TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

NIKO TOIVANEN

A TECHNO-ECONOMIC FEASIBILITY STUDY OF A MULTI-HYDROCARBON RECOVERY SYSTEM FOR GAS POWER PLANTS

Master of Science Thesis

Examiner: University Lecturer Henrik Tolvanen
Examiner and topic approved in the Faculty of Engineering Sciences council meeting on 9th August 2017

ABSTRACT

NIKO TOIVANEN: A techno-economic feasibility study of a multi-hydrocarbon recovery system for gas power plants
Tampere University of Technology
Master of Science Thesis, 97 pages, 11 Appendix pages
October 2017
Master's Degree Programme in Mechanical Engineering
Major: Energy and Biorefining Engineering
Examiner: University Lecturer Henrik Tolvanen

Keywords: Gas power plant, hydrocarbon

The overall focus of this study was to examine how to recycle the unburned fuel gases from gas power plants back into a usable state, instead of the fuel gas being released into the atmosphere. The research objectives were to critically examine the current system and also to find the most suitable technology for recycling the unburned fuel gases back into the process, both technically and economically. Furthermore, the study examined the benefits of the new system. In the literature, similar systems were already found to be used by different sections of the industry, but never on such a large scale or for the purpose of recycling the fuel gases back into the process. To date, a techno-economic feasibility has not been carried out in relation to this subject. Furthermore, modeling results, which describe the behavior of flammable hydrocarbon plumes in the air, are also not in current literature.

This study chose to techno-economically investigate the current situation, various potentials for development and possible solutions for gas power plants belonging to the particular company used as a case-study. Before and during the study, the planning of one potential system and several different safety studies were conducted. As part of the study, interviews were held, hydrocarbons were modeled, and the Excel-based calculation tool was created to assess economic feasibility. The study was carried out through active, primary research where the researcher worked in the target organization.

As a result, problem areas within the current system were found, proving the necessity of the whole study. A more suitable technology with justifications was found to replace the current system. This type of new system could also be more widely adopted within other sectors of the business and amongst other companies. In this research, various elements of different industry sectors which have appeared in the literature are combined and compared to the author's own views and according to the results observed.

From the company's point of view, the state of the existing system and new data results were verified and validated. It was possible, furthermore, to prove the benefits of the new system against the current. Recommendations of this study were continued investment in the development and commercialization of the new system, with a particular focus on the relevant markets and their future, considering tightened rules and requirements from authorities.

TIIVISTELMÄ

NIKO TOIVANEN: Hiilivetyjen kierrätysjärjestelmän teknillis-taloudellinen soveltuvuustutkimus kaasuvoimalaitoksia varten
Tampereen teknillinen yliopisto
Diplomityö, 97 sivua, 11 liitesivua
Lokakuu 2017
Konetekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Energia- ja biojalostustekniikka
Tarkastaja: Yliopistonlehtori Henrik Tolvanen

Avainsanat: Kaasuvoimalaitos, hiilivety

Tämä tutkimus käsittelee kaasuvoimalaitoksien palamattomien polttoainekaasujen kierrätystä takaisin prosessiin sen sijaan, että ne purettaisiin järjestelmästä suoraan ilmakehään. Työn tavoitteena oli tarkastella kriittisesti nykyistä järjestelmää, sekä löytää sopivin teknologia kierrättämään palamattomat polttoaineet takaisin prosessiin niin teknillisesti kuin taloudellisestikin. Lisäksi työssä tarkasteltiin uuden järjestelmän tuomia etuja. Kirjallisuudessa vastaavat järjestelmät ovat jo eri toimialojen käytössä, mutta niitä ei ole koskaan käytetty näin suuressa mittakaavassa tai tässä tarkoituksessa kierrättämään polttoaineita takaisin järjestelmään. Tieteellisesti teknillis-taloudellista tarkastelua ole aiemmin suoritettu aiheeseen liittyen. Myöskään kirjallisuudesta ei ole löytynyt syttyvän hiilivetypilven käyttäytymistä kuvaavia malleja.

Työssä tutkittiin kohdeyrityksen kaasuvoimalaitoksien nykytilaa ja erilaisia kehitysmahdollisuuksia sekä ratkaisuja teknis-taloudellisesti. Työn aikana ja jo ennen sitä, tehtiin yhden potentiaalisen järjestelmän suunnittelua sekä erilaisia turvallisuustutkimuksia. Osana työtä toteutettiin useita haastatteluja, hiilivetyjen simulointia ja Excel-pohjainen laskentatyökalu taloudellisia laskelmia varten. Tutkimus toteutettiin toimintatutkimuksena työnsuorittajan työskennellessä kohdeorganisaatiossa.

Työn tuloksena löydettiin nykytilan ongelmakohdat ja todistettiin kyseinen työ tarpeelliseksi. Työssä löydettiin sopivin järjestelmä korvaamaan nykyinen järjestelmä perusteluiden kera, niin teknisesti kuin taloudellisestikin. Tätä järjestelmää voidaan soveltaa laajemminkin muille toimialoille ja yrityksille. Työssä yhdistetään useita eri kirjallisuudessa esiintyneitä elementtejä eri teollisuuden aloilta ja peilataan niitä omiin näkemyksiin sekä saatuihin tuloksiin.

Yrityksen kannalta tuloksena saatiin todennettua olemassa olevan järjestelmän tila sekä kerättyä täysin uutta dataa aiheeseen liittyen. Lisäksi pystyttiin todistamaan uusia ajattelu- ja toimintatapoja nykyisten sijaan. Suositeltavia toimenpiteitä on panostaa uuden järjestelmän kehittämiseen sekä kaupallistamiseen, erityisesti tulevaisuuden kiristyviä viranomaissäännöksiä ja vaatimuksia sekä markkinoita ajatellen.

PREFACE AND ACKNOWLEDGEMENTS

This Master's Thesis is written for Wärtsilä Finland Oy by following the thesis writing guide of Tampere University of Technology. This Master's Thesis has been one of the most challenging projects related to school and work. It has taught me a significant amount of new and notable ideas and also hopefully opened up new possibilities. With this work, my studies are approaching the end of my time in TUT. These five years have been fabulous especially because of good friends. Thanks to everybody who has been involved in this successful journey.

I would like to thank Stefan Fältén and Juha Laasanen for the opportunity to do this Master's thesis in cooperation with you both. Your enthusiasm and especially Stefan's passion into the subject motivated me greatly. I am also grateful to Henrik Tolvanen for examining this project and giving feedback. I also want to express my thanks to all of the Wärtsilä key persons of this project who have helped me during this project. Special thanks to my old and current Wärtsilä colleagues for creating such a convivial and joyful working atmosphere and inspiring conversations. Furthermore, thanks to everyone who has helped to review and comment on this study.

After all, I would like to thank my other half for taking care of our son while I have spent countless hours on this project. So thank you both, Juuli and my son Eemi, for your continuous support and encouragement to me during my studies and jobs, and especially during this project. Your support is priceless. Last but not least, I would like to thank my parents for invaluable help and support in all matters during my studies.

In Tampere, Finland on 31 October 2017.

Niko Toivanen

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols	Definition	Unit
$A_{n,r}$	Present value factor of periodic payments that have been performed afterward	-
C_0	Initial cash flow	€
C_t	Received cash flow at the end of the year	€
d	Diameter	m
I_0	Initial investment	€
IRR	Internal rate of return	%
n	Investment period	years
NFC	Net cash flow at the end of the year	€
NPV	Net present value	€
PV	Present value factor	-
r	Discount rate	%
t	Time period	years

Notation	Definition
bar(a)	Absolute pressure – relative to the absolute vacuum
bar(g)	Gauge Pressure - relative to the current atmospheric pressure
Nm^3	Normal cubic meter at 0°C and 101,325kPa

Abbreviations	Definition
AC	Activated carbon
ANG	Adsorbed natural gas
API	American Petroleum Institute
ATEX	ATmosphères EXplosibles - EU directives for explosive atmospheres
Atm.	Atmosphere
BLEVE	Boiling liquid expanding vapor explosion
BCF	Billion cubic feet
BTU	British thermal unit
C:H ratio	Carbons and hydrogens ratio
C_2H_6	Ethane
C_3H_8	Propane
C_4+	Butane and heavier hydrocarbons
C_4H_{10}	Butane
C_4H_8	Isobutylene
C_6H_{14}	Hexane
CAPEX	Capital expenditures
CCPS	Center for Chemical Process Safety
CEN	European committee for standardization
CFD	Computational Fluid Dynamics
CH_4	Methane
cif	Average freight prices
CNG	Compressed natural gas
CO_2	Carbon dioxide

COS	Carbonyl sulfide
CPP	Coal preparation plant
CS_2	Carbon disulfide
DF	Dual fuel (engine)
DN	Diameter nominal
EF	Emission Factor
EIA	U.S. Energy Information Administration
EN	European standard
EPA	Environmental Protection Agency
EU	European Union
FERA	Fire and Explosion Risk Analysis
GCV	Gross calorific value
GHG	Greenhouse gas
GPRS	Gas pressure reduction station
GTL	Gas to liquid
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HAP	Hazardous Air Pollutant
Hazid	Hazard Identification
Hazop	Hazard and Operability Study
HCN	Hydrogen cyanide
HFC	Hydrofluorocarbon
HFO	Heavy fuel oil
Hg	Mercury
HVDC	High-voltage direct current
HYSYS	Process simulation software by Aspen
IEC	International Electrotechnical Commission
IR	Infrared
IRMOF-993	Metal-organic framework material for ANG
ISO	Internal organization for standards
IUPAC	The International Union of Pure and Applied Chemistry
kV	Kilovolt
kWh	Kilowatt hour
LEL	Lower explosion limit
LFO	Marine diesel oil
LHV	Lower heating value
LNG	Liquefied natural gas
LOPA	Layer of protection analysis
LP	Liquid petroleum
LPG	Liquid petroleum gas
MMBTU	1,000,000 BTU
MMSCM	Million Metric Standard Cubic Meter
MOF	Metal-organic framework
MWh	Megawatt hour
N_2	Nitrogen
N_2O	Nitrous oxide
NEC	National Electrical Code
NF_3	Nitrogen trifluoride
NFPA	National fire protection association
NG	Natural gas

NGL	Natural gas liquid
NOx	Nitrogen oxides (undefined or mixture)
O_2	Oxygen
O_3	Ozone
OPEX	Operational expenses
OSHA	Occupational Safety and Health Administration
OSHA PEL	Same as OSHA
PCN-14	Metal-organic framework material for ANG
PERC	Propane education & research council
PFC	Perfluorocarbon
PM	Particulate matter
ppm	Parts per million
PRU	Pressure reduction unit
PSA	Pressured swing adsorption
QHSE	Quality, health, safety, and environment
QRA	Quantitative risk assessment
S_2	Sulfur
SA	Simple asphyxiant
SF_6	Sulphur hexafluoride
SFS	A standard approved in Finland
SG	Spark ignited Gas (engine)
SIF	Safety instrumented function
SIL	Safety integrity level
SIS	Safety instrumented system
SOx	Sulphur oxides (undefined or mixture)
SSA	Specific surface area
U.S.	The United States
UEL	Upper explosion limit
UK NBP	The National Balancing Point - United Kingdom natural gas
US	United States
V/V	Volume/Volume
VOC	Volatile organic compounds
WHO	World Health Organization
Z	Compressibility factor

1. INTRODUCTION

A variety of different fuels dominate the energy industry. New innovations within the case-study company's various projects are consistently being introduced, so this study will overview the more significant amongst them. This Master of Science thesis aims to analyze whether current working practices and approaches to the design of power plants are still suitable in the current environment. The thesis is topical because it examines both the design of current and future projects.

A major global challenge of our age is how to deal with the release of hydrocarbons into the atmosphere and the possible consequences. Instead of this expulsion, the spent hydrocarbons could be re-used using different types of fuel energy storages that would help to minimize risks involved in releasing fuel gas to the atmosphere.

These possible changes in the process will likely have an effect on the system's operation. Generally, no change is introduced without a great deal of thorough effort and time to examine how and why it will benefit the system.

1.1 Background

Since the industrial revolution, gas has been an effective and essential part of the energy landscape. Natural gas (NG) is a significant fuel within global energy production, and has a significant role to play in the future. The world is entering an era where fuel gas will increasingly complement solar, wind, and other renewable energy sources, especially in terms of power generation. According to the U.S. Energy Information Administration (EIA), NG is the fastest growing fossil fuel in the world and consumption of it will increase 1.7% per year until 2035. (EIA 2016) An effective gas infrastructure combined with the acceleration of NG expansion are connected by supply and demand. These infrastructure networks are expanding and diversifying globally. This is noteworthy as the world continues to shift towards the electricity power industry. The growth of the NG network and new supply possibilities, such as shale gas and technology innovation, support the creation of a wider and denser network, improved economics, and greater flexibility. According to Evans et al. "*The future of gas will not be the same as the past.*" (Evans et al. 2013).

Power plants produce electricity and heat power. These plants can be operated on a variety of gaseous or liquid fuels. Gas engine power plants can run with multiple different fuel gases. The available products and services should be adapted to meet the customer's needs. A particular power plant customer might have hydrocarbons other than methane

(CH_4) available so the fuel system and engines must be flexible and suitable for various fuels.

The fuel system and engines have gas vents out into the atmosphere either for operational or safety purposes. Typically, these are used for hydrocarbon expulsion after every engine's stop. This leads to harmful emissions in the atmosphere and creates hazardous areas at specific points of the plant.

The baseload power plants run continuously with a few, periodic, maintenance stops. Some of the gas engine power plants may run as a peak power plant in the future. Real-time prices and demand-response programs take advantage of electricity to encourage load shifting by the customer. During the periods when energy demand is increased, e.g. mid-day in the summer, peak facilities are used to generate the additional power needed. Alternatively, load-following power plants supplement the power produced by baseload facilities while adjusting the output to correlate with the hourly demand for electricity. That means that the power plant engines will start and stop multiple times a day and run for only short periods unlike in the past.

Differences in the emissions from different types of power plant classifications will encourage improvement in mitigation strategies as they relate to specific operating conditions. The design and safety of the vent system is consistently being developed to manage and minimize risks and challenges involved in releasing gas to the atmosphere. However, some of the projects have been issued limits on their emissions, which has been a limiting factor for the project. Moreover, some new fuel gases have been introduced with varying properties. These have created new challenges to the plant set-up and design.

1.2 Topic of the study

This Master of Science thesis investigates the possibility of storing hydrocarbons both economically and technologically. In this study, fuel energy storage is integrated with the gas-fired engine power plant, creating a hydrocarbon recycling system. The primary function of this system is to collect 100% of vented gases from the fuel systems and engines for later use. In this study, the major role of the power plant is to support solar and wind power as a peaking power plant thus the amount of the vented gases are notable compared to a similar baseload power plant. The same solution would be applicable to baseload plants but results of the economic analysis may vary. This study investigates the current situation with and without the recycling system.

As a summary, the fuel gases typically contain hydrocarbons, such as CH_4 or propane (C_3H_8). NG, which is one of the fuel gases used, is available from the natural gas transmission network. The transmission pipe connects to the inlet of the power plant's fuel system. The fuel gas is then directed to the engines through the fuel system. The amount of gas is dependent on the engine load. The topic of the study focuses on the vented gases of the fuel system and the engines. The engines under review are typical gas engines.

1.3 Objectives, scope, and limits of the research

The purpose of this study is to thoroughly investigate the case-study company's current system processes, especially in their gas engine power plants. This Master's thesis clarifies the current design of the gas engine power plant and possible technology options for storing the vented fuel gases.

The research objectives are to review and analyze the hydrocarbon expulsion, examine various technology potentials for the closed system and establish which is the most suitable. The research also hopes to define the possibilities of an optimised system for further commercialization and profitability. The study is trying to figure out the bullseye of the multidimensional optimal case.

The main goal of this Master's Thesis is to explore answers to four research questions:

1. *Is a recycling system for vented gases necessary in gas power plants?*
2. *What kind of system technology would be the best to apply?*
3. *What are the benefits of the proposed recycling system?*
4. *Is the optimized system economically profitable?*

The first research question critically reviews the released hydrocarbons and the need for a new system. Simulation tests were conducted to support results from the literature.

The second research question examines the optimum system technology for this case-study. Three different technologies are examined and one is selected and reviewed in this study.

The third research question clarifies the advantages of the new system from the different points of view. Different analysis techniques are applied: e.g. a profitability analysis of the new system highlights its benefits.

The last research question examines the profitability of the vent recovery system in a selection of different situations. Moreover, the sensitivity analysis helps to figure out the most critical parameters economically.

This study is limited to the Company that delivers power plant projects. Furthermore, the Company has a huge and configured spectrum of products, so the power plants and their components vary significantly.

Because the research covers a globally prominent leading supplier, the whole study was conducted without a stand being taken on local legislation or limitations. The scope of the study is limited to the current gas engine power plants where the main task is to operate as a peaking power plant and therefore support renewable technologies such as wind power or solar power. The fuel energy storage system has been examined as a part of the whole system.

The main observed hydrocarbon to the fuel energy storage is CH_4. Other heavier hydrocarbons, such as ethane (C_2H_6), propane, and butane (C_4H_{10}) are observed in some cases.

1.4 Structure of the study

The structure of the study is divided into six different sections: Introduction; Fuel gases; Gas systems for power generation; Fuel energy storage facilities; Research data and methods; results and discussion; and Conclusion, see Figure 1.

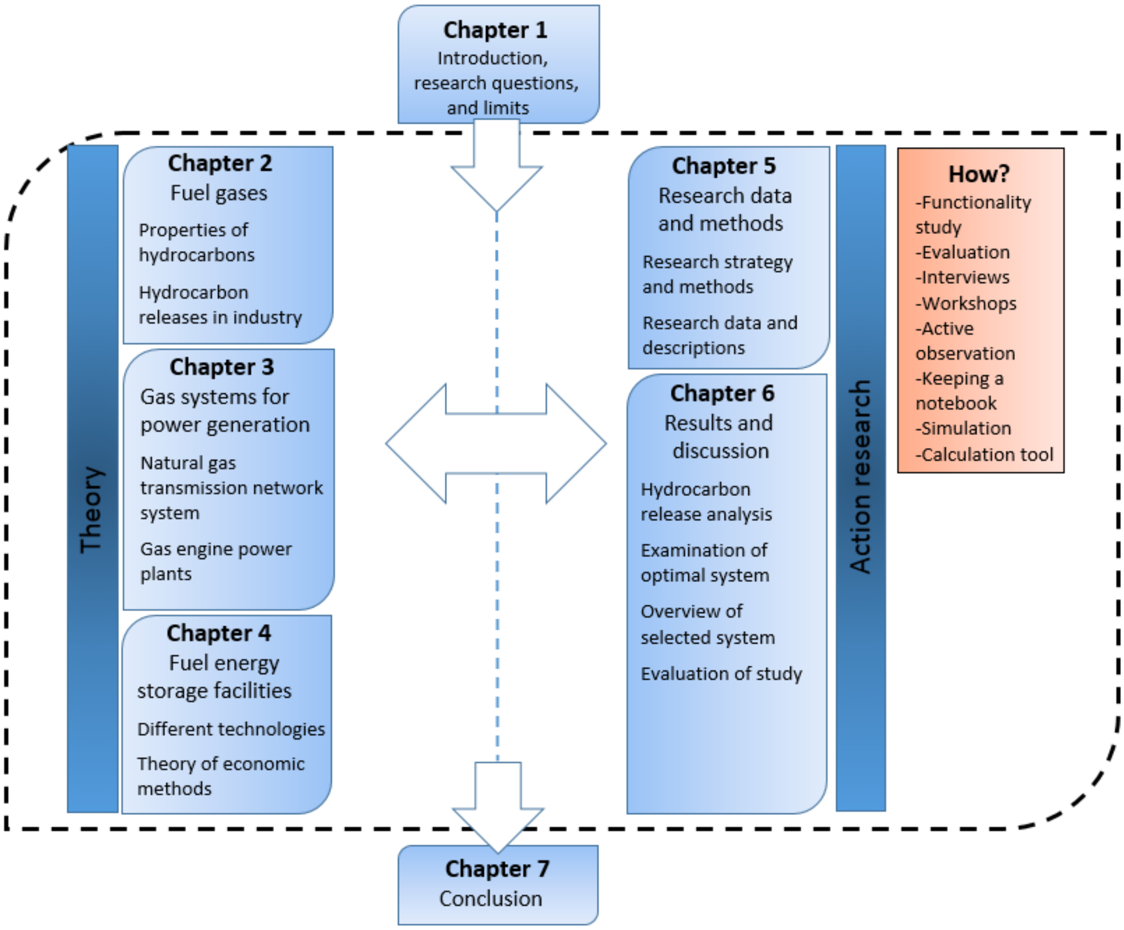


Figure 1: Structure of the study.

Chapter 1: The introduction presents the background, research objective and research questions of the study. It also determines the scope and limits, and presents why the study is necessary.

Chapters 2-4 create the background theory for this study. Chapter 2 and 3 introduce relevant topic literature from various items of research and materials. Chapter 4 illustrates the potential storage technologies and at the same time introduces the scientific theory behind the latest technology.

Chapter 5 describes the study's research methodology and its actual execution. Furthermore, the cases' data for the results and discussion are also presented.

In *Chapter 6* the findings are presented, with analysis, to answer the research questions. At this point, the study and results are connected to the initial theories by discussing and analyzing the findings. This chapter also looks at the implications and limitations of the study, as well as recommendations for future research and development.

The final chapter is *Chapter 7*, which summarizes the whole study from the purpose of the research to the study's conclusion.

2. FUEL GASES

The purpose of this chapter is to introduce the used fuel gases by overviewing properties, impacts, and possible consequences of various fuel gases. The chapter helps to recognize the overall picture later in the results and discussion.

Fuel gas is a complex mixture of different chemical compounds in a gaseous state. The generality of fuel gases contain hydrocarbons such as methane or propane. Fuel gases also contain inert gases such as nitrogen (N_2) and carbon dioxide (CO_2). The composition of fuel gas determines the quality of gas. Fuel gas contains energy and can be for example natural gas, shale gas, coal mine gas, landfill gases, liquid gases, associated gases, biogas or hydrogen. (Wärtsilä 2017c) Common fuel gases and byproducts of natural gas are shown in Figure 2.

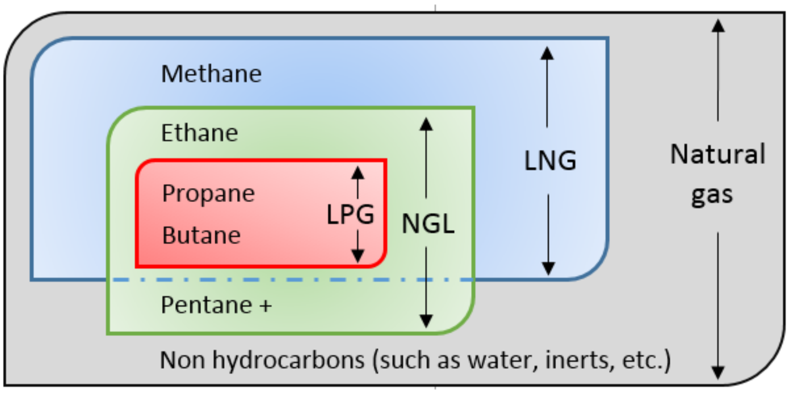


Figure 2: Fuel gases (According Durr et al. 2005).

Natural gas (NG)

NG is fossil and clean fuel from nature. One of the main uses of NG is as a fuel because of its high heating value that is released during the combustion process. It burns without soot or smoke at optimal conditions, and it is one of the world's main fossil fuels. (Park et al. 2017) It is also the most energy efficient fossil fuel because of the highest amount of hydrogen per unit of energy. (Woodyard 2009)

NG is produced from deposits of natural gas and oil in different gas fields on land, underwater, and also from coal beds. NG is usually found in association with reserves of oil because it is trapped in porous rocks beneath the ground. (Park et al. 2017) One of the accepted theories of the origin of NG supposes that hydrocarbons of NG come from organic matter which were trapped within sediments as they were deposited and transformed during a long time into their present form. (Mokhatab et al. 2015)

The composition of NG can vary on different production sources considerable. Different chemical compositions and gas fields can be seen from Table 1. However, the CH_4 is the main component in all types of natural gases. (Park et al. 2017)

Table 1: Examples of natural gas composition of various gas fields (Finnish Gas Association 2014).

Substance	**Contents [%] in various gas fields**				
	Russia	Germany	USA	The Netherlands	Norway
	Urengoy	**Goldenstedt**	**Kansas**	**Groningen**	**Troll**
Methane, CH_4	98.0	88.0	84.1	81.3	93.2
Ethane, C_2H_6	0.8	1.0	6.7	2.8	3.7
Propane, C_3H_8	0.2	0.2	0.3	0.4	0.4
Butane, C_4H_{10}	0.0	-	-	0.4	0.5
Nitrogen, N_2	0.9	10.0	8.4	14.3	1.6
Carbon dioxide, CO_2	0.1	0.8	0.8	0.9	0.6

Table 1 shows that the NG from the Russian is almost pure methane and it is called as "dry gas". Quality of the NG can vary dramatically, even it comes from the same well. The composition is as Table 1 shows; it can also include pentane (C_5H_{12}), heavier hydrocarbons such as traces of hexane (C_6H_{14}), and also hydrogen sulfide (H_2S) and other sulfur components such as carbon disulfide (CS_2) or carbonyl sulfide (COS). Evaporated liquids such as pentane or butane are referred to as natural gas liquids (NGLs) or condensates. The wetness of the gas depends on per cent of NGLs in composition. (Mokhatab et al. 2012)

NG is colorless, tasteless, shapeless gas, with no odor. It is available in the gas fields, in the natural gas pipeline systems, condensed to be liquefied natural gas (LNG) or compressed to be compressed natural gas (CNG) (Woodyard 2009). These gases are typically classified in two different ways (Mokhatab et al. 2015):

1) According to the liquid content of gas: lean or rich. These refer to the amount of potentially recoverable liquids and usually applies to heavier components and ethane and possibly also propane.
2) According to the sulfur content of gas: sweet or sour. These refer to the H_2S content or both acid gases.

LNG, based on methane, is a cryogenic liquid where a limited amount of heavy hydrocarbons will be present. LNG occupies 1/600 of its original gaseous volume at atmospheric pressure and -163°C, and it is vaporized for use as a high-quality fuel. Due to the low volume in the liquid phase, LNG allows more flexibility in transporting and storing. (Nolan 2010, pp. 43) The composition of LNG varies at different origins, see Table 2. The density of LNG is calculated at 101,325 kPa and -163°C, and density of the gas at 0°C and 101,325 kPa.

Table 2: Composition of LNG from different origins (Adapted from Finnish Gas Association 2017).

Origin	Nitrogen [%]	Methane [%]	Ethane [%]	Propane [%]	C4+ [%]	Density of LNG [kg/m^3]	Density of gas [kg/m^3]
Alaska	0.1	99.3	0.3	0.2	0.1	425.0	0.73
Libya	0.9	83.2	11.8	3.5	0.6	479.0	0.85
AVG. of 15 countries	0.4	90.1	6.8	1.9	0.7	456.5	0.80

Table 2 shows that the leanest LNG comes from Alaska and the richest from Libya. The average gross calorific value (GCV) of LNG is 54.4MJ/kg, and the average lower heating value (LHV) of LNG is 48.9 MJ/kg (Finnish Gas Association 2017).

Liquid gases

Liquid gases, such as propane, normally exist in the liquid phase under the relatively low pressure, less than 9 bar(g), at room temperature, and butane at even lower pressure. Propane is one of the most common types of fuels for internal combustion engines alongside with diesel and petrol. Its features make it perfectly suited to the contemporary energy-economy-ecology ideology. Operating with this kind of fuel is preconditioned by its high development supply system, low price and comparatively simple adjustment of combustion engines. (Raslavicius et al. 2014)

Commercial liquefied petroleum gas, also known as LPG, is a gas product from crude oil refining and natural gas purification. Approximately 55% of LPG processed in the US is from NG. LPG primarily consists of propane, butane, some propylene and other light hydrocarbons, for example, isobutylene (C_4H_8), and has many advantages as a natural gas. The composition of LPG can be a mixture of pure propane to various ratios of butane and propane to pure butane. LPG, as well as NG, are flammable fuel gases. (Raslavicius et al. 2014) LPG is liquefied for transport and vaporized again for use as engine fuel. (Nolan 2010, pp. 44) LPG composition could be for example following: propane (C_3H_8) 97.7%, n-butane (C_4H_{10}) 0.6%, i-butane 0.2% and heavier substances 1.5%. LPG should not be confused with LNG or CNG.

2.1 Properties of hydrocarbons

Gas is one of the fundamental states of matter. Other fundamental states are solid, liquid, and plasma. Gas particles have weak intermolecular bonds which allowing them to move freely. There are two types of gases (Jenkins 2008):

1) Pure gas which is made up of atoms or molecules of one type of atom (e.g. oxygen (O_2)), or compound molecules (e.g. CO_2)
2) Gas mixture which contains a variety of pure gases, for example, air.

Pressure and temperature can be used to control the fundamental states of gases. Gases will condensate to liquid or deposit to a solid form when the gas is submitted to certain combinations of temperature and pressure. (Jenkins 2008)

Properties of fuel gases are exactly known and easy to determine by calculation. Typical properties of different hydrocarbons at 0°C and 101,325 kPa are shown in Table 3.

Table 3: Typical properties of different gases at 0°C and 101,325 kPa. (According to Finnish Gas Association 2014; NIOSH 2017a; NIOSH 2017b, NIOSH 2017c, NIOSH 2017d; Nolan 2010).

Substance	Methane	Ethane	Propane	Butane
Molecular formula	CH_4	C_2H_6	C_3H_8	C_4H_{10}
Molecular weight, [g/mol]	16.04	30.07	44.09	58.12
Density, [kg/Nm^3]	0.72	1.35	2.01	2.70
Boiling point (atm.), [°C]	-161.5	-88.5	-42.1	-0.5
Flash point, [°C]	-	-	-104	-60
Ignition temperature, [°C]	650	515	510	490
Auto-ignition temperature, [°C]	537	472	450	365
Explosive limits, vol% in air:				
Lower explosion limit, (LEL)	5.0	3.0	2.1	1.8
Upper explosion limit, (UEL)	15.0	12.5	9.5	8.4
Effective calorific value:				
[kWh/Nm^3]	10.0	17.9	26.0	34.1
[kWh/kg]	13.9	13.3	12.8	12.7
[MJ/Nm^3]	36.0	64.5	93.6	122.8
[MJ/kg]	50.0	47.8	46.3	45.7

Table 3 shows the most relevant data in this study which related to the behavior of hydrocarbons. Temperature, pressure, and oxygen content in the gas mixture will influence the explosion limits. To achieve the explosive range limits, lower explosion limit (LEL) and upper explosion limit (UEL) of a particular gas, the combustible gases must be mixed with air. (Nolan 2010) Flammability of the gas-air mixture is defined by using Equation 1 (Internal report 2017).

$$\frac{Gas\ mole\ fraction}{Lower\ flammability\ limit} = 1.00\ , \qquad (1)$$

where gas mole fraction is the percentage in the mixture of gases [%] and lower flammability limit is referred as to LEL of substance [vol% in the air].

Natural gas and biogas

Methane, also known as methyl hydride, is an extremely flammable gas. Flames, sparks, and smoking can cause a fire. If the gas mixes with the air at right conditions, the explosion is possible. Efficient ventilation, closed gas system, explosion-proof electrical equipment and lighting are solutions to prevent an explosion. (NIOSH 2017a)

Small amount and concentrations of NG do not pose any danger to health. High concentrations of NG will cause a headache, sleepiness, and drowsiness. Methane can cause suffocation if the concentrations in the air are too high. That causes a deficiency of oxygen. On contact with liquid methane (-161°C) can cause frostbites to skin and eyes. (NIOSH 2017a)

Carbon monoxide is a gas which is formed when NG is burning without sufficient amount of oxygen. It usually forms during gas fires, and it is a highly poisonous, odorless and tasteless gas which is slightly lighter than air. Poisonous effect of carbon monoxide is based on very effective oxygen replacing in blood circulation. It can happen already in very low concentrations. (Wärtsilä 2017a)

Raw and treated biogas are flammable gases, but they are not explosive. If concentrations of methane are deficient, between 6-12%, an explosive environment can develop. Different countries have different rules for the technical safety of the biogas plants. (Wellinger et al. 2013)

LNG

LNG does not burn or explode in liquid form, it must evaporate to gas first. LNG vapor is flammable and it will only explode if in an enclosed space and if with the flammable range of LEL and UEL is mixed with air. Ignition energy is deficient so, for example, a small spark is enough to start a fire. (Wärtsilä 2017a)

Liquid petroleum gas

Propane and butane are colorless, odorless, compressed liquefied gases which are extremely flammable gases. Those are heavier than air, so those may travel along the ground, and distant ignitions are possible. (NIOSH 2017c; NIOSH 2017d) According to the Nolan (2010) non-volatile liquid gases can form a "pool" of liquid after spreading out.

