

Crude oil can be easily stored and transported so it is very widely used around the world. The crude oil can be refined and it is possible to get several different kinds of products from it. The refined products vary and their properties are different. Gasoline, diesel fuels, light fuel oil, other fuel oils, kerosene, liquefied gas, bitumen and other special products such as lubricants and ethers (MTBE, ETBE) are the main products refined from crude oil. /16/

4.2.1 Oil Refining and Oil Products

Crude oil contains different kinds of hydrocarbons, nitrogen, sulphur, oxygen and metals. Their proportions vary depending on where the crude oil has been pumped from. When selecting possible processing method, the quality of the crude oil is the determining point. Heavy and more sulphuric crude oils are cheaper than light and low sulphuric crude oils. Lighter crude oils need less processing and it is easier to get more the lighter oil products from it. Oil products are usually mixtures which contain refined components and additives /17; 11, p. 276/.

Oil refining is a complex process and it begins with the removal of salts and other impurities. Then the crude oil is divided into fractions by distilling (in other words by vaporizing) in a distillation column. /18/ The distillation column is a high cylinder-shape tower in which there are several intermediate floors. The crude oil is first heated to 355-370 °C degrees and then it is conducted to the distillation column. /11, p. 275/ Gasoline and other light fractions distillate first because their boiling point is quite low. Petrol, light fuel oil and diesel oil belong to middle distillates. Heavy fuel oil and bitumen stay on the bottom of the distillation column because they have the highest boiling point and stay in fluid form. Formed fractions are further processed after distillation by reducing sulphur content, reforming and cracking. Cracking is a process where molecules are broken down into smaller and simpler form so that the product could be used as a fuel in traffic. /11, pp. 275-276; 18/ Reforming means that the hydrocarbons are modified so that they are in branched or cyclic forms /11, p. 126/. The removal of the sulphur is important because it is a straight way to reduce the sulphur dioxide emissions of the exhaust gases.

4.2.2 HFO and LFO

So when deciding what fuel type could be the best choice, it is important to think what kinds of properties are needed. Gas oils such as diesel oil and light fuel oil have been formed in fractional distillation of crude oil. Gas oils are formed also in cracking and vacuum distillations. Nearly all sulphur is removed from light fuel oil so when using LFO as a fuel the exhaust gases are basically almost free of sulphur. /19, p. 73/

It is important to mixture additives among the oils because they effect on the cetane number, cold filter plugging point and viscosity. The cetane number indicates the combustion speed of diesel oil. If the cetane number is high, diesel oil will ignite faster. A higher cetane number also reduces emissions because the fuel ignites efficiently. /19, p. 74/

When comparing heavy fuel oil and light fuel oil, the main differences are the weight, consistency and sulphur content. Heavy fuel oil contains more sulphur than lighter oils. Heavy fuel oils are produced from the base oil. The base oil can be processed further or it is even possible to use it as such. /19, pp. 76–77/

About 80–90% of the sulphur of the crude oils stays at the base oil. The sulphur content of base oil can vary between 0.3 – 6 %. The best way to be sure that the ready oil products are low sulphuric is to use low sulphuric crude oil. /19, p. 77/ In Finland the limit values for the amounts of sulphur for HFO is 1.0 mass-% and for LFO 0.1 mass- % /20/.

4.3 Natural Gas

Natural gas is one of the fossil fuels which have been formed in anaerobic conditions during several years. /11, p. 123/ Natural gas contains mainly methane CH_4 and it is always the main component of natural gas. The properties and quality of natural gas depend on where it has been pumped from. For example, natural gas from Russia contains 98 % methane and small amounts ethane C_2H_6, propane C_3H_8, butane C_4H_{10}, nitrogen N_2 and carbon dioxide CO_2 /21, p. 6/. The majority of the natural gas reserves are located in the Middle East and Russia, but it is possible to pump it out from Western Europe and Barents Sea /11, p. 277/.

The main difference between the use of oil and natural gas is that natural gas is quite difficult to store. That is why the use of the natural gas demands a good natural gas network. It has been estimated to be possible that natural gas resources are bigger than crude oil resources. If the use of natural gas more or less replaces the use of oil, it is expected that oil reserves will last longer. It is estimated that natural gas reserves will last about 60 years if the consumption stays at present level. /22/

If decided to use fossil fuel as an energy source, natural gas would be the best choice because it is a very environmentally friendly fuel. It neither produces particle emissions or heavy metals nor ash because it is in gaseous form. /22/ Natural gas contains sulphur about 1 mg/m^3. If the fuel contains sulphur less than 100 mg/ m^3, it is said that fuel is sulphur-free. /23, p. 141/

Burning methane does not produce harmful emissions of sulphur oxides unlike burning coal and oil which produce often high amounts of sulphur dioxide (SO_2). Combustion of coal or oil produces particles like PM_{10} and $PM_{2.5}$, but gas causes only very small amounts of the finest particles. /24, pp. 7-8/

When producing exactly the same amount of energy by coal or natural gas, natural gas causes less CO_2 emissions. Natural gas contains more hydrogen relative to carbon than coal. Lower CO_2 emissions are good when thinking of global warming. Even though natural gas produces less carbon dioxide than coal and oil, natural gas contains methane which, however, is one of the major greenhouse gases. Methane is a much more significant factor than carbon dioxide considering the global warming. /24, p. 169; 38/

Natural gas also demands refining because there are quite strict standards for quality of natural gas. For example, the maximum concentrations of carbon dioxide, nitrogen oxides and oxygen in natural gas are given in standards. Natural gas is rarely that pure that it would not need processing at all. It is still much easier to process natural gas than crude oil because crude oil demands so many phases and high temperatures, high pressures and chemical reactions in processes until it is usable. /24, p. 50/

4.4 LNG and LPG

The properties of liquefied natural gas are quite similar than the properties of natural gas when it is used as a fuel. Natural gas is cooled down to -162 °C degree in which case it is in liquid form and called LNG – liquefied natural gas. The volume of liquefied natural gas is 600 times smaller than the volume of the gaseous natural gas. Usually LNG contains 94.7 % methane which is about equal compared into methane content in natural gas. /25; 24, p. 118/

LPG or Liquefied Petroleum Gas is a fuel which is mixture of gaseous hydrocarbons and it is very easily flammable. LPG is stored and transported in liquefied form in gas cylinders. /26/ LPG consist usually of propane C_3H_8 and butane C_4H_{10} /24, p. 52/.

