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MSc Program
Renewable Energy in Central and Eastern Europe

Utilisation of recovered waste heat in natural gas compressor stations

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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"The economic transmission of power without wires is of all-surpassing importance to man. By its means he will gain complete mastery of the air, the sea and the desert. It will enable him to dispense with the necessity of mining, pumping, transporting and burning fuel, and so do away with innumerable causes of sinful waste. By its means, he will obtain at any place and in any desired amount, the energy of remote waterfalls — to drive his machinery, to construct his canals, tunnels and highways, to manufacture the materials of his want, his clothing and food, to heat and light his home — year in, year out, ever and ever, by day and by night. It will make the living glorious sun his obedient, toiling slave. It will bring peace and harmony on earth."

Nikola Tesla, 1905

Affidavit

I, Andrej Miljević, hereby declare that I am the sole author of the present Master Thesis, "Utilisation of recovered waste heat in natural gas compressor stations", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The share of industrial waste heat infeed into district heating systems networks increased over the past couple of years. Industrial waste heat recovery increases systems' energy efficiency factor on the one hand and reduces emissions such as carbon dioxide and mono-nitrogen oxide emissions through the substitution of fossil fuels for heating boilers on the other hand. Therefore, waste heat recovery is a value adding process, both for industries and environment authorities. Nevertheless, waste heat from exhaust gas in natural gas compressor stations has been utilised directly in only few projects.

Highly fluctuating operation hours of gas compressors and therefore unpredictable waste heat streams are the results of variable gas flow in natural gas pipelines. Such conditions make a feasible waste heat recovery operation very difficult. In spite of such an instable operation environment the outcome is analysed in different scenarios in order to proof the feasibility of waste heat recovery unit applications in natural gas compressor stations.

Load scenarios for the compressor station in Weitendorf/ Austria at the TAG Trans Austrian Gas pipeline are compared to each other. Different waste heat recovery technologies such as the steam operated Clausius rankine cycle and simple heat exchanger are taken into consideration. Finally, calculations of utilisation scenarios with different feed-in tariffs for electricity generation, CHP and heat supply are discussed. A risk assessment and a sensitive analysis, in which especially operation and maintenance costs are considered, contributes to a reduction the project uncertainties. Results underline the benefits of direct waste heat utilisation in district heating systems compared to electric power generation for certain feed-in situations.

Table of content

1 INTRODUCTION 1

1.1 MOTIVATION 2
1.2 CORE OBJECTIVE 3
1.3 CITATION OF MAIN LITERATURE 3
1.4 STRUCTURE OF WORK 4

2 TECHNICAL PRINCIPLES 4

2.1 GAS CHARACTERISTICS 5
2.2 ENERGY FUNDAMENTALS 6

3 NATURAL GAS TRANSMISSION AND COMPRESSION 8

3.1 TRANSPORTATION OF NATURAL GAS 9
3.2 NATURAL GAS COMPRESSION 11

4 WASTE HEAT RECOVERY IN COMPRESSOR STATIONS 12

4.1 WASTE HEAT RECOVERY 13
4.1.1 HEAT EXCHANGERS 13
4.1.2 CLAUSIUS RANKINE CYCLE 14
4.1.3 BRAYTON CYCLE 15
4.1.4 ORGANIC RANKINE CYCLE (ORC) 15
4.1.5 KALINA CYCLE 16
4.1.6 WASTE PRESSURE TO ELECTRICITY 17
4.2 STATE OF THE ART 18
4.3 STATUS QUO WITHIN EUROPE 25
4.4 STATUS QUO IN AUSTRIA 27

5 WASTE HEAT RECOVERY IN THE CS WEITENDORF 28

5.1 WASTE HEAT UTILISATION SCENARIOS 32

5.2 RISK ASSESSMENT 42
5.3 WASTE HEAT FOR THE DISTRICT HEATING SYSTEM IN GRAZ 43
5.4 BEST PRACTICE 46

6 CONCLUSIONS 49

LIST OF LITERATURE 51

APPENDIX 63

List of Abbreviations

AEA	Austrian Energy Agency
AEMO	Australian Energy market operator
AG	Aktiengesellschaft
AGGM	Austrian Gas Grid Management
ASME	American Society of Mechanical Engineers
Barg	Bar gauge (pressure above atmospheric pressure)
BMLFUW	Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management
BMVIT	Ministry for Transport, Innovation and Technology
Bm^3	Billion cubic metres
BP	British Petroleum
CARTIF	Centre of Automatisation, Robotics and Technologies of the Information and the Manufacture
CC	Capital costs
CF	Cash Flow
CHP	Combined Heat and Power
Cm	Cubic metre
CO_2	Carbon Dioxide
CS	Compressor Station
CV	Calorific value
DH	District Heating
DHS	District Heating System
DN	Diamètre Nominal (Nominal Diametre)
DPMA	Deutsches Patent- und Markenamt
DS	Distribution System
DSO	Distribution System Operator
EC	European Commission
ECF	European Climate Foundation
EIA	Environmental impact assessment
ENTSOG	European Network of Transmission System Operators for Gas

EPI	Energy Price Index
EU	European Union
FIT	Feed-in tariff
FLH	Full load hours
GCA	Gas Connect Austria Gmbh
GCV	Gross Calorific Value
GDK	Gasdampfkraftwerk (Gas steam power plant)
GE	General Electric
GHG	Green House Gases
GIE	Gas Infrastructure Europe
GMK	Gesellschaft für Motoren und Kraftanlagen
GW	Giga Watt (Power)
GWh	Giga Watt hours (Energy)
GT	Gas Turbine
GTS	Gas to solid
GTW	Gas to wire
HKW	Heizkraftwerk (Heat power plant)
HP	High pressure
HR	Heat recovery
HT	High temperature
HRSG	Heat recovery steam generator
IEA	International Energy Agency
IGU	International Gas Union
ISO	International Organization for Standardization
Km	Kilo metre
LF	Last Fall (Load case)
LNG	Liquid natural gas
LP	Low pressure
LT	Low temperature
LTD	Private Limited company
Mtoe	Millions of tonnes of oil equivalent (Energy)
MW	Mega Watt (Power)
MWh	Mega Watt hours (Energy)
MW_{peak}	Mega Watt peak load (Power)
$MW_{thermal}$	Mega Watt thermal (Power)
$MW_{electric}$	Mega Watt electric (Power)
NASA	National Aeronautics and Space Admission

NGVA	Natural and Biogas Vehicle Association
Nm^3	Normal cubic metre
N.a.	Not available
OGE	Open Grid Europe
OM	Operation Maintenance
ORC	Organic Rankine Cycle
OTSG	Once Through Steam Generator
O&M	Operation and Maintenance
RE	Renewable Energy
REG	Recovered Energy Generation
SDEWES	Sustainable Development of Energy, Water and Environment Systems
SEE	South-East Europe
SNAM	Società Nazionale Metanodotti
SNG	Synthetic natural gas
TAG	Trans Austria Gasleitung
tCO_2e	Tons of Carbon dioxide equivalents
TES	Thermal Energy Storage
TWh	Terra Watt hours (Energy)
TS	Transport system
TSO	Transmission System Operator
UNEP	United Nations Environment Programme
USA	United States of America
US	United States (United States of America)
VPI	Verbraucherpreisindex (Consumer price index)
WEC	World Energy Council
WHR	Waste Heat Recovery
WHRU	Waste Heat Recovery Unit

Greek letters and nomenclature

Δ	Delta
η	Eta
η_{th}	Thermal energy conversion efficiency [%]
ΔQ	Heat transfer [J]
ΔS	Entropy difference [$J\ K^{-1}$]
Δp	Pressure drop [Pa, bar]
ΔT	Temperature difference [K]
CV	[kWh/Nm^3]
H	Enthalpy [J]
f	Darcy friction factor
n	Chemical amount of substance [mol]
p	Pressure [Pa, bar]
Q	Flow rate [$\mathrm{kg\ s^{-1}}$]
Q_m	Mass flow rate [$\mathrm{kg\ s^{-1}}$]
R	Ideal gas constant [$\mathrm{Jmol^{-1}K^{-1}}$]
ρ	Specific density [kgm^{-3}]
S	Entropy [$J\ K^{-1}$]
T	Temperature [K]
U	Reference system
V	Volume [$\mathrm{m^3}$]
W	Wobbe Index [$\mathrm{MJ/Nm^3}$]
°C	Degree Celsius