Propane and butane may also cause a deficiency of oxygen if they accumulate in low ceiling spaces. By inhalation, both substances can be absorbed into the body. The substances might cause effects on the central nervous system. Evaporation of the liquids displace the surrounding air very quickly and can cause a serious risk of suffocation especially in confined areas. Moreover, rapid evaporation of the liquids may cause frostbites (propane -42.1°C and butane -0.5°C). Electrostatic charges can be generated as a result of agitation, flow, etc. (NIOSH 2017c; NIOSH 2017d)

2.2 Hydrocarbon releases in industry

The purpose of this chapter is to introduce how previous studies have described hydrocarbon releases. Investigating the available research helps to determine the most commonly used disposal methods for hydrocarbons, and possible consequences without disposal methods.

According to Environmental Protection Agency (EPA) (2011) industry is not commonly capturing the vented fuel gases. For example, venting and flaring are common solutions in shale gas industry. The physical releases can be generally categorized as following (Nolan 2014):

- Catastrophic failure
- Long rupture
- Open pipe
- Short rupture
- Leak
- Vents and drains
- Normal operational release

Generally, without accidents, combustible gas is released into the atmosphere from safety valves, pressure relief valves or vents, open containers and tanks, vents of storage tanks, and glands of compressors and pumps. (Nolan 2010) EPA has estimated that only 15% of blowback gas from unconventional wells is flared or captured, and majority (85%) is vented to the atmosphere. According to Howart et al., one of Shell's engineers has given a statement that "*Shell never flares gas during well completion in Pennsylvania*". (Howart et al. 2011) Furthermore, according to the Lavoie et al.'s (2017) study, natural gas power plants release 21-120 times more methane than previously has been estimated. The primary source of methane emissions may originate from non-combustion which partially explains why emission factors (EFs) appears so low. The breaking point for NG leak is about 3% of throughput. Bigger leak than 3% will cause a bigger climate effect than burning coal. However, Lavoei et al. (2017) have estimated that leak rate in the whole NG supply system is approximately 1.7% of production. So, total emissions are still below the 3% threshold. (Lavoei et al. 2017)

Table 4 lists some general guideline for substance disposal methods in the process industry.

Table 4: Typical guidelines for substance disposal methods (Adapted from Nolan 2014).

Substance	Vent	Flare	Process	Sewer
Process Vapors (Combustible, non-toxic and toxic)		X	X	
Process Vapors (Noncombustible and toxic)		X	X	
Process Vapors (Noncombustible and non-toxic)	X			
Steam	X			X
Sewer vapors	X			
Liquids				
Process blowdown			X	X
Thermal relief			X	X
Process drain				X
Surface runoff				X

As Table 4 shows, the acceptable disposal methods for hydrocarbons are either flare or back-to-process process option. The table does not provide any listed disposal method for liquids. However, liquids can be evaporated. According to Nolan (2010), process vapors, which are equal to fuel gases, should not be directly vented to the atmosphere due to following reasons:

1. A combustible vapor cloud (plume) may be formed with fire or explosions possibilities
2. It may pollute the environment
3. Vented material is both economic loss and matter loss
4. Harmful health effects both long-term and immediate
5. Poor public image or community is represented
6. Environmental and governmental regulations both local and national
7. Harmful effects, for example, a toxic effect or ignite.

Furthermore, different aspects are affecting the spreading of hydrocarbons after physical releases, such as (Wärtsilä 2017a):

- Gas pressure
- Depth of transmission pipes
- Placement of pipes
- State and property of the ground and soil
- Terrain
- Weather conditions
- Placement in building and way of construction.

The pressurized fuel gas is released as a gas jet and it may be directed in any direction depending on the environment. Different surrounding structures and equipment may deflect all or part of the gas. Often very turbulent flow of released gas will easily mix with the air. This reduces the velocity of the discharging gas jet. Various obstacles (e.g. end piece of the pipe, structures or pipe racks) are disturbing the momentum forces of the gas jet. The release forms a vapor cloud that normally disperses into the atmosphere if it is not ignited. However, the hydrocarbon cloud might ignite later causing the explosion in a relatively confined area. Congestion, wind, and high-pressure flow will spread the gas in both vertical and horizontal dimensions while the gas is continuously mixing with the oxygen of the air. The discharging gases are initially too rich to catch fire, but with turbulence effects and dispersion, the cloud will achieve the flammable limits (LEL & UEL) rapidly. (Nolan 2011)

2.2.1 Possible consequences of hydrocarbon accidents

Before combustion process can occur, hydrocarbon substances must first be in vapor condition. This an inherent property for any gaseous substances. In some cases, combustion process of liquids will occur if significant vapor emission rates for flammable molecular concentration are presented. Therefore, gaseous hydrocarbon releases are relatively more dangerous than liquid hydrocarbon releases. (Nolan 2011)

Flash point, limits of flammability, auto-ignition temperature, gas group, and vapor density are the risk parameters of the gas or vapor explosion. The lowest temperature where the gas or vapor ignites and where the flame is spreading across the liquid pool surface is called the flash point. It is not relevant for LPG or NG because of their capability of forming to the flammable mixture at any temperature. Auto-ignition temperature is the lowest temperature where combustible fuel mixture can spontaneously ignite. If the substance is heated before burning in the air, ignition temperature should have been noted. (Jespen 2016)

The minimum molecular concentration of vapor or gas where the flame propagation can occur after ignition has been affected is defined by LEL value. This is an important parameter when one determines, for example, hazardous areas. Further information about hazardous areas in *Chapter 3.2.2.* (Jespen 2016)

Different types of hydrocarbon fires are listed below (Nolan 2014, pp. 87-90):

- Jet fire
- Pool fire
- Flash fire

Jet fire is caused by combustion of gas or a liquid continuously released under-pressure for example from a high-pressure gas pipe. That creates turbulent diffusion flames in a particular direction. (Nolan 2010, pp. 68)

Pool fire is also turbulent diffusion fire where flammable vapors of the liquid or condensed gas are burning above the liquid pool surface and increasing fire area rapidly. The convective heating of pool fire is much less than convective heating of jet fire. (Nolan 2014, pp. 88-89)

The flash fire is caused by the intense and sudden ignition of flammable gas, vapor or mist cloud. However, the flame speed of the flammable cloud is not high enough to explode to the lack of confinement. The thermal radiation and fires cause the greater part of the damage because the flame moves at subsonic velocity. The flash fire does not produce an overpressure, but it will damage structures. (Nolan 2014, pp. 89)

According to **ISO9886 (2004),** human body reaches pain threshold at 43°C skin temperature. For safety reasons, escaping could be possible only if the pain threshold is reached in less than 2 minutes. In that case, performing incidence related activities are not possible. (IFV 2016) Further details about effects and consequences of fires and explosions are found in ***Appendix A***.

Combustible vapors have two different explosive mechanisms: detonations and deflagrations. The differences between these are the speed of the flame and pressure. The deflagration is the most common mechanism, and here the flames propagate at subsonic speed. The pressure may be 4-5 times bigger than starting pressure. In a detonation, the flames are traveling at supersonic speed, and pressure may reach at best 15-20 bar(g). (Jespen 2016, pp. 185) Different types of explosions are listed below:

- Process system explosion (detonation)
- Vapor cloud explosion
- Boiling liquid expanding vapor explosions (BLEVEs)

Any non-flammable or flammable liquefied vapor can cause a BLEVE. The liquid will vaporize rapidly, and vapor will remain expanse in a vessel rapidly in BLEVE. (Shaluf 2007) BLEVEs are classified into three different types, see Table 5.

Table 5: Types of BLEVE (Adapted from Shaluf 2007).

Type of BLEVE	Caused by
Cold BLEVE	Spontaneous catastrophic failure: *Tank weakness, corrosion, fatigue or flaw construction*
Hot BLEVE	Superheating limit explosion initiated by sudden pressure drop (i.e., finite failure), leading to catastrophic failure: *Pressure relief valve set too high or not sized properly to keep pressure below set pressure*
BLEVE	Catastrophic failure initiated by finite failure: *Boiling response to rapid depressurization results in crack propagation and tank failure*

BLEVE can also cause a hazardous fireball which is very hot, large and elevated cloud of burning vapor or gas which is moving in the atmosphere on currents of air. It emits intense thermal radiation over long distances igniting all combustible material in its path. The cloud will not explode if it is enriched above the UEL. According to Shaluf's (2007) article, the world has verified 74 BLEVE incidents which caused 635 injuries and 1,427 fatalities in the period between 1926 and 1986. (Shaluf 2007)

Estimation of an explosion is a difficult task, and the consequences will depend on (Jespen 2016):

- Type of oxidizer and fuel
- Fuel concentration and size of the flammable cloud
- Intensity of ignition source
- Location of ignition point
- Location, type, and size of explosion vent areas
- Size and location of structural equipment and elements
- Various mitigation schemes

Table 6 lists general hazards of fuel gases under typical process conditions and operations:

Table 6: General hazards of fuel gases under normal process conditions and operations (Adapted from Nolan 2014).

Commodity	Explosion	Pool fire	Jet fire	Smoke
Methane	X		X	
LNG	X	X	X	
Propane	X		X	
Butane	X		X	
LPG	X	X	X	X

Table 6 shows that all of the listed commodities have optimal properties for the explosion, even though air and propane mixture is well-known to be a bit more reactive creating higher overpressure than air and methane mixture. (Nolan 2014, pp. 94) However, air and the natural gas mixture will probably explode when all of the following items are valid (Nolan 2014, pp. 96):

- Obstacles create turbulence.
- The flame front accelerates to high velocities if the area is large enough.
- The acceleration of flame front requires at least 100 kg flammable mass.

Moreover, as Table 6 shows, the byproduct of LPG fires, and most of the fossil fuels, for example diesel fires is smoke. The combustion process in other commodities is so clean that there is no byproduct such. Narcotic gases, such as carbon monoxide (CO), CO2 and hydrogen cyanide (HCN), cause the main dangers of smoke for human respiration. (Nolan 2014, pp. 98)

The combustion process needs several principal elements to keep up the fire, or it will be extinguished. Especially, different flammable materials, such as dust, might boost the combustion process and help it to spread. (Nolan 2014)

According to Hemmatian et al. (2013), LPG is one of the most critical substances involved in domino accidents. Figure 3 illustrates the main origin of domino accidents.

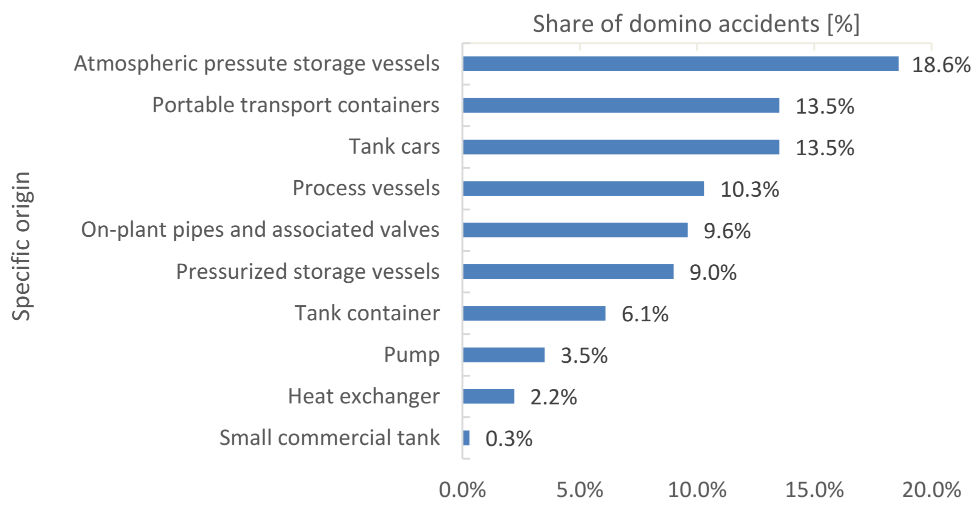


Figure 3: Specific origin of domino accidents (According to Hemmatian et al. 2013).

Mechanical failures, such as overpressure, leaking, corrosion or relief valve failures were the root causes of the accidents. (Hemmatian et al. 2013)

According to Nolan (2010), "*general fire and explosion protection engineering philosophy*" in order of importance should be following:

1. The immediate exposure to hazardous consequences, e.g. fire and explosions should be prevented.
2. Inherently safe facilities should be provided.
3. The objective and prescriptive requirements of governmental regulations and laws should be met.
4. An acceptable level of hazardous risks (e.g. fire and explosion) to the general public, the employees, local and national government, the allied industry, and the company and its stakeholders should be achieved.
5. The company's economic interest (both short-term and long-term impacts) should be protected.
6. An organization's guidelines, standards, and policies should be complied with.
7. The interest of business partners should be considered.

8. A cost-effective and also practical approach should be achieved.
9. Space implications should be minimized.
10. The operational needs and desires should be responded.
11. The reputation and prestige of the company should be protected.
12. The deliberate opportunities for terrorist incidents or employee or public-induced damages should be eliminated or prevented.

2.2.2 Health and environmental impacts of releases

According to World Health Organization (WHO), air pollution is a major environmental risk to health. Countries can reduce the burden of disease by lowering levels of air pollution both long- and short-term. Lung cancer, heart disease and both acute and chronic respiratory disease are just examples. (WHO 2017)

Particulate matter (PM) is affecting to more people than any other pollutant. Nitrates, sulfate, ammonia, black carbon, sodium chloride, mineral dust, and water are the major components of PM. Exposure to high concentrations of small particles will increase mortality and morbidity. Even shallow concentration of the small particles has health impacts. (WHO 2017)

Ozone (O_3) is formed in the troposphere as a result of a complex set of reactions that involve volatile organic compounds (VOCs) and nitrogen oxides (NOx). Excessive ozone pollution in the air can have a marked effect on human health. It can trigger asthma, cause breathing problems and lung diseases and also reduce lung function. Currently, it is one of the major concern in Europe because of the increase in rates of daily mortality and heart diseases. (WHO 2017)

Nitrogen dioxide (NO_2) and Sulfur dioxide (SO_2) has also health impacts. Long-term exposure to NO_2 is increasing the symptoms of bronchitis in asthmatic children. Also in the Europe and the U.S. growth of reduced lung function is linked to NO_2. SO_2 can cause different respiratory system diseases and irritation of the eyes and also affect the function of the lungs. (WHO 2017)

Environmental effects and impacts can be categorized to local, regional and global zones. (Beccari et al. 2005b) A more exact division is shown in Figure 4.

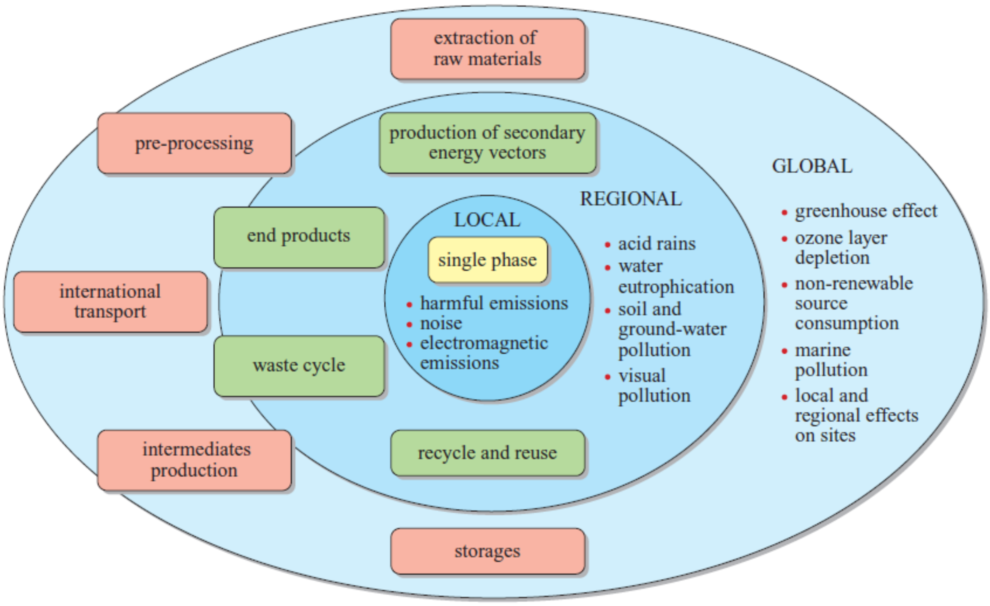


Figure 4: Environmental effects (Beccari et al. 2005b).

One of the environmental concerns is the climate change which is caused by increased amounts of greenhouse gases (GHGs) in the atmosphere. The two most important GHGs are CO_2 and water vapor. Other powerful GHGs are methane (CH_4) and nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). (Edenhofer et al. 2014) According to Antes et al. report, propane is not a direct GHG when released into the air. Propane vapor is chemically reactive, and commonly it is removed by natural oxidation in the sunlight or flushed down by precipitation. Propane vapor is withdrawn from the atmosphere faster than it has any impact on global climate or becoming well mixed. So, propane emissions are not connected to the global climate impacts. (Antes et al. 2009)

Researchers believe that only long-term solution to limit the rise in global temperatures is to halve global emissions of greenhouse gas. The EU committed itself to reducing overall GHG emissions by at least 20% by 2020 compared with 1990 levels. (Eurogas 2017)

Even though the main component of NG is methane, it still has clean-burning properties as a fuel and also low content of pollutants in the combustion process. Emissions from combustion process are extremely low when operating the engine in gas mode operation. The specific carbon dioxide emissions are typically reduced by 20%, and nitrogen oxide (NOx) emissions are reduced by 85-90% if compared with heavy fuel oil (HFO) or marine diesel oil (LFO) operation. At the same time, particulate emissions and Sulphur oxides (SOx) are almost eliminated. (Woodyard 2009)

However, the emissions from engines' tailpipes and smokestacks do not give a realistic view of emissions. There is always a risk of, for example, leakage of the methane when the natural gas is produced or transported in the pipelines. Reshetnikov et al. have listed the three primary sources of gas emissions from NG industry:

1. Emissions from the pipeline network systems which are high pressured and long-range transportation of the natural gas, for example, leakage from underground NG storage capacities and at linear parts of pipeline networks and all kind of repairing and maintenance of the compressor stations and pipelines.
2. Emissions from the gas producing, for example, flaring and venting of the gas at wells (Emissions from the process).
3. Emissions from distributing the gas to the end users in the low-pressure network (Emissions from leakage). (Reshetnikov et al. 2000)

Researchers have estimated that range of 2.3-7.7% of the methane produced at one of the US fields was escaping to the atmosphere. This range of values is not including the additional losses of the pipeline or distribution system. (Tollefson 2012) It has also been estimated that the leakage of methane during transporting of the natural gas in Russia is ranging from 1.0% to 2.5%. In the US losses are ranging between 1.0% and 2.0%. (Lelieveld et al. 2005) Moreover, the end users' possible pipeline system from the pipeline network through the engine might leak, vent or let the methane go through without combustion process (Wärtsilä 2017a).

Figure 5 shows the emissions of the fossil fuels which are suitable for energy production of the industry.

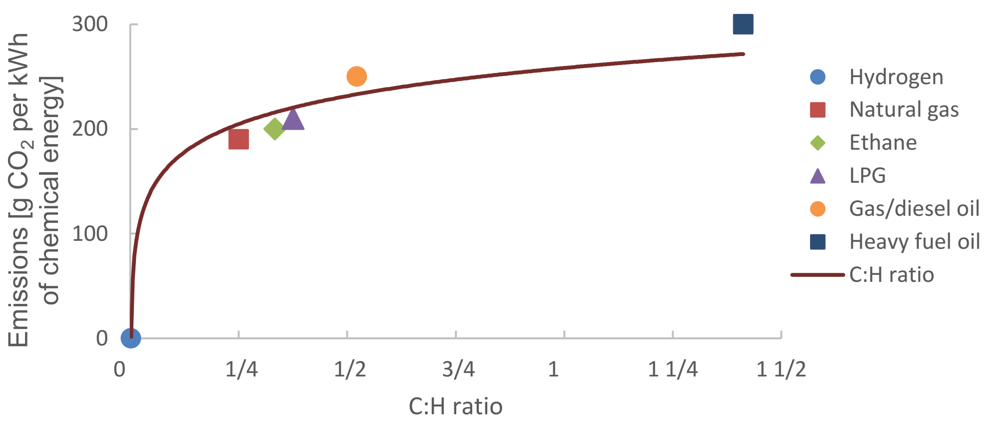


Figure 5: Emissions of fuel combustion (According to MacKay 2008).

Figure 5 shows that emissions are depended on the C:H ratio of substance. CO_2 emissions are formed from the carbon molecules. Carbon dioxide emissions of natural gas are the lowest in relation to the comparison fuels. Due to the hydrocarbon composition of the methane, carbon dioxide emissions of the burning natural gas are approximately 25-30% lower than on oil and 40-50% lower than on the coal. Particulate emissions, heavy metal emissions and ash formation also are non-existent, thanks to the gaseous form of the fuel. (Eurogas 2017) For other emissions of combustion gas, the emission values of natural gas and liquefied petroleum gas can be supposed approximately to be the same. Other fuels, such as wood and coal, which have a considerably higher C:H ratio, get only little bigger emission values, due to the exponential trendline.

3. GAS SYSTEMS FOR POWER GENERATION

The following chapters introduce a distribution network of natural gas, and gas power plants by describing the basic principles and the overall path from the natural gas source to the end-user. The transmission network together with the power plant creates the gas systems in this study.

One of the basic requirements for life on Earth is an energy source. For example, photosynthesis transforms sunlight into food and food is stored energy for organisms. Still, the only limited amount of energy is available for our use, such as solar power. Because of that, all of the available energy will be used. The key question is *how* it is used.

The most common way of utilizing gas as an energy source is to burn it, so the stored energy will be free. (Wärtsilä 2017a) Figure 6 shows the total energy consumption internationally by different energy sources, see Figure 6.

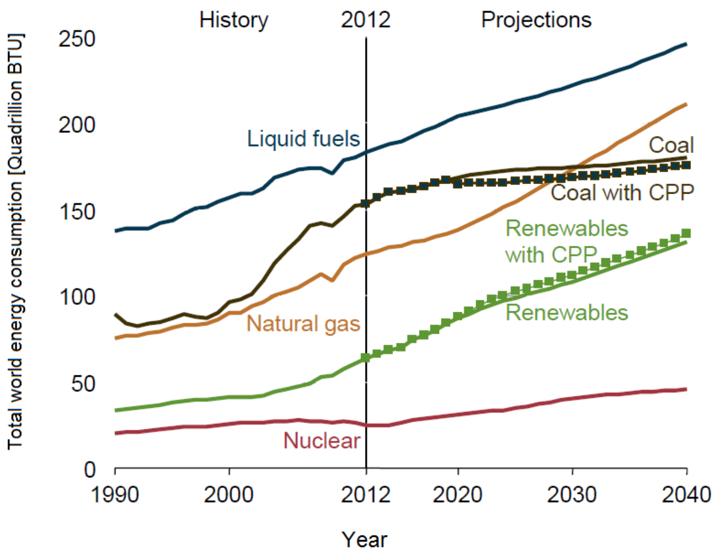


Figure 6: Total worldwide energy consumption by various energy sources (Adapted from EIA 2016).

As shown in Figure 6, and as Mokhatab et al. have mentioned in their article, over the past two decades, natural gas trade and consumption have been increasing steadily. NG has also strengthened its position in the world energy statistics even the economic slowdown declined demand of the natural gas in 2009. (Mokhatab et al. 2015) Global energy trend of energy sources is that use of the solid fuels will decrease at the same time when the use of the gaseous fuels will increase. (EIA 2017b)

3.1 Natural gas transmission network system

The purpose of this chapter is to introduce where the fuel gases are from and how these gases are transferred, for example, to a power plant. The chapter helps to figure out the pipeline infrastructure and complexity of it. This helps the reader to recognize the overall picture later in results.

The natural gas industry is a fast-growing infrastructure. NG can be transported as either CNG or LNG. Pipeline network is used to transport different oil products, for example, natural gas, from supplies to the end users. The natural gas network can also transport biogases, but biogases need upgrading before the injection into the network. The gas industry performs the transportation. (BP 2017)

According to the BP's statistical review, the proven worldwide reserves of NG were 186.9 trillion cubic meters in 2015. The reserves will cover the current production for 52.8 years. Distribution of proved gas reserves was in the Middle East 42.8%, in Europe and Eurasia 30.4%, in Asia Pacific 8.4%, in Africa 7.5%, in North America 6.8% and in South and Central America 4.1% in 2015. (BP 2017)

3.1.1 Overview of transmission network system

Natural gas transmission path from the wells to the end-users involves a series of pipelines because the transport distance from a supply to the end-user may be thousands of kilometers. At the moment, technologies used to transport the natural gas to the market are gas pipeline system and LNG transportation. (Mokhatab et al. 2012) Figure 7 shows all of the commercial and potential technologies.

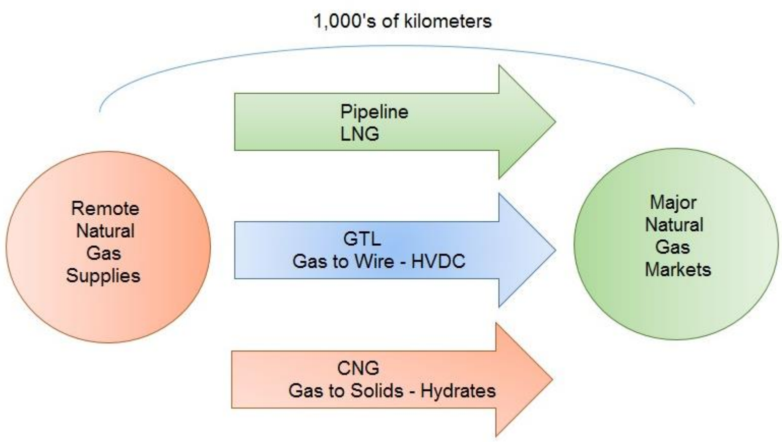


Figure 7: Alternative methods of moving gas to market (Adapted from Mokhatab et al. 2012).

Fully commercial technologies in Figure 7 are pipeline and LNG technologies. GTL (Gas to liquid) and Gas to wire – High-voltage direct current (HVDC) technologies are commercial, but requiring technology development to improve efficiency. CNG and Gas to Solids – Hydrates are in research and development stage. They are not commercial, and projects are not yet sanctioned. (Mokhatab et al. 2012) According to the Beccari et al. (2005a), both distance and gas volume are affecting to cost of the transport. Figure 8 shows the best options for the industry for onshore transport natural gas to market, based on volume and distance, see Figure 8. It is based on in-depth studies of energy, finance and politics to get the most appropriate technologies for the utilization of gas fields located in remote regions (Beccari et al. 2005a, pp. 772).

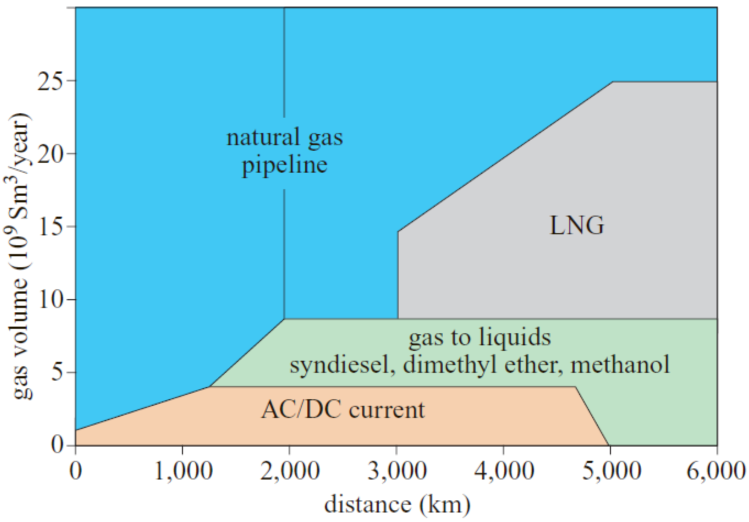


Figure 8: The best options for industry for onshore bringing gas to market (Beccari et al. 2005a, pp. 772).

As can be seen in Figure 8, the transportation of LNG is not lucrative if onshore transport distance is less than 3200km. (<1600 km offshore). LNG is usually more attractive economically with distances, which are greater than above-mentioned due to the high initial investment costs. (Durr et al. 2005)

The main function of natural gas pipeline system is transport natural gas from various sources (e.g. from wells) to the end users through a network of pipeline segments and interconnected pipes. The transmission pipelines of the network include flowlines and lines for gathering, transmission, distribution, and service. Generally, the gas pipeline network system consists of pipelines, gas and liquid storages, pump and compressor stations and other needed components for the operations for example valves. (Melaina et al. 2013) Figure 9 shows the pipeline system overview from sources to the end users.

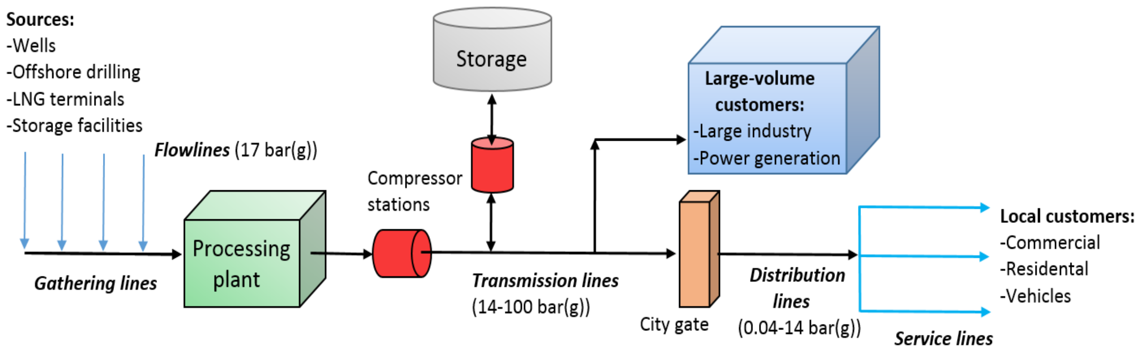


Figure 9: Natural gas pipeline system (Adapted from Melaina et al. 2013; Ríos-Mercado et al. 2015).

As can be seen in Figure 9, the network includes three major types of pipelines: gathering, transmission, and distribution lines, which are usually buried underground. The main differences between the pipeline systems are the specifications of minimum and maximum downstream and upstream pressures and their physical properties, such as diameter, material, and stiffness. The diameters are ranging from 100 mm to 1220 mm. (Ríos-Mercado et al. 2015)

Raw gas is gathered and produced from natural gas or oil fields. The wells and fields of NG are the starts of the natural gas pipeline system. Gathering lines collect the gas from multiple flow lines and transfers the flow of the gas through a processing plant after the gas has left the producing source. (Melaina et al. 2013) The flowlines are typically working on around 17 bar(g) and are buried 1.2 meters underground (Ríos-Mercado et al. 2015). The processing plant removes gases such as propane and LPG, water vapor and other undesirable substances if the initial quality of the product is not satisfying for the use as a fuel. (Melaina et al. 2013)

Transmission lines convey the gas across long distances to or from compressors to a storage or distribution facilities. (Melaina et al. 2013) Transmission lines are typically working on at a pressure of approximately 14 bar(g) to 100 bar(g). The pipeline transmission network is pressurized by using compressor or compressor stations to maintain the pressure difference for moving the gas. (Melaina et al. 2013) Often station consists of multiple types of compressors or compressor units depending on the size of the stations. The size of stations, as well as a number of compressors or units, is depending on the flow of the gas in the pipeline. (EIA 2007)

The gas pressure in the pipeline decreases quickly due to frictional losses, so compressor stations are usually located every 80 to 160 kilometers. (PST 2015) The main types of the compressors units are either centrifugal or reciprocating type of compressors which receive the gas at pressures between 14 bar(g) and 40 bar(g) and compresses it up to 70-100 bar(g). (Mokhatab et al. 2012; Ríos-Mercado et al. 2015)

Distribution and service lines do not include further compression. Compressor stations of transmission line systems compensate for all friction losses along the entire transport path. Because of high pressure of the long-distance transmission pipelines, the end users have to reduce the pressure for their needs by using pressure reduction stations. The end user can be a local customer or large-volume customer (Melaina et al. 2013) Distribution system to the local customer usually work at a pressure of around 0.04 bar(g) up to 14 bar(g) and operates below their capacity for safety reasons (Ríos-Mercado et al. 2015). The end user in this study is a large-volume customer who produces electrical power.

A gas network system may vary in size significantly in different countries. For example, in the U.S. a wide gas network system may extend several hundreds of pipelines all over the country and tens of compressor stations. However, these large pipeline networks are typically divided into subnetworks from the market standpoint. Each subnetwork is assigned to a specific gas operator who is cooperating with other operators and handling all the gas contracts. Then again, transmission network in Belgium is much more restricted when compared for example to the U.S. or Russia. Belgium has only 20-40 pipelines and 4-8 compressor stations. (Ríos-Mercado et al. 2015)

3.2 Gas engine power plants

The purpose of this chapter is to introduce what type of power plant is using the fuel gases. The chapter helps to figure out the fuel system of the power plant. It also helps the reader to recognize what has to be taken into account when designing systems which are using previously described fuel gases.

Case company’s gas and multi-fuel power generation plants are solutions for baseload, intermediate, peaking and standby operations. Power plants are based on internal combustion engine units which are typically 4-19 MW multiple units. The gas power plants can run on NG, LPG and various biogases depending on the used engine type. (Wärtsilä 2017d) Figure 10 illustrates a simplified scheme of the gas power plant, see Figure 10.