4.5 Optional Fuels – Bio Energy

Bio energy is renewable energy which is produced from bio masses. Trees, field crops and bio waste, for example, are biomasses. Combustion of biomasses releases only that amount of carbon dioxide that the living organisms have earlier bound so bio energy is very environmentally friendly and carbon neutral fuel. /27/

The use of the biofuels does not produce greenhouse gases as much as fossil fuels produce. Harmful sulphur dioxide and heavy metal emissions are also reduced by using more bioenergy. Bio energy is a good alternative to replace the use of the fossil fuels. /27/

4.5.1 Biogas

Biogas is a mixture of gases and other substances and it is one of the renewable biofuels. It is possible to produce biogas from bio waste, slurry, biomasses of fields or dung. Biogas is formed when these organic biomasses decompose in anaerobic conditions by rotting. Anaerobic bacteria and micro-organisms break down the organic matter to simpler compounds and contribute to the degradation process. Biogas is usually produced in the biogas reactors, in which one are favourable conditions for the degradation process (for example warm enough). The content of biogas can vary and it depends on the quality of the biomass and the process method selected. /28/ Biogas contains usually mainly methane about 35–80% and carbon dioxide 20–65% and also other substances like water, nitrogen 0–25%, ammonia and hydrogen sulphide 0–2 %. /23, p. 144/

Natural gas contains mostly only methane (98%) and the main substance of biogas is also the methane. It is possible to use biogas instead of natural gas even though it contains slightly less methane than natural gas. Biogas requires some processing before it is usable fuel in internal-combustion engines, for example water and sulphur need to be removed. It is also possible conduct bio gas into natural gas network but before it is possible the biogas requires additional purifying. /28/

4.5.2 Biodiesel

Biodiesel is one of the renewable fuels and it is not toxic. Biodiesel is also a biodegradable fuel /29, p.1/. Biodiesel is produced from living biomasses. Suitable plants are for example sugarcane, corn, soy, sunflower seeds, palm oil and rapeseed. /30/

The vegetable oils contain mainly the triglycerides, which are esters of glycerine. The production of biodiesel includes different phases but a very important phase is transesterification. In transesterification the triglycerides of vegetable oils are esterified with alcohol. Usually methanol is used in the transesterification process because it is cheap and available easiest. /29, p. 11, p.13/

It is possible to use the biodiesel as such (B100) or it is possible to mix it with petroleum diesel. The marking B100 means that biodiesel is 100 % biodiesel. Marking B50 would mean that the biodiesel contains 50% biodiesel and 50 % petroleum diesel. /29, p. 22/

4.5.3 Bio-oil

Bio-oil is known also as pyrolysis oil and is produced from biomasses just like other bio fuels. It is possible to use pyrolysis oil instead of heavy fuel oil in energy production, because their properties are quite similar. The use of pyrolysis oil is possible in traffic if the oil is refined. /31; 32/

Pyrolysis is a process where biomass is heated rapidly to 500-600 °C degrees in anaerobic conditions and then the biomass vaporizes. The vaporized gas is cooled down and the gas condenses into oil /32/. The lower heating value of pyrolysis oil can vary between 18 – 23 MJ/kg, in comparison the lower heating value for heavy fuel oil is about 41 MJ/kg /23, p. 155/. So even if the properties are quite similar for both, it is still easier to get more energy from heavy fuel oil if the net calorific value is only thing under the review.

4.5.4 Bio-ethanol and Bio-methanol

The use of methanol and ethanol as fuels will definitely increase in the future and especially use of the bio versions of them. Methanol or methyl alcohol CH_4O is the simplest alcohol /11, p. 282/. Ethanol or ethyl alcohol C_2H_6O contains one carbon atom and two hydrogen atoms more than methanol.

Methanol and ethanol do not accumulate in food web and they dissociate in the atmosphere by hydroxyl radicals. Both methanol and ethanol are very water-soluble substances and it is possible for them to descend down to the earth with the rain. Because of their water-soluble properties they do not bind to the soil but they can be carried into the ground water. Methanol and ethanol are classified substances and it is stated them to be non-hazardous for nature. Methanol and ethanol are also biodegradable. /33; 34/

Usually alcohol-based fuels are produced from plants which contain sugar or starch. Good raw materials for alcohol-based fuels are for example sugarcane, potato, corn and sugar beet. It is also possible to produce methanol from cellulose plants, such as straws and logs of wood. The production of bio methanol is possible with pyrolysis and gasification. Gasification is a thermic process where the substance (raw material) reacts and dissociates into gaseous compounds in high temperature and a fuel gas mixture is formed /35, p.8/. The synthetic gas (which always contains mainly hydrogen and carbon monoxide /35, p. 8/) is formed in gasification and it is possible to be refined into methanol. Ethanol is produced from sugar plants with fermentation and distillation processes. It is also possible to produce ethanol from starch plants (potato or cellulose plants) using the hydrolysis process. The hydrolysis means “the splitting (lysis) of a compound by a reaction with water (WWD)”/36/. It is possible to use alcohol-based fuels as such or use them as subcomponent of petrol. /23, p.97/

5 EMISSIONS OF THE COMBUSTION

5.1 Combustion Process

The combustion reaction always causes emissions. Others are harmful and others less harmful. Carbon dioxide (CO_2) and water vapour are normal emissions in all combustion processes. Nitrogen oxides and sulphur oxides are classified as harmful emissions. Hydrocarbons, carbon monoxide and particles will be formed if the combustion process is incomplete and they are also harmful emissions. Carbon monoxide will be formed if there is not enough air in the combustion process: /11, p. 134, p.130/

$$2\,C + O_2 \rightarrow 2\,CO \qquad (1)$$

Combustion always demands fuel, oxygen and temperature which is high enough. Thermal energy is formed when the chemical elements of fuel react with oxygen in the combustion process. /11, p.122/ Complete combustion is always the main objective, because that is how it is possible to get all the energy to be released. If the combustion is complete, carbon dioxide will be formed (2). All the fossil fuels consist of different kind of hydrocarbons. The hydrogen also reacts with the oxygen in a combustion process and the end product is water (H_2O). /11, pp.129–130/

$$C + O_2 \rightarrow CO_2 \qquad (2)$$

Fossil fuels contain also sulphur, so when combusting for example heavy fuel oil, the sulphur dioxide will be formed (3) /11, p. 130/. It is also important to remember that even if the used fuel does not contain nitrogen, the NOx emissions are still formed in combustion process because the air contains about 78 vol-% of nitrogen (N_2). /11, p. 123, p. 124/

$$S + O_2 \rightarrow SO_2 \qquad (3)$$

5.2 Carbon Dioxide

Carbon dioxide is an important part of the biodiversity of the nature. Humans produce carbon dioxide every time they breathe out and the living organisms use carbon dioxide and water in the photosynthesis. So carbon dioxide is not that dangerous gas but act of humans and industrial development has increased the concentration of carbon dioxide in the atmosphere. /37/