List of Tables

Table 1: Different types of industrial heat sources (Miljević after UNEP, 2006)

Table 2: Advantages and disadvantages of WHR utilisation in CS (Miljević, 2015)

Table 3: WHRU in CS for external utilisation (Miljević, 2015)

Table 4: Types of GE Oil and Gas WHRU (Miljević after Jammu, 2013):

Table 5: ORC-WHRU manufacturers (Miljević after ORC, 2009)

Table 6: Depreciation scenario for the WHRU (Miljević, 2015)

Table 7: Load scenario P1 – heat production only (Miljević, 2015)

Table 8: Load scenario P2 – heat production only (Miljević, 2015)

Table 9: Load scenario P3 – heat production only (Miljević, 2015)

Table 10: Load scenario P1 – electricity production only (Miljević, 2015)

Table 11: Load scenario P2 – electricity production only (Miljević, 2015)

Table 12: Load scenario P1 – CHP (Miljević, 2015)

Table 13: Relevant parameters of the WHRU in CS Ruswil (Miljević after Transitgas AG, 2015)

List of figures

Figure 1: Different segments of the natural gas supply chain (AEMO, 2014)

Figure 2: Global Pipeline gas and LNG trade flows in 2014 [bm^3] (BP, 2015)

Figure 3: Annual exports of Russian pipeline gas in 2013 [bm^3] (Autonomous Non-Profit Organisation “TV-Novosti”, 2015)

Figure 4: Types of applied compressors (Miljević after Mokhatab and Poe, 2012)

Figure 5: Clausius Rankine cycle applied for waste heat recovery (Hedman, 2008)

Figure 6: CHP application in a biomass plant with Organic Rankine cycle (Rowshanzadeh, 2010)

Figure 7: GE Oregen ORC cycle scheme (GE Oil and Gas, 2011)

Figure 8: Enagás compressor station Almendralejo, Spain (Google Maps, 2015)

Figure 9: Trans Austria Gasleitung (TAG Gmbh, s.a.)

Figure 10: CS and WHRU in Weitendorf (Digital Globe Inc, 2015)

Figure 11: Gas turbine GE Nuovo Pignone PG25+ (Meher-Homji et al., 2008)

Figure 12: WHRU in Weitendorf (Küttner Energy & Enviornment Gmbh, 2011)

Figure 13: Percentage of bypassed operating hours per gas turbine (1-3) from 2011-2015 (Miljević, 2015)

Figure 14: Estimated distance between the WHRU and the DHS connexion point (Digital Globe Inc, 2015)

Figure 15: Scheme of the heat exchanger connexion for DH (TAG Gmbh, 2015)

Figure 16: Load scenarios for DH utilisation (Miljević after TAG Gmbh, 2015)

Figure 17: Operating hours' comparison CS/ WHRU for the period January 2014 until August 2015 (Miljević after TAG, 2015)

Figure 18: Sensitivity of the annuity in variation to the OM costs per year according to P1 Scenario (Miljević, 2015)

Figure 19: Sensitivity of the annuity in variation to the O&M costs per year according to P2 Scenario (Miljević, 2015)

Figure 20: Sensitivity of the annuity in variation to the O&M costs per year according to P3 Scenario (Miljević, 2015)

Figure 21: Sensitivity of the annuity in variation to the O&M costs per year according to P1 Scenario (Miljević, 2015)

Figure 22: Sensitivity of the annuity in variation to the O&M costs per year according to P2 Scenario (Miljević, 2015)

Figure 23: Sensitivity of the annuity in variation to the O&M costs per year according to P1 CHP (Miljević, 2015)

Figure 24: Generated $MWh_{electric}$ per quarter in from Q1/2014 until Q3/2015 (Miljević after TAG, 2015)

Figure 25: Peak load capacity assumption for DHS of Graz on cold winter days, 2014-2050 (Miljević after Grazer Energieagentur GmbH, 2014)

Figure 26: WHR plant scheme of the facility in Ruswil (Transitgas AG, 2015)

1 Introduction

The global share of fossil fuels of the primary energy mix in 2050 will equal 59-77%. The share of renewable energy (RE) will rise up to 20-30% in 2050. (WEC, 2013)

These very clear projections indicate that the use of RE will not be sufficient to cover energy demands at all and fossil fuels are going to play a major role. However, in order to meet future demands current energy converting technologies and systems must be used in a much more efficient way (Çomakli et al., 2015). Natural gas is the cleanest fuel in-between all fossil fuels. The on-going replacement of coal and oil fired heating systems with innovative natural gas fired boilers is an important step towards a reduction of GHG worldwide. Furthermore, the implementation of cogeneration and waste heat recovery systems can increase energy efficiency factors of current energy production from 35-55% up to 90% (Çomakli et al., 2015).

1.1 Motivation

According to the IEA and the WEC natural gas will be the most important energy source by 2050 (IGU, 2015). In a great measure, natural gas is going to be transported via pipelines to the consumers. Remaining quantities will be used for power generation will be liquefied into LNG for oversea transportation.

On average, every 114km of natural gas pipeline one compressor stations is increasing the pressure of the transported gas from 20-50 up to 60-120barg. Depending on the ISO power of the turbine which is running the gas compressor waste heat streams are released into the stacks and to the environment.

The EU is a natural gas net importer and 2942 TWh were consumed in the community in 2013. The gross consumption equals 4500 TWh (2013) and in 2014, 32% of consumed natural gas in the European Union was from Russian origin (GIE, 2015), which underlines the importance of Russian pipeline gas supply. The EU has energy efficiency goals for 2050 in order to make use of certain energy saving potential. One major goal is the introduction of measures, which increase the energy efficiency of current fossil power generation and district heating (ECF, 2010). With the purpose of quantifying the energy saving potential of different waste heat streams in the natural gas compressor station in Weitendorf, Austria, following four criteria are analysed in this thesis:

- Efficiency criteria - saved energy $[kWh]$ per volume $[m3]$ of exhaust gas $[kWh/m3]$
- Emission criteria - saved emission in CO / CO_2 / CO_2e / NO_x
- Operating efficiency - based on full load hours and FITs
- Utilisation criteria - based on local energy demand

Results will point out how energy can be saved profitable in the first place and how indirectly emissions can be reduced locally by the substitution of fossil fuel combustion in the second place.

1.2 Core objective

The main idea is to link natural gas, which is a fossil fuel, to the subject of RE, and environmentally friendly alternative energy production. The outcome is a theoretical approach in an interdisciplinary field, which can be realised in practice.

Results shall help DSO's of heat networks in realising that a higher diversification in sources of supply, and especially in DHS a decentralisation of heat supply may help to increase security of energy supply. Further, proofed best practice gives TSO's the possibility of stepping into a forerunner role among natural gas grid operators through implement energy efficiency measures.

Finally, the feasibility of the waste heat recovery unit (WHRU) at the compressor station Weitendorf along the TAG pipeline should be analysed by discussing various operation scenarios. Perspectives and suggestions for further research are presented.

1.3 Citation of main literature

For the theoretical part handbooks, such as the "Handbook of Natural Gas Transmission and Processing", and published scientific papers are used as essential sources. Important researchers and scientists regarding this subject are Tony Cleveland from Cleveland Engineering Services Ltd, Roberto Carapellucci and Lorena Giordano from L'Aquila University in Italy, Piero Colonna and Emiliano Casati from Technical University of Delft, Wojciech J. Kostowski and his research team form Silesian University of Technology, Poland, Bruce Hedman from the Institute for Industrial Productivity, Washington.

Recently published documents such as papers from conferences, data sheets from manufacturers are the base for the technology description. The TAG GmbH provided the project documentation for the case study scenarios. Further, relevant parties such as Energie Steiermark Wärme GmbH have been included in the research process.

1.4 Structure of work

The work is divided into a theoretical and practical part. Beginning with a description of natural gas transmission systems and gas compression in chapter 2, waste heat recovery and state of the art technologies will be analysed. Basic knowledge on topic relevant thermodynamically cycles is provided.

Further, big scale and ready technologies for thermal energy utilisation in CS along natural gas pipelines will be discussed on global scale in part 3. Theoretical and technical potentials will be addressed on a global scale. Manufactures and their solutions are described, followed by the core subject the case study Weitendorf. The applied technology of the WHRU will be explained and in order to present results a positive business case will be presented as well as various scenarios. The argumentation will be based on data, current market prices and interviews with experts.