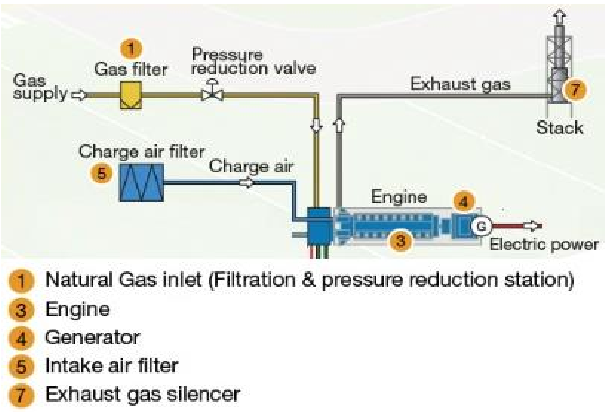


Figure 10: A simplified scheme of gas-fired power plant (Adapted from Wärtsilä 2017d).

Figure 10 shows how natural gas flows from the pipeline system (Gas supply) to the power plant area through the gas filter and pressure reduction station before the engine can use it. Engines, generators and auxiliary modules are surrounded by steel structure building creating the engine hall. Engines and systems are operated and monitored from the control room and utility block. Exhaust gases go to the exhaust gas silencer stacks which are located outside the engine hall. The power plant area can also include for example different tanks, treatment systems, pits, radiators, pipelines, roads, etc. Overall picture of a power plant site is shown in Figure 11. (Wärtsilä 2017d)

Figure 11: Example of site area (Adapted from PEi 2016).

A layout of the power plant might vary depending on the site.

3.2.1 Fuel gas system

The purpose of the fuel gas system is to provide the engine with a continuous and reliable supply of clean fuel gas at the required pressure depending on the engine load. The fuel gas system for Wärtsilä spark ignited gas (SG), and dual fuel (DF) gas engines contain the following parts or subsystems (Wärtsilä 2017b):

- Gas piping
- Gas main shut-off valves
- Gas regulating unit

Option parts or subsystems are the following (Wärtsilä 2017b):

- Flow metering unit
- Gas pressure reduction station (GPRS)
- Low-pressure gas compressor unit
- Gas filtration unit

Figure 12 illustrates the gas path through the fuel system to the engine. The engines and compact gas ramps are located inside the engine hall.

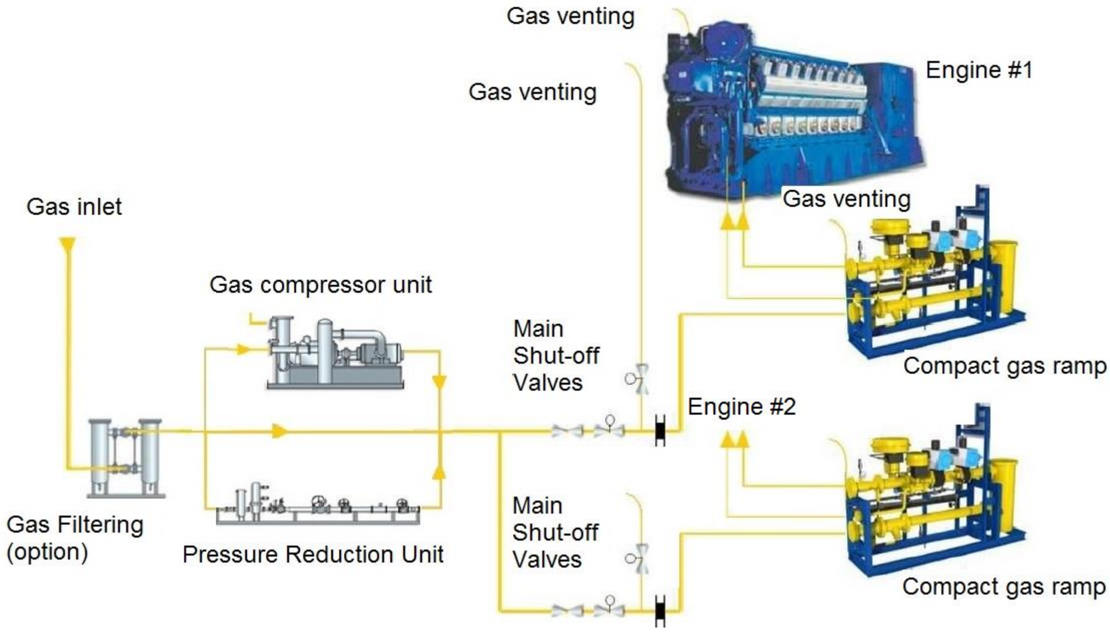


Figure 12: Process diagram of fuel gas system (Adapted from Wärtsilä 2017b).

Each component has its own function. Gas filtering unit determines the quality of the gas by separating dust and solids from gases to protect following devices, such as pressure regulation units and engines. On-demand gas compressor unit or pressure reduction station are adjusting the operating pressure before the main shutoff valves, typically 8 bar(a) on NG. The compact gas ramp is adjusting the gas pressure to the engine depending on the load of the engine. A gas vent is used to depressurize and vent different parts of the fuel gas system, either for operational or safety purpose. Each fuel system, after the main shut-off valves, contains three (3) gas venting pipes, which are releasing unburnt fuel gas to the atmosphere for above-mentioned reasons. (Wärtsilä 2017b)

3.2.2 Safety in design

Safety in design covers whole lifecycle and all stages of it. Figure 13 shows all of the affecting safety factors for plant design.

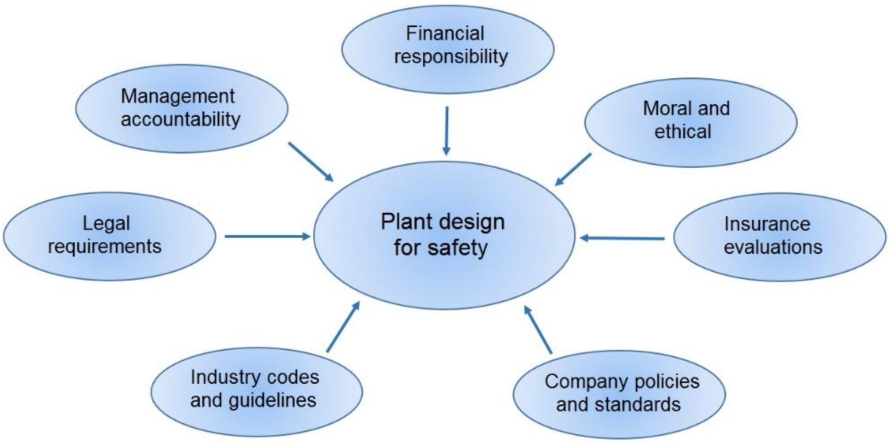


Figure 13: Safety in plant design (Adapted from Nolan 2010).

As can be seen in Figure 13, there are many variables which affect the unity of safety. Depending on the situation each of these has their own weight value (Nolan 2010).

According to Nolan (2010) some of the related safety features in the process industries are following:

- Process safety priority
- Avoidance of atmospheric releases
- Minimization of leak points
- Piping protection
- Spacing
- Utilization of industry standards

Risks can be minimized by using different safety studies, such as Quantitative Risk Assessment (QRA), Fire and Explosion Risk Analysis (FERA), Hazard Identification (Hazid), Hazard and Operability Study (Hazop) or Layer of Protection Analysis (LOPA). According to Puskar (2013), some of these risks can be minimized by using different methods to describe the overall safety level and risks of the system, for example, safety instrumented systems (SIS) and safety integrity levels (SILs). SIS as the overall system may contain safety instrumented functions (SIFs). Each SIF has own SIL. The SIL describes from 1 to 4 the SIF's probability of the failure. 1 is the highest level. (Puskar 2013)

Standards and directives

Standards are for keeping safety at its current level. Standards are also reducing costs of construction and operation. At the same time, they also improve inter-operability for example of gas systems. Figure 14 shows technical responsibility.

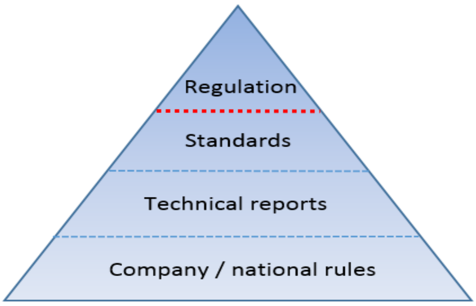


Figure 14: Technical responsibility (Adapted from Marcogaz 2013).

Figure 14 shows that rules, reports, and standards are supporting the regulation.

International, European, and national organizations have the authorization to confirm the content of the standard. International Organization for Standardization (ISO) approves standards with ISO prefix. EN prefix represents standards which are approved by European Committee for Standardization (CEN). Finnish Standards Association approves standards with SFS prefix in Finland. The majority of SFS standards are originally EN standards. Prefixes can be combined, for example, SFS-EN, when the standard, in this case, is valid in Finland and also in Europe. (SFS 2017)

The standards concerning the natural gas are SFS-EN standards which present acceptable technical solutions in Finland and Europe. These standards are mainly relatively general, and the purpose of instructions is to simplify various actions. The latest edition of standards is usually a starting point. Standards include the actual text and appendices. The appendices can be the essential part of the standard and guide the second appendices. (SFS 2017)

Standards related to the NG are shown in ***Appendix B.*** The majority of European standards of industrial gas installations are shown and listed in ***Appendix C.***

Fuels such as NG have safety standards which have created by a group called the National Fire Protection Association (NFPA). NFPA provides and advocates standards and consensus codes, conducting research, education, and training to reduce the burden of fire and other hazards internationally. The following codes are related directly to fuels (Puskar 2013):

- **NFPA 54**, the National Fuel Gas Code
- **NFPA 31**, the Standard for the Installation of Oil-Burning Equipment.
- **NFPA 58,** the Liquefied Petroleum Gas Code

NFPA 54 is a safety code for example installation of fuel gas appliances, piping systems, and related accessories. **NFPA 31** covers liquid fuels' storing, supply pipes and installation of stationary appliances. **NFPA 58** applies the use and storage of liquefied petroleum (LP) gases. (Puskar 2013).

Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA), which are federal U.S. agencies, have main legal requirements for the management of process safety. The main industry standards include NFPA Fire Codes, API Recommended Practices, and Center for Chemical Process Safety (CCPS) guidelines. (Nolan 2010)

Density, explosive limits, and flash point of vapor and gas are the essential characteristics for hazardous area zone classification. (Jespen 2016, pp. 26) The objective of the EU's area classification (ATEX) is to avoid the installation of unsafe devices in areas where they can cause an explosion risk. ATEX name comes from ATmosphères EXplosibles (Wärtsilä 2017b). Various hazardous area standards are listed in Table 7.

Table 7: Different hazardous area standards by region (Adapted from Wärtsilä 2017b).

Region	Standard
EU	ATEX - Based on the IEC Standards
USA	NFPA 70 "NEC", articles 500 & 505
Others	IEC, API 500 & 505, local standards

The duration of the explosive atmosphere depends on zone classification. Table 8 describes zone definitions and durations.

Table 8: Classification of hazardous locations as stated in ATEX directive 1999/92 and durations of explosive atmosphere (Adapted from Jespen 2016).

Zone	Description	Duration of explosive atmosphere
0	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is present continuously or for long periods or frequently.	>1000 hours/year or >1hour/shift
1	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is likely to occur in normal operation occasionally.	10-1000 hours/year
2	A place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapor or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only.	1-10 hours/year or <1 min/shift

According to Hartwell et al. (2017), classification of hazardous locations and durations of explosive atmosphere shown in Table 8 are consistent with **NEC 505**.

4. FUEL ENERGY STORAGE FACILITIES

The heat content of, for example, methane can be stored by using liquefaction, compression, or adsorption process (Chang et al. 2013). The following *Chapter 4.1* gives the reader an introduction to long and short-term storages of natural gas in the pipeline network. Next chapters after that focus mainly on large-volume customer's own recovery fuel energy storage facilities. These three different solutions also are working as starting points for this study in the examination of the optimal system.

4.1 Overview of pipeline network storage facilities

The purpose of this chapter is to introduce to long and short-term storages of natural gas in the previously described pipeline network. The chapter helps the reader to recognize the difference between network storages and later described end-user storages.

Different fuel gases, such as natural gas, are stored and withdrawn for a number of various reasons. It is used to meet typical demand, unanticipated supply shortage, or as a strategic reserve during a low-priced market. Gas storages and withdrawal processes play a major role in maintaining a stable natural gas market.

Large quantities of natural gas can be stored underground in salt formation caverns, mined underground caverns, depleted gas or oil reservoirs at high pressure or converted to a liquefied natural gas via a cryogenic process. Generally, a lot higher pressures are used for the larger stored volume of gas. Storage facilities can be either baseload or peak shaving facility. (Abraham 2015) Figure 15 shows different types of underground natural gas storage facilities for baseload.

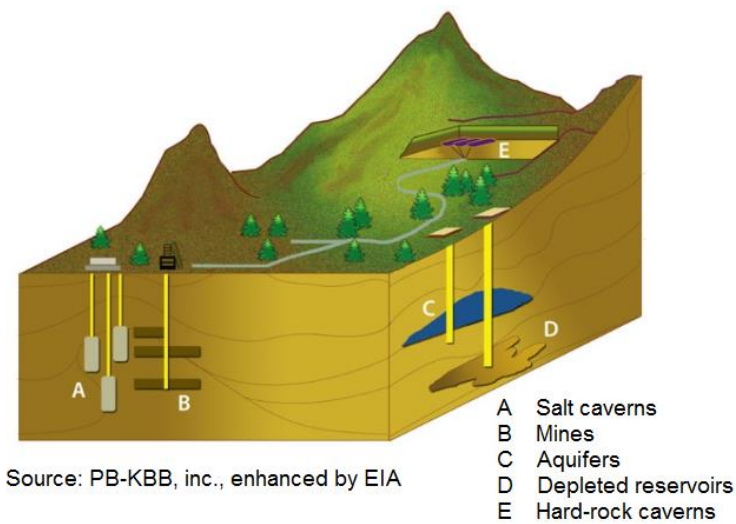


Figure 15: Types of underground natural gas storage facilities (EIA 2017a).

Typically, baseload facility's working capacity ranges from 35 Billion Cubic Feet (BCF) to 100 BCF of natural gas. Whereas working capacity of peak load facility is between 0.25 BCF and 5 BCF of natural gas. Peaking facilities are typically used to meet short-demand peaks where a large volume of natural gas is required for a short period (Abraham 2015)

The withdrawal process of storage is similar to a natural gas gathering application. NG is withdrawn through the same well in which it was originally used. Once the natural gas is withdrawn, it is compressed and sent through pipelines for use for example in power generation. (Abraham 2015)

Storage options, mentioned above, are related to the natural gas transmission network. The following chapters are going through different available storage options for example to end-user.

4.2 Adsorbed natural gas

The purpose of this chapter is to present the first available technology, for storing the hydrocarbons, which can be used by the end-users. The chapter helps to figure out the overview of the technology by describing the theoretical background and available materials.

Adsorbed natural gas (ANG) is one solution for storing the natural gas. Highly porous materials are used to store natural gas molecules at low pressures densely. Different carbon adsorbents can store from 10% to 20% of the total weight at lower than atmospheric pressure onto a surface of the solid porous material. (Wegrzyn 1996)

The amount of usable gas successfully delivered from the storage system is the key when evaluating the performance of ANG storage system. This is generally defined as the volume of gas which is obtained from the storage system when the pressure is reduced for example from 35 bar(g) to 1 bar(g), usually at 25°C. This parameter is referred to as the delivered volume per volume (V/V). The storage capacity is greater than its delivery capacity, typically by about 15%. For some carbons, it might be even 30% because of the significant amount of CH_4, which is held by an adsorbent at less than 1 bar(g). (Cook et al. 1999)

The long-term deliverability of the adsorbent is another criteria of importance. The adsorption of CH_4 on the adsorbent should be totally reversible in an ideal ANG system. However, non-methane species are removed from the composition of NG using guard beds. All of the hydrocarbon gases possess better adsorption potential than CH_4. Often it is thought that pre-adsorption in guard beds targets to these heavier gases. Moreover, the most of the common odorant species also possess greater adsorption potentials than CH_4, for example, ethyl and methyl sulfide. (Cook et al. 1999)

Right chosen adsorbent materials and also design of the tank can help to minimize thermal change problems, which occur during desorption and adsorption cycles. (Cook et al. 1999)

4.2.1 Theoretical background of adsorption

Adsorption is a phenomenon where the molecules of fluids or gases are sticking to the surface of a solid material. The phenomenon is a bulk or volume phenomenon, and the adsorption process strongly depends on temperature. The phenomenon of absorption is totally different where molecules of fluids or gases are dissolving in another solid or fluid substance. So, these phenomena should not be mixed up with each other. The term for both phenomena is called sorption. (Keller et al. 2005) Figure 16 demonstrates the difference of the phenomena based on Keller's book (2005), see Figure 16.

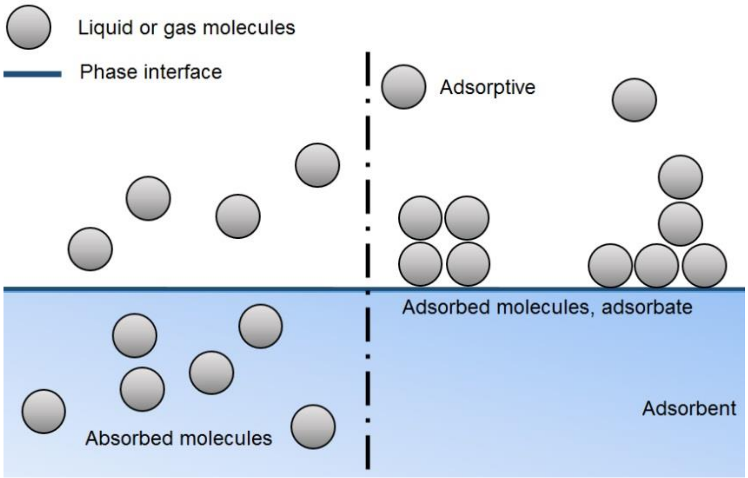


Figure 16: Absorption and adsorption (According Keller et al. 2005).

On the right is shown the adsorption and on the left is shown the absorption phenomena in Figure 16. As can be seen in Figure 16, the difference between the phenomena is evident. Adsorptive is a substance which molecules have the capability of being adsorbed. Adsorbate means the adsorbed substance. The adsorbent is the bulk substance where the adsorption takes place. (Keller et al. 2005)

4.2.2 Adsorbent materials

Different materials with pore structures, such as aluminosilicates, organic frameworks, and carbonaceous materials are adsorbent materials and commonly used for example for storing gaseous fuels. However, other purposes of use exit also. (Zhang et al. 2004)

The three relevant parameters should have been considered when choosing adsorbent materials: specific area, reversibility, and selectivity. The specific area is directly linked to the adsorption capacity, which is approximately 200 for methane by using metal-organic framework (MOF) adsorbents. A pore volume and higher surface area are related to a greater storage capacity. Reversibility considers the ability of the adsorbent to release the adsorbed material during the desorption process and also allowing the regeneration of the material for a new cycle. Selectivity defines the use of given adsorbent which is adjusted to the molecular geometry and the diffusion rate of the adsorbed material. (Feroldi et al. 2016) According to Mason et al. (2014), "*the amount adsorbed is determined per unit mass, not volume, of adsorbent*.".

Table 9 illustrates properties of different adsorbents.

Table 9: Properties of different types of solid materials and their adsorption capabilities of methane from various authors (Adapted from Feroldi et al. 2016).

Adsorbent	Specific area [m^2/g]	Temperature [K]	Pressure [MPa]	V/V
Metal-Organic Framework (PCN-14)	2176	290	3.5	230
Metal-Organic Framework (IRMOF-993)	1892	298	3.6	181
Activated carbon (Mineral carbon)	3290	298	4	166
Zeolite-carbon	932	298	3.5	127
Activated carbon (Coconut shell)	1587	275	3.5	>75
Zeolite-carbon	1127	273	1.013	67.9

The specific surface area (SSA) is the most important factor for adsorbent because the adsorption is a surface phenomenon. Specific surface area [m^2/g] is the total surface area of a solid per mass unit. It is affected by the surface roughness, porosity, and geometry (Zdravkov et al. 2007). The porosity of surface is the most important property for gas storage applications (Zhang et al. 2004). Pore sizes are classified below by the IUPAC, see Table 10. Presence of the pores determines the adsorbed form of CH_4 storage at room temperature and low pressure. These pores must have compatible to the CH_4 molecule. It means that the methane molecule must have approximately twice larger distance between pore walls than the molecule diameter. (Feroldi et al. 2016)

Table 10: Pore size classifications (Adapted from Zdravkov et al. 2007).

Specified types of pore	diameter, d [nm]
Macro	d > 50
Meso	2 < d < 50
Micro	0.4 < d < 2

Even though Table 10 shows the values for specified types of pores, it is not an easy task to define the size of pores exactly. The pore size has not a precious meaning if the geometrical shape of the pores has not been defined and well known. (Zdravkov et al. 2007)

Typically, SSA of activated carbons is between 500 and 3000 m^2/g. The highest experimental value of SSA of MOF according to Farha et al. (2012) is about 7000 m^2/g (Farha et al. 2012). The best possible materials for gas storage applications are MOFs, activated carbons, and zeolites. (Chang et al. 2013)

Activated carbons

Activated carbons, well known as ACs, have high adsorption capacity and good availability because it is the most widely used in the industry. (Feroldi et al. 2016) It belongs to the carbonaceous materials which have potential to store the gas by adsorption (Chang et al. 2013). The most of the carbonaceous materials, typically waste materials like oil palm biomasses are good sources to produce AC. (Rashidi et al. 2017) Furthermore, different raw materials such as food wastes, wood sawdust, synthetic polymers and agricultural wastes are good sources to produce AC (Feroldi et al. 2016). According to that, AC is renewable and artificial carbon product with the wide internal surface area and porous structure which is highly developed. (Sacsa Diaz et al. 2011)

AC has a large adsorption capacity because of the pore volumes and surface area. Surface area is from 400 to 1,000 m^2/g, and pore volumes are up to 0.2 to 1.0 cm^3/g. (Sacsa Diaz et al. 2011) ACs have the highest ANG energy densities and because of that the also highest storage capacities. (Menon et al. 1998)

Metal-organic frameworks (MOFs)

Metal-organic frameworks are crystalline and porous materials that comprise metal or metal oxide connected by organic compounds. Metal oxides are well known as “nodes” and organic compounds as “linker”. (Sacsa Diaz et al. 2011) MOFs’ theoretical limit for SSA is generally 10,500 m^2/g. However, Farha et al. (2012) have theorized limit for the SSA approximately to be 14,600 m^2/g, if not higher. NU-100[31] and MOF-210[30] are the top MOFs for being adsorbents because they are close to ultimate experimental limit for solid materials (Farha et al. 2012)

Other adsorbents

Aluminosilicate materials, such as zeolites, are generally used as adsorbents, but also as molecular sieves and catalysts. Zeolites are the most reported physical adsorbents for CO_2 capture in journal literature and the patent. However, zeolites can easily lose their adsorption capacity for methane with time due to preferential adsorption of moisture. Moreover, SSA of zeolites is a structural limitation, for example, SSA greater than 1000 m^2/g is not attainable. (Menon 1998)

4.3 Compressed natural gas

The purpose of this chapter is to present the second available technology, for storing the hydrocarbons, which can be used by the end-users. The chapter helps to figure out the overview of the technology.

CNG is produced by compressing the conventional NG to less volume than it occupies at the standard atmospheric pressure. It is stored gas at a high pressure, normal pressure or low pressure in purposely designed tanks. Generally, it is stored and transported in a container at a pressure between 200 bar(g) and 248 bar(g), typically in cylindrical shapes metallic cylinders. (Khan et al. 2015) Storage options for compressed natural gas are following:

- Pipeline
- Cylinder(s)
- Spherical tank(s)
- Mounded bullet(s)

Figure 17 shows CNG system for vehicles and system's equipment.

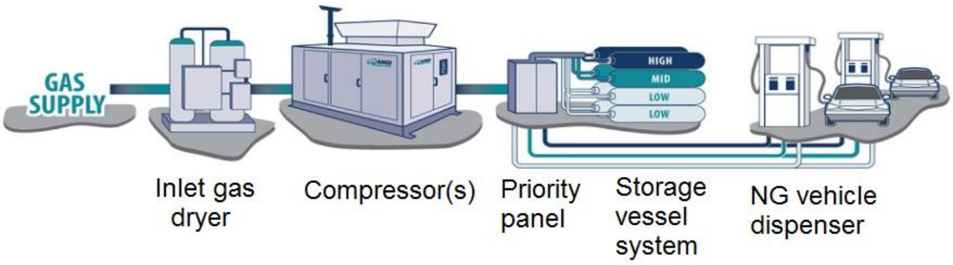


Figure 17: CNG system (Adapted from CNGCenter 2017).

CNG can be stored at high, normal or low pressure in the cylinders. Typically high-pressure cylinders are ranging to more than 410 bar(g). Normal pressure cylinders are between 140 and 175 bar(g). Low-pressure cylinders are in the range of 34 bar(g). Furthermore, natural gas can be stored short-termly in the pipeline system by using a process called line-packing. This kind of storage can be used to optimize the gas pipeline operation. (Frankel 2010)

4.4 Liquefied natural gas

The purpose of this chapter is to present the third available technology, for storing the hydrocarbons, which can be used by the end-users. The chapter helps to figure out the overview of the technology.

Liquefied natural gas (LNG) is the cryogenic liquid form of NG, which is obtained by cooling the NG to -162°C. Typically the natural gas is diverted from a pipeline, pretreated, liquefied and stored until needed. The stored LNG is re-gasified back into the system or transported away in the liquid phase. Figure 18 illustrates the process of a conventional baseload LNG plant. (Lim et al. 2013)

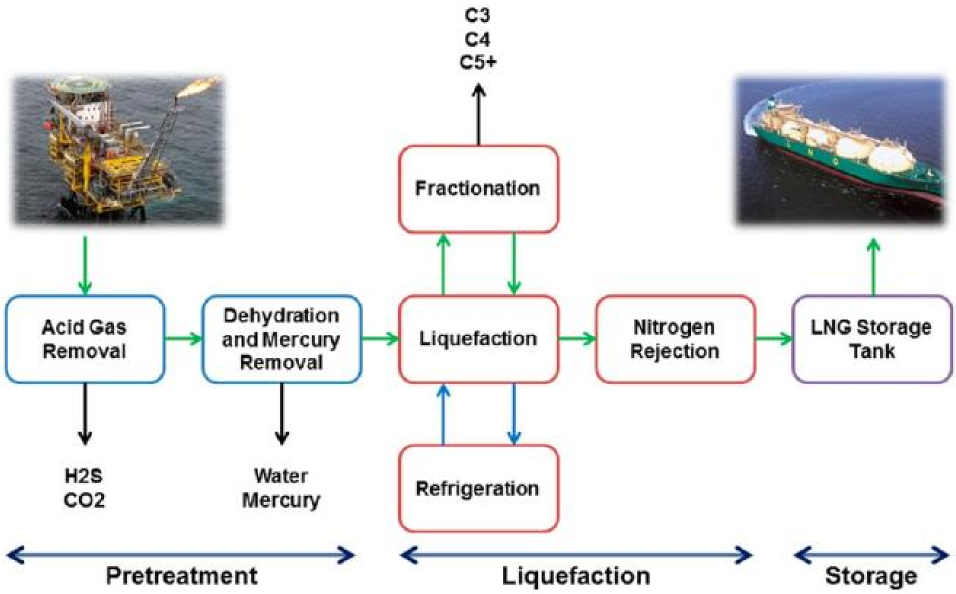


Figure 18: A baseload LNG process (Lim et al. 2013).

Depending on the gas source, the untreated natural gas must be pretreated before it can be liquefied. This process consists of three following steps: 1) Removal of acid gases, such CO_2 that can freeze in the pipelines in certain concentration limits. 2) A dehydration process to remove water from the gases to avoid freezing. 3) Mercury removal to protect the aluminum heat exchangers from corrosion. So the purification process removes variety of impurities such as CO_2, water, H_2S, mercury, hydrogen, nitrogen, Sulphur, oxygen and higher hydrocarbons to prevent equipment damage caused by solids formed during cooling and internal corrosion. (Lim et al. 2013)

LNG can be stored in specially designed tanks. After storing it can be used back to the system by using re-gasification or it can be sold and transported to the customer. Due to the characteristics of LNG, these storage tanks, as well as other associated equipment, should meet the rigorous design standards. (Lim et al. 2013) LNG in the terminal is standard LNG at 1 bar(g) and -163°C. LNG transfer to intermediate storage is cold LNG at 3 bar(g) and -150°C. LNG transfer to the customer is saturated LNG at 8 bar(g) and -130°C. Other option to transfer it to the client is to use subcooled LNG. The easiest solution to create pressure is to increase temperature. (Wärtsilä 2016b)

4.5 Economic methods

The purpose of this chapter is to introduce the theory behind the economic analysis of the selected system. The chapter describes what has been calculated and what equations have been used.

The profitability of the planned investments is dependent on the coming true cash flows in proportion to the basic investment. Investment expenditures, the annual profits and costs, a lifetime of the investment, and imputed rate of interest affect the profitability of the investment. However, in some cases investments must be made for example for safety reasons, or to protect the environment. These investments are called mandatory investments. Investment can also be an expansion investment for the addition of the production capacity. Moreover, by expansion investments, the company can direct to a new market. Other investment types are repair investments and investments to research and development. Repair investments are trying to renew the worn out or damaged capital of the company or attempting to reduce the costs. (Niskanen et al. 2013)

Investment funds are divided into Capital Expenditures (CAPEX) and Operational Expenses (OPEX). All of the funds which are used to upgrade or acquire physical assets like property, equipment or industrial buildings are belonging to CAPEX. Funds which are used on a daily basis, ongoing in order to run a specific system are belonging to OPEX. (Schaschke 2014)

Payback method

Payback time shows how many years it takes before the net yields that have been received from the investment exceed the investment expenditures. So by using payback method, that time when the net yields from the investment are altogether equal to the investment expenditures is determined. Payment time is related to the profitability of the investment. The shorter payment time, the better investment. The payback time does not pay attention to the time value of money. If the time value of money is taken into account, the payback time can be calculated by using discounted payback method, see Equation 2. When the rate of discount is taken account, the payback period is typically longer. (Niskanen et al. 2013)

$$a_{n,r} \cdot NCF = I_0 \quad , \tag{2}$$

where $a_{n,r}$ is present value factor of periodic payments that have been performed afterward (-), r is the discount rate (%), n is investment period (years), NFC is net cash flow at the end of the year (€), and I_0 is initial investment (€).

Net Present Value method (NPV)

According to the investment theory, NPV method is the most recommended accounting method theoretically. The function of NPV is to compare non-simultaneous performances during common time. Investment expenditures are taken off from the estimated Net Cash Flows (NCFs) which are discounted for the present using the rate of discount. Salvage value will be taken into consideration if the investment has some value after its lifetime. (Niskanen et al. 2013)

Present value factor (PV) is calculated following by using Equation 3 (Brealey et al. 2011):

$$PV = \frac{C_t}{(1+r)^t} \ , \tag{3}$$

where C_t is a received cash flow at the end of the year (€), t is a time period in years, and r is a discount rate (%).

Net present value is calculated following by using Equation 4 (Brealey et al. 2011):

$$NPV = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \ , \tag{4}$$

where NPV is a net present value of the investment (€), C_o is an initial cash flow which is typically negative value (€).

Internal Rate of Return (IRR)

The internal rate of return of the investment is the rate of discount where the NPV of investment is zero. Straightforward, in other words, the present values of the cash outflows and inflows are equal. The bigger the internal rate of return is, the more profitable the investment is. (Niskanen et al. 2013)

IRR is calculated following by using Equation 5 (Brealey et al. 2011).

$$NPV = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} = 0 \ , \tag{5}$$

where r is an internal rate of return (%) when NPV is zero.

5. RESEARCH DATA AND METHODS

This chapter describes how this study has been carried out and what has been done. In this study calculations and results are based on different cases. Details about these cases and inputs for calculations are shown in following chapters.

5.1 Research strategy and methods

The study was carried out as a multi-stage process, where the topic is formulated and clarified, the literature is reviewed, the data is collected and analyzed, and finally reported. All of the methods and different references are selected to answer extensively to research questions. The selected strategy of the study was an action research. It involved both empirical and theoretical investigation of the phenomenon using multiple sources.

The literature study and also data of *Chapter 5* are the base for the result. This project had a strong development and the operational presence during the study because of the topical subject. References and thoughts that were received from the literature were combined as one entirety. By doing this, a comprehensive group of justifications for every point of view was obtained. Furthermore, a logical entirety of a theory with empirical are combined. Attention has been paid to the different points of view of the objective of the work. Figure 19 represents the progress of the study in practice.