Methane and carbon dioxide are greenhouse gases but however the carbon dioxide is the best known greenhouse gas which is released by burning fossil fuels specially oil and coal. Natural gas is also a fossil fuel but it does not produce as remarkable amounts of carbon dioxide as oil and coal. But in general the only way to reduce the CO_2 concentration in the atmosphere is to avoid using fossil fuels. The combustion of renewable fuels does not increase the CO_2- concentration in the atmosphere because green organisms have earlier bound carbon dioxide in photosynthesis. About 75 % of the CO_2- emissions are the consequences of combustion of fossil fuels. /11, p. 141; 37/

One way to reduce the emissions of carbon dioxide is to begin to use more natural gas as a primary fuel. Natural gas contains relatively more hydrogen and less carbon than oil and coal /38/. If natural gas is used instead of light fuel oil to produce exactly the same amount of energy, natural gas will produce only 40 % of that carbon dioxide amount that would be released by using LFO. /11, p. 141/

5.3 Nitrogen Oxides (NO_2, NO) and Nitrous Oxide (N_2O)

When talking about NOx emissions, it means nitrogen monoxide and nitrogen dioxide /39/. Almost all of the emissions of nitrogen oxides are from the industry and energy production. Traffic and sea transport cause also a huge amount of nitrogen emissions. /11, p. 135/

Nitrogen oxides are formed in combustion processes and they contribute to the development of ozone. Ozone in the troposphere is formed when nitrogen oxides react with the hydroxyl radicals of the air or with the ultraviolet radiation (UV). Ozone is one of the harmful greenhouse gases. Combustion processes usually produce only nitrogen monoxide, but in time it oxidizes and turns into nitrogen dioxide and other compounds of nitrogen. Nitrogen acid is formed when nitrogen oxides react in the atmosphere. This nitrogen acid can descend down to the earth with the rain. /40; 41/

It is more difficult to try to decrease the emissions of nitrogen oxides than for example emissions of sulphur, because nitrogen emissions depend only partly on what fuel type has been used. It is possible to influence on the sulphur dioxide emissions by choosing fuels which contain lower amounts of sulphur, by cleaning exhaust gases (scrubber) or by binding sulphur during the combustion process. Nitrogen oxides are formed during the combustion process and the only ways to reduce nitrogen emissions are to adjust the combustion process or use SCR-method (Selective catalytic reduction). /42/

Nitrous oxide is also one of the greenhouse gases and its share of all greenhouse gases is 6 % formed in the year 2014 in the United States (the total emission mass was 6,870 Million metric tons of CO_2 equivalent in the U.S. in 2014). In comparison the percentage of carbon dioxide was 81 % in 2014. /43/

If we compare the N_2O concentration now in the atmosphere and in the pre-industrial time about 300–400 years ago, the concentration rate is 13 % bigger nowadays. Nitrous oxide is formed for example from land use, nitrogen fertilizers and combustion processes and it is able to stay in the atmosphere even 120 years. /37/

5.4 Sulphur Dioxide

The combustion of fossil fuels (coal, oil, peat) cause the majority of the emissions of sulphur dioxide but also the marine traffic is one of the SO_2 emissions producers /11, p. 134/. International Maritime Organisation made a decision that the sulphur content is allowed to be max 0.1 mass- % in the sensitive areas because it is important to reduce sulphur dioxide emissions and improve air quality and the state of the seas /44/. The European Union accepted the sulphur directive in 2012 and the directive came into force in the Baltic Sea, North Sea, English Channel and in the sea area of North America in the beginning of 2015 /45/. Fuel which contains only 0.1 mass-% of sulphur is only allowed to use in these areas or other alternative is to use a scrubber which is able to reduce the SO_2 emissions about 90 %. These regulations are going to spread also wider in other sea areas of the European Union in the beginning of the year 2020. Then the limit for sulphur content in other sea areas is 0.5 mass-%./45/

5.5 Carbon Monoxide

Carbon monoxide (CO) is the product of incomplete combustion /46/. Carbon monoxide is a colourless gas and it consists of one carbon and one oxygen atoms. Carbon monoxide is a little lighter than air (molecular mass for CO is 28.01 g/mol). Carbon monoxide is broken to carbon and carbon dioxide in 400–700 °C degrees temperature. /47/

It is important to avoid incomplete combustion because the carbon monoxide reacts with the hydroxyl radicals (OH^-) and the end product is carbon dioxide, which is one of the greenhouse gases. Carbon monoxide is able to stay in the atmosphere about four months and it is also possible that carbon monoxide descends down to the earth with the rain. /47/

5.6 Particles

The size of particles varies and they are classified by the length of the diameter. If the diameter is under 10 µm, the particle belongs to the class of PM10. Particles which belong to the PM10 class are also called coarse particles. Marking PM2.5 means that the diameter of particle is under 2.5 µm and they are called fine particles. In Finland about half of the fine particles are from abroad and the remaining half is from combustion processes and traffic. /48, 49/

However, not all of the particles are from combustion processes because there are also particles in the air, such as pollen, which occurs naturally. The amount of particles has however increased because of industry and combustion. Incomplete combustion processes cause fine particles (PM2.5) which are the most harmful to the health. /48, 49/

Fine particles are very easily carried to the respiratory system. They can also transport other harmful substances, such as sulphur compounds and other carcinogenic substances, with them to the body. There is an estimation that harmful dosage of small particles is between 30-150 µg/m^3 per day. The limit value for PM_{10} has been set to the level 50 µg/m^3 in Europe. /50/ The limit value for fine particles ($PM_{2.5}$) is 25 µg/m^3 /51/. It is very difficult, though, to set exact limit values for particles because for some people already small amounts can be harmful /50/.