Furthermore, legal aspects will be considered. In the final part, conclusions and perspectives especially for TSO's and DSO's will be presented.

2 Technical principles

"Within waste heat recovery technology, the terms bottoming cycle, topping cycle, and combined cycle are used. A bottoming cycle is a thermodynamic cycle which generates electricity from waste heat, as opposed to a topping cycle, in which waste heat from electricity generation is rejected to the environment (cooling water, atmosphere), or used for heating purposes in industry or for district heating purposes (cogeneration). In a combined cycle these cycles are combined for electricity production by connecting two heat engines in series." (Paanu et al., 2012)

2.1 Gas characteristics

The focus of this thesis is the evaluation of WHRU in natural gas pipeline systems. Recently, other gaseous energy carriers such as Biogas are also injected into the grid and influence the gas quality. Because of great storage capacities, it is expected, that soon or later other gaseous fuels such as SNG, Bio-SNG, Algae-Methane, Methane, Bio-Methane, Hydrogen and solar synthesis gas will be also injected into the natural gas grid. (NGVA Europe, 2014)

One of the most important chemical properties of a gaseous energy carrier is its quality, which is defined by the content of various components. This specific composition defines the caloric value. Gas with a higher CV has a higher energy content and therefore it is a more valuable gas than gas with a low CV.

Mostly, the origin of the natural gas defines its quality because different natural gas fields contain different gases. The gross calorific value $[kWh/Nm^3]$ of average natural gas which is transported via the TAG pipeline in Austria equals 11,3 kWh/Nm^3 (AGGM, 2015).

The reason why the impact of the calorific value is influencing the quality is based on the principles of the ideal gas constant. Namely, on the chemical substance $[n]$ interrelates with gas volume. The ideal gas formula is stated below. (NASA, 2014a)

$$p \cdot V = n \cdot R \cdot T$$

In consequence of the the inconstancy of the CV, which basis on the correlation of its chemical amount of substances $[n]$ and changing ambient temperatures, the gas industry uses the so-called Wobbe index.

$$W = \frac{CV}{\sqrt{\rho}}$$

As above defined, the Wobbe the index $[W]$ is described as the CV of the gaseous fuel divided by the square root of the specific density $[\rho]$. The standard Wobbe index for natural gas is stated with 49-53 MJ/Nm^3. (Mokhatab and Poe, 2012)

2.2 Energy fundamentals

Thermal energy is related to latent energy, which is a result of potential energy, and to chemical energy (Kinetic energy in particles). Heat losses are a result of not using thermal energy property. In other words, Exergy is the result of energy minus losses. Enthalpy $[H]$ indicates how much energy is stored within a certain system $[U]$ and is called internal energy. As later on explained, pressure $[p]$ and the volume $[V]$ play a major role in gas transmission and compression. An isenthalpic process, is defined by a constant Enthalpy $[H]$, which does not change. An adiabatic process instead, is defined as the expansion of a gaseous fuel with no heat exchanged. (NASA, 2014b)

$$H = U + pV$$

In order to understand how HR systems can be applied in practise it is essential to comprehend the second law of thermodynamics, which is

$$\Delta S = \frac{\Delta Q}{T}$$

Entropy $[S]$ stands for a certain disorder within a thermodynamic system. The condition change in entropy $[\Delta S]$ is equal to the heat transfer $[\Delta Q]$ divided through the temperature $[T]$ (NASA, 2014b). A typical case of entropy surplus is that gas in pipeline flows always from high pressure towards lower pressure conditions. As result gas can be transported by increasing the pressure with a compressor unit.

$$\Delta S \geq 0$$

This formula explains that the entropy change $[\Delta S]$ cannot be smaller than zero. Adapting that content to the thesis subject, it means that heat cannot be lost but only transferred from A to B.

$$\eta_{th} = \frac{Q_{out}}{W_{in}}$$

Thermal energy conversion efficiency $[\eta_{th}]$ is mostly stated in percentage and is the measure for energy conversion as result of the total power output $[Q_{out}]$, divided through the power input $[W_{in}]$.

Within a heat load duration curve diagram the supplied power $[MW]$ is stated on y-axis and the duration $[h]$ is specified on the x-axis. In common literature the chart is also called load curve profile. (Minister of Natural Resources Canada, 2005)

In order to transport gas as efficient as possible through the natural gas pipeline the gas pressure $[p]$ must be increased precisely. For calculating these changes of pressure conditions, the pressure drop $[\Delta p]$ must be known. The Darcy-Weisbach equation is a fundamental principle of fluid dynamics and applied to pipelines the formula is defined as following:

$$\Delta p = \frac{f}{2} \frac{\Delta L}{d} \rho u^2$$

Primarily, pressure losses $[\Delta \mathrm{p}]$ in gas pipelines are a result of friction related to roughness of pipe inside wall. As above displayed in the formula, pressure loss can be calculated if the length of the pipe $[\Delta L]$, the diametre of the pipe $[d]$, the velocity of the natural gas $[u^2]$ and the fluid density $[\rho]$ are known.

The total costs of gas compression are influenced by generated power and emissions. For both, the operator has to pay a certain amount of money, for example for purchasing electricity or for avoiding NO_x emissions. In order to save expenditures during pipeline operation, the inlet pressure must be stated in order to overcome the pressure drop $[\Delta p]$. (Steinar Guðmundsson, 2010).

Another subject relevant law is the effect, which explains how gas is changing its temperature when it is throttled during the Joule-Thomson expansion. The change in temperature experienced by the gas during expansion depends not only on the initial and final pressure, but also on the manner in which the expansion is carried out. This Joule-Thomson effect describes how temperature difference $[\Delta T]$ is effected by the the gaseous fuel at constant enthalpy coming from high down to a low pressure. It is the description of what happens when natural gas is shifted via pipelines and the gas is cooling down with the decrease of pressure $[\Delta p]$ and passed distance. (Mokhatab and Poe, 2012)

3 Natural gas transmission and compression

Natural gas is compressed during the transportation from the well, where the gas initially is moved from the underground deposit up to the surface. It is separated from oil and water and later purified in the gas processing plant. This is the first so-called upstream segment. In the midstream phase natural gas is transported to the distributors. Therefore, the medium is compressed before injected into the natural gas transmission grid as displayed in Figure 1. If the energy carrier is not transported via pipeline to its customers, it is liquefied to LNG and shipped or transformed into electricity in a power plant. Finally, the natural gas is odourised and distributed in the downstream section to it's final consumers such as households and commercial clients. (Nasr and Connor, 2014)

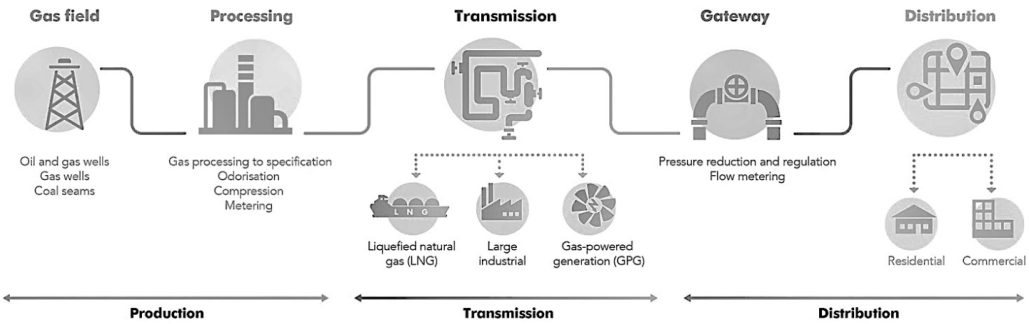

Figure 1: Different segments of the natural gas supply chain (AEMO, 2014)

Gas grid operators call appropriate gas, which is in accordance with their grid specifications, pipeline gas (Mokhatab and Poe, 2012). LNG is liquid gas, which is stored close to its boiling point around -160 °C because of its low density which is half as dense as H_2O. (Nasr and Connor, 2014)

3.1 Transportation of natural gas

Mostly natural is gas is transported via pipelines or LNG carriers. Since the beginning of unconventional gas production, such as shale gas, LNG market shares have been increased significantly. In order to detect potentials for WHRU applications it is important to understand how the gas is shipped from vendors to costumers (Mokhatab and Poe, 2012). In figure 2, global trade flows are distinguished into pipeline gas and LNG. In the year of 2014 the EU imported 146,3 bm^3 of pipeline gas and 43,1 bm^3 of LNG gas (BP, 2015).