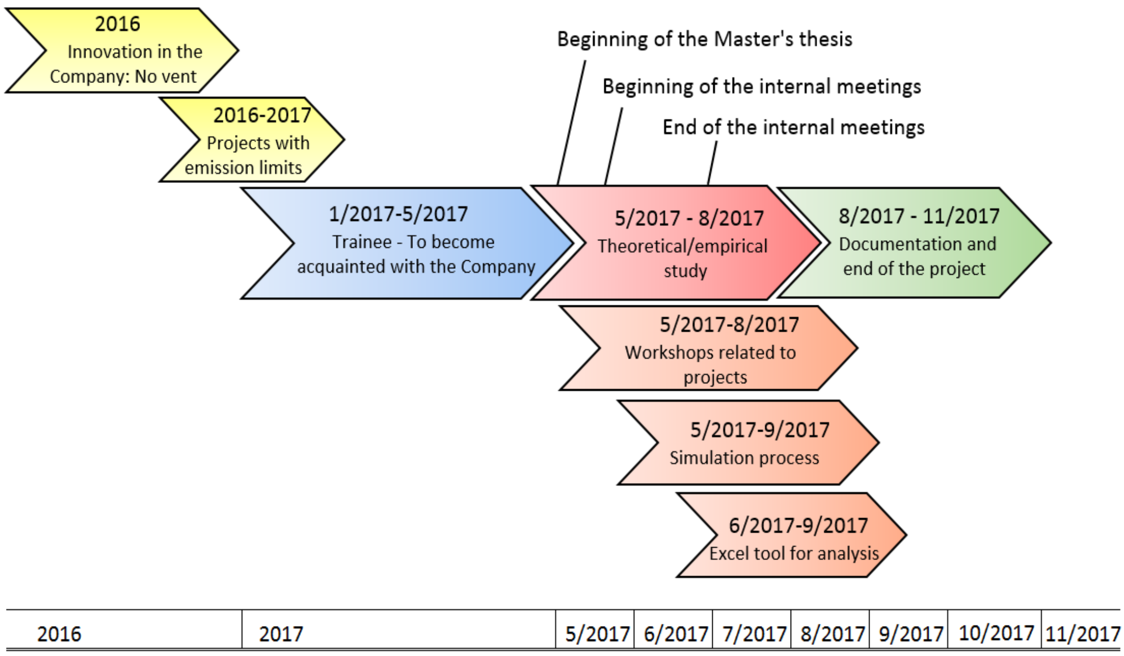


Figure 19: Timeline of the study.

In 1995, on the high-pressure gas system, a blowdown philosophy was already implemented to take vent gases from the system: from 350 bar(g) to 30(g) bar into the partial recovery. During 2015, multiple calculations and safety overviews were done related to the venting setup to get optimal venting times and smaller initial clouds. In 2016, controller of this study got an idea: No venting to the atmosphere with a system approach to integrate vents. Between 2016 and 2017 power plant projects started to have issues with emissions, especially with VOC emissions. (Fältén 2017)

This Master's thesis was launched to support the "no vent" idea. In this study, a theory was examined widely, particularly at the beginning of the study by searching the literature. After this, it was moved to an empiric study by observing project-specific cases.

The material was obtained from the target environment in six different ways: 1) Qualitative study, in more detail functionality study, 2) Evaluation, 3) Active and unstructured interviews, 4) Active observation, 5) Keeping a notebook of ideas, and 6) Simulation.

In functionality study, all of the needed information was gathered from the Company's database, for example dimensioning the fuel system for economic calculations. In evaluation method, the current system was overviewed, and working methods were learned. Active and unstructured interviews were done in internal meetings with the key persons, which were typically the Company's experts. In addition, some external help was used to get background information. In addition to these, discussions and brainstorming sessions with the controllers of the work were actively used. These sessions produced plenty of different thoughts and ideas. The active observation was done in various workshops. Data to the simulation process was gathered from various company's internal sources. The simulation was needed to support analysis of the hydrocarbon releases.

The major information gathering methods were unstructured interviews with the key persons, project specific workshops, results of the excel calculations, and the simulation results. These were primary data sources. The database of the Company was used as a secondary source of data. The information was also gathered by using active observing. Observations and the major points of the workshops and conversations were recorded in the study diary. Moreover, other relevant information, such as Skype calls and meetings, were recorded in the study diary.

The calculation tool was created for economic analyses in Excel. In the excel tool, the user can dimension the fuel system. Based on these dimensions, the tool calculates the mass of the selected fuel inside the fuel system and engines. Different mass amounts are used to calculate the vented mass in the different start and stop scenarios for various plant outputs. Based on results, the tool calculates economic statistics: payback, discounted payback, NPV, and IRR. Additionally, a sensitivity analysis was done by using same calculation tool.

5.2 Case company

This work is carried out in cooperation with Wärtsilä Finland Oy, a branch of the Wärtsilä Corporation. Wärtsilä is a globally prominent leading supplier of innovative technology and total lifecycle solutions in the marine and energy sectors. Its business is divided into three main parts: Marine solutions, Energy Solutions, and Services.

In 2016, the Wärtsilä Corporate group's total revenue were 4,801 million euros, of which 943 million euros came from the Energy Solutions. Energy solutions encompasses engine power plants, liquefied natural gas (LNG) terminals and distribution systems and large solar power plants. Last year, (2016) the installed capacity of the power plants delivered by Wärtsilä to 176 different countries worldwide was 63 GW. (Wärtsilä 2016a)

5.3 Studied power plant description

Data in this chapter was used to determine the number of engines for vented masses. Economic analyses have been done based on the vented masses.

The total electrical output of the power plant is determined to range from 60 MW to 250 MW in this study, see Table 11. The output is related to a number of engines. Used engines are typical gas engines with 10 MW output at 100% load. All of the calculations are based on 100% load.

Table 11: Power plant sizes.

Case	Number of engines	Plant Output [MW]
Case A	6	60
Case B	15	150
Case C	25	250

The power plant is peak load power plant which will operate during times of peak demand. In this case, the main purpose of the power plant is to support power generation of a solar and/or wind power. Duration of one peak is one hour. Four different scenarios were chosen according to the starts and stops of engines: 4, 6, 11, and 22 starts and stops per each day. In every case, all the engines are behaving in the same way: all engines are starting and stopping at the same time.

5.4 Studied fuel system description

Data in this chapter is used to determine the gas capacity of the fuel system. The determined capacity is also used in the modeling of hydrocarbon releases.

The fuel system is a significant part of the calculations because of the mass of the vented gas is in the fuel system pipes. After every stop, the fuel system is emptied by using gas ventings. The fuel system is similar as shown in the previous chapter: “Fuel gas system”. Figure 20 presents the fuel system for calculations.

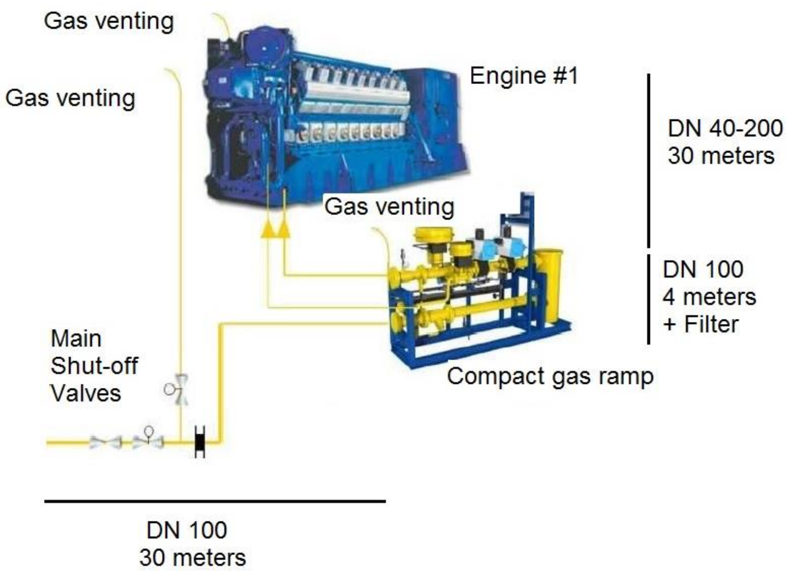


Figure 20: Fuel system for cases (Adapted from Wärtsilä 2017b).

The pipeline from the main shut-off valve to the compact gas ramp is estimated to be approximately 30 meters length with pipe size DN 100. The volume of the compact gas ramp is estimated to be approximately 0.35 m^3 including the pipes and the filter. Piping between the compact gas ramp and the engine was approximately few meters of DN 100 pipe. In this study, each engine has 20 cylinders, and all of the components such as gas manifolds are taken into account according to internal specific engine drawings. The leakage between pistons and liners have been recycled back to combustion process by using an internal loop.

Mass of the gas in the fuel system was calculated by using pipe volumes and gas densities at specific circumstances. Before the compact gas ramp, the temperature was estimated to be 25°C and pressure 7 bar(g). After the gas ramp, estimations were following: Pressure 4 bar(g) and temperature 23°C.

5.4.1 Modeled hydrocarbons behavior description

This chapter describes how the hydrocarbon releases are modeled, and what parameters have been used based on the fuel system capacity.

The simulation was performed with ANSYS Fluent CFD software. The first phase of the simulation was to demonstrate gas release from the gas phase to the atmosphere and try to determine the phase of the released substance. The main interest of the second phase was to determine the height of the flammable plume with 2 m/s wind speed. Results from the first phase were used in the second phase.

Figure 21 shows the simulation geometry. Inlet pressure was 300 kPa.

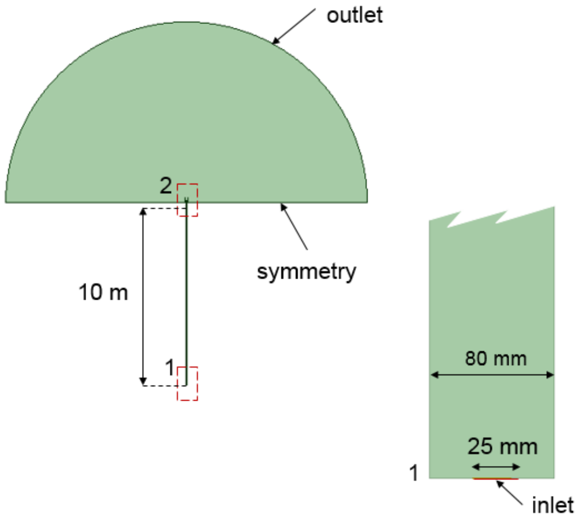


Figure 21: Simulation geometry (Internal report 2017).

Figure 21 shows that the inlet is numbered with number 1 and encircled as red. Outlet, which is the venting head, is numbered with number 2.

Figure 22 illustrates the end piece of the pipe. Pipeline included bore type ball valve according to the internal manufacturer document. Solution methods were following:

- ANSYS Fluent CFD
- Steady state

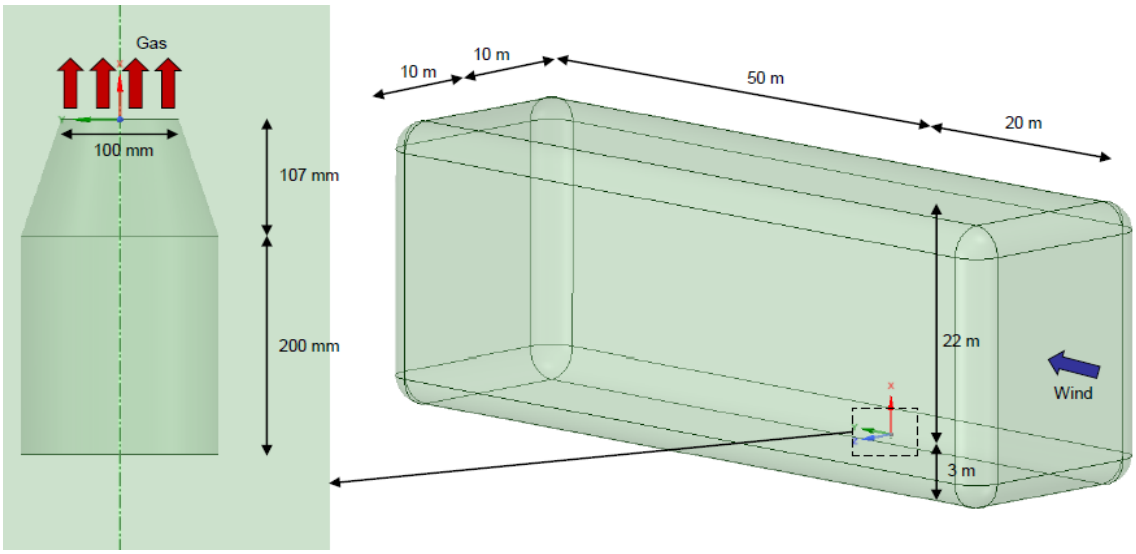


Figure 22: Geometry of the gas vent end piece and investigated environment boundaries (Internal report 2017).

Boundary conditions

All of the modeled gases were hydrocarbons: methane, ethane, propane, and butane. Inlet pressures of the released gas were 300 kPa at a temperature of 25°C. Gas released from gas phase to the atmosphere, so it mixed with the air at 25°C and 1 atm. The density of the gas mixture was calculated by using ideal gas law. The modeling takes gravity into account.

5.5 Studied storage systems description

This chapter describes the various storage systems for examination of the optimal system. Additionally, main components of each system and basic operational principles have been presented.

The storage system, which will store all of the calculated fuel gas masses, is integrated to the fuel systems' venting pipes. Vented gases, which are estimated to be dry gases, are at 5 and 8 bar(a) pressures in the fuel system(s)' venting pipes before entering the process of the storage system.

The capacity of the storage is dependent on the power plant size, used fuel, and a number of starts and stops. The basic principles of the different storage systems are shown in *Chapter 4* for each storage options. The components of each system are shown in Table 12.

Table 12: Components for each storage option.

Case	Guard bed	Pipe-lines	Valves	Stor-age(s)	Compressor unit(s)	PRU	Treat-ment	Liquefac-tion
ANG	x	x	x	x	x			
CNG		x	x	x	x	(x)		
LNG		x	x	x	x		x	x

In Table 12, pressure reduction unit (PRU) is optional for CNG. It is needed to reduce the pressure if the pressure in the storage is too high for use in the fuel system.

5.5.1 Adsorbed natural gas

Figure 23 demonstrates the recirculation process of the NG from the vent to back to process by using ANG solution.

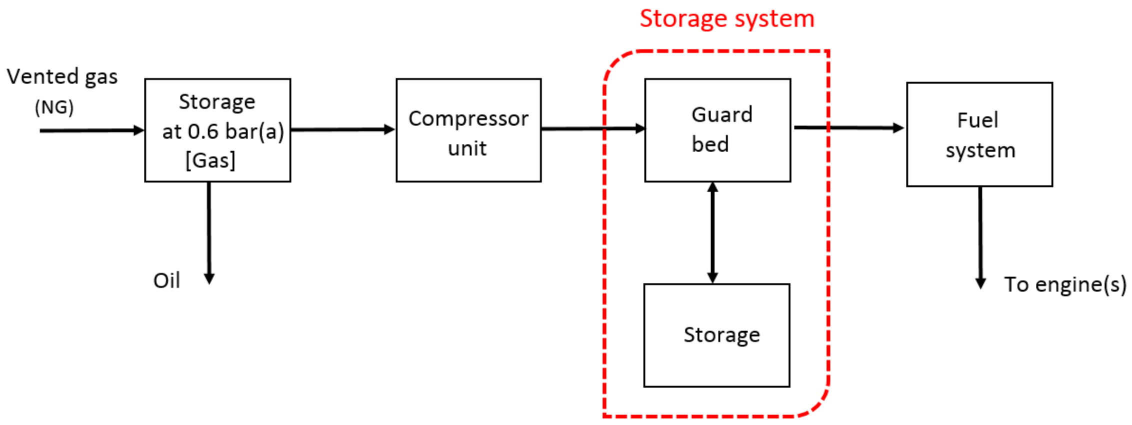


Figure 23: Basic layout for ANG storage system (Adapted from Cook et al. 1999).

Vacuumed storage gathers the vented NG to the intermediate storage. The pressure of the storage is 0.6 bar(a) After that, the gas is compressed to 35 bar(g) to main storage. Non-methane species are pre-adsorbed to the guard bed.

A reverse process can be used to unload the main storage and combine the non-methane species back to the methane gas. After that, the gas can be used back to the fuel system.

5.5.2 Compressed natural gas

Vented gases, such as NG or LPG, can be directed back to the fuel system or store in vessels by using compression. The following figure shows the recirculation of the vented gas.

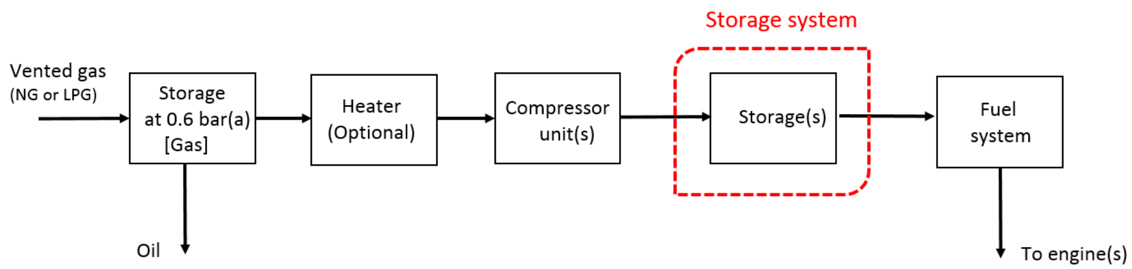


Figure 24: Basic layout of CNG storage system, also known as vent recovery system solution (Adapted from Fältén 2017).

Figure 24 illustrates the storage solutions for spark engines which are using NG or LPG as a fuel. The heavier hydrocarbons will need the heater due to properties of the heavier hydrocarbons.

Like in ANG technology, gases can be gathered from the system to the intermediate under pressure storage by taking advance of vacuum. After that, the gas is compressed to the required pressure (6-12 bar(a)) and stored in the storage system. The gas can be used back to the fuel system from the storage system.

5.5.3 Liquefied natural gas

Pretreatment and liquefaction process can be used for both pipeline gas and vented methane gas from the gas power plant. The component of the pipeline gas and vented gas are determining what kind of the pretreatment process is.

Figure 25 illustrates the LNG process steps. The figure does not show for example compressors.

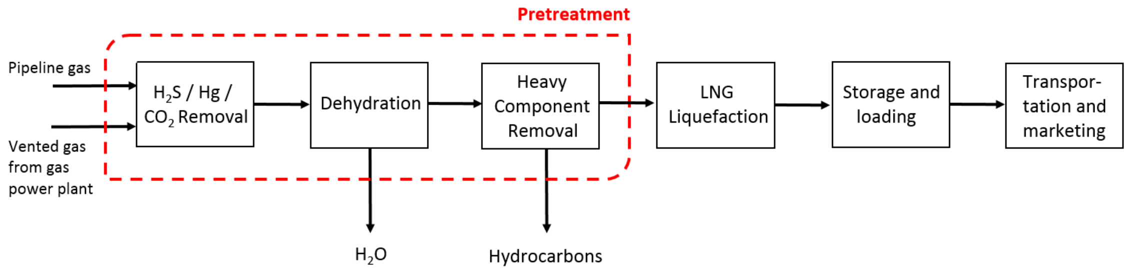


Figure 25: Basic layout of LNG process solution (Adapted from Wärtsilä 2016b).

LNG can be used back to the system, or it can be sold and transported to the customer by using different container or truck vessel solutions. Bullet tanks are the most common storage options for mini and small-scale liquefaction plants. The tanks are typically vacuumed and multi-layer insulated or vacuum and perlite. Operating pressures are from 0.5 bar(g) to 4 bar(g). (Wärtsilä 2016b)

5.6 Economic data for the optimal system

Based on the examination of the optimal system (see *Chapter 6.2*), economic calculations and data are only available to the selected system (reference Figure 24, Figure 34, and Figure 35). The economic calculations are based on the working solution for natural gas. All of the component prices are approximate prices, and calculations and results are based on the selected values.

All of the investment cost for fuel energy storage systems were found with various references. The prices are based on the real values but can vary project-specifically, especially if the system or the type of fuel changes. Investment feasibilities are calculated by using a payback method with and without taking into account time value of money. Additionally, calculations have been done by using the Net Present Value method (NPV) and Internal Rate of Return method (IRR). Prices are including extra ±5% margin, and analysis has taken into account ±10% margin.

Table 13 shows the estimated lifetime of the investment, used imputed rate of interest, and estimated salvage value of the investment.

Table 13: Data for economic analyses.

Economic data	Value
Lifetime of the investment [years]	20
Imputed rate of interest [%]	10
Salvage value [€]	0

Capital expenditures and operational expenses

CAPEX scope is divided into three group: 1) Mechanical equipment supply and installation, 2) Electrical, and instrumentation and control, and 3) Project indirect costs. The civil and structural costs are not estimated because the system should be modular and simple to install. Also owner costs, such as legal fees, insurance costs, etc. are not taken into account.

Table 14 shows the CAPEX data. Unit(s) are the major equipment. In this study, units are including electrical, and instrumentation and control equipment. The prices have been rounded off to the nearest thousand.

Table 14: CAPEX data of optimal system for each power plant size (Reference Table 11).

Cases	Unit	Price [€]
Case A	Storage vessel unit(s)	50,000
	Compressor unit(s)	29,000
	Piping	5,000
	Project indirect costs	15,000
Case B	Storage vessel unit(s)	75,000
	Compressor unit(s)	29,000
	Piping	13,000
	Project indirect costs	23,000
Case C	Storage vessel unit(s)	100,000
	Compressor unit(s)	29,000
	Piping	21,000
	Project indirect costs	28,000

Different valves, such as shut-off valves and safety valves are included in the units. Part of required piping is also included in the units. Piping is generally power plant specific, so calculations have taken into account 10 meters external piping per engine. Project indirect costs include distributable labor and materials, container(s) and shipping, and commissioning. Design and engineering costs are not taken into account.

OPEX is estimated to be 5% of CAPEX per year.

Fuel price

The fuel priced are checked from the available monthly statistics for each case. Table 15 shows used case prices.

Table 15: Fuel trade prices for natural gas in different market areas (According EIA 2017; YCharts 2017; IndexMundi 2017).

Cases	Market area	Trade price [$/MMBTU, LHV]
Case 1	U.S.	3.17
Case 2	Russian	4.98
Case 3	EU	5.41

Because of the 100% recovery percent of the storage system, all of the vented gases are calculated as saved money according to fuel LHV, which is estimated to be 47,130 kJ/kg for natural gas in this study. LHV may vary depending on the hydrogen content of the used fuel. The used exchange rate of US dollars to Euros is 0.89 on 27th of June, 2017 (ECB 2017).

6. RESULTS AND DISCUSSION

The discussion and evaluation of the results presented in this study are divided into topics which are answering the research questions of this study. These research questions have also been presented at the beginning of the work: *Is a recycling system for vented gases necessary in gas power plants?; What kind of system technology would be the best to apply?*; *What are the benefits of the proposed recycling system?*; and *Is the optimized system economically profitable?*

Importance of the study from the point of the view of Company was to show that system design could be simpler. Answers to research questions have been logically categorized to order which have been mentioned above. All of these issues have been reviewed from a different point of view. This chapter also includes evaluation of the study and future review. In the evaluation chapter, for example, the novelty value of the study is described.

6.1 Hydrocarbon release analysis

Hazardous situations with hydrocarbons are caused by gas leakage or release and from their consequences. These include gas fires and explosions as well as inhalation of natural gas or carbon monoxide. According to John R. Puskar, there are three different main reasons for the hazardous situations: people, policy or equipment issue. (Puskar 2013) If the system is designed to be safe, it generally is. However, all kind of external hazards or design limits are "weak spots" for the design. Unfortunately, it is impossible to protect processes from every eventuality, but as many potential events as possible have to be taken into consideration.

A combustible vapor cloud, also known as a plume, is modeled in the next chapter. Modeled results have confirmed that combustible hydrocarbon plume, with the possibility of fire or explosion, can be formed in normal operation. This flammable plume is creating hazard zones, which can have an effect for example to the layout design. There is always the possibility to the various accidents when explosion risk is even small, especially if the domino effects or damaging of surround environment is possible. The flammable plume might not be a risk in a free environment, where it can burn freely in the air without causing any concrete damage. However, the plume will increase environmental pollutants and harmful effects.

Moreover, the modeling results confirm previous facts from the available literature. Referring to Nolan's guidelines, venting to the atmosphere is not suitable disposal method for hydrocarbons for various reasons, which have been described in *Chapter 2.2*. Specific health and safety issues of hydrocarbons can be seen in *Chapter 2.2.2*.

According to available literature, flare or recirculation back to process are only acceptable solutions for combustible process vapors. In normal operation, there should not be hydrocarbon leakages or releases from the gas system. That kind of data supports the result that recycling system would be necessary, in cases, where hydrocarbon release is happening during normal operation.

Additionally, hydrocarbon releases are not suitable due to the overall safety and health objectives, which are to uncover the risks and to reach a fully satisfactory for people. For example, flammable vapor clouds, fire hazards, explosions, embrittlement and potential domino effect due to fire or explosion should be considered. For instance, toxic substances, asphyxiation hazards, cryogenic hazards, ergonomics and climate conditions should be considered.

However, it is common practice in industries to release hydrocarbons to the atmosphere as described in *Chapter 2.2*. One reason for that might be the operating costs of the various complex systems. Venting might be the easiest and cheapest available solution because it does not require complex systems when comparing to the flare or capturing system. For each complex problem, there is always a solution that is concise, clear, simple and often wrong. However, the vented gas is a waste of usable gas, which could be used as a fuel creating savings in fuel cost.

As a summary, something has to change based on the results. So, the necessity of this study has been proven as well as the time of this study, and fact whether the research made any sense. As from the present situation, one can be noticed that the study is in every way relevant.

6.1.1 Modeling results

Because of different properties of hydrocarbons, modeling helps to understand how hydrocarbons act after being released into the atmosphere and to verify the extent of the possibly flammable area. Modelling should help to recognize what actually happens and are previously mentioned literature results and discussion valid. The used data and methods are described in *Chapter 5.4.1*. Modelling also supports the decision, is the recycling system necessary.

The first results of the modeling were focused on the velocity and phase of the released gas in 2D. Total pressure at the top surface of the vent was from 1130 Pa to 1607 Pa when the inlet gas pressure was 300 kPa. The maximum total pressure was achieved with the methane and the lowest with the butane. The pressure was from 373 Pa to 527 Pa and velocity was 24.0 m/s to 54.6 m/s on the top surface of the vent. Figure 26 demonstrates the mass fractions of the simulated hydrocarbons.

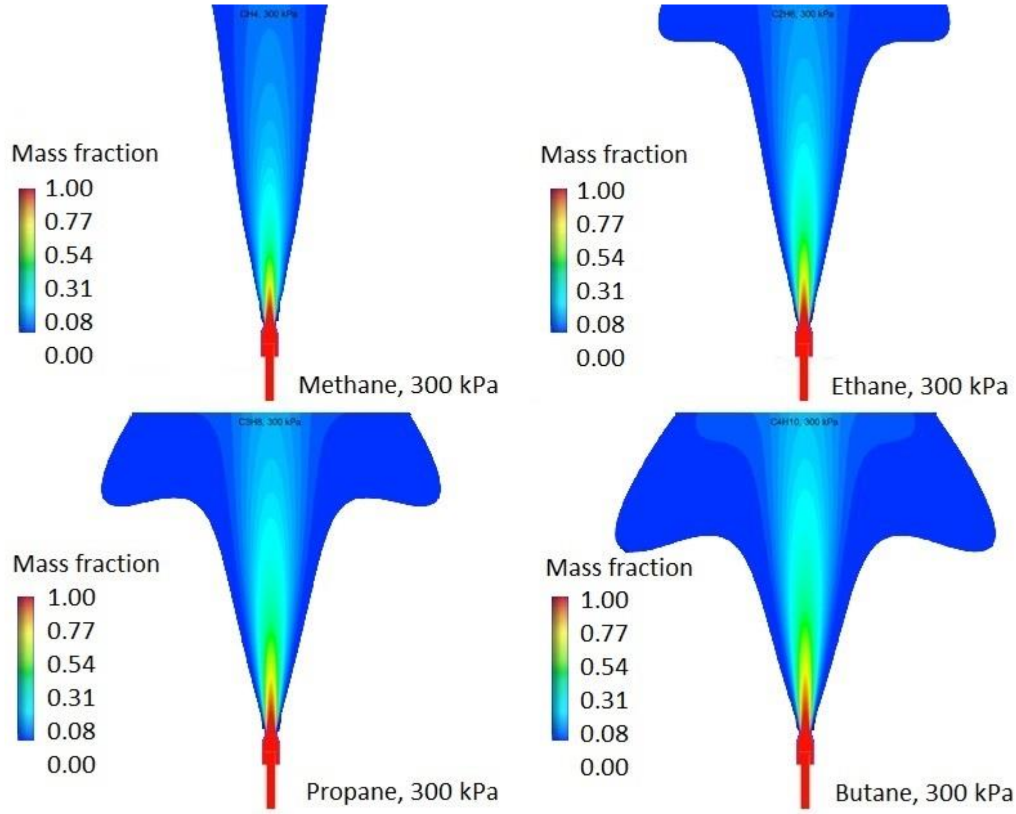


Figure 26: Mass fractions of different hydrocarbons in initial operating conditions. Hydrocarbons are released into the air from the venting head, see Chapter 5.4.1 Inlet pressure 300 kPa. Up: On the left methane, on the right ethane. Down below: On the left propane, on the right butane. (Internal report 2017)

As can be seen in Figure 26, the shape of the heavier hydrocarbons' gas plumes such as ethane, propane, and butane are mushroom-like unlike the methane's plume shape with lower mass fractions. The heavier substance also spreads wider and forms more bent plume with lower mass fractions. In Figure 26, downwards bending is strongly depending on the densities of the hydrocarbons in lower mass fractions, see Table 16.

Table 16: Relative densities of hydrocarbons at 0°C and 101,325 kPa.

Substance	Density [kg/Nm^3]	Relative density
Air	1.28	1.00
Methane	0.72	0.56
Ethane	1.35	1.05
Propane	2.01	1.57
Butane	2.70	2.11

The density of the methane is lower than the air so can be estimated that plume of methane will not be bent like the others, even though the domain of Figure 26 is not showing what takes place with a higher one. According to the simulation, there is no great difference in the shape of the gas plume with different inlet pressures (300 kPa, 400 kPa, and 500 kPa).

Only methane has the slightly different shape of the gas plume when the inlet pressure is 500 kPa. Generally, the shape of the plume is quite similar with all inlet pressures even though the velocity at the top surface of the vent was ranging approximately 4-13 m/s following the inlet pressure

The results for the second stage of modeling were in connection with the bending of the plume. The main interest was to clarify the height and length of the flammable plume. The used mass flows, temperatures, and boundary conditions were taken from the 2D simulation. More information is described in *Chapter 5.4.1*. Mass flow values are from the 0.277 kg/s to 0.439 kg/s. Figure 27 shows the size of the plumes in initial operation when the LEL-100 is achieved, according to Equation 1. So it shows the behavior of the hydrocarbons in case of leakage.

The grid in the background is metered (1-meter x 1-meter), and the wind speed is 2 m/s from right to left. In this case, the colors of the plumes are simulating the height of the plume.

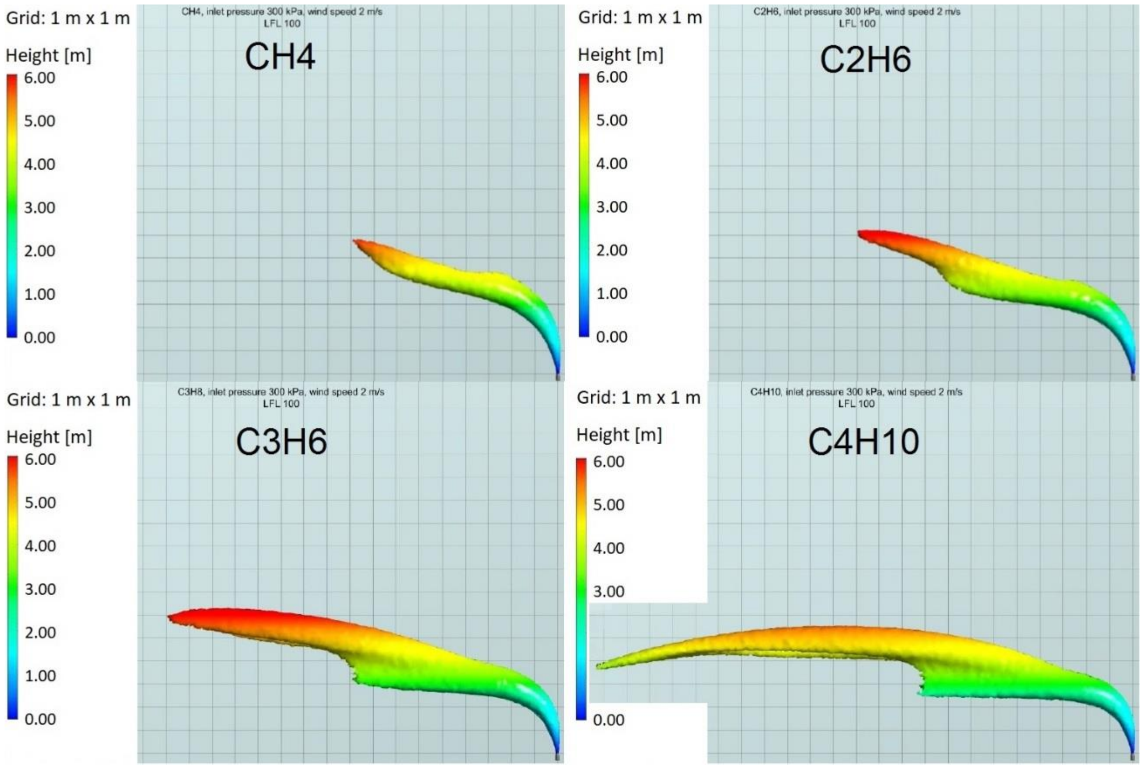


Figure 27: Flammable plumes in initial operation conditions: inlet pressure 300 kPa, wind speed 2 m/s, LEL-100. Up: On the left methane, on the right ethane. Down below: On the left propane, on the right butane. (Internal report 2017)

Figure 27 shows that flammable plume can be formed with fire or explosion possibilities in the initial operation. The flammable plume of methane is 5.90 meters high unlike the plume of butane is 5.66 meters high. The lengths of the plumes are following: 9.00 meters for methane and 23.50 meters for butane. According to simulation, wind speed does not have a significant impact on height or length of the plume. Wind speed affects to the slope of the plume.