5.7 Environmental Effects of Emissions

The emissions of combustion cause several effects on environment and also for human. All emissions are not necessarily so dangerous, but some emissions cause huge environmental issues around the world. The most serious emissions are carbon dioxide, nitrogen oxides and sulphur dioxide. Carbon dioxide causes greenhouse effect and nitrogen oxides and sulphur dioxide cause acidification.

5.7.1 Acidification

Especially sulphur dioxide and nitrogen oxides cause acidification of soil and water bodies. Acidification means that oxides of metalloids react with water and acid is formed. So sulphur dioxide reacts in the atmosphere and sulphuric acid H_2SO_4 is formed and the nitrogen oxides turn into nitric acid HNO_3. /11,p.137/ Acidification is a harmful consequence of these sulphur and nitrogen oxides emissions because it has effect on the natural ability to avoid and neutralize acidification. /42/

The acid conditions contribute to the release of ions of aluminium and heavy metals. These ions are very toxic for organisms and plants. In the worst case, the dissolve ions of metals can cause poisonings and other harmful effects for living organisms in the water (for example for fishes). /11,p.137;42/

Nitrogen and sulphur oxides emissions are not only local problems. They can spread even hundreds of kilometres from the source of emission. They can descend down to the earth and water systems with rain. They can also descend down for example with particles (dry deposit). Lime, which is an alkaline substance, occurs naturally in many places and it prevents acidification. For example the areas in north are so rugged and there are limited amounts of lime naturally. These areas are the most vulnerable for the acidification. /42/

5.7.2 Climate Change

The climate change is a consequence of greenhouse effect, which is one of the serious environmental threats. The greenhouse effect means in general that the concentration of greenhouse gases has increased in the atmosphere. The greenhouse effect prevents the thermal radiation of the sun to reflect back to the space from the Earth's surface. Carbon dioxide is the most known greenhouse gas and it is released specially by the combustion of fossil fuels. Methane and nitrous oxide also intensify the greenhouse gas effect and their shares are together 17 % of all greenhouses gases produced in U.S in the year 2014. /11, pp. 140–141; 43/ Later in this study, in Chapter 6, it is compared how the used fuel (HFO or natural gas) affects the emissions of carbon dioxide.

The majority of the ultra-violet radiation is absorbed into the stratosphere which is located about 15 – 50 kilometres altitude. Thermal radiation and visible radiation and some of the ultra-violet radiation are able to get through atmosphere to the Earth. There is also radiation from the Earth to the space but it has different wave length than the radiation from the sun has. The carbon dioxide of the troposphere absorbs parts of this radiation from ground to the space. Without this absorption the temperature on the Earth would be about -16 ˚C degrees. So on the other hand the greenhouse gases are necessary that the temperature of the Earth would be potential for the life. /11, p. 140/

However, the greenhouse effect is due to the fact that the concentration of greenhouse gases has significantly and fast risen. That is why the atmosphere does not release the radiation away from the Earth as efficiently. The increase of greenhouse gases has caused the rising of temperatures, warming of oceans and lakes and melting of glaciers. The melting can cause the rising of surface of the seas and the tropical storms can become more frequent. /11, p. 142/

6 REDUCTION OF EMISSIONS

This is the empirical part of this study and the basic information of this research is given. The reductions of emissions, which have been achieved by gas conversions, are focused on in more detail and the results are gathered in tables. The engine types, which were studied, and information of them were gathered to excel-sheets as the information was found. The engine type, form (V or In-line), output (kW), design stage, load (%) and rpm were the most important details which had to be found out before having a closer view for the emissions. Several discussions with the Group Manager and Environmental Expert helped to find the right persons, databases and documents where to get the needed information.

A few projects, in which some of the gas conversion types (DF, SG or GD) have been executed, were selected to more detail study. The power plants which were selected to this study are located in Malta, Mexico, Equatorial Guinea and Ecuador. The DF and SG conversions are ongoing in Malta with gas conversion of eight engines. When the conversion project is finished there will be four DF engines and four SG engines. The 34DF conversions have been executed in Mexico (two engines) and in Equatorial Guinea (two engines). The GD conversion has been executed in Ecuador.

At first the objective was to select suitable gas conversion projects for this study. Altogether about 30 gas conversion projects have been executed by the Project Centre Finland and some of them have been executed several years ago. The old project documents and the needed information on them were slightly challenging to find, because some of the power plants do not exist anymore or the engines have been removed somewhere else. When the suitable projects had been selected, the next step was to research what the type and the design stage of the engine have been before the conversion and what they are now. In addition to knowing the engine type, it was also important to know the design stage and output. Without knowing the design stage, it was impossible to find the right data where the amounts of emissions and other needed information had been given. The internal databases, archives and project contracts were researched to find all the necessary data. Also discussions with project managers and engineers were good sources of information.

The design stage tells the technical properties of engine. The engine with newer design stage has usually some changes on technical side which can affect, for example, the output rate or emissions. There might also be some changes in the components or in the design in general. Sometimes the change can be small but sometimes very remarkable. In one conversion case the design stage of the engine was so old that the performance manual for that design stage was not easily found. That is the reason why that project as well as some other projects needed to be left out of this study. In the Performance Manual all the necessary technical details of the engine, for example the output, emissions, fuel characteristics, consumption of lubricating oils, noise levels, operating data and the lifecycle of components, are given.

The emission data was the most interesting and most important part from this study’s point of view. In most of the Performance Manuals the emission data was given in form ppm-vol, which is not suitable value when different engines, with different combustion methods, and outputs are compared. The main goal was to get the emission data in form g/kWh.

In few cases, especially in the DFc conversion cases, no information about emissions were found. The only way to find out the emissions of DFc engine, would have been the visit to the power plant to measure the emission levels and analyse the characteristics of the fuel. The scope of the work, timeframe and the lack of suitable resources prevented this kind of action. For that reason these DFc engines were left out of this study. Also the emission data of GD engine was challenging to find and some of the emissions are still missing in spite of active inquiry.

6.1 PerfPro Calculation Tool (Version 2016.1.)

The PerfPro calculation tool was used as a help to find out the wanted emission data. The PerfPro tool has been designed by two Wärtsilä employees and their team and it is only for internal use. The PerfPro gives operational data of engines. The results of PerfPro are based on the data of Performance Manuals, and the data of Performance Manuals are based on the measurements done in the performance tests.