Another possibility would be the immediate generation of electricity, which is also called GTW technology. The distribution to the consumer happens via the electricity grid. Further, expensive GTS technologies, such as the usage of gas hydrates could be applied for the transport from producer to the costumer in future. Also pure methane, hydrogen or LPG could be produced, stored and distributed. But all mentioned transformations of the medium itself, such as increasing pressure, lowering temperature in order to change the phase to liquid or purification are reducing the overall self-conversion efficiency of energy production and distribution process.

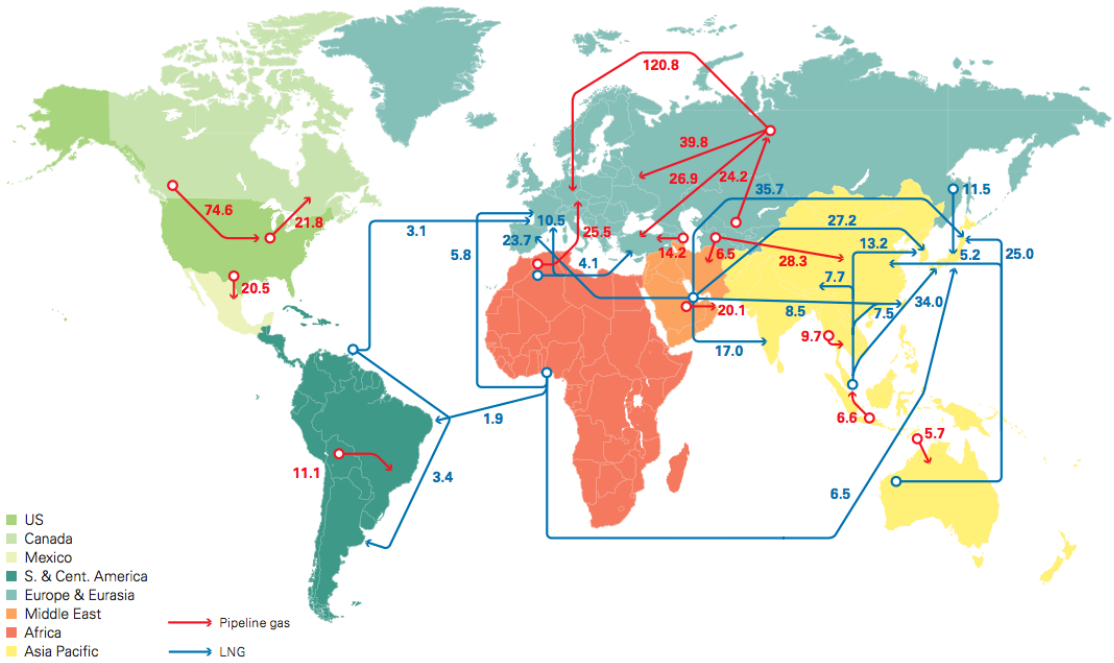

Figure 2: Global pipeline gas and LNG trade flows in 2014 [bm^3] (BP, 2015)

Followed by the EU, USA, Turkey and China are biggest pipeline gas importers. Major LNG importers are Japan, EU and China. A subject relevant matter of fact is that

whether via pipelines or via LNG carriers, natural gas is always compressed during its way to the final consumer. Therefore, the biggest potential for WHR occurs on LNG liquefaction plants, CS stations along long pipelines and UGS sites, where gas is compressed and injected into underground storage facilities. (Pillai et al., 2015)

The highest gas trade sales take place between Russian and the EU (GIE, 2015). The below displayed figure highlights the main import routes of Russian pipeline gas into the EU zone. As below in figure 3 outlined, main pipelines are the North Stream, Yamal, Soyuz, and the Bratsvo pipeline. The displayed South stream pipeline was finally cancel by the beginning of 2015 because of violation of EU legislation. The new route, the so-called Turkish stream, is planned to enter Turkey and later the EU at the Turkish/Greek border.

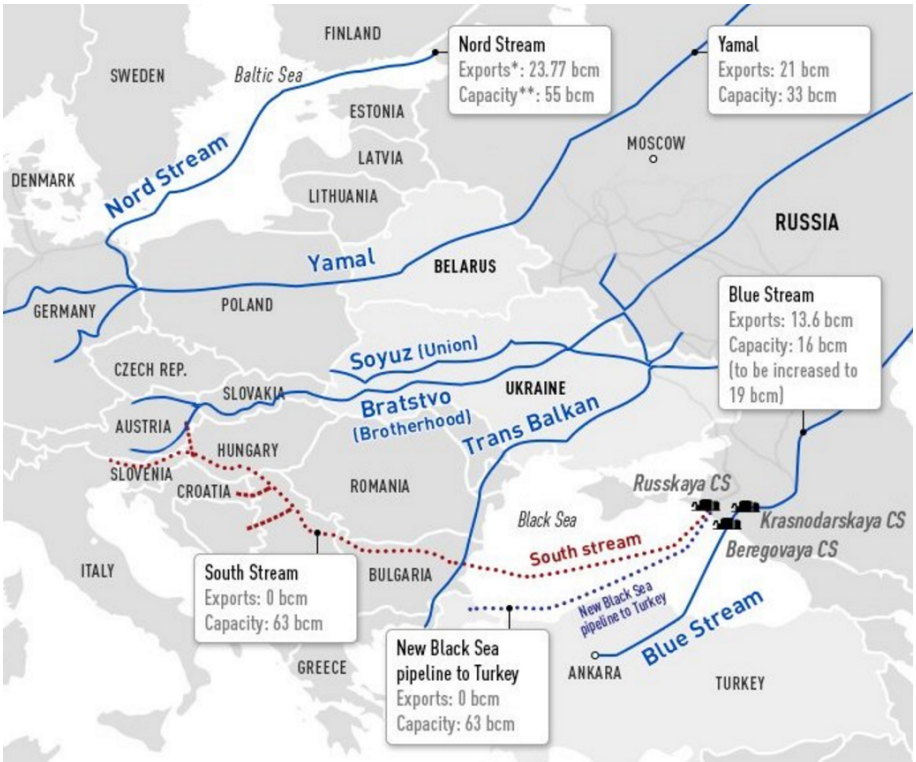

Figure 3: Annual exports of Russian pipeline gas in 2013 in bm^3 (Autonomous Non-Profit Organisation “TV-Novosti”, 2015)

Natural gas pipelines, which are operated within the territory of EU, must be in conformity with EU legislation such as the Third Gas Directive and Regulation 715, which was replacing the Second Gas Directive and Regulation 1775.

Mostly, important energy projects such as pipeline projects gain the status of projects of common interests. Nevertheless, it is quite difficult for third parties such as Gazprom to discuss on framework guidelines and network codes. (Yafimava, 2013)

3.2 Natural gas compression

In order to transport the natural gas through a pipeline or to transform it into a liquid phase the pressure must be increased. The process of increasing and decreasing the pressure within the pipelines is essential and guarantees safe and well-performing operation. Beside of the processing facilities, the most important components of a gas transportation systems are compressor, metering and regulation stations.

In general, only two different types of compressors are used along pipelines, reciprocating and centrifugal compressors. The compressors are driven by different types of mechanical drivers such as gas turbines, electric motors or reciprocating internal combustion engines. (Hedman, 2008)

As below subdivided, the main differences are based on the supplied energy carrier, which is natural gas or electricity. Gas can be injected from the pipeline directly while the latter has to be distributed by an electricity grid and often transformer stations have to be built close by in order to reduce the electric potential for the motor operation. (Mokhatab and Poe, 2012)

Most of the time gas turbines drive centrifugal compressors, booth onshore and offshore (Steinar Guðmundsson, 2010).