As can be seen in Figure 27, the plumes are huge, particularly for length due to initial operating conditions. Figure 27 simulates the endless gas leakage. In normal operation, only certain mass of gas will come out from the venting pipe. This means that mass flow will decrease as a function of the time. The release time depends on the process parameters, such as pipe volume, the density of gas and orifice diameter. If the plumes were as the Figure 27 shows, the hazardous areas would be enormous.

These results are simulated with velocities from the 24.0 m/s to 54.6 m/s at the top of the surface, depending on the hydrocarbon. The reality can be entirely different and especially plume of heavier hydrocarbons might bend downwards with the lower velocities. Moreover, this type of simulation is known to be very conservative, and the random variations are minimized, due to steady state default value.

The density of the methane is approximately 50-60% of the air so methane would be expected to be buoyant after the venting and the simulation confirmed it. According to that, heavier hydrocarbons would be expected to go downwards and spread to a lower elevation, such as trenches, ditches in the worst case. However, it is surprising that the heavier flammable plumes are not going downwards in the first meter. As can be seen in Figure 27, only butane is slightly starting bend downwards after 7 meters. Reason for that might be the molecular composition of the hydrocarbon-air mixture, the velocity at the top of the surface of the vent, the wind speed, and simulation methods.

In this point, based on the above results, it can be said that heavier fuel gases may not form the flammable plume which is bent downwards to the ground in operational release due to the simulation of initial operation. Despite that, the sizes of the flammable plumes are enormous in the air and different risks are possible.

However, to get more accurate results, simulation of methane and butane have taken into account time and decreasing mass flow from the described fuel system as a function of the time. Previous simulations of initial operation give some kind of vision how all of these four hydrocarbons (CH_4, C_2H_6, C_3H_8, and C_4H_{10}) will behave in the air. As a summary, now only the lightest and the heaviest hydrocarbon of previously mentioned hydrocarbons have been simulated.

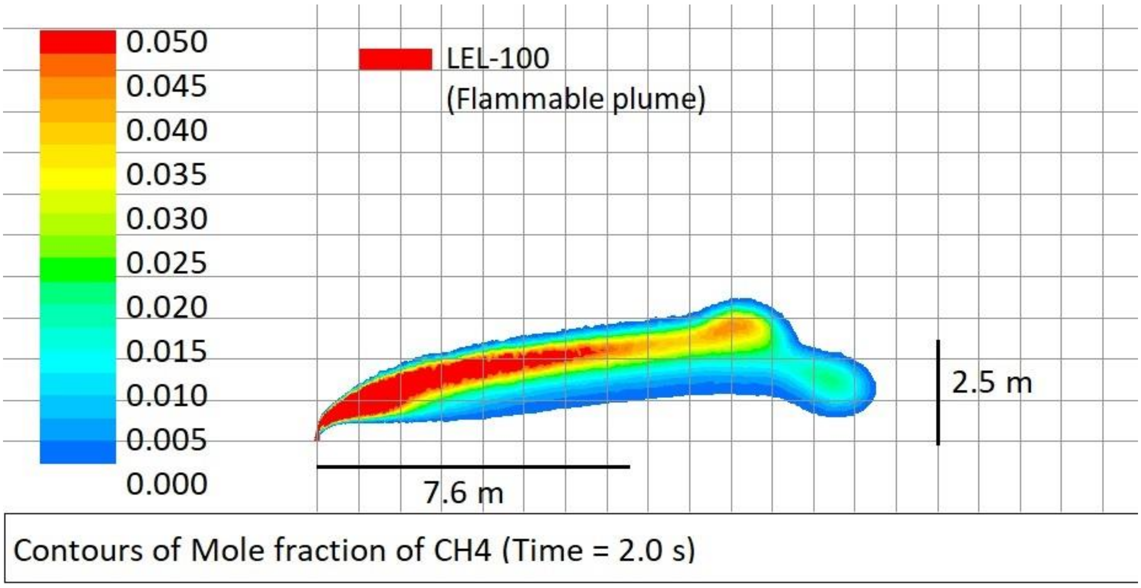


Figure 28: Methane plume after 2 seconds of venting (Internal report 2017).

Figure 28 shows that combustible methane plume with explosion or fire possibilities can be formed in normal operation. The flammable plume is 7.6 meters length and 2.5 meters high after 2 seconds of hydrocarbon release. The color of the plume illustrates the contours of mole fraction and the red color shows the flammable area (LEL-100). Other colors are non-flammable but still increasing environmental pollutants, harmful effects, and health effects.

As can be seen from Figure 29, when more time elapses, the mass flow will start decreasing. The plume shapes more and more as a horizontal wind.

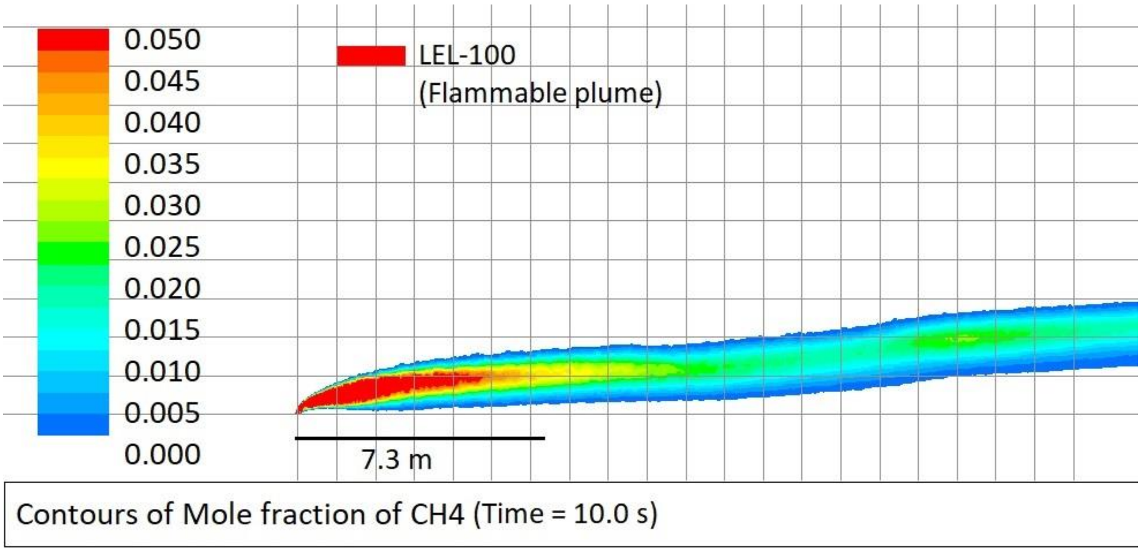


Figure 29: Methane plume after 10 seconds of venting (Internal report 2017).

Figure 29 shows that the length of flammable methane plume is now only 5 meters and it is just a few meters high after 10 seconds of venting. However, the length of the LEL-

100 plume is 7.3 meters due to tiny flammable particles in the middle of the non-flammable plume. Within 8 seconds the size of the flammable plume has halved. Lower contours of mole fractions are affecting out of the domain, increasing emissions in the wide area.

This illustrates very well how different results have been achieved by using different presumptions. Still, it is good to remember that time of the venting might vary in the reality. Venting, when hydrocarbons are released, might take just a few seconds.

Next figures illustrate venting of heavier hydrocarbon with same presumptions as earlier.

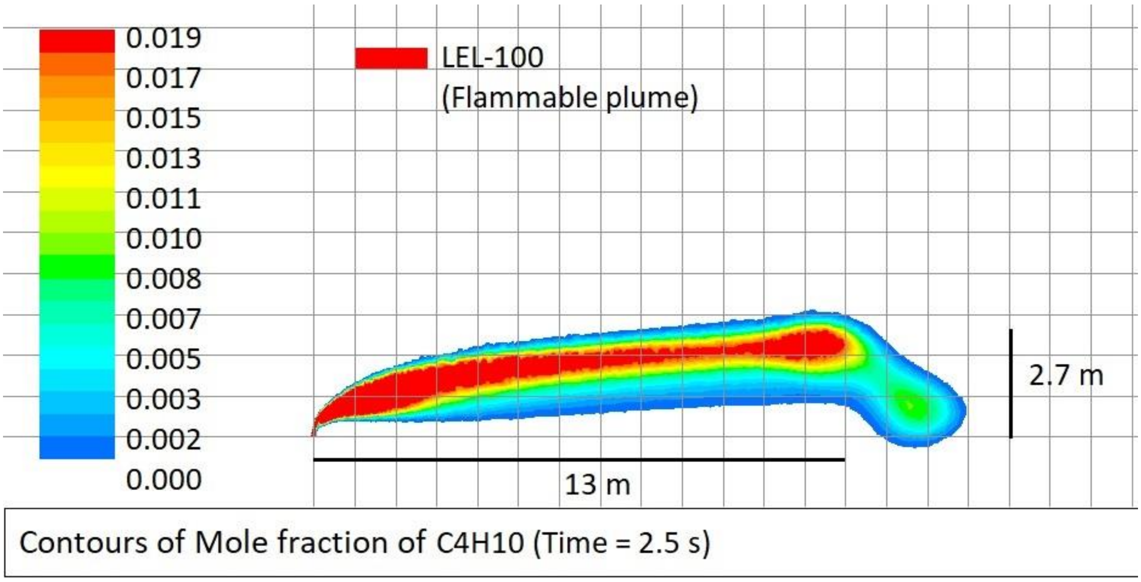


Figure 30: Butane plume after 2.5 seconds of venting (Internal report 2017).

Figure 30 shows that the length of the butane plume is 76% longer compared to the methane plume after few seconds of releasing. Merely non-flammable tail of the plume is bent downwards. The reason for the bending is initial low inertia at venting pipe (inlet diameter (25 mm) increases to main diameter (80 mm), see Figure 21) and greater density compared to the air until the wind catches the plume.

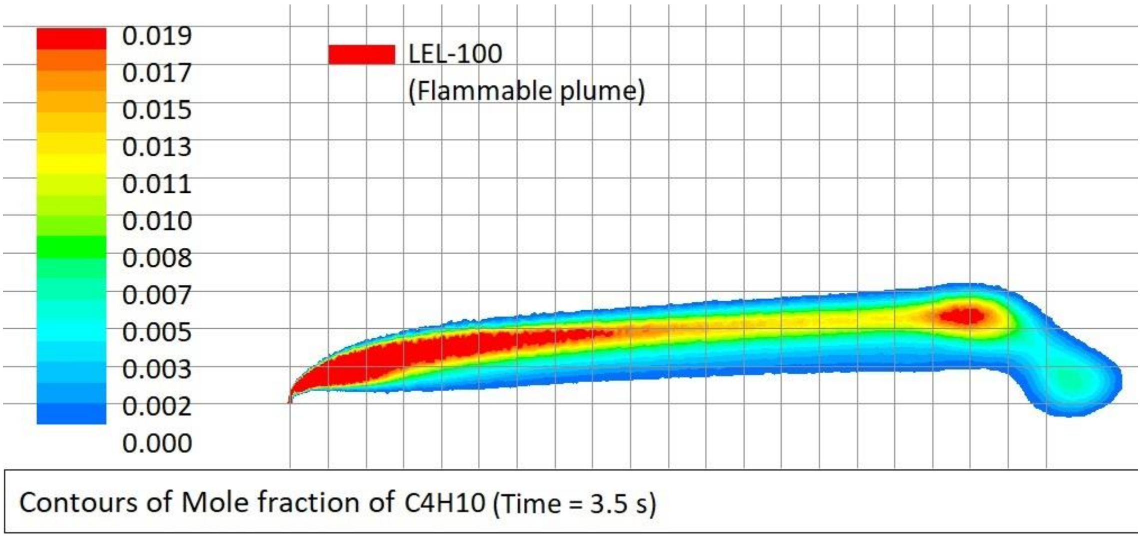


Figure 31: Butane plume after 3.5 seconds of venting (Internal report 2017).

As can be seen, the butane plume splits flammable plume far away from the major flammable plume, see both red areas in Figure 31. The length of the flammable area can create challenges because vented butane forms enormous hazardous area just in a few seconds. However, that area does not exist so long period that it could be a threat. Still, it is a risk which must consider.

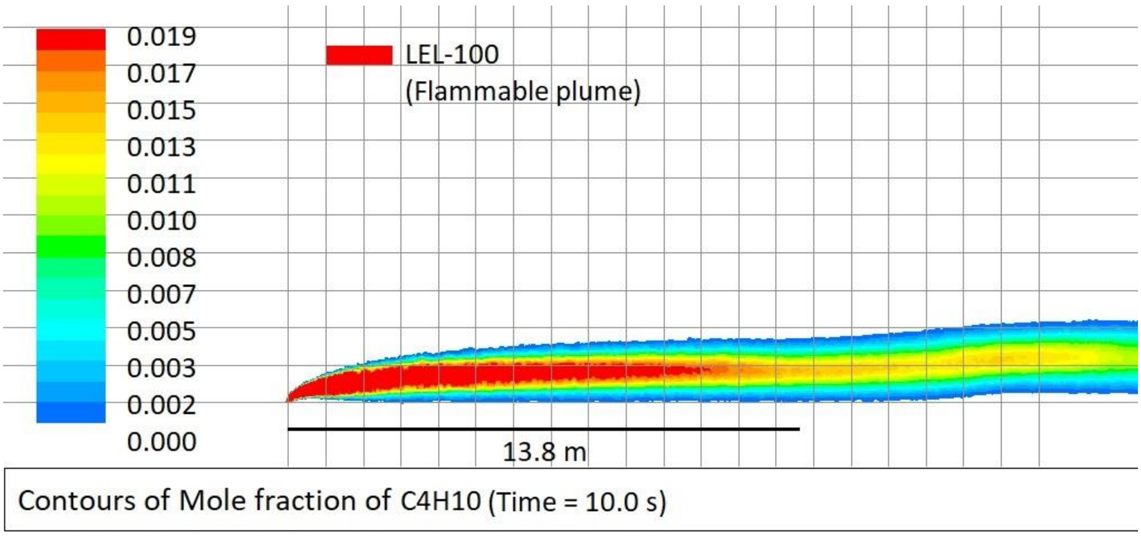


Figure 32: Butane plume after 10 seconds of venting (Internal report 2017).

Figure 32 shows that the flammable plume's length is totally 13.8 meters after 10 seconds of the venting butane, containing even the small flammable particles in the tail of red area. However, smaller contours of mole fractions are affecting much wider area compared to the methane plume. Moreover, the plume is not bent downwards, even though the relative density of butane is 2.11 compared to air at 0°C and 101,325 kPa, see Table 16.

Based on the modeling results, can be said that combustible hydrocarbon cloud can be formed with explosion or fire possibilities. Moreover, simulations have focused more on the flammable area, but despite that, can be seen that non-flammable areas are quite enormous. This means that hydrocarbon release will create an environmental pollutant and various harmful effects even the plume would not catch fire at all.

Lengths of the butane are quite long and should be taken into account in design and layout design because the release of heavier hydrocarbons increases the risks. These kinds of plumes are environmental pollution even though plumes are not flammable. It can easily decrease, for example, visibility of the airplanes if the airport is near to the hydrocarbon release source. Heavier gases, such as propane or butane will collect in lower elevations. Gases will not dissipate from congested areas. However liquid hydrocarbon releases can spread, runoff, or be contained to a lower surface elevation. According to Nolan (2011), vaporization may occur if gases are volatile, dissipation and when the vaporization rate is equal to the spread rate. The liquid hydrocarbons can form a pool after spreading out depending on the viscosity of non-volatile hydrocarbon liquids. A pool of the heavier hydrocarbons can also form on the water and to drift in the direction of the wind. The lighter ends of the liquids will evaporate, and finally, bacteriological digestion and wave action will break up the residual oil if the ignition does not occur. (Nolan 2011)

The wind or ventilation of a building might lead to an explosive cloud in a hazardous area containing hot surfaces. This could cause a gas fire or explosion. Especially, simulations of this study are only taking into account specific laminar wind and given initial data. As described earlier in theory part, all kind of obstacles such as building or mountains might affect the wind rose and at the same time to spreading of the fuel gas plume. When the wind direction and the wind speed changes, all of the results will be different. More discussion in Chapter 6.4.2.

6.1.2 Health, safety, and environment aspects

Safe design in the early design progress involves the integration of control measures and successfully achieving a balance without compromising the safety, environment or health. Hydrocarbon releases are proofed risk. Safety priority can be depended on three different items: streamline, safe, and optimizing CAPEX and OPEX. Streamline might be a fast solution, safe might be a good one and optimizing might be a cheap solution. However, if one choose two of these, one cannot get the third one.

Designers should have a strong influence especially during the planning and design stages of a project. All of the decisions can affect the safety, environment, and health from the commission to the operation, maintenance and eventually to demolishing. Each decision can control, reduce, or avoid the risks which are involved. The result of unwanted scenarios might cause an unwanted trip to electricity production or massive environmental damage, loss of human life, enormous economic loss, etc.

Environment

Consequences from released hydrocarbons into the environment varies depending on the fuel. In addition to wasting a source of energy, such as NG, which is mostly methane, is a potent greenhouse gas. It significantly contributes the climate change.

As the modeled results have shown, the plumes, where mole fractions of substances exist, are quite massive. According to Lavoie et al. (2017), CO-locations of CH_4 emissions at power plants are more widely spread than the domain of the modeled plumes can even show. Especially horizontal distance of CH_4, when the parts per million (ppm) is increased, is quite long, approximately a few kilometres. Despite that, the content of substances is shown as ppm. For example, the content of CH_4 is not such big compared to the content of the normal air. In fact, in Lavoie et al.'s article, refineries are a much greater problem than power plants due to a wider area of spreading. However, it does not close the issue of power plant emissions. The overall change might starts moving from small factors which can show the example of their operation by reducing the emissions.

Emissions are entirely different during the peak operating hours than emissions during periods of startup and shutdown. So the emission research and measurements should be done during the full range of operations to figure out and develop more robust emission factors (EFs). Moreover, gas can play a significant role in helping EU meet the goals and mitigating climate change. However, if the gas is released as non-used, it will not contribute to achieving this aim.

Health

Hydrocarbon release might affect to health only in large amounts as have been mentioned in the literature review. By breathing outdoor air, everyone is exposed to low levels of methane. Additionally, all kind of population will increase the levels of methane.

Methane and ethane gas are relatively non-toxic because it does not have an **OSHA PEL standard,** unlike propane and butane. Health effects of methane and ethane are associated with being a simple asphyxiant (SA). (NIOSH 2017a; NIOSH 2017b; NIOSH 2017c; NIOSH 2017d) For example, toxic substances, asphyxiation hazards, cryogenic hazards, ergonomics and climate conditions should be considered. Despite this, the fuel gases do not only include for example 100% methane but instead, a composition of it is as described in chapter "Fuel gases".

In addition, venting might cause some noise. This might be a problem, especially in high-pressure systems at night.

However, the health impacts can be examined from several points of view. Good examples are different foods. According to Koli et al. (2015), the dark chocolate, which is cocoa containing food, has health benefits, such as the capability to lowering the blood pressure. At the same time, people are blaming chocolate for getting fat. So health benefits are depending on the current situation and especially research worker, who is reviewing benefits or disadvantages.

Safety

A hydrocarbon release into free environment might not be such critical issue when thinking about fires or explosions. It is a risk, which must be taken into account. One might believe that only relevant matter is molecules, no matter what happens for example to the environment. However, this other related point of views than fires and explosions, such as health or environment impacts must be taken into account also.

A gas release into a building may lead to a gas fire and explosion. It is important to prevent any leaks by examining regularly and carefully the gas system for leakage. Referring to *Chapter 2.2*, all kind of releases to the atmosphere are safety problems. Moreover, there are some other items than process safety priority or minimization of leak points, which would be relevant for the current design, such as piping protection and drainage. However, the different standards, which are presented in *Chapter 3.2.2* and other items are struggling against each other. In some cases, venting to the atmosphere may be acceptable, in some cases not.

As a summary, standards are offering guidance, ensuring safety while maximizing availability, providing vigor while not stifling innovation. However, standards are still discouraging users from gaming the standards. The industry is more interested in cost control, ensuring safety, process reliability and availability, establishing predictive maintenance, competence training and evaluating, developing processes and safety expertise. We are living in the litigious world. The meaning of the safety might vary depending on the person: Does one want to analyze the caused injuries and deaths or duration of the shutdown of the power plant? In some cases, the shutdown might mean that the whole island is without electricity so it might be a significant risk and consequences are unknown in this case. If the safety is not examined as a coherent whole, one can save money and time. However, that type of wide overviewing would be suitable with unlimited money. Moreover, safety requires more than just following codes or standards.

6.1.3 Impact to layout of site

The layout of the site can face challenges due to hazardous zones, which are formed by gas plumes. That kind of plumes might spread to any direction depending on the various aspects which are affecting the spreading of fuel gas. These aspects have been gone through in modeling results. Due to spreading of fuel gas to any direction and size of the plume, the layout of the site has to be thought carefully. All kind of flammable substances, for example, dust, will increase the danger of the modeled plumes.

The risks of the plume can be reduced by placing risky devices more far away. If the placing of devices far does not succeed or the devices cannot be ATEX classified, it will be much easier to move to the closed system solution. Moreover, the location of the site might not be available in the early design which creates some challenges to the layout design.

The windrose has the enormous effect on the layout design. Pressure wave caused by the possible explosion danger to the environment must take into consideration in the layout of the site, see ***Appendix A.*** Explosion danger targets are for example fixed chemical containers and pressure vessels, pipe systems and transport containers of dangerous materials.

Gas ramp

The gas ramp includes venting to the atmosphere as Figure 12 shows. If the compact gas ramp is located outside the engine hall, one of the venting pipes can be removed.

According to Finnish government's decree from the safety of the handling of the natural gas, the gas pressure reduction unit, such as gas ramp unit, can be placed either in the interior or on the exterior according to the input pressure. If the input pressure is over 4 bar(g) and lower than 16 bar(g), gas pressure reduction unit must be placed on the exterior by using constructions which protect from mechanical damages. It might also be placed on the interior with own separate area where exiting is possible; it is classified as explosive atmosphere and class of the zone is 2. The room must be directly equipped with at least two leading ventilation ducts; one placed directly on the floor and other to the top or ceiling of the wall out. Referring to that, at least compact gas ramp should be located in another place than currently.

Electric equipment

For example, released heavier hydrocarbons might end up on the roof of the engine hall. In some cases, radiators might be on the roof. Radiators are electricity equipment and radiating heat when operating. Such an explosive plume might face the radiators in the worst case. However, the consequences may be minimized in the free environment, because the gas plume just explodes without damaging for example walls or structures. It will not leave the permanent traces of the fire. Despite that, it is forbidden to burn gas outdoors without control.

As earlier has mentioned, the weather conditions such as wind and terrain are affecting to spreading and directions. All electricity equipment or hazardous areas should have been located correctly due to that.

A gas detector detects the presence of combustible, flammable and toxic gases. It is part of a safety system and used to detect for example a gas leak. Sensors can identify hazardous gas leaks. The operation mechanism classifies different types of detectors. These types are electrochemical, catalytic bead, photoionization, infrared (IR) point/imaging and ultrasonic. Gas detectors should be located correctly in different hydrocarbon cases. The location should be taken into account the densities of the air and substances. If the plume is inside the engine hall or pipe leakages, the substance might be on the floor or in the other case on the top of the building.

Buildings

The hydrocarbon release to the atmosphere increases the number of ATEX areas. Plume forms zones, which can be near the buildings. The ventilation system of engine hall maintains the temperature in the engine hall at a suitable level, and in some setups, it provides combustion air for the engine. The plume from the vent might end up in the building through the ventilation system. So, these zones should be far away from the buildings because for example ventilation system might drain that plume inside the building.

Moreover, the mass flow of the ventilation system is so big, that outdoor air is absorbed in a big area. Well thanks to that, drained plume might not achieve the LEL. If the plume ignites for some reason, it might cause damages inside the building, for example, multiple collapsing of the walls.

Fuel gases in the free environment can move even into a small slot. Depending on the density of the fuel gas, it might be in the air or on the ground. A number of doors should have been minimized because sojourn in the engine hall is forbidden excluding the commission or maintenance according to the manuals. So, one door should be enough to each slot of the building because there should not be moving back and forth.

Fuel pipes

Fuel pipes are located on the ground. Heavier hydrocarbon leak will end up to the ground immediately causing unpredictable consequences. Risks can be minimized by covering the pipes by using channel or double-walled technology, see Figure 33.

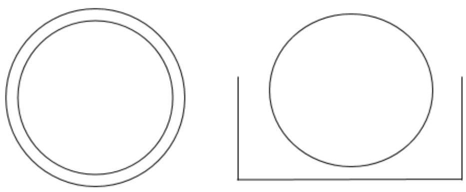


Figure 33: Double-walled pipe (left) and channel for the pipe (right).

Despite small additional costs, the pipes of fuel system should be using some kind of channel or bunker, which collects the heavier hydrocarbon leakages, to minimize the risks. Moreover, double-walled pipes are also decreasing the risks. Now consequences of all kind of pipe ruptures, leakages, etc. are also minimized. Heavier hydrocarbons could easily lead to some sort of pit from the bottom of the channel.

Roads

Roads are not such big problem with the plumes. However, the location of the compact gas ramp should be as far as possible from the engine hall so the vented gas would not end up in the engine hall. Relocation of the compact gas ramp might cause changes in the roads also. Roads should be located as far as possible from the critical components, such as GPRS.

6.2 Examination of optimal system for fuel gas recovery

This study both inspects and compares the CNG, LNG and ANG system technologies. Each system has own advantages and drawbacks. The main overview of each solution can be seen in Table 17. The table compares relative densities in different temperatures and pressures for methane-based NG.

Table 17: Overview of different storage methods.

Case	Temperature [°C]	Pressure [bar(g)]	Density [kg/m^3]	Relative density (V/V)
NG	25	1	0.7	1
ANG	25	35	140	200
CNG	25	200	160	229
LNG	-163	1	466	665

Table 17 shows, that the ANG system can work under 35 bar(g) as optimal, and it can store approximately the same amounts of NG as the 200 bar(g) CNG tank with the same tank volume by using MOF adsorbents. Due to that, the ANG solutions provide much better storage characteristics than CNG storage. Carbon materials for ANG are applying the storage systems at pressures which are substantially below than what is usually required for contemporary CNG solutions. Thanks for the low pressure, ANG is much safer and more efficient than CNG. Furthermore, this automatically means reduced costs and improvements to safety. ANG does not need for example liquefaction process or face the boil-off challenges as LNG does.

The ANG solution has attractive advantages, such as the flexible design of the storage tanks, low costs in small scale and provided safe operations especially when it is used in the transportation applications (El-Sharkawy et al. 2015). The capital and operating costs of compression are quite low due to required low pressure.

ANG faces some challenges, such as heat management, gas composition, and deliverability. According to Feroldi et al., ANG technology has a high possibility to influence the utilization of the NG and bio-methane in the transport sector. It still needs to overcome the difficulties of storage and gas desorption. (Feroldi et al. 2016)

Some companies are providing the ANG solutions, but these are typically only for methane-based fuels. The price of the ANG solution depends critically on the adsorbent material. For example existing gas infrastructure might be one problem to overcoming. The current gas network has already been built, and it has been diligently updated, so rejection of it may be a massive threshold. Still one of the biggest problems with the ANG solution is to find right adsorbent materials which would work in large-scale. As a summary, the ANG solution has some formidable challenges to overcome before ANG are likely to find widespread use.

On the other hand, the LNG solution is unprofitable without continuously liquefaction process due to expensive investments in the pretreatment and liquefaction process. According to LNG expert, the LNG solution could work if the pipeline gas with the vented gases of the gas power plant would be directed to the liquefaction process. If the constant liquefying on a full effect is not possible then the liquefaction process is not cost effective solution.

According to the Lim et al. (2013), cost breakdown of the LNG value chain is following: Liquefaction 41%, storage and regasification 21%, shipping 20%, and exploration and production 18%. The major parts of the costs are liquefaction process and storage. Vented gas amounts may support the liquefaction process, but in this study, the major focus is to solve hydrocarbon release problem, not the increased efficiency of other procedures. Moreover, for heavier hydrocarbons, liquefaction process can be a procedure by using simply compression.

However, if the solution would be using LNG technology, then for example selling the LNG could be one solution. At that time, there would be LNG production and electricity generation at the same time. It is not studied, how the peaking power plant and LNG liquefaction production would work together. Power plant and solar power are integrated to support each other, so why not peaking power plant and LNG production if the need is real? One solution is to share plant infrastructures. New gas power plant could be built next to existing LNG plant to share infrastructure.

CNG technology is quite well studied and used for example in the fuel industry. It is a good option for reuse and transit using fast or time fill. As Table 12 shows, CNG does not require complex extra systems and investment should be quite small compared to other system technologies. Especially, the compression in this study will require less power than for example ANG solution, due to the required low pressure. Moreover, the CNG solution is relatively simple with the correct tank type.

Dismantling speed of CNG technology is just related to the temperature, pressure, and optional heater. Dismantling speed can be easily controlled by using correct pipe sizes and power of compressor. Moreover, CNG system does not face the heat management problems, such as ANG and LNG does.

The major reasons for suitability of CNG technology are the simple process and fuel flexibility. Both ANG and LNG needs almost the same components as CNG and in addition to them still, own special components, see Table 12. So, it is quite clear that CNG is the cheapest and simplest solution for this case even though compressors would need more power than estimated in CNG solution. CNG technology can be used also for multi-hydrocarbons in the gas phase.

6.2.1 Selection of optimal system

Selection of optimal system is based on the realities of the present. For this case, low capital investment, multi-hydrocarbon possibility, and easy solution were main priorities.

Referring to the examination results, only suitable storage technology with multi-hydrocarbon possibility for this case is CNG based solution. Overviewing of selected system is done in next chapter.

It was well-known that CNG system technology would be one of the suitable storage methods for this case already before the beginning of the study due to fuel flexibility. However, the information increases the hunger, so some of the available technologies were taken into account also.

As described earlier, LNG solution is unprofitable and impossible without continuous liquefaction process. Amounts of the vented gases are so small in this study that LNG is not an optimal system for this case.

On the other hand, ANG solution is still under the development. Moreover, lack of the large-scale studies and information, such as the price of adsorbents, are dropping this system out of this study.

In addition, all of them are requiring at least same components as CNG solution. That means, that capital investment should be lowest by using CNG solution. Referring to the examination results, only suitable storage technology with multi-hydrocarbon possibility for this case is CNG based solution. Overviewing of selected system is done in next chapter.

6.3 Overview of selected system

The chosen system for this case is using CNG technology: compression. The major function of the chosen system is to recycle the vented fuel gases back to process and at the same time avoid the operational releases. According to Thompson et al. (2009), gas storage technologies and facilities require more additional investments than ever due to gas demand fluctuations.

6.3.1 Technical

The closed-loop re-uses the energy that was previously released to the atmosphere and increases safety as no open vent terminals are needed at the powerhouse. The recycling system is integrated into the entire fuel system, and it can be used multiple different ways, see Figure 34. This system is "vent recovery system" forward from this.

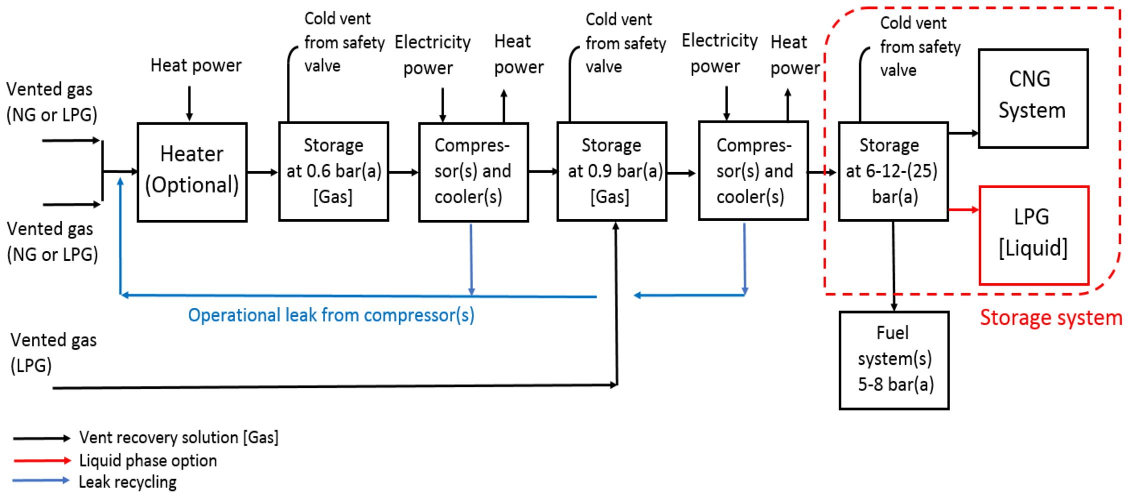


Figure 34: Vent recovery system (Adapted from Fältén 2017).