When starting to use the tool the wanted engine type, cylinder configuration, speed and load must be selected. If the selected engine uses liquid fuel, it is possible to select predefined fuel from the down box or it is also possible to specify the fuel yourself. After that it is possible to define the ambient conditions, for example the temperature, altitude, humidity and air pressure.

In the second section the site conditions need to be specified. After that it is possible to start to simulate the engine behaviour according to the information given in the design stage section. In the last section the characteristics and summary of selected fuel type, design conditions, extreme conditions and site conditions, in which the results are valid, are given together with the information about exhaust gas flow, temperatures, electricity production and exhaust gas emissions. The exhaust gas emissions, in form g/kWh, were the most important part because the purpose of this study was to research the reduction of emissions.

6.2 Reduction of Emissions

Usually the emissions are higher (per g/kWh) if the load is less than 100 %. On 100 % load the process is nearest to the complete combustion process. In some cases it is possible that the ambient conditions in the power plant prevent to use the engine on full load. For example, the ambient conditions (temperature, altitude and air pressure) are so challenging in the power plant in Mexico that the engines are not able to run on full load (100 %). The emission rates must be calculated according to the real outputs and loads (for example in Mexico the loads are 85 % in HFO engine and 78 % in DF engine).

The results of this study are only theoretical. It is not possible to make 100 % sure conclusions that the emission levels given in this study are exact because the amounts of emissions depend on so many different aspects. The ambient conditions, used fuel type and its sulphur content, variations on load, running hours and the age of the engine are the factors which affect the emissions and part of these factors can change many times during the operation year.

Finding out the exact and real amounts of reduced emissions would have been taken years of analysing, samples of fuels and knowing the exact running hours and loads. The amounts of reduced emissions are theoretical in this study but the results are calculated based on the measurements done by standards. The PerfPro calculation tool is based on standard ISO8178 and its referenced documents (for example ISO15550-2002 E and ISO3046), which are necessary for the application of the ISO8178 document. The emission data given in this study is in the ambient conditions accordingly; air temperature 25 ˚C, pressure 100 kPa and air relative humidity 30 % /52/.

All the results, for the diesel engines, are based on using HFO as a fuel if anything else is not mentioned. HFO contains 1 w/w-% sulphur and the lower heating value (LHV) is 41 100 kJ/kg. The table below gives detailed information about the content of HFO. /52/

Table 3. The fuel characteristics of HFO 1 -% S (based on the information given by PerfPro calculation tool).

Substance	**Mass-%**
Water, H_2O	0,26
Sulphur, S	1,00
Ash	0,02
Nitrogen, N	0,34
Oxygen, O	0,55
Carbon, C	86,18
Hydrogen, H	11,65

The emission calculations for the gas engines are based on using natural gas as a fuel. The natural gas contains 95 % methane, 2 % ethane and 3 % propane. The pilot fuel, which is used in DF engines, is LFO and it contains 0.1 w/w -% sulphur and the lower heating value is 42 905 kJ/kg, if anything else is not mentioned. The table (4.) below provides information of the characteristics of LFO in more detail. /52/

Table 4. The fuel characteristics of LFO 0.1 -% S (based on the information given by PerfPro calculation tool).

Substance	**Mass-%**
Water, H_2O	0,12
Sulphur, S	0,05
Ash	0,01
Nitrogen, N	0,22
Oxygen, O	0,34
Carbon, C	86,20
Hydrogen, H	13,06

6.2.1 W18V50 SG Conversion in Malta

Four W18V46 engines running on HFO are going to be converted into W18V50 SG engines running on natural gas. The basic information of both engines are given in the table below. /53/

Table 5. The main characteristics of 46 and 50 SG engines.

	W18V46 HFO	**W18V50 SG**
Output (kW)	17 550 kW	18 810 kW
Design Stage	C4	A
RPM	500	500
Load (%)	100 %	100%

Based on the information of Table 5 the theoretical amounts of reduced emission are calculated by using the PerfPro tool and the results can be seen in the column chart (Figure 1.) below. /52/

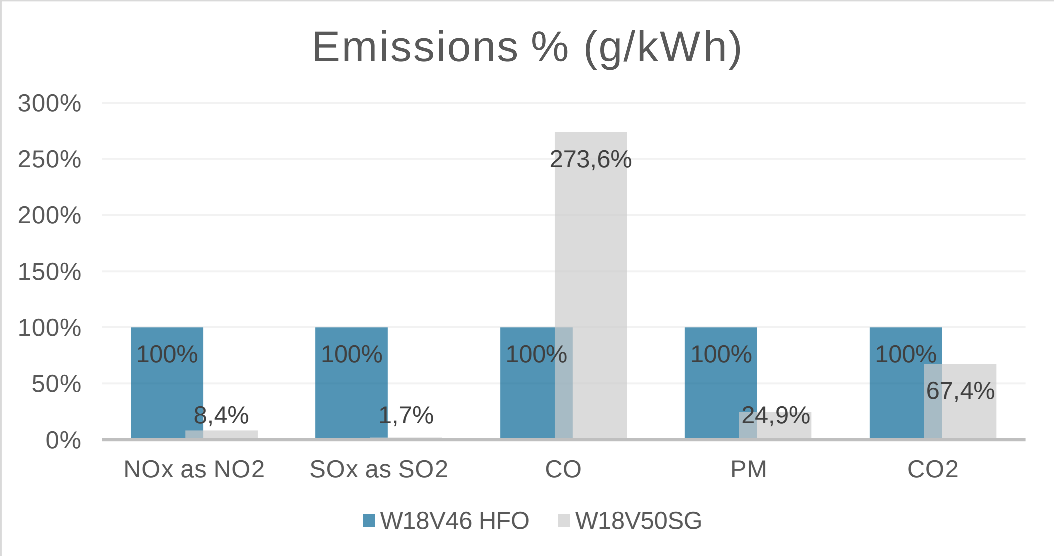

Figure 1. The reduced emissions on W18V50SG engine.

6.2.2 W18V50 DF Conversion in Malta

Four W18V46 engines running on HFO are going to be converted into W18V50 DF engines running on natural gas and the pilot fuel, LFO, contains 0.1 w/w - % sulphur. The basic information of the both engines are given in the table below /53/.