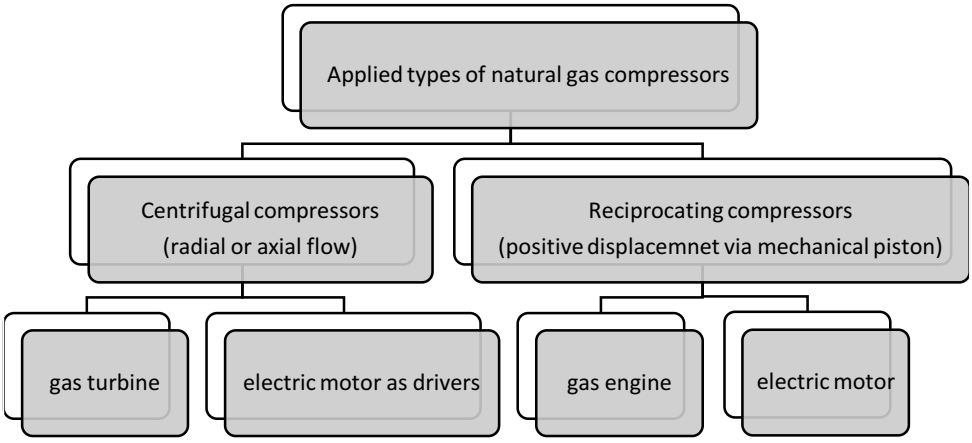

Figure 4: Types of applied compressors (Miljević after Mokhatab and Poe, 2012)

Energy and environmental regulatory authorities push European and North American natural gas transmission system operators to decrease flue gas emissions from gas turbines, which are harmful for the environment. Especially if settlements or cities are located close by, technologies such as the Selective Catalytic Reduction are used to decrease NO_x emissions. As an example, the German TSO Open Grid Europe implemented such measures at the CS Elten. (OGE, 2015)

Another upcoming trend is that TSOs are replacing existing gas turbines which are operated with mixture of compressed air and natural gas with modern electric compressors. According to pipeline operators, this technology has been recently preferred because of better compressor performance at part or half load operation. (TAG Gmbh, 2015)

Further, in comparison with gas turbines, electric driven compressors cause less emissions. Non-contact magnetic bearing systems have nowadays hardly any frictional losses and reduce OM costs because lubricants are used less. The same technology is also applied for magnetic levitation systems for railways and non-contact magnetic bearing energy storage facilities, which are tested recently. (Institute of Process Technology, Process Automation and Measuring Technology, s.a.)

4 Waste heat recovery in compressor stations

The EU utilised 26,4 TWh of recovered heat in CHP applications during 2013 out of waste energy (EU Commission, 2015). The reasons why WHRU are so popular are based on the fact, that the application directly increases the overall efficiency of the process. Other advantages, which occur indirectly, are the reduction of pollution by reducing exhausted gas, the reduction in material sizes such as flue gas handling equipment or stacks and finally the auxiliary energy consumption for pumping and venting. Further, UNEP classifies industrial waste heat sources in three categories:

- Low temperature energy sources (30°C-230°C)
- Medium temperature energy sources (230°C-650°C)
- High temperature energy sources (650°C-1650°C)

As displayed in table 1 the exhausted gas from standard gas turbines, which are mostly used in CS, is classified as a medium waste heat energy source. (UNEP, 2006)

Table 1: Different types of industrial heat sources (Miljević after UNEP, 2006)

Type of industrial waste heat sources	Tmin [°C]	Tmax [°C]
Steam boiler exhausts	230	480
Gas turbine exhausts	370	540
Reciprocating engine exhausts	315	600
Heat treating furnaces	425	650
Drying and baking ovens	230	600
Catalytic crackers	425	650
Annealing furnace cooling systems	425	650

In compressor stations exhausted off gas contains heat, which can be utilised for internal or external use. From a thermodynamic perspective, it would make more sense to use the energy nearby the source because of losses, which cannot be avoided. Mostly energy is produced far away and provided to big consumers, such as cities or factories and losses are increasing together with the increasing distance in between producer and user. Most common technologies, which are applied for industrial WHR are cycles, which are continuously fed with an energy input such as typical steam cycles or so-called Rankine cycles. The main difference is the working fluid within the cycle, which operates as an energy carrier. Because of the the importance of such thermodynamically cycles for waste heat utilisation along natural gas pipelines the most important ones are discussed in the following chapters 4.1.2 until 4.1.5. Other cycles, such as the Uehara, Maloney and Robertson, STIG, which is also called Cheng cycle (Carapellucci and Giordano, 2012), are not considered in this thesis. (Fankam Tchanche, 2010)

4.1 Waste heat recovery

4.1.1 Heat exchangers

Heat exchangers are units, which can transfer from one medium to another. Approaching CS, heat exchangers are used for transferring the exhausted flue gas to

a recipient, which can utilise this heat directly. There are several type of heat exchangers which can be applied in CS such as tube heat exchangers, pipe heat exchangers, economisers, etc.

The once-through steam generator (OTSG) is the most considerable HRSG, which is already applied in CS in the EU. Basically, it is applied in that way so that the waste heat stream from the topping cycle transferred to the bottoming cycle.

4.1.2 Clausius Rankine cycle

This technology, also called steam Rankine cycle, is together with the Brayton cycle one of the most common and proven technologies for waste heat recovery. The very simple system is based on a boiler, which is producing steam by heating up the water. The steam is under pressure and operates the steam turbine, which is coupled to the generator. The theory of a typical Causius Rankine cycle explains the performance of a closed thermodynamic cycle, in which fluids convert to heat and then to mechanical work. This fluid must be under pressure, it vaporises and expands. This fluid escapes to another stage of lower pressure. As a result, some kind of work such as electricity for instance can be generated. (U.S. Environmental Protection Agency, 2012)

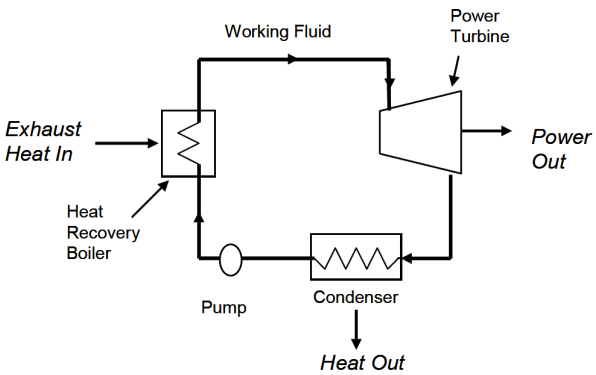

Figure 5: Clausius Rankine cycle applied for waste heat recovery (Hedman, 2008)

In most of the cases distilled water, which evaporates in the boiler to steam, is used as the working fluid. The the cycle is connected to the condenser at vacuum conditions which leads to higher yield by ensuring a higher difference in pressure $[\Delta p]$. In order to gain even higher efficiencies $[\eta_{th}]$ in practise the working fluid can be changed to organic ones. In general, this system $[U]$, outlined in the following figure

below, is used in most of gas fired power plants or common heat recovery steam generators. (Hedman, 2008).

4.1.3 Brayton cycle

The Brayton process, also called Joule cycle, is based on 4 step open thermodynamic cycle in which air from outside in compressed into combustion chamber. The compressed gas operates a gas turbine which can operate a generator and produce electricity for example. The exhaust gas from the turbine is exhaust to the atmosphere.

With components such as a compressor, combustion chamber, turbine and a heat exchanger the system is very similar to the Clausius Rankine cycle. The Brayton cycle can be applied booth for closed and open systems. If the systems are closed. Instead of a mixture of air and natural gas an alternative fuel gas injection, such as helium or CO_2 can be taken into consideration (El-Wakil, 2002).

4.1.4 Organic Rankine cycle (ORC)

As the name already says, the system is based on Clausius Rankine technology with the main difference that organic fluids such as hydrocarbons and siloxanes which can operate with inlet temperatures from 150°C up to 400°C. The technology is used for power generation and CHP. Better cycle conversion efficiencies $[\eta_{th}]$ can be reached with the application of aromatic hydrocarbons and off gas temperatures above 280°C.

Globally, every fifth ORC united is applied on WHRU (Vélez et al., 2012). This heat recovery technology is especially suitable for prime movers such as reciprocating engines, gas turbines and fuel cells (Casati, 2014). Focusing on the average temperature of exhausted gases from gas turbines, which variegate from 370-540°C, ORC technology is reasonable for CS along natural gas pipelines (UNEP, 2006).