Figure 34 shows the combined vent recovery system for NG and LPG fuels. The intermediate under pressure storage drains vented gases, such as NG or LPG from the current system. This storage is called a buffer tank. The reason for using partial vacuum pressure in the storage is to minimize compressor size, reduce vessel size, and to achieve a fast vent function.

After the buffer tank, needed compressions and storages are depending on the used fuel. NG can be directly compressed to the 6-12 bar(a) end storage using three (3) compressor stages. On the other hand, LPG can be compressed like the NG, or vented LPG can be directed to the 0.9 bar(a) storage and after that, it can be compressed to the 12-(25) bar(a) end storage using three (3) compressor stages. Each storage includes a cold vent for emergency situations.

There are three different options for using the end storage (6-12 bar(a)) depending on the fuel and engine type:

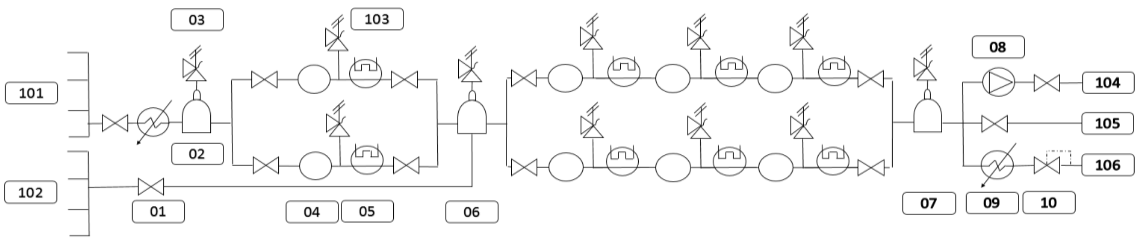
1) Back to fuel system
2) To the CNG storage
3) To the liquid phase

Items 1 and 2 are for engines which are using NG as a fuel. NG can be directed back to the fuel system from the 6-12 bar(a) storage, for example, immediately after the successful start, or it can be used within a next start. The second option is to continue compression to the high pressure and store the compressed gas in the external CNG vessels. This option requires CNG storage solution with new components. In that case, the storage can be used later.

However, the source of the external CNG storage solution is not limited to the vented gases, and it uses entirely different components, such as high-pressure compressors when compared the vent storage solution. For example, pipeline gas can also be a source to the external CNG system. The CNG storage solution is not able to work without the vent recovery system, but the vent recovery system can work without the CNG storage solution due to operational leaks. Operational leaks from the compressor(s) include rod packing leaks and possible vents during the stops are depending on the type of the compressors.

Items 1 and 3 are for engines, both spark and diesel, which can use LPG as a fuel. LPG can be directed back to the fuel system from 12-25 bar(a) storage, where it can be stored as gas or liquid phase.

Figure 35 shows piping and instrumentation diagram of the selected system referring to process simulation software HYSYS by Aspen, see ***Appendix D***. It includes both SG and liquid gas (LG) solutions.



Item ID	Description
01	Shut-off valve
02	Storage 1
03	Safety valve
04	Compressor stage
05	Cooler stage
06	Storage 2
07	Storage 3
08	Pump
09	Heater
10	Regulating valve

Item ID	Description
101	Vent gas inlet 1
102	Vent gas inlet 2
103	Cold vent
104	Liquid outlet
105	To the CNG system
106	To the fuel system

Figure 35: Piping and instrumentation diagram of the selected system.

Figure 35 shows the system and describes all of the symbols. The system includes two identical lines: one for operating and one for backup. Moreover, both lines can operate at the same time if mass flow requires. The cold vent from the storages is only for an emergency situation

As described earlier depending on the used fuel, the heater before storage 1 is optional. Total required power of compressor stages is depending on the incoming mass flow and storage pressure. It can be said that emptying speed of the fuel system(s) and engine(s) is directly proportional to the compressor power. Total required power of compressor stages is calculated by using HYSYS for various mass flows and pressure levels.

Required powers for the compressor(s) for emptying one earlier described NG fuel system and engine in 4 minutes are following: To achieve 6 bar(a) at storage 3, the total required compressor stages power is 8 kW. On the other hand, to achieve 12 bar(a) at storage 3, compressor stages are requiring total 14.8 kW power. Working time of the compressor(s) is 4 minutes and the adiabatic efficiency of the compressor stages is 0.8. If the system needs empty, for example, 6 engines at the same time during 4 minutes, required power of compressor stages is 66.6 kW to achieve 6 bar(a) at storage 3.

Depending on the pressure and temperature, the phase of the LPG may be both liquid and gas. Especially, the liquid LPG requires all of the compressor stages which are shown in ***Appendix D***. Depending on the engine type, LPG can be directly used to back to the fuel system, if engines type is SG. If the engines are diesel engines, the phase of LPG can be liquid.

Technical challenges

The biggest technical challenges of the system are related to properties of different hydrocarbons. For example, the cold vent is not possible to liquid propane, so the liquid propane should be preheated before cold venting in an emergency situation. Also under pressure storage might need heater due to phase mixture of LPG.

Different fuels will act differently in the same circumstances. One might be in gas phase, other in liquid phase. Even though the size of the storage does not have just significance economically either, the physical size of the storage will affect layout design on the site. Figure 36 illustrates the PT-diagrams of different hydrocarbons.

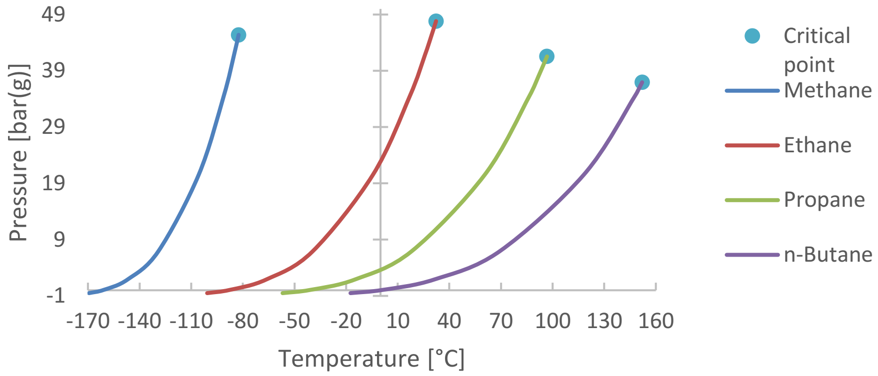


Figure 36: PT diagrams of hydrocarbons calculated by using HYSYS.

Figure 36 shows that liquefaction of methane is much harder to achieve than liquefaction of propane or butane. The left side of the curve is a liquid phase, and the right side of the curve is a gas phase. It is good to notice that if heavier hydrocarbons are drained to the under-pressure storage, the phase of heavier hydrocarbons can be a mixture of gas and liquid. This means that under pressure storage should be heated before the compressors can even work.

One problem with LPG storages is increased number of the main origins of domino accidents as *Chapter 2.2.1* has described. However, if the design, installation, and maintenance of relief devices are taken care of, then the risks can be minimized. Still is good to remember that human factor keeps having a major influence in domino accidents, especially in developing countries (Hemmatian et al. 2013). Therefore, the training of maintenance and plant operation has a huge role in safety.

Layout

The site area can be minimal, and it can contain really challenging sections for layout designing. In that case storage size is a very crucial factor. A bigger storage will need more space than smaller one. The size class is quite different depending on the stored phase, and for example, the layout designers can think about advantages of that. According to HYSYS calculations at temperature 44°C and pressure 14 bar(g), the volume of liquid propane is 15 times smaller than the volume of gas propane at same conditions, when the phase changes.

The plant needs to take the boundaries outside the plant site into account, for example, residential areas, places of worship, hospitals, schools and other major public areas. This means that installations should be located within safety distances. Referring to the **NFPA 58,** CNG storage, compressor, and dispenser should be located 3 meters from residential buildings, borders, and public roads. Additionally, the above-mentioned units should be located 15 meters from the railway. However, **ISO** standards have generally quite different safety distances. Referring to the **ISO** standards, CNG storage, compressor, and dispenser should be located 10 meters from the residential building, 3 meters from building openings, 5 meters from borders, 5 meters from other fuel storages and 5 meters from public roads.

Storage vessels can be located on the ground inside the fenced area. Additionally, vessels should be in the concrete bunker. One possible safe location for storage vessels are underground in the concrete bunker. However, that might face some challenges with the civil design due to extra work and costs. Despite that, it is still the safest location for the liquid storages.

Capacity of storages

Required mass capacity of storage varies depending on the plant output, fuel system capacity, number of stops, and used fuel, see Figure 37 and Figure 38. The plant output is related to a number of engines. Storage capacity can be varying depending on the system pressure and temperature.

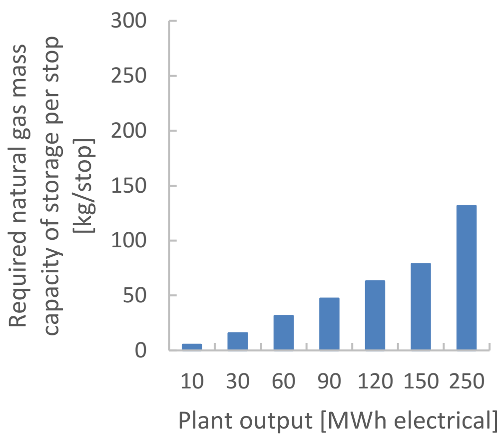


Figure 37: Required mass capacity of natural gas storage as a function of plant output if all engines are stopped.

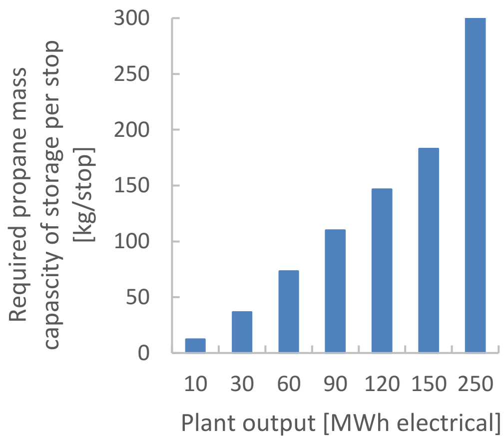


Figure 38: Required mass capacity of propane storage as a function of plant output if all engines are stopped.

Figure 37 and Figure 38 illustrate that the required mass capacity for storage varies depending on the used fuel if the volume of the fuel system is the same as in *Chapter 5.4*. Mass of propane is approximately 230% greater than the mass of natural gas in the identical fuel system due to densities of hydrocarbons.

However, actual gases do not follow the equation of ideal gas quite accurately. Several different functions have been developed for the determination of compressibility factor. These are dependent on pressure and temperature. (Raiko et al. 2013) Compressibility factors (**Z**) are shown for each hydrocarbon by using Peng-Robinson equation in ***Appen-***

dix E. This compressibility factor has to take into account in the design. Storage capacities, which have calculated by HYSYS, are including the change of the compressibility factors.

One SG engine, which is using NG as fuel, needs approximately 5 m^3 buffer tank (initial pressure 0.6 bar(a) and final pressure 1 bar(a)) at 25°C, and 2 m^3 storage (initial pressure 6 bar(a) and final pressure 12 bar(a)) at 25°C.

6.3.2 Benefits

It can be said that the safest location for the fuel gas is contained in the fuel gas system. That can be achieved by using a closed system, such as vent recovery system. Benefits of vent recovery system are divided into four different parts, see Figure 39. All of the parts are described and discussed in more detail in the following section titles.

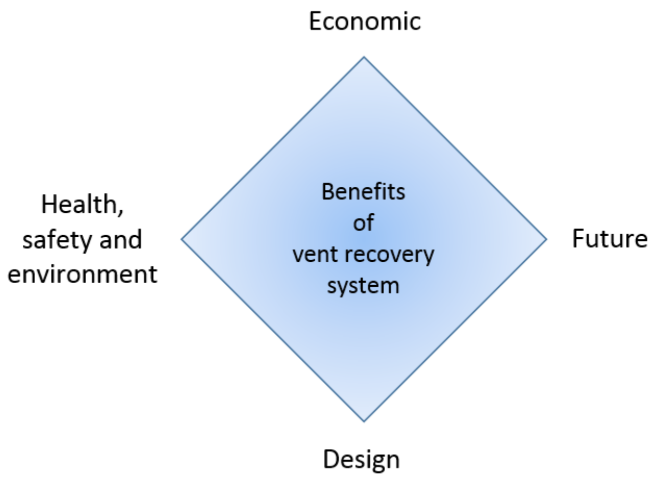


Figure 39: Benefits of vent recovery system.

As earlier have been mentioned, one of the biggest problems is hydrocarbon release to the atmosphere due to emissions and risks. Controlled closed system, such as vent recovery system, can stop the venting to the air. By adding fuel energy storage technology to existing and new gas engine based power plants, the system will enable customers to have instant power while reducing emissions, saving fuel and increasing safety.

Economic

Vent recovery system will have multiple economic benefits. Economic benefits can be divided into three parts: fuel, design, and emission benefits.

The first economic benefit is fuel savings. Without the vent recovery system, fuel savings are not applicable. Can be said, that current venting system is unprofitable. So, the user of the vent recovery system can utilize all of the fuel which is bought and even earn the investment money back. Analysis based on the fuel savings are gone through in *Chapter 6.3.3*. Sensitivity analysis takes account the future.

The second economic benefit is related to the design. The current design includes, for example, long venting pipes which rise above the roof along the wall of the engine hall. Thanks to the recycling system, for example, the unprofitable piping costs will decrease. The ground level piping does not need any extra expenses which are formed for example by the installation.

On the other hand, current venting to atmosphere requires hazardous zones classified items. These might increase the costs, in particular on the site. Moreover, ordering and getting the ATEX classified items might be hard. With the vent recovery system, this is not necessary anymore. The vent recovery system has removed some hazardous areas and at the same time the need for ATEX classified items related to, for example, venting heads.

Moreover, with the vent recovery system, the external participant, such as consultancy, will not take care of the design. This means that they cannot charge for needed information or workshops, which are related for example to safety studies, hazardous areas, risks or plumes. This will increase the efficiency of the procedures because all kind of explanation of the system or functions of the components for external sources takes time.

With the vent recovery system, health, safety, and environment design costs will be reduced, and agenda of the different workshops and studies will be shorter. When the risks of the plumes are minimized, various safety studies, described in *Chapter 3.2.2* can be reduced related to this subject. This automatically saves time and money. Workshops are requiring multiple specialists and people to spend days in the workshops. Many consults will come to lead workshops where multiple experts have to be involved. It is critical to be there and support the issues by using knowledge but that time could have been utilized differently also. For example, these safety workshops are bonus tasks to for example technical experts, not their primary tasks. However, if the selected system is waterproof, no plumes, no leaks, etc., the workshops and safety studies related to this subject will be cut out in the future.

As a summary, one significant economic benefit is related to the win-win situation. When the customer invests more money in the system, the Company will earn more money, at the same time when design costs are lower for the Company. This makes win-win situation possible. Less design means better design in this case. By developing the vent recovery system design to modular, project costs can easily be reduced.

The third economic benefit is related to the emissions. With the vent recovery system, the emissions are reduced as mentioned earlier. Now the only fuel-based emissions come from the exhaust gas stack in the power plant. This might make possible to get new projects to the places or countries, where emissions have earlier been an issue and limiting factor. Value of this is hard to estimate because of lack of the information about the rejected projects and reasons for rejecting.

Moreover, emissions are costs. Global warming potential (GWP) of CH_4 compared to the CO_2 is shown in Table 18.

Table 18: Global warming potentials (According to Solomon et al. 2007).

Substance	Global warming potential for given time horizon		
	20 years	*100 years*	*500 years*
CO_2	1	1	1
CH_4	72	25	7.6

Table 18 shows that 1 kg of CH_4 causes 25 more warming over a 100-year period compared to 1 kg of CO_2, so the methane GWP is 25. According to the Litterman (2013), the present value of CO_2 damages is typically thought to be in a range between 5 \$ to 35 \$ per ton of CO_2. The government of U.S. has estimated this present value to be 20 \$ per ton. (Litterman 2013) Referring to the U.S government value, estimated present value of the CH4 should be 500\$ per ton. Despite that, the actual cost of CO_2 would be much higher. According to the Moore et al. (2015), climate damages are much wider than expected. This means that the social costs of emissions are much bigger. It is good to remember that slower economic growth automatically leads to a lower discount rate. However, for example, 100 years is the quite long time period. Hopefully, CO_2 emissions are decreasing little by little or the price of emissions will increase more and more. Especially, during that time, emissions should be decreased significantly.

However, CO_2 is not the only emission of the carbon compound which is reduced by using the vent recovery system. For example, according to EPA, average $PM_{2.5}$ health-related benefits of VOC emissions are valued at 280\$ to 7,000\$ per ton across a range of eight urban areas. (EPA 2011) That range is quite enormous and non-trustable, but as can be seen, even VOC emissions have some kind of economic value.

Design

The vent recovery system has a huge effect on the design of the plant. The closed system removes the possibility of all the simulated plumes which might be caused by venting setup. At the first time for example terrain and wind is not such a big challenge than earlier.

So, the vent recovery system is minimizing the risks by being the bulletproof solution in normal operation. There is no need to worry about flammable hydrocarbon plumes around the site or how the properties of hydrocarbons will act in different conditions anymore. Only external hazard or emergency situation might cause a leakage or release with the closed system. Thanks to that, designing of equipment locations should be easier than in the past.

By using the vent recovery system, hazardous areas related to the new system are also well-known and can be located far away from for instance the engine hall. Now the ventilation of engine hall cannot, for example, drain the plume inside the engine hall. Corner of the site area is one possible place, where the system does not cause any harm to surrounding or people. However, this might increase the costs of the system, as earlier described.

When the limiting factors, such as hazardous areas, are gone from the design, it is much easier to design the layout of the site. This is very relevant due to site area. The site area might be a tiny area or located near the airport. Typically, layout design should be as standardized as possible, but it might not be the smartest design. Change of the layout might increase layout design costs, but at the same time removing components and related problems. All of these affect the safety. When various problems are removed, the total cost will be lower than earlier.

Moreover, designers do not have to focus so much on the boundaries outside the power plant site thanks to reduced emissions. In addition, vent stack size, venting pipe dimensions or noise is not a problem anymore.

As a summary, the recycling system opens a totally new playground for designers with limitless possibilities. The recirculation system might not be the easiest solution compared to a vent stack or a flare stack system, but it appears to be the best option in this case. Moreover, this kind of system could work for example with the biogas in biogas plants. Just by combining multiple process technological solutions, risks are minimized and problems are gone.

Future

The future topic is related to the fuel flexibility and emissions. Customers will buy the power plant which can use available fuel gas. Due to that fuel flexibility is a significant advantage. However, new fuels in the future, which are containing heavier hydrocarbons are creating challenges with the venting to atmosphere. With the vent recovery system, any of these difficulties are not a problem anymore. Moreover, the behavior of different hydrocarbons is controlled. There is no need to think about how hydrocarbons will act when they are released to the atmosphere. Moreover, maximizing the energy of the fuel will be more and more important in the future.

The multi-fuel capability of the system also gives the advantage of changing the fuels in the future. Depending on the cost and availability, either methane, ethane or propane can be used. However, the fuel expenses must be in the balance with the productivity, availability, and usefulness. Fuel flexibility with the fuel efficiency automatically reduces the price of the electricity for consumers. The operator can select the cheapest fuel for producing electricity without wasting any of the bought energy.

According to the European Commission: "*It shows that current policies and market conditions will deliver neither our 2030 targets nor our long term 2050 objective of 80 to 95% GHG emissions reductions".* However, legislation will be more demanding in the future to achieve these goals. In some point, something must change. This automatically means that recycling procedure shows the right way for everyone, not only for the case company. Recirculation thinking way might spread to other processes and industries also. There are a lot of different processes where is some kind of a waste. That waste, just like the vented gases, could be recirculated back to process. It automatically increases the efficiency of the process.

Health, safety, and environment

Uncontrolled hydrocarbons may cause a hazard or escalate ongoing hazards. One of the most important benefits of the vent recovery system is the minimization of the risks. The closed system allows the first time a possibility to detect for example the leakages from the pipelines. Moreover, when the combustible plume is not any kind of threat, the hazardous areas, also known as ATEX zones, all over the site are not anymore such critical issue. Thanks to the vent recovery system, the site area contains less ATEX areas, and for example, safety distances can be minimized.

The vent recovery system also reduces levels of air pollution both short- and long-term. The environmental impact is reduced when the hydrocarbons are directed back to the process instead of vented to the atmosphere. However, it is not known how much is the venting of the power plant in relation to the health hazards brought for example by the exhaust gases.

Urban areas, where the population concentration is high, are typically VOC-limited, so reducing VOCs is the most effective way to lower ozone level. However, often downwind suburban areas and rural areas are NOx-limited, so ozone concentrations are reduced most effectively reducing NOx emissions rather than reducing VOCs. In areas, between these, ozone is comparatively insensitivity to NOx and VOC changes. (EPA 2011) A recycling system would reduce emissions. According to EPA (2011), reduction of emissions would lower for example formation of ozone, the incidence of ozone-related health impacts, and human exposure to ozone.

If the gas is captured rather than vented, the emissions of HAPs and VOCs are reduced. Without emissions, there is no suspended particles and gases which are degrading visibility by scattering and absorbing light. Often higher relative humidity levels and higher concentrations of fine particles such as sulfates in the air are reasons for higher visibility impairment levels. According to EPA, one direct significance to the quality of life is good visibility. (EPA 2011) The visibility for the boundaries outside the power plant site is also significant. Everyone outside the boundaries of the power plant site will benefit from better visibility, for example, airplanes while landing and take offing from the airports.

6.3.3 Economic analysis

The analysis in this chapter is based on the fuel savings from the vented natural gas. If the gas can be used instead of wasting it, it saves money automatically. The amount of vented natural gas is calculated using fuel system dimensions and different cases as earlier described. Other economic benefits are not taken into account in the analysis.

Fuel savings

Vented fuel gas is wasted fuel gas. The vent recovery system will recirculate vented fuels back to the process, or alternatively, the vented gases can be stored. Amount of saved fuel, earlier wasted fuel, is depending on the plant size, the main purpose of the plant, starts and stops of the engines, and capacities of the fuel systems.

Used fuel type is affecting factor as well as the price of the fuel gas. Various storage cases for different fuels are shown earlier in Figure 37 and Figure 38. The economic profitability can be achieved using the closed system and at the same time, the fuel efficiency is increased.

All of the calculations have been done using natural gas as a fuel. Generally, LPG will achieve bigger savings due to higher price compared to the NG. Next figures illustrate the various fuel savings with different fuel trade prices. Cases A, B, and C in the figures are power plant sizes which are described in *Chapter 5.3*.

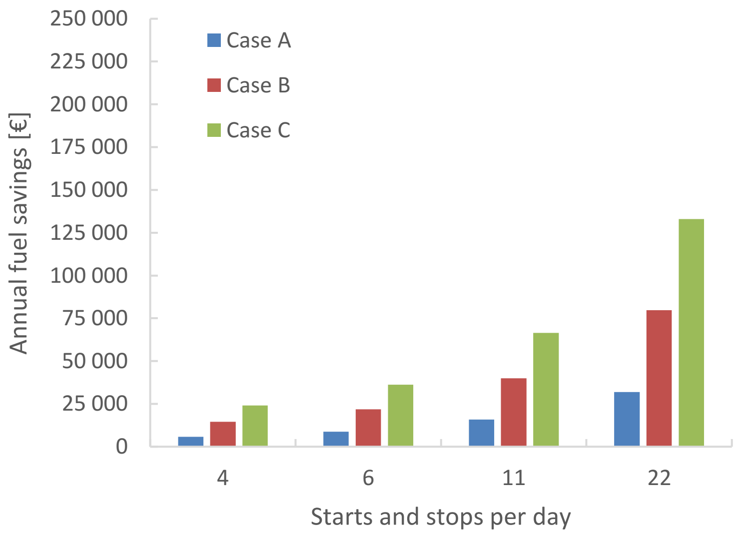


Figure 40: Annual fuel savings which are referring to trade price of US Henry Hub, Case 1, 3.17$/MMBTU in May 2017.

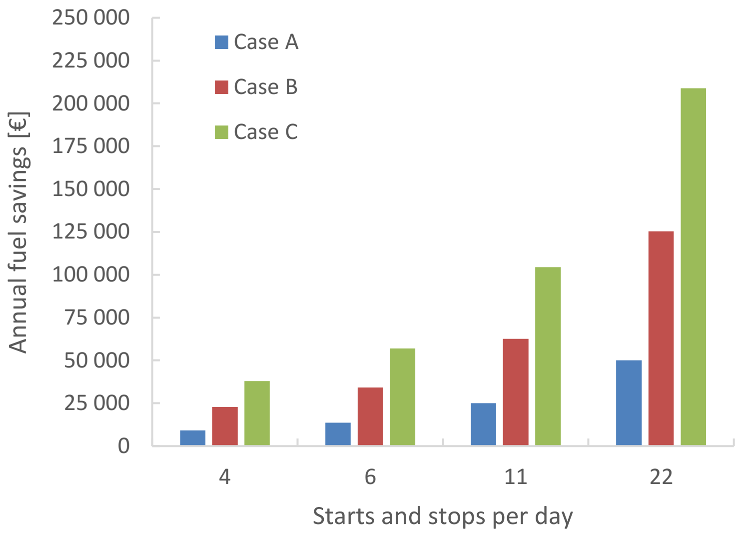


Figure 41: Annual fuel savings which are referring to trade price of Russian natural gas monthly report, Case 2, 4.98$/MMBTU in June 2017.

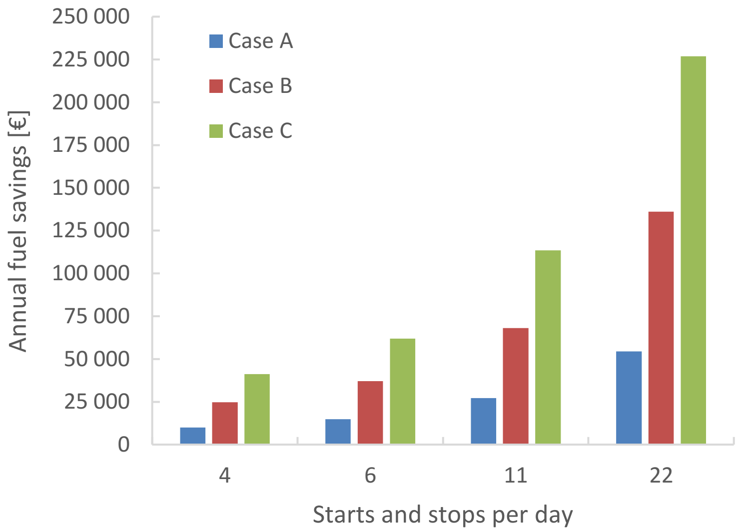


Figure 42: Annual fuel savings which are referring to trade price of European natural gas month report, Case 3, 5.41$/MMBTU in June 2017.

Figure 40-Figure 42 illustrates the effects of the size of the power plant and a number of starts and stops, as well as trade price, to the fuel savings. The process parameters, such as density of the gas, pipe sizes and lengths of the fuel system also influence the fuel savings. As can be seen, for example, Case B power plant saves 21,750 € per year with 6 starts and stops per day in U.S. market. On the other hand, fuel savings of Case B power

plant are increased to 37,120 € in EU market. The reason for higher savings is a number of engines. More engines, more wasted fuel.

As mentioned earlier, all of the vented gases are wasted money. Four different starts and stops scenarios have been calculated. 22 starts and stops per day which is the worst scenario might not happen every day around the year. Starts and stops from 4 to 11 are more reliable and possible scenarios. The calculations are based on the trade prices of the natural gas, which were following: 3.17 $/MMBTU in the US (Case 1), 4.98 $/MMBTU in Russia (Case 2), and 5.41 $/MMBTU in EU (Case 3).

As Figure 40-Figure 42 show, the annual fuel savings will automatically change when the price or the number of the starts and stops change. Increased and decreased spot price effects powerfully to the fuel savings calculated using low fuel price, under 10 $/MMBTU. For example, 1 $/MMBTU change in the US means approximately 32% change in savings. Moreover, infrastructure will modify the results of the fuel savings. LNG is roughly 10 times more expensive than pipeline gas, which means 10 times more savings. More discussion about this topic in *Chapter 6.3.4*.

The following economic calculations and results are based on the fuel savings because these are the only economical profits from the system. Recirculated fuel gas back to process is automatically saved money. Economic benefits are gone through in *Chapter 6.3.2*. Estimation of the monetary value of the emissions reductions or climate effects etc. is quite hard. Literary has given some values referring to specific case and investment, but these are not taken into account in the investment analysis. The discussion about these has been only done.

Capital expenses and operating expense

CAPEX of the investment is shown earlier in *Chapter 5.6*. Like in every project, the starting price of the project or investment might be different from reality. As can be seen in Table 14, the price of compressor unit(s) is same for each case due to estimated default capacity of compressor unit(s) for all cases.

Compared recycling system to the current system, only compressor unit(s) and storage vessel unit(s) are extra costs. Other costs, such as commissioning or piping are costs also without the recycling system. However, according to the fuel flow diagram, the current system requires three venting pipes per engine. In that case, for example, piping is much higher cost, or at least the same cost, compared to the recycling system costs.

New technology and development process will always cost. Costs might be bigger in the first place, but it might reduce other costs, for example, HSE or ATEX design costs, and have other benefits. Furthermore, without development process, nothing will change.

The costs of building in different regions can vary significantly. Commodities, site assumptions, and project equipment can vary widely from project-to-project for a given technology. The extra costs can be created for example from routes and location of pipes. It is good to remember that saving in the initial investment components or methods might cause a bigger OPEX in the future. One good example about saving in the wrong place is piping material. The black steel is much cheaper than the stainless steel. However, if the black steel is pickled and painted, it is much expensive than the stainless steel.

OPEX includes, for example, electricity bill from the system, maintenance and service costs. One of the biggest issues, economically, to fuel energy storages is OPEX. To achieve the most profitable fuel energy storage system, the OPEX should be near 0% of CAPEX. One reason for rejection of the investment is too high OPEX. However, calculations have been done with the estimated 5% of CAPEX value.

Payback analysis

Payback periods of vent recovery system for each case is shown in following figures. The payback analysis is done by using natural gas amounts and prices. The first analysis includes all of the listed CAPEX. The second analysis includes only extra components for current design: storage and compressor units. The main reason for that is to show, that real project costs will be increased only by the extra components. The current venting to atmosphere situation requires at least the same costs without payback capability due to for example material costs, ATEX components, and safety analysis.

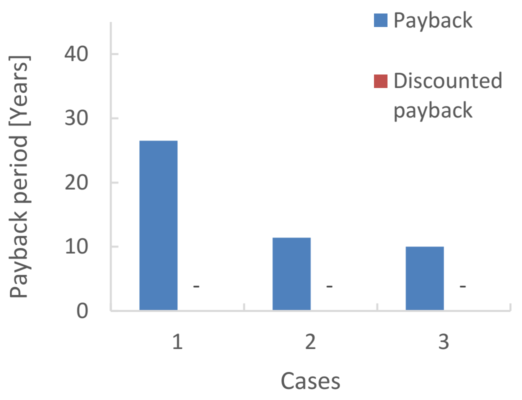


Figure 43: Payback periods for vent recovery system (Case A power plant with 6 starts and stops per day).

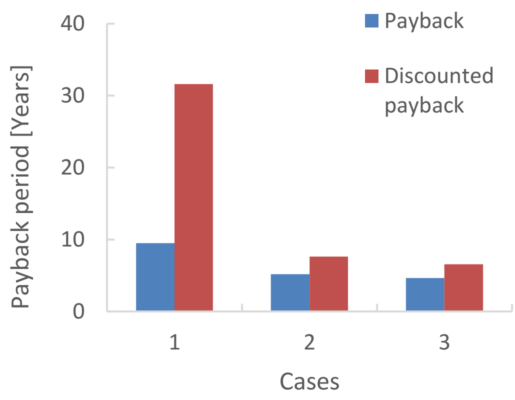


Figure 44: Payback periods for vent recovery system (Case B power plant with 6 starts and stops per day).

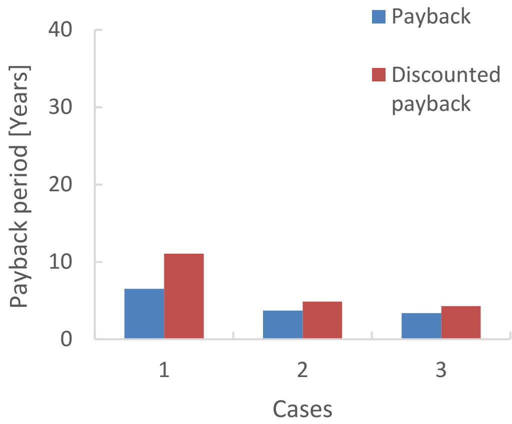


Figure 45: Payback periods for vent recovery system (Case C power plant with 6 starts and stops per day).