Table 6. The main characteristics of 46 and 50 DF engines.

	W18V46 HFO	**W18V50 DF**
Output (kW)	17 550 kW	17 550 kW
Design Stage	C4	B
RPM	500	500
Load (%)	100 %	100%

Based on the information of Table 6 the theoretical amounts of reduced emissions are calculated by using the PerfPro tool and the results can be seen in the column chart (Figure 2.) below. /52/

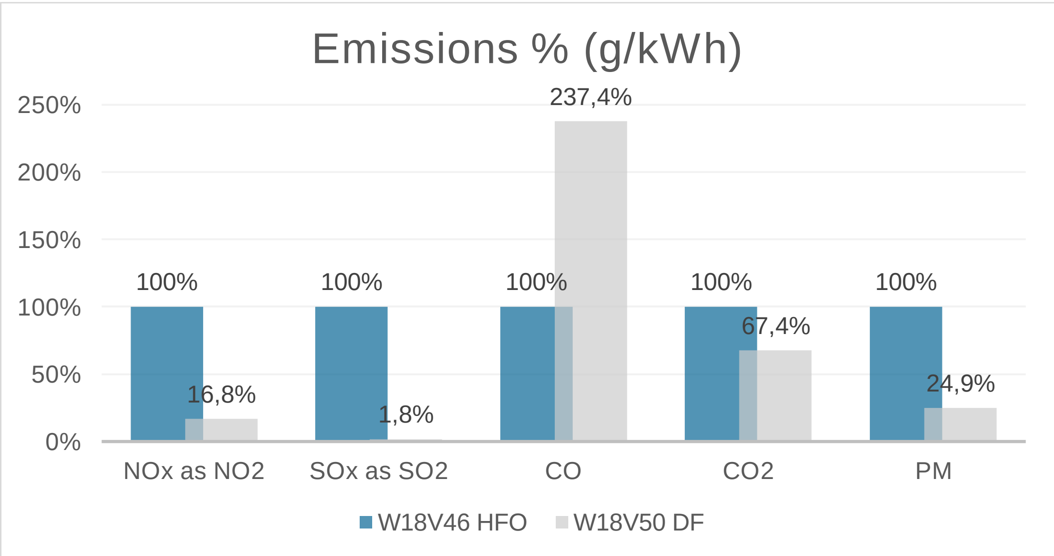

Figure 2. The reduced emissions on W18V50DF engine.

6.2.3 W18V34 DF Conversion in Mexico

In Mexico two W18V32 engines running on HFO have been converted into W18V34 DF engines running on natural gas. In Mexico the ambient conditions prevent to use the engines on full load, so in this case the partial loads had to be taken into account.

The W18V34DF engine is not the portfolio engine, only the W16V34DF and W20V34DF engines are manufactured in the factory, so the emission data is based on the information of the 20V34DF engine. It is possible to base the calculation on the emission data of 20V34DF engine, because the amounts of emissions stay basically at the same if the data is given in form g/kWh. Only the number of cylinders and output differs. The basic information of both engines are given in the table below /53/.

Table 7. The main characteristics of 32 and 34 DF engines in Mexico.

	W18V32	**W18V34 DF**
Output (kW)	6870 kW	6700 kW
Design Stage	B2	B
RPM	720	720
Load (%)	85 %	78 %

Based on the information of Table 7 the theoretical amounts of reduced emissions are calculated by using the PerfPro tool and taking into account the partial loads. The results can be seen in the column chart (Figure 3.). /52/

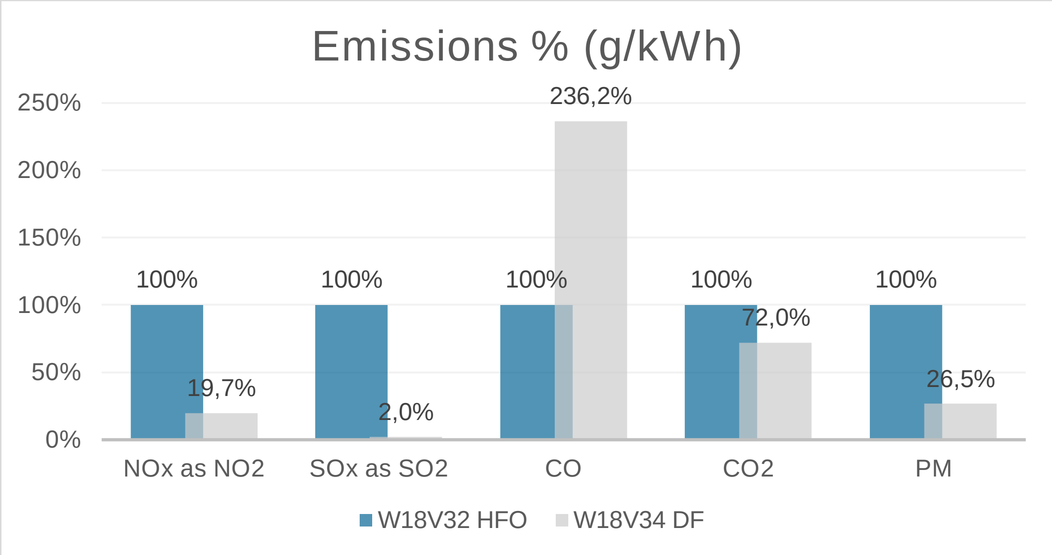

Figure 3. The reduced emissions on W18V34DF engine in Mexico.

6.2.4 W18V34 DF Conversion in Equatorial Guinea

In Equatorial Guinea two W18V32 engines running on HFO have been converted into W18V34DF engines running on natural gas. In Equatorial Guinea the 32 engine is able to run on full load, but the load for the gas engine (34DF) is only 83 % /53/. The basic information of both engines are given in Table 8 below. In this case, such as in Mexico, the emission data of gas engine is based on the data of 20V34DF engine.

Table 8. The main characteristics of 32 and 34DF engines in Equatorial Guinea.