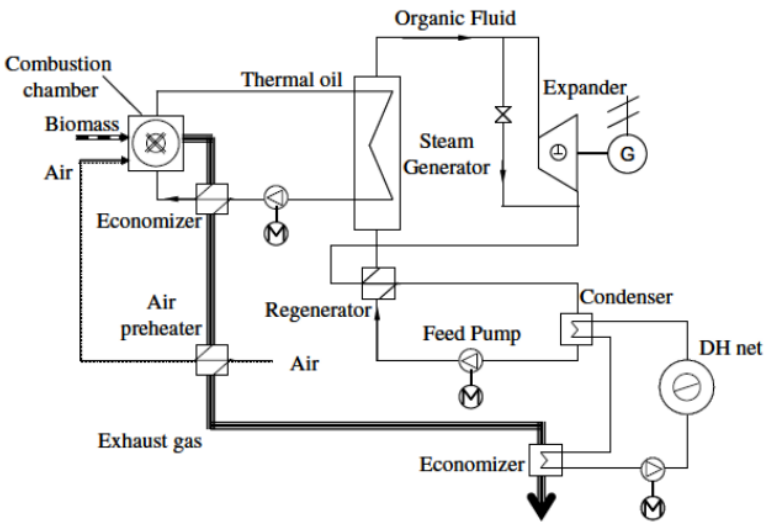

Figure 6: CHP application in a biomass plant with Organic Rankine cycle (Rowshanzadeh, 2010)

Because of the complex stabilisation of the organic working fluid and the strict environmental requirements within an ORC, special components such as a predesigned vaporiser, a preheater and a recuperator have to be installed additionally. Through a ORC WHR in a natural gas compressor station up to 16000 tCO_2 / year can be saved (Saavedra et al., 2010). Moreover, lots of researchers are testing the performance of supercritical ORC applications. For example, GE developed a super Critical CO_2 Rankine Cycle which can be applied in combination with radial expanders.

4.1.5 Kalina cycle

This thermodynamic process was invented and named after Alexander Kalina, who was born in Odessa and later immigrated to the USA where he founded a company named Exergy. In 1993 Exergy and General Electric started a cooperation in which Kalina's technology should be used for combined cycle systems in 50 MW to 150 MW range. GE and Exergy worked on a combined cycle plant that will operate on an overall self-conversion efficiency of 62%. (Subbarao, 2009)

The Australian company Enhanced system technology (2015) proofs that that the Kalina technology, which allows to produce more electrical energy from a certain heat

source in comparison with the ORC, is a rational alternative to common applied technologies.

"The main components include a vapor turbine-generator, evaporator, separator, condenser, recuperator exchangers and a feed pump. The working fluid is an ammonia-water mixture, 82% ammonia by weight. The conspicuous efficiency advantage characteristic of the Kalina cycle is realized from the heat exchange processes of the heat acquisition in the evaporator and the heat rejection in the condenser. Additional efficiency is achieved by the recuperator exchangers. These gains are made possible by the variable boiling and condensing characteristics of the ammonia-water mixture working fluid as it varies in concentration at different points in the cycle." (Mlcak, 2002)

Due to the high Ammonia content, it is still difficult to handle Kalina cycles, which are applied in WHRU worldwide. In addition, Ammonia boils not as water constantly but at different temperatures (Wall, 1989). These circumstances make the technology very expensive, especially when applying it on low scale projects. Supervisory systems have to be adjusted and maintenance precisely.

An important breakthrough was made in 1997 in California, where Leibowitz and Mirolli successfully demonstrated that the Kalina cycle can be used for a stable 3 MW power generation. The heat source came from exhausted gas from a GT. Typically, the technology is applied on geothermal power plants, industrial waste heat units in cement factories, refineries, glass and metal producing factories and other industrial plants. (Recurrent Engineering LLC, 2013).

4.1.6 Waste pressure to electricity

Contrary to the application of WHRU in CS where released heat streams are utilised, pressure drops are utilised within transfer stations between TS and DS for power generation (Cleveland and Mokhatab, 2014). In comparison to compressor stations, regulating stations are mostly located nearby the consumer, where the natural gas pressure level is reduced from 30-80 bar down to 0,2 - 4bar. Instead of a compressor, a turbo expander generates power out of the pressure drop $[\Delta p]$.

Such a project was realised by Swiss engineering company Dr. Eicher+Pauli AG (2009) in Arlesheim, close to Basel in Switzerland. As an outcome annually 18

$GWh_{electric}$ are provided to the settlements closed by. Advantages are low investment and OM costs; disadvantages are additional heat supply controlling the gas expansion.

4.2 State of the art

Different technological approaches of WHRU are presented in this section. High pressure ranges, rigorous safety requirements for construction along natural gas pipelines and little costumer acceptance towards unknown WHRU manufactures results in an assessable market of WHRU producers. Moreover, most of the below described solutions are based on ORC and heat recovery steam generator and only approaching medium and big scale applications in gas transmission systems.

Theoretical and technical potentials for WHRU applications in CS is analysed on a midterm and long term perspective. The difference between the theoretical and technical method of analysing is that first in taking only physical parameters such as countries into account. Contrary, technical potentials have to be investigated on issues such as technology limitations and market specific risks. (Resch et al., 2008)

The exhausted thermal energy can be recovered internally and externally (Carapellucci and Giordano, 2012).

"Exhaust heat from gas turbines can be recovered externally or internally to the cycle itself. Of the various technology options for external heat recovery, the combined gas–steam power plant is by far the most effective and commonly used worldwide. For internal heat recovery, conventional designs are based on thermodynamic regeneration and steam injection, while innovative solutions rely on humid air regeneration and steam reforming of fuel."

Most promising is the external utilisation, also called open cycle technology, because air is injected to the gas and in GT f.e. higher heat loads are exhausted.

Within a natural gas compressor station, waste heat is often used for station heating purposes or for internal electricity generation. In the table below most important advantages and disadvantages of different types of waste heat utilisation are listed.

Electric energy production is feasible because most of gas compressor stations are located faraway from big cities, where pipelines transport natural gas from the well to the final consumer. A connexion to the electrical grid is not always possible because of high investment costs or long and difficult permission procedures. Rising substantial public awareness and critics on the construction of new transformer stations are making it difficult to realise ORC based WHR solutions close to nature reserves and settlements.

Table 2: Advantages and disadvantages of WHR utilisation in CS (Miljević, 2015)

Type of WH utilisation	Advantages	Disadvantages
Electricity to grid	• Revenues • FIT • No capacity limitations	• Low energy conversion efficiency • High investment costs • High OM costs • Grid connexion costs
Heat to DHS	• Revenues • FIT • Low investment costs • energy conversion efficiency • no capacity limitations • Low OM costs	• no heating demand in summer • Grid connexion costs
Electricity for internal use	• no grid connexion costs • capacity limitations • no revenues	• Low energy conversion efficiency • High investment costs • High OM costs
Heat for internal use	• High energy conversion efficiency • Low investment costs • low OM costs	• capacity limitations • no heating demand in summer
Heat to thermal energy storage	• High energy conversion efficiency • Reasonable OM costs	• no heating demand in summer • high investment costs

Focusing on geographical differences, USA and Canada are forerunners concerning the application of WHRU along natural gas pipelines. A lot of know how was generated by US and Canadian universities together with the support of the American Society of Mechanical Engineers (ASME), which organises the International seminar on ORC power systems. (University of Liège and Ghent University, 2015)

Further research was done by Tony Cleveland, who published a paper called New pipelines, new opportunities at the 4th International Pipeline Conference International Pipeline Conference in Calgary in 2002. Cleveland first connects the topic of WHRU with space heating and district heating in cities and presented case studies and financial figures on international conferences. Further, North America obtains the greatest theoretical potential for WHRU along pipelines. In the USA only, 1.400 installed compressor stations are a proof of great potential of waste heat recovery along gas pipelines according to Gauri Potdar (Ormat Technologies, s.a.). Utilising the waste heat from one out of 10 CS, approximately 700 MW of clean energy could be generated.

According to Bruce Hedman (2008) between 90 to 100 CS in the USA can be used for WHR application and the potential of electricity generation with ORC technology equals 500-600 MW_{peak}. Considering thermal energy utilisation for heating homes much higher outputs could be reached due to higher efficiency factors. As below displayed, most of installed WHRU are based on ORC technology and installed in North America.