The calculated payback period is shown with the blue color and discounted payback period with the red color in Figure 43-Figure 45. As described earlier, cases 1, 2, and 3 are different fuel trade prices in U.S., Russian, and EU. Cases A, B, and C in the figures are power plant sizes which are described in *Chapter 5.3*.

Figure 43 shows that the discounted payback time for vent recovery system for Case A power plant is not available due to the discount rate. The discounted net cash flows are decreasing faster than the payback period is achieved. Payback periods are varying from 10 to 26 years. However, it is still more profitable than the current venting system because the payback period can be calculated and some savings can be achieved.

If in the examination other pecuniary advantages have also been used, the results could be separate. Furthermore, the fuel savings can be a huge pecuniary advantage in the future already mere. Today's investment may be extremely profitable in the future.

For the bigger power plants, the discounted payback periods of the vent recovery system are lower than 10 years almost in every case, see Figure 44 and Figure 45. The discounter payback periods are good ones, from 4 to 7 years, especially with the fuel trade prices of Russia (Case 2) and EU (Case 3). Investment is profitable when the assumed lifetime of the system is a way longer than the discounted payback period. Due to short payback periods, it should be quite easy to market this kind of investment compared the current situation.

Following figures illustrate the payback periods of the vent recovery system's compressor and storage units.

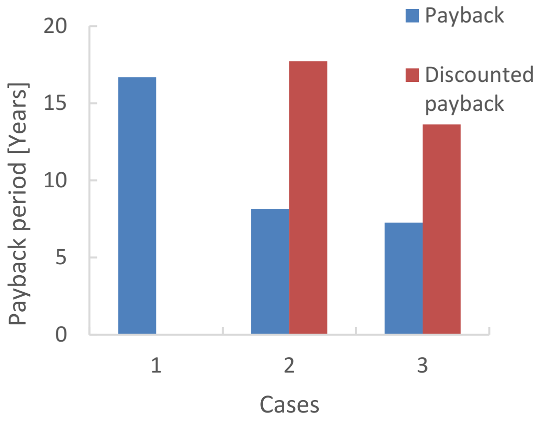


Figure 46: Payback periods for vent recovery system's compressor and storage units (Case A power plant with 6 starts and stops per day).

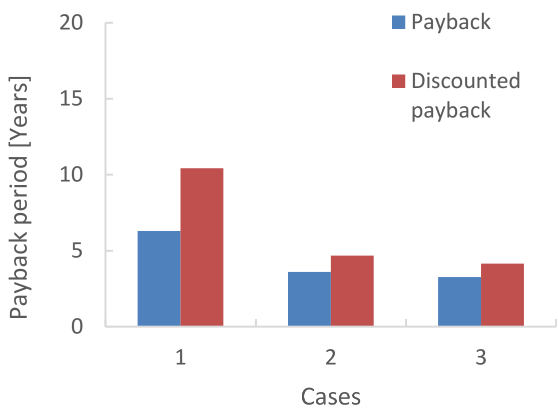


Figure 47: Payback periods for vent recovery system's compressor and storage units (Case B power plant with 6 starts and stops per day).

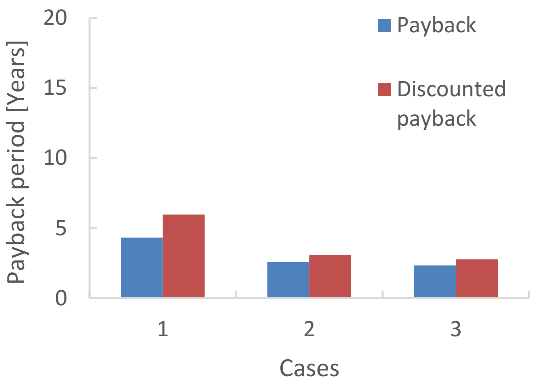


Figure 48: Payback periods for vent recovery system's compressor and storage units (Case C power plant with 6 starts and stops per day).

As Figure 46 shows, the discounted payback time for vent recovery system's compressor and storage units for Case A power plant (Case 1) is still not available due to the discount rate. This case will never pay back itself because the discounted net yields are less than 100 euros after 35 years.

Moreover, discounted payback period with fuel prices of Russia and EU are also quite long, from 13 to 17 years, but still less than the expected lifetime of the investment. So, economically examined this way is not space, the investment exists or not, due to longer payback periods.

Figure 47 and Figure 48 show that the discounted payback of Case B and C power plants is varying from 3 years to 10 years. As earlier for the whole system, the payback periods for the vent recovery system's compressor and storage units for bigger power plants are much better. Now when the CAPEX is decreased, the periods are roughly halved when compared to the whole system. Especially, with the Russian and EU prices, the discounted payback periods are less than 5 years. An assumed lifetime of the system is a way longer than any payback period.

However, the payback period is strongly depended on the fuel price and number of starts and stops. As can be seen in Figure 40-Figure 42, amounts of saved money are varying from 5,800 € to 226,843 €. The analysis might change when the running program or used fuel changes in reality. More about critical parameters in *Chapter 6.3.4*.

Moreover, CAPEX and OPEX, as well as discount rate and a lifetime of the investment, will affect the results. The results can look good on the paper, but it is good to remember that the analyses have not taken into consideration extra expenses. Extra expenses can be created for example by piping, legislation, or maintenance, and that is why those are hard to estimate. Moreover, interest market will affect the results. According to ECB (2017), the interest rate is roughly 1%. If the interest rate is going up for example in 5 years, the used discount rate will also increase along with the interest rate.

Net Present Value (NPV) analysis

NPV of vent recovery system for each case is shown in the following figure, see Figure 49.

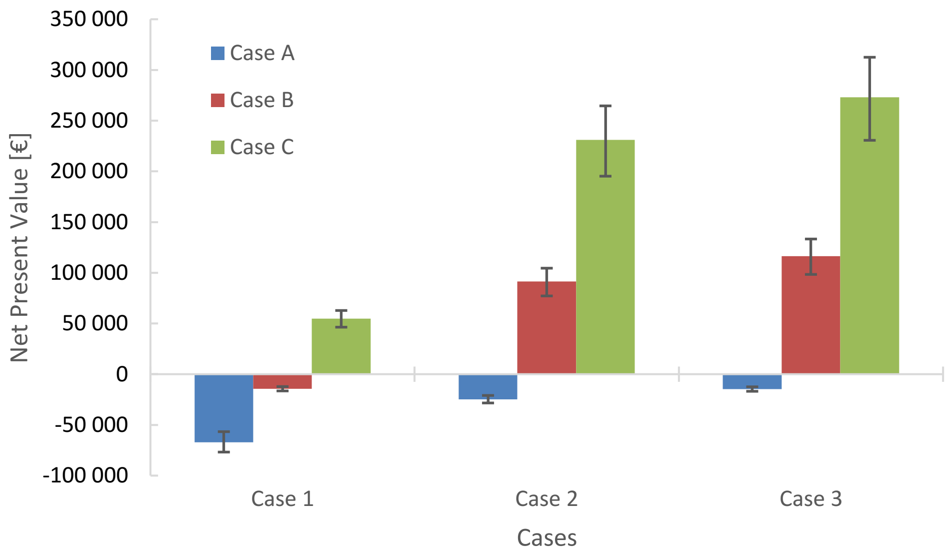


Figure 49: NPV for vent recovery system with 6 starts and stops per day.

In NPV figure, the columns illustrate the NPV with 0% margin. Black vertical line illustrates possible varying of the NPV. Varying is formed by using price marginal and analysis marginal, see *Chapter 5.6*.

NPVs of vent recovery system for Case A power plant and for case 1 of the Case B power plant are negative values from -67,000 € to -15,000 €. Well, will the negative NPVs automatically kill the potential closed system investment? Actually, a negative NPV illustrates that the present value of the investment costs exceeds the present value of the investment revenues at the assumed discount rate. So, any investment will have a negative NPV in case of the used discount rate is high enough. So, the estimated costs should be economized, sources of the investment revenue should be upgraded, and discount rate should be checked if necessary and possible. Even though the values would be still negative after doing the enchantment, the investment might be mandatory. In that case, money is not the determinant. Even the negative NPV can be a profitable investment for the company, but it does not fill the return expectations of the investors due to the selected discount rate.

However, the NPVs of the vent recovery system for bigger plants are positive excluding the case 1 of the Case B power plant. Now the positive NPVs with 0% margin are varying from 91,000 € to 273,000 € depending on a number of engines and fuel prices. This means that if one puts money in the investment, one will get more money back later. Moreover, all the positive values of NPV exceed the expectations of the investors. If the company has extra money, all investments with the positive NPV should be carried out because those will increase the yields. If the available money is limited, negative NPV will not be worthwhile to go to invest. Economically it is worth to think, whether the money is unused with the zero interest or the investment produces at least something. For bigger plants, the NPV is more than just something.

The following figure illustrates NPV values of the system's compressor and storage units, see Figure 50:

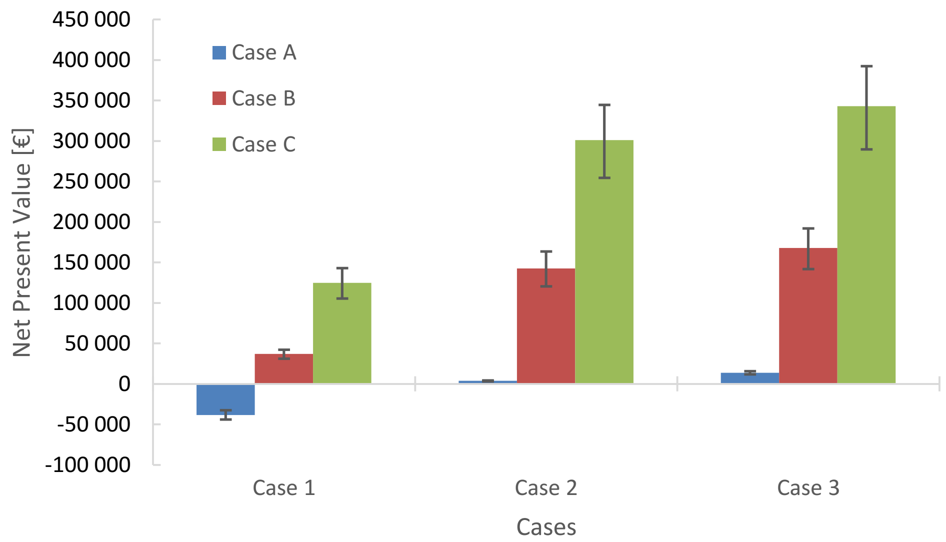


Figure 50: NPVs for vent recovery system's compressor and storage units with 6 starts and stops per day.

Figure 50 shows that only Case 1 of Case A power plant has negative NPV. Other NPVs with 0% margin vary from 4,000 € to 340,000 €. These results are giving similar discussion and conclusion with the discounted payback periods. As a summary, the investment is profitable almost in every case in this study.

Internal rate of return (IRR) analysis

IRR analysis does not take into account the margin of NPV. IRRs of vent recovery system and specific components for each case are shown in Table 19. All IRR values, which are bigger than the discount rate are profitable investments.

Table 19: IRRs of vent recovery system and its specific components for different cases.

Plant size	Fuel price	IRR of vent recovery system	IRR of specific components of vent recovery system
Case A	Case 1	-2.5%	1.8%
	Case 2	6.1%	10.7%
	Case 3	7.7%	12.5%
Case B	Case 1	8.4%	14.9%
	Case 2	18.7%	27.6%
	Case 3	21.0%	30.5%
Case C	Case 1	14.3%	22.7%
	Case 2	26.7%	39.0%
	Case 3	29.6%	42.9%

Table 19 shows that IRRs of Case A are varying from -2.5% to 7.7% for the system and from 1.8% to 12.5% for the specific components. The cases with IRR values from -2.5% to 6.1% are unprofitable. Other IRR values from 10.7% to 42.9% are profitable when comparing to the discount rate. As can be seen, IRR analysis supports the results of the payback analysis and NPV analysis. The results show that the investment is economically profitable in this study. The only question might be: Does the company have enough initial capital to carrying out of the investment? Well, the investment is not such big, and if the current liabilities are available, the investment should be performed.

IRR does not take into account initial capital absolutely. If the initial capital for investment is small and IRR quite significant, the final money amount can be smaller compared to the bigger initial capital and smaller IRR. However, if the company has unlimited money in the use, different investments should be made in order based on the IRR, from the biggest IRR to the smallest one. In that case, the absolute money is maximized. If the company has just a few different investments, the absolute money might be a crucial factor.

6.3.4 Sensitivity analysis

The analyses and results in this chapter are divided into three parts: partial sensitivity analysis, best and worst-case analysis, and the interdependence of the fuel price and payback period analysis.

Data for analyses is analyzed to be as Table 20 shows. The normal case is the same case as earlier described.

Table 20: Data for sensitivity analysis.

Case	Fuel price [$/MMBTU]	CAPEX [€]	OPEX [% of CAPEX]	Lifetime of investment [years]	Interest rate [%]	Number of starts & stops / day
Normal	4.98	140,000	5	20	10	6
Best	16.00	104,000	3	30	5	11
Worst	3.00	200,000	7	15	15	1

Table 20 shows that normal fuel price referred to the Russian price. The best price is selected to be same as LNG price in 2014. The worst price is the same price lowest U.S. price in few years.

Fuel price can vary a lot due to various factors. Weather affects the prices because end-users may need more heating or cooling and that correlates directly to the consumption of end-users. However, natural gas prices are also related to crude oil prices. Any threat to the supply of oil and/or spare capacity, for example, wars, natural disasters, terrorism or political unrest in major oil producing countries, will impact the price of oil. The supply and demand of the oil, market shares and the value of the US Dollar also impact to the price of oil. Moreover, the analyzed price is partly based on the BP's historical data, see Figure 51.

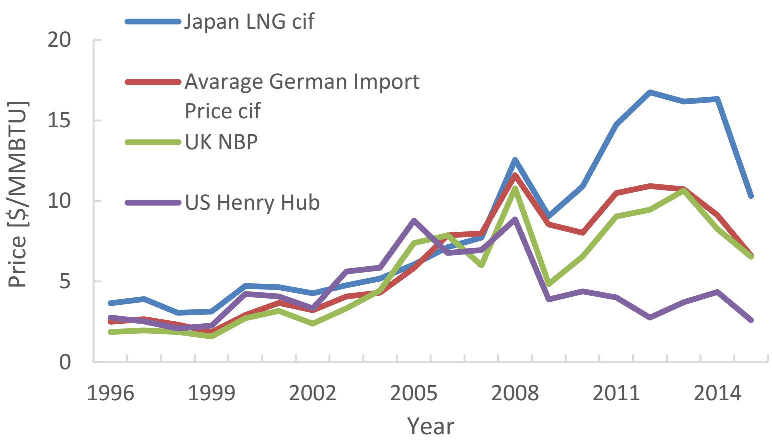


Figure 51: Natural gas prices from 1996 to 2015 (Adapted from BP 2017).

At the moment fuel price is quite low because the prices were falling in all regions in 2015. LNG is typically more expensive than normal pipeline gas, but the price of Japan LNG also dropped due to Fukushima Nuclear Disaster in March 2011. However, the prices of the fossil fuels have to increase in the future.

Literature is supporting the 'growth of the fuel price' vision. EIA has estimated that U.S. spot price will grow about 8% in a year (EIA 2017a). According to Rautkivi (2017), the US price will stay at around 3 $/MMBTU level until around 2025. Estimations have been done that in 2029 the average price should be nearly close to 4 $/MMBTU. It means that the economic benefit of the investment will be automatically roughly 30% better. It also means that the wasted amount of fuel gas is 30% more valuable than before. So the pay-back time of the investment will be much shorter in the future if the spot price starts to grow up. However, when the market price goes up, more rigs will be opened. If the production increases, the prices will go down. The natural gas producers will close their rigs and wait for the better times to re-start their production due to the low price of the natural gas. That is a typical supply and demand example from the market. Due to that, it is quite hard to estimate future prices.

Partial sensitivity analysis

The partial sensitivity analysis overviews how the one-factor-at-a-time change of 5 different parameters will affect to the NPV of case B power plant. Zero point of change (0%) is selected to be the same as previously for vent recovery system of Case B power plant, see *Chapter 5* and the normal case of Table 20. Fuel price is using case 2's price as a zero point. Figure 52 shows the sensitivity analysis with ±30% change of normal case parameters.

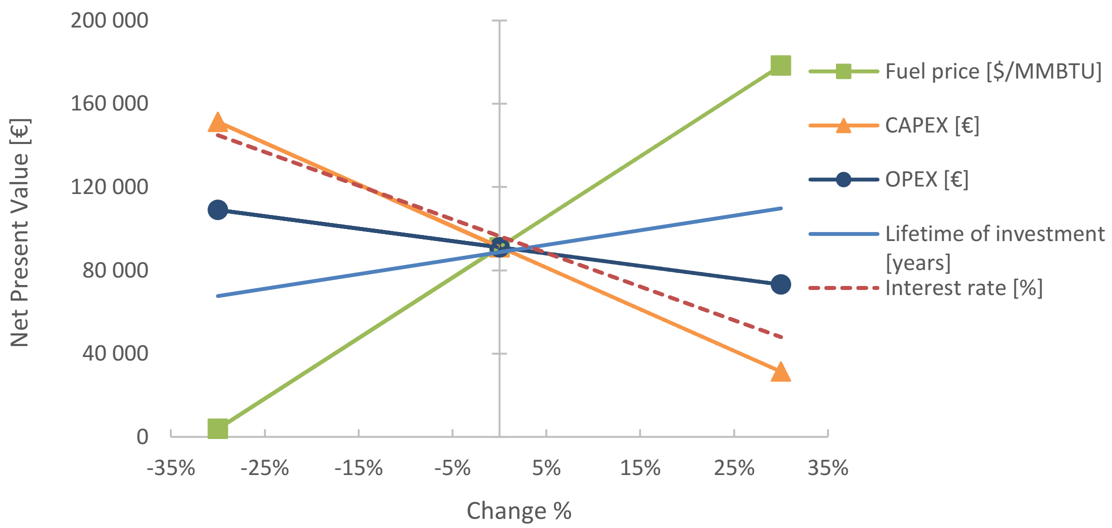


Figure 52: Partial sensitivity analysis of NPV of vent recovery system for case B power plant with 6 starts and stops per day.

Figure 52 shows that other parameters will affect more than the others. The gradient or the slope of the lines will determine how critical parameter is. The steeper line, more critical parameter. However, the figure does not illustrate the relation between the parameters.

The fuel price, as well as a number of engines, and starts and stop (which are not shown in the figure due to the identical line with fuel price) will affect as much to the NPV results. The reason is simple, those are equal factors to the annual savings and at the same time only factors which are creating savings. Figure 52 shows that fuel price, as well as the number of engines, and starts and stops, will affect the most to the NPV. If the price of the fuel is changed -30%, which means that the price is approaching 3 $/MMBTU, the NPV of the normal case would be near the 0 € instead of 91,000 €. In that case, it economically does not matter, does the vent recovery system exits or not.

The second sensitive parameter is the CAPEX of the investment. However, this parameter has approximately 32% weaker effect to the NPV than the fuel price parameter. Moreover, that parameter acts reverse way with the change when compared to the fuel savings, because it increases costs of the investment. In this case, -30% change means that NPV will increase 66%.

The third sensitive parameter is the interest rate. It has approximately 55% weaker effect to the NPV than the fuel price parameter. This parameter also acts like the CAPEX parameter. Figure 52 shows that if the interest rate decreases 30%, the NPV will be 62% higher.

The weakest effect to the NPV possesses a lifetime of investment and the OPEX of investment. Their effect is only 20-25% of the effect of the fuel price parameter. Figure 52 shows that 30% shorter lifetime decreases the NPV 27%. On the other hand, 30% lower OPEX increases NPV 20%.

Best and worst-case analysis

This analysis reviews overall sensitivity by using best and worst cases. Best and worst-case analysis is done for Case B power plant. It deviates from the partial sensitivity analysis in fact that all the parameters are changed in one go according to Table 20. Figure 53 shows the results of this analysis.

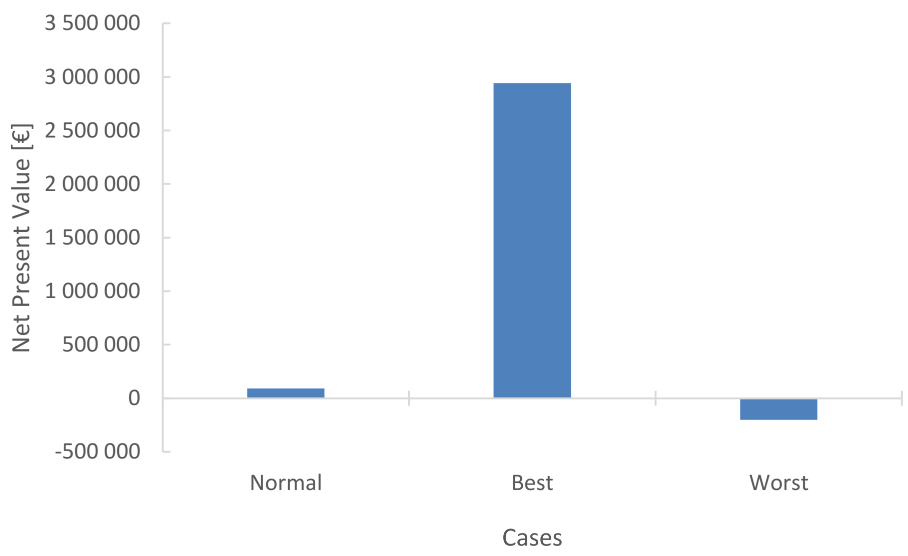


Figure 53: Best and worst-case analysis for Case B power plant.

Figure 53 shows that the NPV of the best case is 2,942,000 €. The NPV of the worst case is -201,000 €. By the analysis, can be said that the results have become opposite in a chosen extreme cases. Figure 53 shows that the investment is not profitable in the worst case. However, in that case, the NPV is still approximately same than the value of CAPEX. So the time value of money and OPEX are paid with fuel savings.

In fact, this is the almost same situation as with the current system. The current system is unprofitable, but the NPV of the current system is way higher than the CAPEX of the system after the lifetime of it. Moreover, the vent recovery system includes multiple various benefits compared to the current system.

On the other hand, NPV of the best case is almost 3,000,000 €. However, both best and worst case are extremities, so the result of the normal case, 91,000 €, is the most reliable result.

Interdependence of the fuel price and payback period analysis

Customers will want to as short payback time as possible. Figure 54 shows the interdependence of the spot price and payback period of vent recovery system. These analyses have not taken into account the time value of money due to the margin of the future spot price.

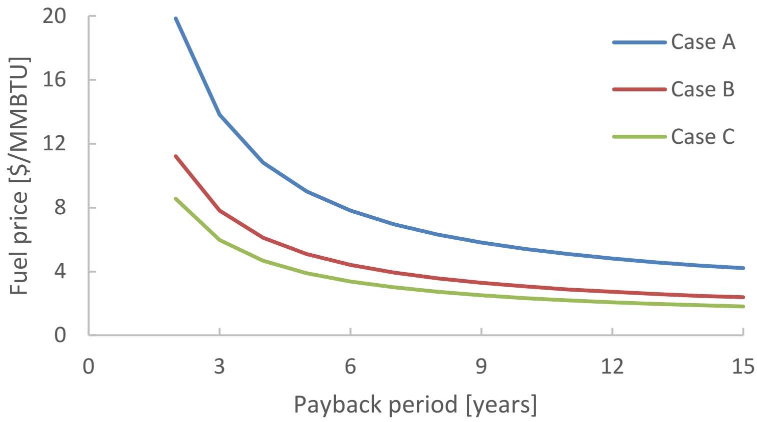


Figure 54: Payback period for vent recovery system with 6 starts and stops per day referring to fuel price.

Figure 54 shows that Case A needs 70% higher fuel price than Case B, and Case B needs 31% higher fuel price than Case C, to achieve 2 years payback period. Shorter payback period is achieved when the spot price is a little bit higher than currently. For example, 3 years payback of vent recovery system of Case A power plant is achieved when the fuel price is 13.83 $/MMBTU. As earlier Figure 51 illustrated, 13.85 $/MMBTU had been the spot price a few years ago.

Figure 55 shows the interdependence of the spot price and payback time of vent recovery system's compressor and storage units.

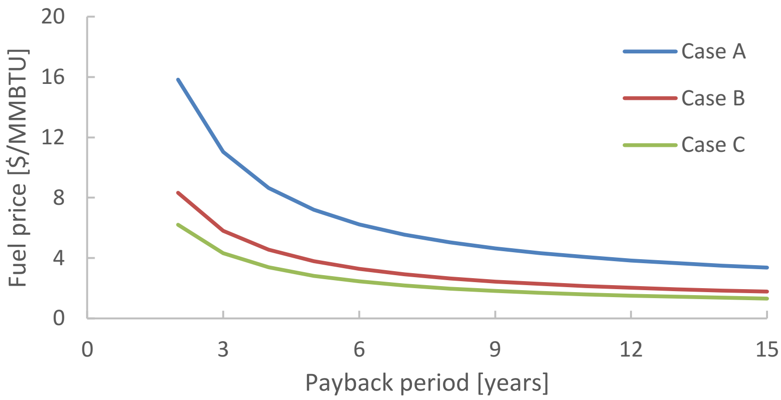


Figure 55: Payback period for vent recovery system's compressor and storage units with 6 starts and stops per day referring to fuel price.

Figure 55 shows that 2 years payback time for vent recovery system's compressor and storage units of the Case B plant can be attained when the spot price is 8.35 $/MMBTU. On the other hand, 2 years payback time for vent recovery system's compressor and storage units of the Case A plant can be achieved with the spot price 15.87 $/MMBTU. This price is almost the same than Japan's cif price for LNG in 2014, see Figure 51.

Various islands and other locations are without access to the natural gas pipeline network. However, the power plants, which are producing electricity to the isle, will need the fuel gas. So the only option is LNG. That is an amazing opportunity for the real business case because of the lack of the pipeline infrastructure. The LNG is much more expensive than pipeline gas. So the power plants, for example, in the islands will vent much more expensive fuel gas to the atmosphere than, for example, power plants, which are using pipeline gas.

When other benefits would have been taken into consideration in the analyses in addition to the fuel savings, the results would be considerably better. However, it is challenging to measure these other advantages in the money because they probably would bring uncertainty with them to the analyses.

6.4 Evaluation of the study

This study is relevant due to both current and future scenarios for this type of power plant. The engines are improving constantly, and as mentioned earlier, the available fuel for customers will steer the direction of these improvements. Moreover, maximizing the energy production from a fuel-type will become more and more critical in the future. Particularly as all fossil fuels will continue be used in the future. The burning question is *how* those fossil fuels are used. One cannot just afford to lose fossil fuel energy due to a lack of technology. This means that combustible processes and fuel efficiency must be improved.

This study has found the answers to the initial research questions. The reliability of the study has been found to be good. *Chapter 5* increases the case study's reliability because on the basis of the data, the calculations and simulations of the study can be carried out again. All of the used data is available, and the theory is introduced. However, the unstructured interviews could be seen to be more unreliable. If questions had been asked multiple times, more results would have been generated. Moreover, there is always a risk that interviewees may have expressed views that were not their own opinion on a particular matter, or where they did not have full knowledge of the field of study. Despite this, all the gathered data from the discussions has been filtered and mirrored to the existing literature.

The validity of the study is divaricated. Validation was strong from all angles with the exception of the economic analysis. The economic results were achieved using selected values. The results are valid, however, if some values changed (e.g. in a real project) the results of the economic analysis would also change, as shown in sensitivity analysis. Moreover, the economic analysis includes multiple variables. These include fuel system dimensions, power plant size, number of starts and stops, used fuel price level, and components of the system. Despite this, the results are the normative base for real-life projects.

The study describes the venting system and possible issues of the power plants for the first time in literature. However, different industry practices (such as those within the oil industry) have been widely reviewed in available literature. This study has also shown, for the first time in available literature, a techno-economic feasibility analysis and benefits of the system using specific case-studies. All of the information collated here was previously available, but until now no-one had closed the circle. It is important to remember that everything is affected by everything else.

Moreover, this study has produced a set of a real data values, and a discussion about hydrocarbon venting to the atmosphere (even though the results are simulated and are very conservative). This kind of simulations has not been seen before. As far as this research has shown, this is the first modeled behavior of hydrocarbons in available literature. Furthermore, this type of holistic system thinking is not publicly used or in industry processes yet.

The study results support the view that vent designs should be changed to the system that was examined here. Further benefits can be shown by continued process development and further investigation. Still, it is good to keep in mind what will be substantial and to whom. Is safety the priority, regardless of future costs? It is difficult to estimate which aspect is the most important parameter when creating a new power generation system.

The study and whole Master's thesis project was successful and kept within schedule. The next chapters describe the importance of technology development and the development process in the future.

6.4.1 Importance of technology development

Generally, company operation and ongoing efforts to improve system processes have changed. Ongoing changes in the operating environment of companies have created new possibilities for them to achieve a competitive advantage, especially in terms of their emissions. These ongoing changes also make changes in the development process necessary. From the beginning of the 1960s, companies have had to adapt to meet the demands of new markets (Alasoini 2010). The world has changed and developed extremely quickly over the last six decades. The changes have been economical, technological, social, political and cultural. We are living in the middle of these changes so their entirety might be difficult to perceive (Sydänmaanlakka 2004). Figure 56 shows the role of innovation.

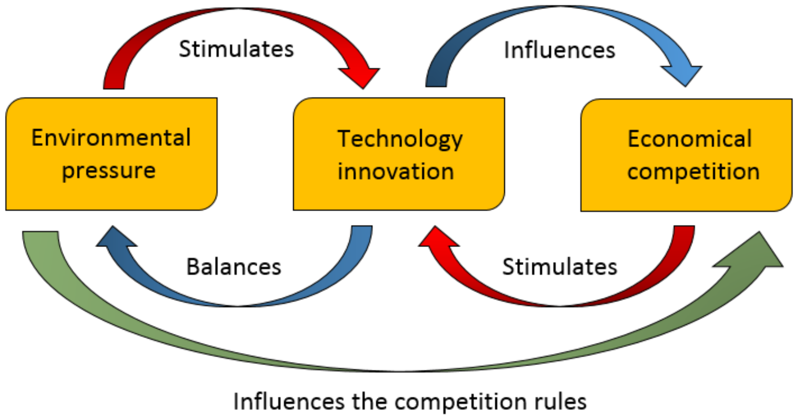


Figure 56: The role of innovation (According to Beccari et al. 2005b).

In addition to efficiency, quality and flexibility, progression in innovation must also be taken into consideration when producing more customer-oriented products and services that are faster and more reliable than in the past. (Alasoini 2010) According to Sydänmaanlakka, in a traditional economy companies operate in a closed system. These can have tightly regulated operation models, organizational structures where the protection of their own process knowledge and innovations are typical in operation. (Sydänmaanlakka 2009, pp. 33)

The current system of protectionism can no longer be the operational norm. Utilizing and sharing creativity and innovation are necessary. Customers will have varying emission limits and fuel types, and these can be limiting factors to later projects. The world changes hourly as it also has changed through the decades, see Figure 57.

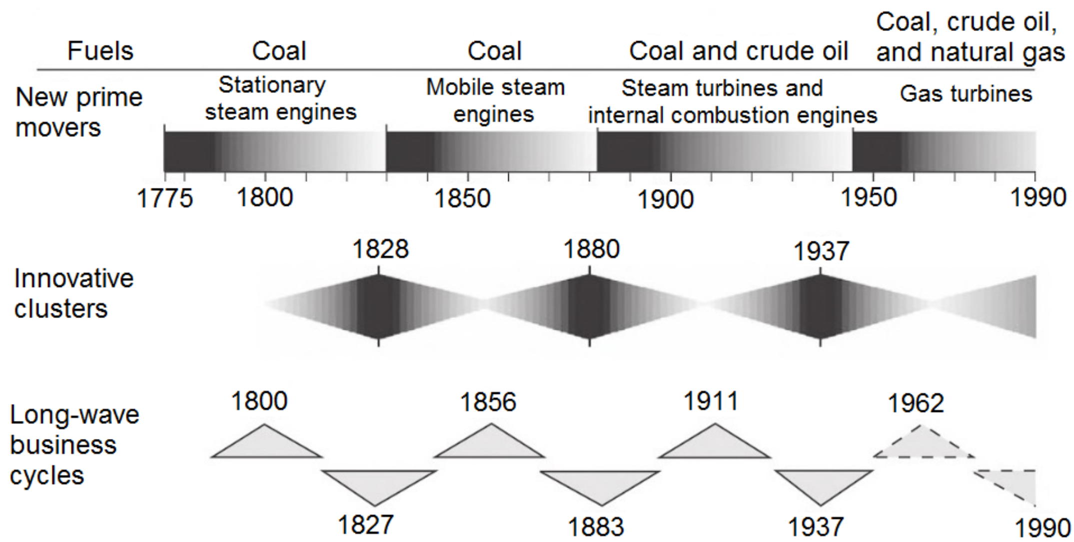


Figure 57: Timelines of the main energy eras, innovative clusters and long-wave business cycles in the years 1775-1990 (Cleveland 2009).

Figure 57 shows, that innovations boost business and this concept continues to push us forward today. Companies and their employees must embrace this change now and in the future. One must think about ‘the bigger picture’, and not just look for the easiest solution, which has been standard industry practice until now. Companies can achieve their uniqueness by focusing on the development of standardization, flexibility, and quality. Therefore it is smart to utilize these sectors.