	W18V32	**W18V34 DF**
Output (kW)	8280 kW	6700 kW
Design Stage	C	B
RPM	750	7500
Load (%)	100 %	83 %

Based on the information of Table 8 the results are calculated by using the PerfPro tool. The partial load of 34DF engine has been taken into account and the theoretical amounts of reduced emissions can be seen in column chart (Figure 4.) below. /52/

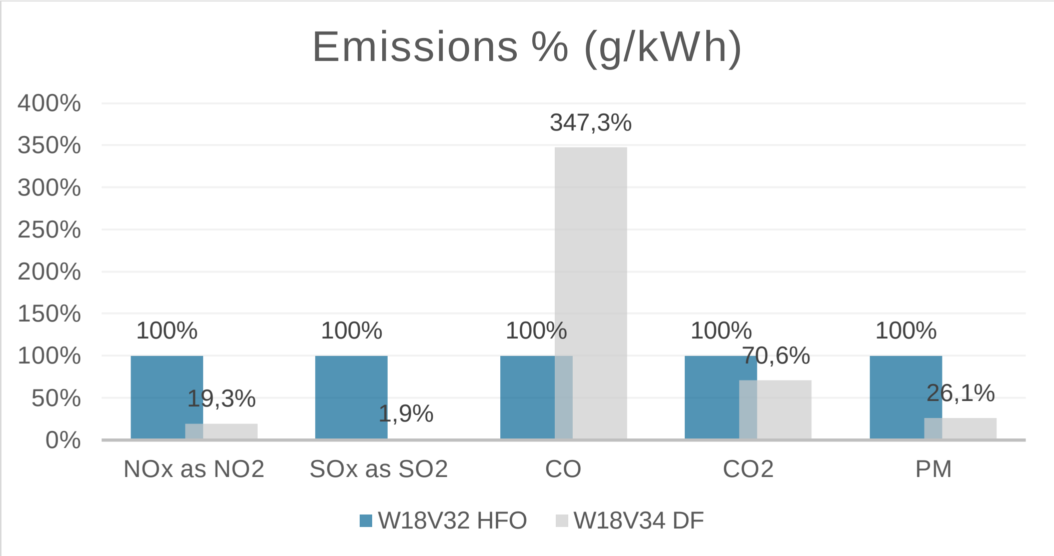

Figure 4. The reduced emissions on W18V34DF engine in Equatorial Guinea.

6.2.5 18V32LN GD Conversion in Ecuador

The 18V32LN engine is nowadays a non-portfolio engine. The old name is Wärtsilä 32 Vasa engine and the abbreviation LN refers to Low NOx. So the engine is optimised to produce lower NOx emissions. The GD conversion is possible to execute for Vasa 32 and Wärtsilä 46 engines. /9/ This case is different compared to other cases in this study, because the old engine has not been compared with the converted engine. Only a comparison between different fuel types was made and how they affect the amounts of emissions. The GD engine is able to run on heavy fuel oil, light fuel oil and natural gas. The column chart (Figure 5.) shows how the used fuel type influences the emissions /54/.

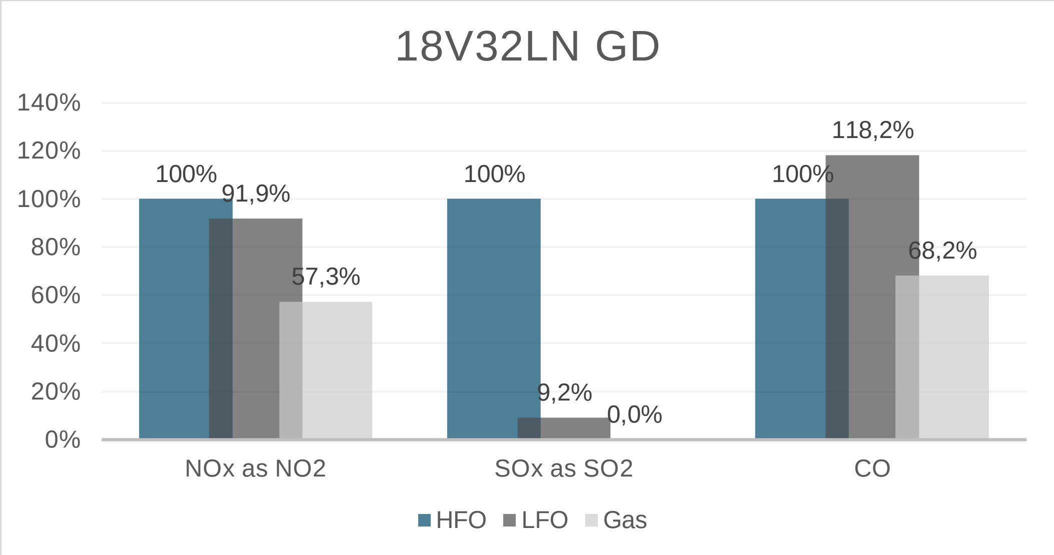

Figure 5. The influence of the fuel type on the emissions on 18V32LNGD engine.

The maximum contents of sulphur and nitrogen in the fuels and the emission data are given in the document sent by Senior Environmental Expert. The maximum content for sulphur is 0.2 w/w-% in LFO and 2.0 w/w-% in HFO. The maximum content for nitrogen is 0.2 w/w-% in LFO and 0.6 w/w-% in HFO. The emissions depend on the ambient conditions but these values are calculated in the conditions of ISO3046 and the load is 100 %. /54/

6.2.6 The Impact of Sulphur Content on Sulphur Dioxide Emissions

The sulphur content of fuels is the major factor which affects the sulphur dioxide emissions. This comparison was made only in order to clarify the impact of sulphur content on the SO_2 emissions. The engine type used in this case is the same as in Equatorial Guinea. Table 9 gives the information of the used fuels.

Table 9. Heavy fuel oils with different sulphur contents.