Followed by North America, Europe and the Russian federation has great technical potential on midterm and long term perspectives regarding the application of WHRUs. Gazprom, the Russian TSO, operates 436 stationary and mobile compressor stations with an average number of 3 GT per CS, each with an average ISO capacity of 12,2 MW / GT. In total, 4100 gas turbines are operated along the Gazprom grid. Main Russia-related publications regarding energy efficiency in CS have been published by Universities such as Gubkin Russian State Oil and Gas University and Ufa State Petroleum Technological University, together with the research centre Vniigaz Gazprom in Moscow. Viktor Zyuzkov published a dissertation on different methods of improving the energy efficiency of compressor stations during the reconstruction of main gas pipelines. Gazprom supports investigation on this subject actively because more of 50% of installed GT have been operated for more than 50.000 hours, 11% of all GT have been working for more than 100.000 hours. (Kuznetsova, 2015)

Due to the ongoing reconstruction of old CS and the high technical potential of 5 GW_{peak} (10% of installed capacity) along the Russian gas pipelines, it is expected that WHRU will be applied in future in order to cut down energy losses. Along the ongoing pipeline project, Power of Siberia II, 8-10 CS with GT ISO capacites of 16-32 MW will be installed. The pipeline will connect Russian gas fields, located close to Baikal lake

with the Chinese gas grid and is expected to operate constantly. Due the neighbourhood of the cities of Tomsk and Novosibirsk, the CS could supply heat to the local DHS. (Napravleniye Dalniy Vostok, 2014)

Table 3: WHRU in CS for external utilisation (Miljević, 2015)

Country	CS, State	Operator	Pipeline	Pipe	Technology provider	WHR
				[Inch]	[Company]	[MW_{peak}]
Austria	Weitendorf, Steiermark	TAG Gmbh	Trans Austria Gasleitung	36"	Küttner	17,0
China	Unkown	Petrochina	Western China Pipeline	n.a	GE Oregen	17,0
China	Unkown	Petrochina	Western China Pipeline	n.a.	GE Oregen	17,0
China	Unkown	Petrochina	Western China Pipeline	n.a.	GE Oregen	17,0
USA	Culbertson, Montana	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	4,0
USA	Garvin, Minnesota	TC PipeLines, LP	Northern Border Pipeline		Ormat Technologies	4,0
USA	Peetz, Colorado	Trailblazer Pipeline	Trailblazer Pipeline	16"	Ormat Technologies	4,0
USA	Manning, North Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	2,5
USA	Glen Ullin, North Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	3,5
USA	St. Anthony, North Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	4,0
USA	St. Anthony, North Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	5,5
USA	Wetonka, South Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	5,5
USA	Clark, South Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	5,5
USA	Estelline, South Dakota	TC PipeLines, LP	Northern Border Pipeline	42"	Ormat Technologies	5,5
USA	Earlville Station, Iowa	Northern Natural Gas	Northern Natural Gas	26"	Ormat Technologies	3,0
USA	Goodsprings, Las Vegas	Kern River Gas Transmission	Kern River Pipeline	36"	Ormat Technologies	5,0
Canada	Rosetown, Saskatchewan	TransGas Limited	TransGas Pipeline	16"	Turboden	0,8
Canada	Coleville, Saskatchewan	TransGas Limited	TransGas Pipeline	16"	Turboden	0,8
Canada	Gold Creek Station, Alberta	NOVA Gas	TransCanada Pipeline	48"	Ormat Technologies	6,5
Canada	Kerrobert Station, Saskatchewan	Alliance Pipeline LP	Alliance Pipeline	36-42"	Ormat Technologies	5,5
Canada	Loreburn Station, Saskatchewan	Alliance Pipeline LP	Alliance Pipeline	36-42"	Ormat Technologies	5,5
Canada	Estlin Station, Saskatchewan	Alliance Pipeline LP	Alliance Pipeline	36-42"	Ormat Technologies	5,5
Canada	150 Milehouse, British Columbia	Spectra Energy Corporation	British Columbia Pipeline	36"	Ormat Technologies	4,5
Canada	Savona, British Columbia	Spectra Energy Corporation	British Columbia Pipeline	36"	Ormat Technologies	4,5
Canada	Sumit Lake, British Columbia	Spectra Energy Corporation	British Columbia Pipeline	36"	Ormat Technologies	4,5
Canada	Hixon, British Columbia	Spectra Energy Corporation	British Columbia Pipeline	36"	Ormat Technologies	4,5
Canada	Australian, British Columbia	Spectra Energy Corporation	British Columbia Pipeline	36"	Ormat Technologies	4,5
Switzerland	Ruswil, Luzern	Transitgas AG	Transitgas Pipeline	36"	Unkown	7,1
Spain	Almendralejo, Extremadura	Enagás S.A.	Cordoba-Badajoz Pipeline	32"	Ormat Technologies	4,7
Thailand	Unkown	Unkown	Unkown	n.a.	GE Oregen	17,0
TOTAL	**30 CS**					**195,9**

All WHRU manufactures references at CS are listed in table 3. Some projects are still on-going are not finished yet. As displayed, majority of the WHRU have been delivered by Ormat Technologies. In total 30 projects have been realised as far. Based on references, publications and technology descriptions each WHRU producer is evaluated by it's market position.

Ormat Technologies Inc. has implemented more than 20 WHRU along natural gas pipelines worldwide. All projects are based on ORC technology and most of them are generating electricity. As in table 2 displayed, the unit size equals from 0,8 MW up to 6,5. Ormat Technologies installed the first ORC WHRU in a natural gas CS in 1999 in North America and is considered as the global market leader. (Ormat Technologies, 2013)

GE invested in WHR business since the cooperation with Exergy (Kalina technology) in the 1990ies. As a result, the segment has presented GE Oregen, which is not based on the Kalina cycle but on a ORC. The unit transfers heat from WHR through one oil and two fluid loops to generate as an output power up to 5-17$MW_{elctric}$. The liquid organic fluid cycle, filled with Cyclopentanes, is displayed in the scheme below, as well as the other two cycles. GE claims that Oregen reduces OM costs in comparison to steam cycle operated WHRU due to the compact form, low cycle refilling costs. (Burrato et al., 2007) A main advantage is that GE Oil and Gas is a world leader in GT manufacturing after acquiring Nuovo Pignone from Italy in 1993 and focuses on serial production. As below listed, GE offers various types of WHRUs and offers a huge range of units for waste heat stream temperatures from 50-600°C, reaching capacities from 0,1 to 200 MW_{peak}. After the acquisition of Calnetix Technologies in 2010, the position of GE within the WHRU has become stronger. (Jammu, 2013)

UTC Technologies, also known as Pratt & Whitney is a USA based company which is specialised on production and integration of micro turbines for CHP applications (ORC, 2009). The company is no longer producing WHRU for CS stations (Ormat Technologies, 2013).

Atlas Copco is a Swedish manufacturer, which is specialised on the production of natural gas compressors and expanders. The ORC solution for WHR called EGI-5 is a CHP stand alone unit which is uses a tetrafluoroethane called R134. The Atlas Copco WHRU is applied on two gas turbines, where the off gas (485°C) is recovered via a thermal oil cycle. The unit is generating 2 $MW_{electric}$ out of an average mass flow input of 68 tonnes per hour. (Atlas Copco Gas and Process Division, s.a.)