This Master’s thesis is important to the Company to improve understanding of processes and in the development of new ideas. This study is a preliminary solution to the situation of the present design. Design needs to improve to the next level, without using minor modifications to the current system. The study also introduces other possibilities for future research and works as the basis for those studies and development processes.

6.4.2 Development process

Further development of the process based on this study would be possible, and is recommended. The development process can be divided into short-term and long-term actions. Short-term actions can be investigated at low cost, for example, using simulations. Long-term actions require more substantial investment, such as a pilot plant. Author’s recommendations for the development process are following:

1) More simulations and studies to demonstrate the benefits of the closed system (short- and long-term)
2) The vent recovery system design from end to end (short-term)
3) Optimizing the external CNG system of vent recovery system (short-term)
4) Testing the vent recovery system in situ (long-term)
5) Commercialization of the vent recovery system (long-term)
6) Exploring new technologies for development (short- and long-term)

The feasibility of the selected system, as examined in this study, should be explored further.

In the first action, the hydrocarbons require further research to demonstrate the benefits of a vent recovery system. This further research can be divided into 2 parts: real-life venting emissions from the power plants and behavior of released hydrocarbons.

Advantages of the proposed system will need more study in real-life applications if one hopes to numerically firm up these advantages. Examples of what can be examined further include the emission amounts of the engines and the fuel systems in situ, and what kind of running programs operators use. How much can the emissions be influenced in situ and how significant are the changes when viewed holistically.

Behavior of hydrocarbons should be also explored further. One simulation should look for what happens when the released gas plume hit obstacles, for example, a few meters from the venting head. Another simulation could overview what happens during turbulent winds. According to the Finnish Wind Atlas, local windiness is dependent on temperature differences at a grand scale and distribution and temperature differences across a country, its seamounts and the quality of the surface and forms on a smaller scale. In addition to the wind patterns and the local terrain, especially the low pressure and its central course will affect the prevailing winds. A simulation should show that will the plume be directed downwards in extreme circumstances.

Additionally, a simulation of what happens when the released heavier gas changes phase after being emitted to the atmosphere is recommended, especially for LPG, which needs the simulation to demonstrate the benefits of a vent recovery system. Furthermore, simulations of the movement of the liquid gas on the floor in the engine hall or on the ground would be useful to help solve the problem of leakages that end up in the engine hall.

The second short-term action is that the selected system should be designed from end to end. All of the required components should be dimensioned and reviewed by experts, especially by those who are external to the company and who are more likely question the system.

The third action is that the storage of CNG systems should be optimized, and prices of the CNG system should be internally established. Any possible subcontractors should be clarified, and prices for these agreed.

After the short-term actions, the fourth action is that the new system should be tested in situ. The new system needs to be a commercial solution where costs are kept as low as possible. The cheapest and easiest solution would be modular for specific projects. A modular solution needs to include equipment that is well-known to everyone, so that any commissioning is as easy as possible. The new system should also be easy-to-use for site operators.

The fifth action is related to commercialization. The system's commercialization starts after the successful tests. At this point, the design should be modular and easy to install.

The sixth action is related to the other systems. As mentioned in *Chapter 2.2*, the second option for avoiding having to vent to the atmosphere involves a flare solution. The flare solution may be as viable an option as the vent recovery system, particularly for existing power plants. However, a flare system does not have the same benefits as a recovery system. Using flare, for example, does not make fuel savings possible or decrease emissions. Moreover, global trends in the gas markets are economic and environmental drivers, so the flare solution still requires more internal study and a techno-economic feasibility analysis. One solution for flare use could be to direct the gases through the storage to the exhaust gas stack, where the flame of the flare is hidden. However, according to Nolan (2010), auto-refrigeration of propane or butane at low temperatures must be taken into account when designing the flare system, especially in the flare header.

If the technology used in the ANG solution is developed further in the future, it may also prove to be a suitable system. However, it requires more accurate studies globally. When more research and results are available, it should be explored again.

To summarize, vent recovery or the flare solution should be integrated into the current system. However, the recycling concept within each system and process, (and not only that of the fuel system) should also be considered. An example process could be between the hot air of the generator duct and the ventilation air of the engine hall. Instead of wasting energy here, it should be used as efficiently as possible.

7. CONCLUSION

Gas power plants have multiple unburnt fuel gas vents going up from the fuel systems and engines to the atmosphere for operational and safety purpose. Due the increase in renewable energy sources, the function of these power plants is changing from a baseload type to the peak load type. The change will increase the amount of vented gases as emission limits simultaneously tighten.

The objective of this study was to review and analyze the hydrocarbon expulsion, examine various technology potentials for the closed system and establish which is the most suitable. Part of the research was also focused on defining the possibilities of an optimized system for further commercialization and profitability.

This study has provided an overview of the technological challenges of the releasing system as well as having shown model results of hydrocarbon releases. According to Nolan's (2010) safety features, venting of fuel gases to the atmosphere is not a suitable option for process industries. This is due to health, safety, and environmental concerns.

Four different hydrocarbons were modeled and the study's findings proved its necessity. These hydrocarbons were methane, ethane, propane, and butane. Each hydrocarbon has different properties, such as density or explosion limits, etc. Gas clouds formed from the vents have the ability to cause hazardous situations because they cannot be controlled in the open air. Both leakage and normal operation scenarios were modeled. In normal operation, lengths of the flammable hydrocarbon plumes were from 7.3 m to 13.8 m after 10 seconds of venting. Lengths of the non-flammable plumes were much longer.

This study analyzed three different technologies required to meet hydrocarbon release challenges: ANG, CNG, and LNG technologies. Subsequently, the study identified that the CNG technology was the optimal for current application, and a process diagram was created for the vent recovery concept.

All benefits of the vent recovery system have been collated and the target of an optimized multidimensional application has been achieved. The vent recovery system creates multiple possibilities for design and fuel flexibility. The system makes fuel savings possible, improves the safety of power plants and makes them more environmentally friendly. Emission requirements and safety within the working environment will play an increasingly important role within power plants business. It is no longer adequate to merely make a cost/benefit analysis of power plant investments. The evaluation of any new investment must balance a number of diverse factors, including, amongst others, its safety and its environmental impact.

Finally, economic analysis and sensitivity analysis were conducted on the vent recovery system based on selected components. Three different power plant cases from 60 MW to

250 MW were examined with various fuel prices. The vent recovery system is economically profitable in most cases based on the study's calculated results. However, the most sensitive parameters for the profitability of the vent recovery system are fuel price, power plant size, and the number of starts and stops.

A whole host of new ideas or solutions have been introduced to further the development process. A significant amount of further study is required, but this work acts an initial proof that something should be done and can be done to design and produce a techno-economically more efficient gas engine fuel system. The vent recovery system has applied multiple different processes to technical challenges and produced working solutions. The study has fulfilled the present design boundary conditions whilst also being suitable for stricter conditions in the future. Moreover, gas storage technologies and facilities require more additional investments than ever due to gas demand fluctuations. This new solution for gas plants could help to solve the multiple problems of previous and current practices within the gas industry.

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9. APPENDICES

APPENDIX A: Effects and consequences of fires and explosions.

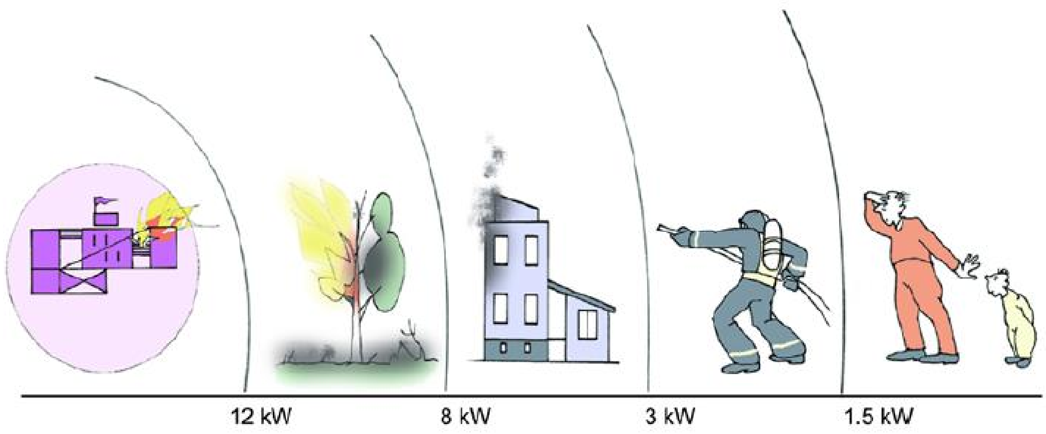

Figure 58: Effects of thermal radiations (TUKES 2015).

Table 21: Physiological effects of thermal radiation on bare skin (Adapted from Federal Emergency Management Agency, 1988).

Radiation intensity [kW/m²]	Time for severe pain [seconds]	Time for 2nd-degree burns [seconds]
1	115	663
2	45	187
3	27	92
4	18	57
5	13	40
6	11	30
8	7	20
10	5	14
12	4	11

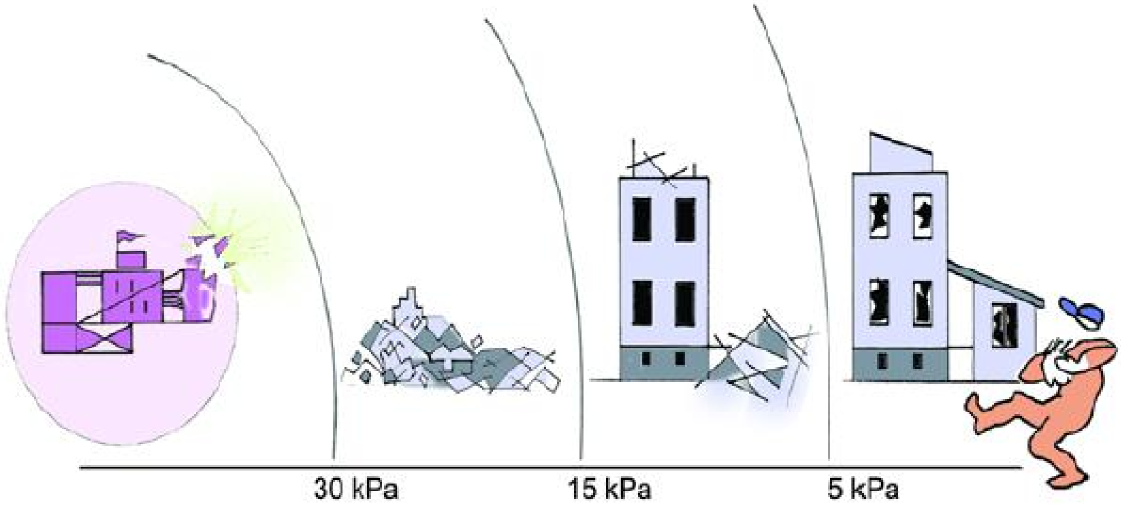

Figure 59: Effects of overpressure by explosion (TUKES 2015).

Table 22: Example effects of overpressure by explosion (Adapted from Federal Emergency Management Agency, 1988).

Peak Overpressure [kPa]	Expected damage
0.2	Occasional breakage of large windows under stress
2	Some damage to home ceilings: 10% window breakage
7.0-35	Windows usually shattered: some frame damage
7	Partial demolition of homes, made uninhabitable
5.5-7.0	Range serious or slight injuries from flying glass and objects
14	Partial collapse of home walls and roofs
14-20	Non-reinforced concrete/cinder block walls shattered
17-84	Range 1-90% cardrum rupture among exposed population
17	50% destruction of home brickwork
28-21	Frameless steel panel building ruined
35	Wooden utility poles snapped
35-48	Nearly complete destruction of houses
69	Probable total building destruction
100-200	Range for 1-99% fatalities among exposed populations due to direct blast effects

APPENDIX B: Natural gas standards in Finland according to TUKES.

Table 23: NG standards in Finland (According to TUKES).

Standard	Description
SFS-EN 1473	Installations and equipment for liquefied natural gas. Design of onshore installations with a storage capacity between 5 t and 200 t.
SFS 5717	Maakaasun siirtoputkiston sijoittaminen suurjännitejohdon tai kytkinlaitoksen läheisyyteen
SFS-EN 1555-1	Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Part 1: General
SFS-EN 1555-2	Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Part 2: Pipes
SFS-EN 1555-3	Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Part 3: Fittings
SFS-EN 1555-4	Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Part 4: Valves
SFS-EN 1555-5	Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Part 5: Fitness for purpose of the system
SFS-EN 1775	Gas supply. Gas pipework for buildings. Maximum operating pressure less than or equal to 5 bar. Functional recommendations
SFS-EN 1776	Gas infrastructure. Gas measuring systems. Functional requirements
SFS-EN 12007-1	Gas infrastructure. Pipelines for maximum operating pressure up to and including 16 bar. Part 1: General functional requirements
SFS-EN 12007-2	Gas infrastructure. Pipelines for maximum operating pressure up to and including 16 bar. Part 2: Specific functional requirements for polyethylene (MOP up to and including 10 bar)
SFS-EN 12007-3	Gas infrastructure. Pipelines for maximum operating pressure up to and including 16 bar. Part 3: Specific functional requirements for steel
SFS-EN 12007-4	Gas infrastructure. Pipelines for maximum operating pressure up to and including 16 bar. Part 4: Specific functional requirements for renovation
SFS-EN 12007-5	Gas infrastructure. Pipelines for maximum operating pressure up to and including 16 bar. Part 5: Service lines. Specific functional requirements
SFS-EN 12186	Gas infrastructure. Gas pressure regulating stations for transmission and distribution. Functional requirements
SFS-EN 12279	Gas supply systems. Gas pressure regulating installations on service lines. Functional requirements
SFS-EN 12279/A1	Gas supply systems. Gas pressure regulating installations on service lines. Functional requirements
SFS-EN 12327	Gas infrastructure. Pressure testing, commissioning and decommissioning procedures. Functional requirements
SFS-EN 12583	Gas infrastructure. Compressor stations. Functional requirements
SFS-EN 12732 + A1	Gas infrastructure. Welding steel pipework. Functional requirements

Standard	Description
SFS-EN 13645	Installations and equipment for liquefied natural gas. Design of onshore installations with a storage capacity between 5 t and 200 t
SFS-EN 14620-1	Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C. Part 1: General
SFS-EN 14620-2	Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C. Part 2: Metallic components
SFS-EN 14620-3	Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C. Part 3: Concrete components
SFS-EN 14620-4	Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C. Part 4: Insulation components
SFS-EN 14620-5	Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0 °C and -165 °C. Part 5: Testing, drying, purging, and cool-down
SFS-EN 15001-1	Gas infrastructure. Gas installation pipework with an operating pressure greater than 0.5 bar for industrial installations and greater than 5 bar for industrial and non-industrial installations. Part 1: Detailed functional requirements for design, materials, construction, inspection and testing
SFS-EN 15001-2	Gas infrastructure. Gas installation pipework with an operating pressure greater than 0.5 bar for industrial installations and greater than 5 bar for industrial and non-industrial installations. Part 2: Detailed functional requirements for commissioning, operation, and maintenance
SFS-EN 16348	Gas infrastructure. Safety Management System (SMS) for gas transmission infrastructure and Pipeline Integrity Management (PIMS) for gas transmission pipelines. Functional requirements
SFS-EN 16723-1	Natural gas and bio-methane for use in transport and bio-methane for injection in the natural gas network. Part 1: Specifications for Bio-methane for injection in the natural gas network
SFS-EN 16726	Quality of gas. Group H

APPENDIX C: European standards of industrial gas installations.

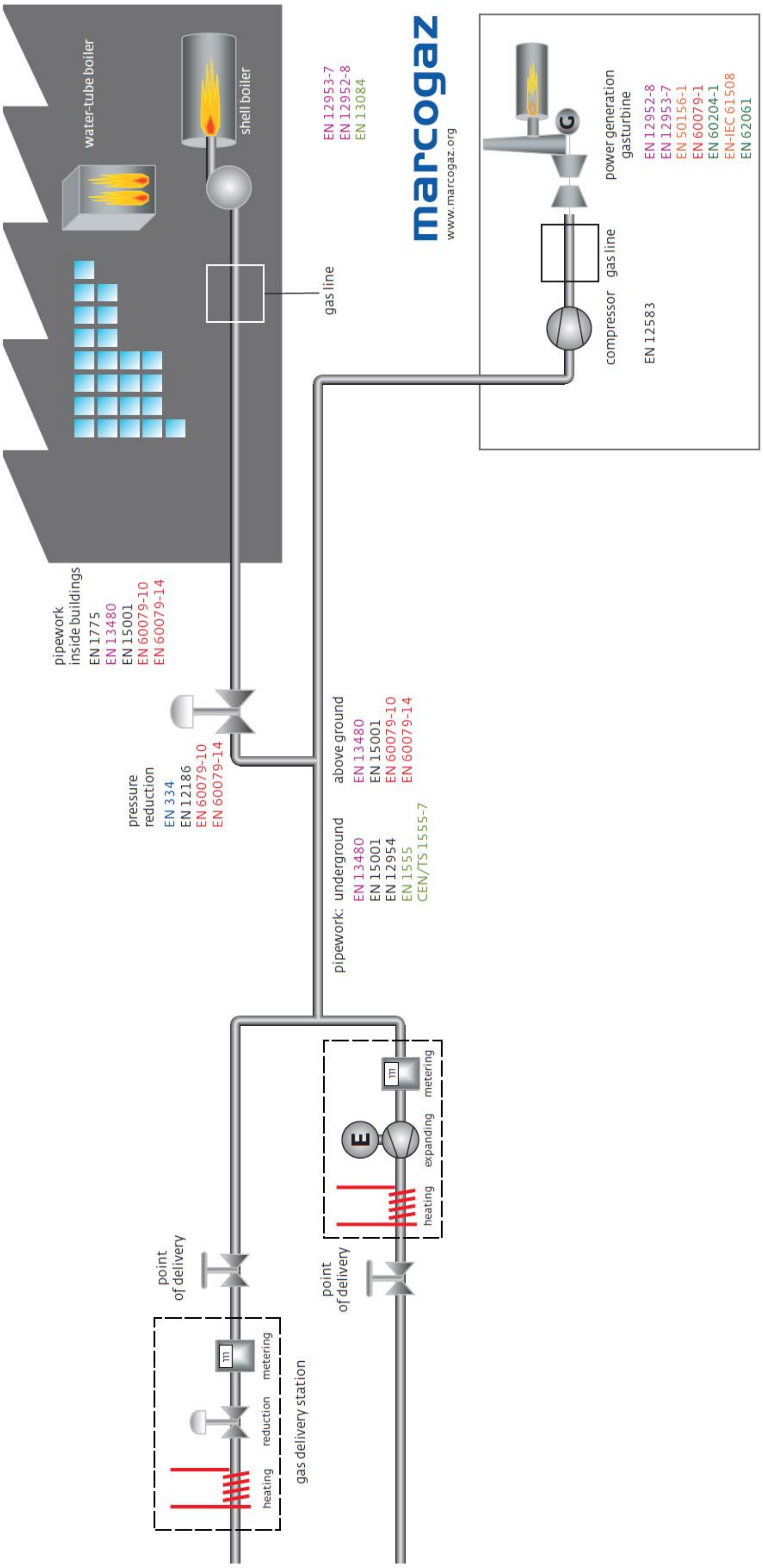

Figure 60: European standards of industrial gas installations (Marcogaz 2017).

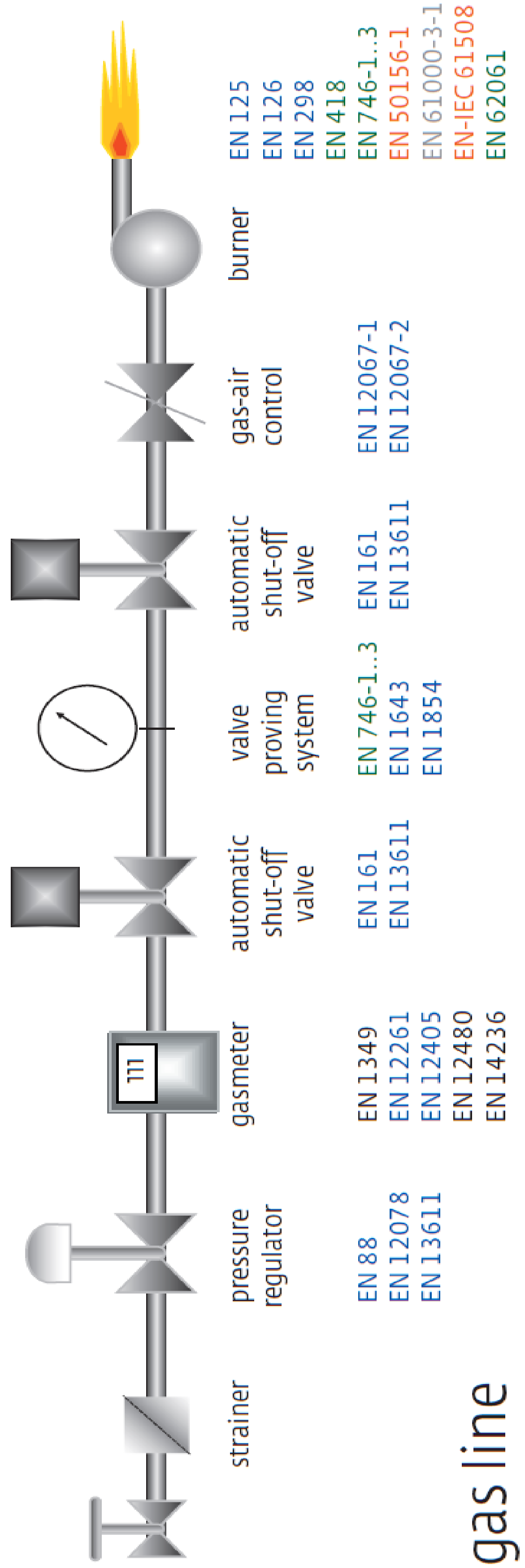

Figure 61: European standards for gas line (Marcogaz 2017).

Table 24: European standards and descriptions (According to Marcogaz 2017).

Directive/ Standard	Description
98/37/EC MD	**Machinery Directive**
EN 418	Safety of machinery - Emergency stop equipment, functional aspects - Principles for design
EN 746-1	Industrial thermo processing equipment - Part 1: Common safety requirements for industrial thermo processing equipment
EN 746-2	Industrial thermo processing equipment - Part 2: Safety require-ments for combustion and fuel handling systems
EN 746-3	Industrial thermo processing equipment - Part 3: Safety require-ments for the generation and use of atmosphere gases
EN 60204-1	Safety of machinery - Electrical equipment of machines - Part 1: General requirements (IEC 60204-1:1997)
EN 62061	Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems (IEC 62061:2005)
2004/108/EC EMC	**Electromagnetic compatibility (EMC)**
EN 61000-3-1	Electromagnetic compatibility (EMC)
2004/108/EC	Electromagnetic compatibility (EMC)
94/9/EC ATEX	**Equipment explosive atmospheres (ATEX)**
EN 50154	Electrical installation in explosive atmospheres
EN 60079-10	Electrical apparatus for explosive gas atmospheres - Classification of hazardous areas
EN 60079-14	Electrical apparatus for explosive gas atmospheres - Electrical installations in hazardous areas
97/23/EC PED	**Pressure Equipment Directive**
EN 12583	Compressor stations fuels for the boiler
EN 12952-8	Water-tube boilers and auxiliary installations - Part 8: requirements for firing systems for liquid and gaseous
EN 12953-7	Shell boilers - Part 7: Requirement for firing systems for liquid and gaseous fuels for the boiler
EN 13480-1	Metallic industrial piping - Part 1: General
EN 13480-2	Metallic industrial piping - Part 2: Materials
EN 13480-3	Metallic industrial piping - Part 3: Design and calculation
EN 13480-4	Metallic industrial piping - Part 4: fabrication and installation
EN 13480-5	Metallic industrial piping - Part 5: Inspection and testing
2004/22/EEG	**Measuring instruments**
EN 1359	Gas meters - Diaphragm gas meters

EN 12261	Gas meters - Turbine gas meters
EN 12405	Gas meters - Conversion devices - Part 1: Volume conversion
EN 12480	Gas meters - Rotary displacement gas meters
EN 14236	Ultrasonic domestic gas meters
90/396/EEC GAD	**Appliances burning gaseous fuels**
EN 88	Pressure governors for gas appliances for inlet pressures up to 200 mbar
EN 125	Flame supervision devices for gas burning appliances - Thermo-electric flame supervision devices
EN 126	Multifunctional controls for gas burning appliances
EN 161	Automatic shut-off valves for gas burners and gas appliances
EN 298	Automatic gas burner control systems for gas burners and gas burning appliances with or without fans
EN 676	Automatic forced draught burners for gaseous fuels
EN 1643	Valve proving systems for automatic shut-off valves for gas burners and gas appliances
EN 1854	Pressure sensing devices for gas burners and gas burning appliances
EN 12067-1	Gas/air ratio controls for gas burners and gas burning appliances - Part 1: Pneumatic types
EN 12067-2	Gas/air ratio controls for gas burners and gas burning appliances - Part 2: Electronic types
EN 12078	Zero governors for gas burners and gas burning appliances
EN 13611	Safety and control devices for gas burners and gas-burning appliances general requirements
89/106/EEC CPD	**Construction Products**
EN 1856	Chimneys - Requirements for metal chimneys
EN 1775	Gas pipe work for buildings - Maximum operating pressure < 5 bar
EN 12186	Gas supply - Gas pressure regulating stations for transmission and distribution - Functional requirements
EN 12583	Gas supply systems - Compressor stations. Functional requirements
EN 12954	Cathodic protection of buried or immersed metal structures. General principles and application for pipelines
EN 13084	Free-standing chimneys
EN 15001	Pipework MOP 0.5 up to 60 bar for industrial gas installations, design
2006/95/EC LVD	**Low Voltage**
EN IEC 61508	Functional safety of electrical/electronic/programmable electronic safety related systems - Part 5: Examples of methods for the determination of Safety Integrity Levels
EN IEC 61511	Functional safety - Safety instrumented systems for the process industry sector
EN 50156-1	Electrical equipment for furnaces and ancillary equipment Part 1: Requirements for application design and installation

92/42/EEC	**Efficiency Requirements for new hot-water boilers fired with liquid or gaseous fuels**
EN 303-3	Heating boilers - Part 3: Gas-fired central heating boilers - Assembly comprising a boiler body and a forced draught burner
EN 303-7	Heating boilers - Part 7: Gas-fired central heating boilers equipped with a forced draught burner of nominal heat output not exceeding 1000 kW
EN 656	Gas-fired central heating boilers - Type B boilers of nominal heat input exceeding 70 kW but not exceeding 300 kW
EN 677	Gas-fired central heating boilers - Specific requirements for condensing boilers with a nominal heat input not exceeding 70 kW
EN 13836	Gas fired central heating boilers - Type B boilers of nominal heat input exceeding 300 kW, but not exceeding 1000 kW

APPENDIX D: The vent recovery system calculated by using HYSYS.

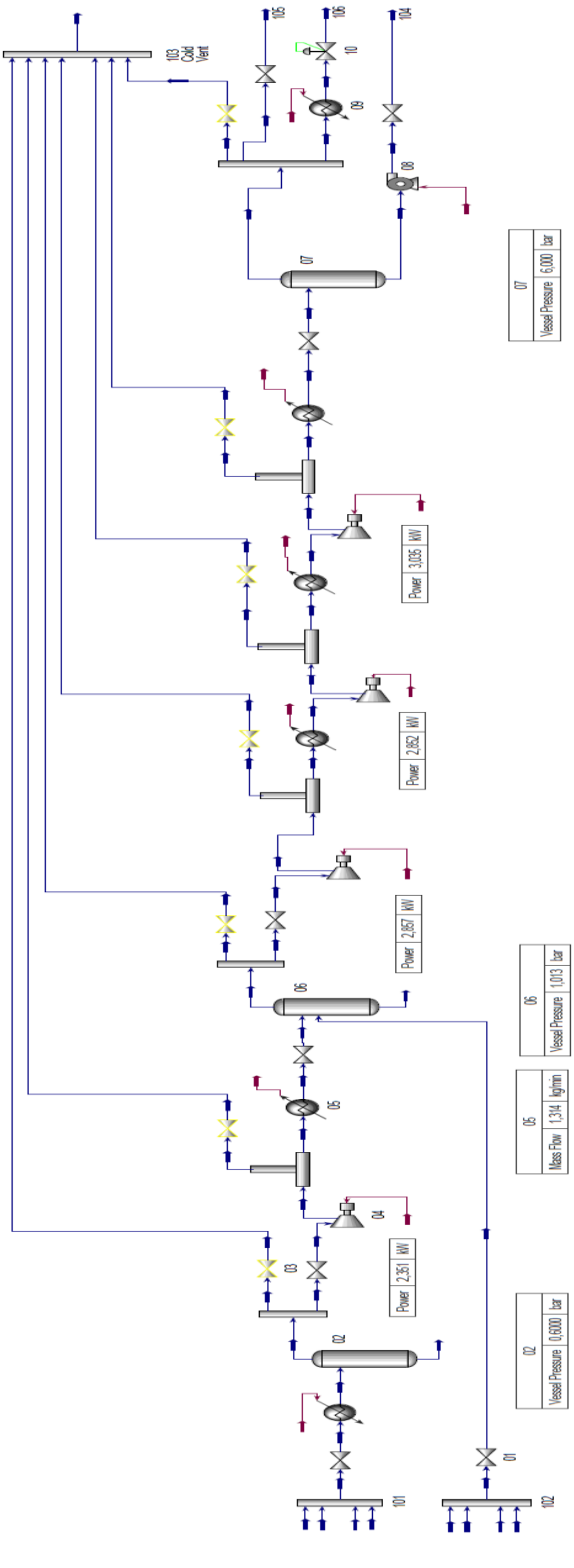

Figure 62: HYSYS model.

APPENDIX E: Z-Factors for different hydrocarbons.

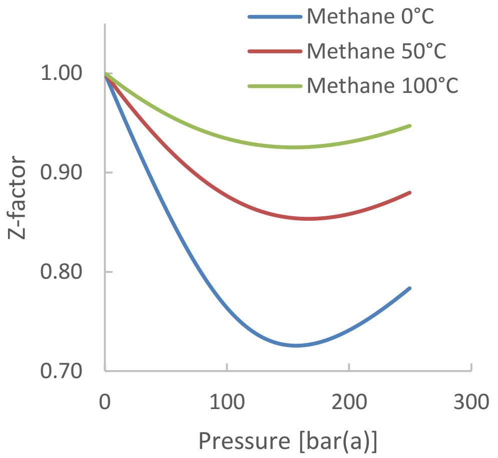

Figure 63: Z-Factors for methane calculated by using HYSYS.

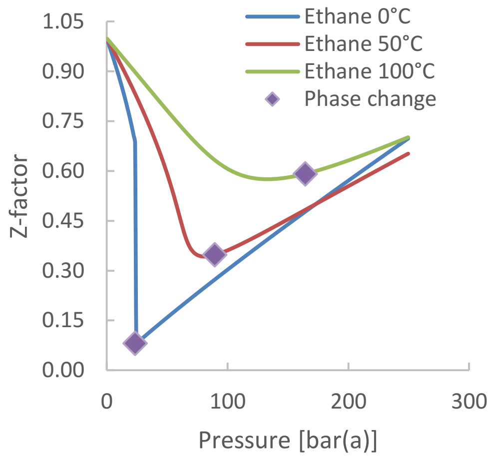

Figure 64: Z-Factors for ethane calculated by using HYSYS.

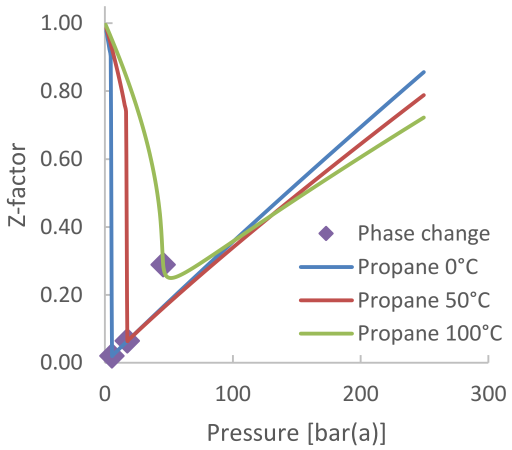

Figure 65: Z-Factors for propane calculated by using HYSYS.

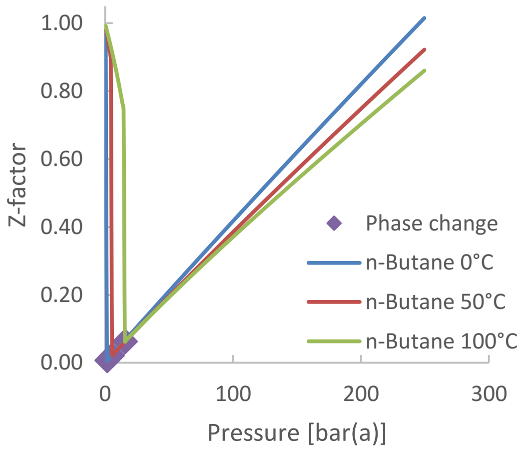

Figure 66: Z-Factors for n-butane calculated by using HYSYS.