Lower Heating Value	The Sulphur content
41 100 kJ/kg	1.0 % S
40 400 kJ/kg	1.9 % S
39 800 kJ/kg	3.4 % S

The sulphur emission calculation for W18V32 engine was made using the fuels mentioned in Table 9. The SO_2 emissions only were focused on this case. The column chart below shows how the sulphur content of fuel affects the amounts of SO_2 emissions. /52/

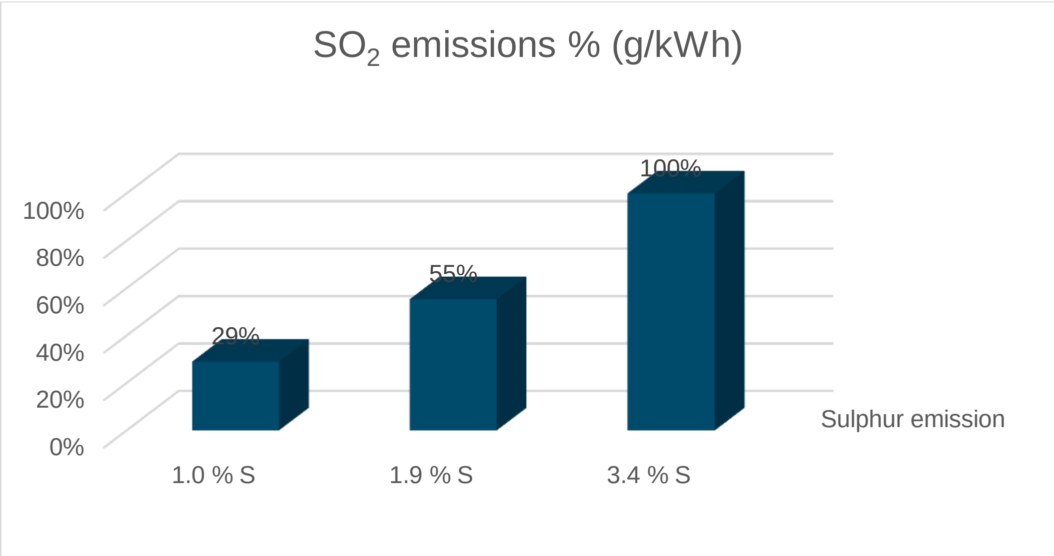

Figure 6. The effect of the HFO's sulphur content on the SO_2 emissions.

The only way to reduce the sulphur dioxide emissions is to choose low sulphuric fuel. The impact of low sulphuric fuel is huge, as it is possible to see from Figure 6.

7 CONCLUSIONS

The objective of this thesis was to research how much the gas conversion affects the amounts of the exhaust gas emissions. As mentioned earlier in this study, the reduction of exhaust gas emissions and the harmful substances of the exhaust gases are very important actions to slow down the climate change. Especially the carbon dioxide is one of the most harmful emissions which contribute to the global warming and climate change. Also the reduction of sulphur dioxide and nitrogen oxides is important to prevent the acidification.

The gas conversion is one remarkable development which can affect the emission levels and decrease them. As it has been mentioned earlier, the results of this study are theoretical. Many things such as the fuel type, the real ambient conditions, different loads, the maintenances of the engine and the age of the engine or power plant have effects on the amounts of emissions. Every case in this study is an individual project. The results were calculated according to the engine type, output, rpm, design stage and load so it is not reasonable to compare the results of different projects with each other.

The engines which were selected to this study were not equipped with the exhaust gas cleaning devices. For example, the carbon monoxide emissions could be reduced by a catalytic converter. It would also be possible to equip the engines with a scrubber or use the SCR - method (Selective Catalytic Reduction) to reduce sulphur dioxide and nitrogen oxides emissions. Generally these exhaust gas cleaning devices are less used in the power plants but in wide use in the marine markets. Usually the country, where the engine or the power plant is located, defines the emission targets which need to be followed. If it is not possible to stay under the limit values, the only way is to take in use the exhaust gas cleaning devices.

It is possible to see from the column charts that the carbon dioxide emissions on a gas engine can be even 32 percentage points less per one kWh than on a HFO engine. It is quite a remarkable amount if we think about the whole lifecycle of an engine. Every combustion process produces always carbon dioxide, but by selecting a cleaner fuel type it is possible to reduce CO_2 emissions. The natural gas is a cleaner fuel and contains less carbon than the heavy fuel oil so the carbon dioxide emissions are lower with the natural gas.

The used fuel type and its sulphur content are the only things which affect sulphur dioxide emissions. That is possible to see in Figure 6. The natural gas is basically sulphur free fuel, so its effect on the SO_2 emissions is remarkable. After the gas conversion, the sulphur dioxide emissions can be even 1/58 (per one kWh) of the amount that would be produced by using heavy fuel oil. Also the particle and nitrogen oxides emissions are lower when switching the heavy fuel oil to natural gas. Because of the gaseous form of natural gas it does not produce ash and that affects the particle emissions. The ash is produced more by combusting heavy fuel oil because it contains more impurities (e.g. metals) as it has been mentioned in Chapters 4.3 and 4.2.1. It is possible to see from Tables 3 and 4 that already light fuel oil itself contains less ash than the heavy fuel oil.

The NOx emissions are also lower after the gas conversion. Natural gas contains only a very small amount of nitrogen, so the NOx emissions are due to the nitrogen content of air. The NOx emissions of DF and SG engines are about 80 (DF) and 90 (SG) percentage points lower on natural gas than on heavy fuel oil. The lean burn method on gas engines affects NOx emissions because the combustion temperatures are lower as mentioned in Chapter 3.4.

It is possible to see from the column charts in Chapter 6 that the amount of carbon monoxide increases in all gas conversion cases except in the LN GD case. The difference is probably due to the differences in combustion processes in gas and diesel engines. The injection of the fuel (is it high pressure or low pressure injection), the fuel/air mixture concentration, ignition process, combustion temperatures and pressures affect combustion process and emissions. The carbon monoxide is a sign of incomplete combustion. That does not have effect on the performance of engine, because it is still possible to get about the same output on natural gas and heavy fuel oil. The carbon monoxide is a gas which contributes to the global warming indirectly. Only for humans the carbon monoxide can be fatal, if it is breathed.

The gas conversion is a cost intensive investment. The execution requires detailed engineering, logistics and site installation activities. Most of the existing engine components need to be removed and the new components to fitted in. The materials and tools logistic can sometimes be challenging due to the installation location. The price of oil and gas as well the gas infrastructure availability has effects on the willingness to invest in the gas conversion project. The gas conversion improves the performance of the engine, because after the conversion engine is basically a new one. The fuel consumption, the fuel costs and the amounts of harmful emissions decrease after the gas conversion. The heating value is higher on natural gas than on heavy fuel oil so the natural gas is not needed that much to get the same amount of energy. The gas conversion has also positive effects on the periods between maintenances so the maintenance costs decrease too. When thinking of all these positive effects, it could be concluded that in long term the gas conversion is an environmentally friendly and cost- effective investment.

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