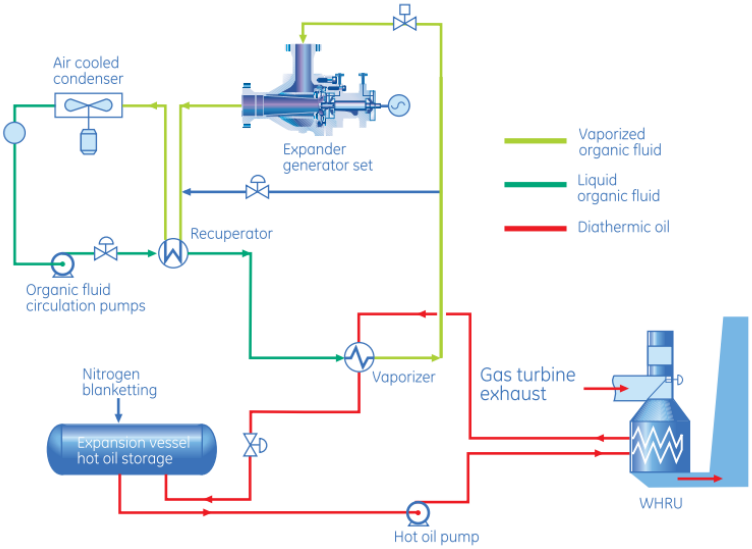

Figure 7: GE Oregen ORC cycle scheme (GE Oil and Gas, 2011)

The Italian based company called Turboden from Brescia is a part of Mitsubishi Heavy Industries. The company specialised on the production of WHRU with ORC technology up to 4$MW_{electric}$ power output. The company is also focusing on CHP and solar thermal applications. (Turboden, 2015)

Table 4: Types of GE Oil and Gas WHRU (Miljević after Jammu, 2013):

Technology type of GE WHRU	Capital costs [€/MW]	WH temperature [°C]	Capacity [MW_{peak}]
ORC with radial expander	high	50-300	< 0,75
Kalina Cycle	high	190-370	apr. 50-200
ORegen	medium	250-430	4-17
Super Critical CO_2 Rankine cycle with radial expanders	medium	375-520	n.a.
ORC with screw expander	medium / High	75-300	n.a.
Steam Rankine	low	480-600	> 0,5

Maxxtec Gmbh is a German based company and specialised on on the production of heat exchangers (up to 10 $MW_{thermal}$) and WHRUs based on the ORC cycle. The Maxxtech ORC-WHRU has a maximum capacity of 3 $MW_{electric}$ and is delivered in combination with a tube heat exchanger. (Maxxtec Gmbh, 2014)

Enertime is a French manufacturer which has 2 WHRU in the product portfolio, the Rainbow and Orchid unit. The output of the units are limited by 0,3 and 5 $MW_{electric}$

and a maximum inlet temperatures of 200°C. Most of the applied gas turbines can not meet this low temperature ranges. (Enertime, 2015)

Table 5: ORC-WHRU manufacturers (Miljević after ORC, 2009)

Manufacturer	Origin	Global market position
Atlas Copco	Sweden	Medium
Enertime	France	Low
Exergy	Italy	Low
GE Oil and Gas (incl. Calnetix Technologies)	USA	Medium
GMK	Germany	Medium
Maxxtec	USA	Low
Ormat	USA	Strong
Turboden (Mitsubishi)	Italy / Japan	Medium
UTC Power	USA	Low
Triogen	Netherlands	Low

The Spanish research centre CARTIF, together with Universidad de Valladolid and Universidad Nacional de Colombia published (2012) a market review of ORC for the conversion of low-grade heat for power generation which is focusing on economic feasibility. The application of ORC in CS is feasible if technology can be provided by less than 2000 € /kW. (Vélez et al., 2012)

If unit costs will come down to reasonable prices contracting models for WHRU can become also in Austria an interesting niche market. According to Hinterberger (2011) the US contractor model is a successful one and helped US based manufactures to sell more units in last decade.

Addressing the potential of pressure expansion power modules for pressure regulating stations in DS, Siemens Turbomachinery Equipment GmbH is a global leader (HGC Hamburg Gas Consult GmbH, s.a.). Moreover, RMG Honeywell is manufacturing turbo expanders with an inlet pressure range of up to 70 bar and nominal power capacity of 550 $kW_{electric}$. (Honeywell Process Solutions, 2011)

Risks such as a long-term fail-out of natural gas supply because of high production costs or too high taxation have to be taken into consideration. Geopolitical conflicts can surely influence on gas transmission negatively and must been taken into consideration before WHR becomes a scope of the pipeline project. Further, WHRUs shall not be applied, if the CS itself is situated in a very environmental sensitive area.

Globally speaking, environmental impact assessments (EIA) are not binding procedures in all countries and if so, they are not executed according to international standards. Even if national legalisation does not obligate project owners to undertake EIA, operators should accomplish these procedures in respect to local population and because of biodiversity and environmental reasons. For example, the Myanmar-China oil pipeline project was very controversial in terms of environmental impacts and public acceptance. (Earth Rights International, 2011)

But even in countries such as Myanmar WHRU could deliver alternatively generated power to rural areas, where there is no access to electricity grid.

4.3 Status quo within Europe

In 4 projects within the EU exhausted gas is recovered in natural gas compressor stations externally. For heating and sanitary water purposes waste heat is only recovered in Ruswil compressor station in Switzerland and directly utilised. The CS and WHRU are operated and maintained by Transitgas AG together with GE Nuovo Pignone, the gas turbine manufacturer.

Figure 8: Enagás compressor station Almendralejo, Spain (Google Maps, 2015)

Another forerunner in the EU is the Spanish TSO Enagás, S.A., which contracted the Catalan Abantia group for the project realisation of a WHRU at the gas compressor

station Almendralejo (Abantia, 2015). Another ORC WHRU was realized in Huelva/ Spain at the LNG regasification plant. (Saavedra et al., 2010)
In the above displayed CS the ORC is feeded with the off gas from the turbocharges and the generated power is utilised within the station and capacities up to 4,6 MW_{peak} can be sold to the market. Enagás, S.A. recently invested in various feasibility studies regarding the recovery of waste heat in compressor stations and the application of micro turbines in order to increase the overall energy efficiency ratio along their natural gas grid (Enagás, 2007). Another technology, patented by Hans-Jürgen Ciesielski in 1999, uses the waste heat as an additional input of thermal energy for an additional gas compressor within the same station (DPMA, s.a.). Bertsch Energy Deutschland GmbH, part of Bertsch group, delivered heat recovery steam generator for the gas compressor border station Mallnow between Germany and Poland. The recovered heat fires an additional 20 MW gas compressor within the station. The CS is operated by Gascade Gastransport Gmbh. (Gascade, 2015)

According to the mentioned references in Germany, Spain, Switzerland other projects were realised in Austria and Italy. The Italian pilot site was operated by the Italian TSO Snam in Italy for a short period of time. (Transitgas AG, 2015)

One reason, why this type of alternative energy source is not used for DH purposes currently is that the legal situation with the EU is complex. Namely, the Third Gas Directive and Regulation 715 obliges TSO's to stick to an unbundling, as explained in the following:

"Unbundling is the separation of energy supply and generation from the operation of transmission networks. If a single company operates a transmission network and generates or sells energy at the same time, it may have an incentive to obstruct competitors' access to infrastructure. This prevents fair competition in the market and can lead to higher prices for consumers. Under the third package, unbundling must take place in one of three ways, depending on the preferences of individual EU countries: Ownership Unbundling where all integrated energy companies sell off their gas and electricity networks. In this case, no supply or production company is allowed to hold a majority share or interfere in the work of a transmission system operator. Independent System Operator where energy supply companies may still formally own gas or electricity transmission networks but must leave the entire operation, maintenance, and investment in the grid to an independent company." (EC, 2015)

According to the scope of this thesis, the WHRU along natural gas pipelines shall not be considered as an commercial energy production facility. The focus is definitely to highlight energy saving and efficiency potentials and to address reduction of GHG.

4.4 Status quo in Austria

With an exception of the CS in Weitendorf, Austrian gas compressor stations have not been considered as an additional industrial heat source due to high investment, operation and distribution costs. This is one reason why the utilisation has not been economically interesting for DH operators. This may change in future if Austrian energy agency is going to treat DH from WHRU along natural gas pipelines as common industrial waste heat such as from steel or cement industries.

In order to point out potentials regarding energy savings with the Austrian natural gas grid the Austrian Ministry for Transport, Innovation and Technology (BMVIT) contracted Energy Research Austria in order to do relevant research. As a result of this profound research a Smart gas grid position paper was published in 2011. Hinterberger (2011) is addressing in his publication potentials within Austria, which are limited on the TAG pipeline CS and CHP applications in combination with ORC technology and biomass combustion. Ratified on the 1st of January 2015 the Austrian energy efficiency law, so called Bundes-Energieeffizienzgesetz, is an action plan and obligates an increase of energy efficiency up 20% until 2020. The law is binding DSO's to ensure secure energy supply. As stated in "Anhang I, part 2, j & k" the utilisation of waste heat in close by companies as well as the utilisation the district heat system are acknowledge measures for achieving Austrians 2020 goals. (Federal Chancellery of Austria, 2015). TSOs are excluded to that law, though the policy makers have been doing steps toward a general higher concern towards energy efficiency action.

Addressing general acceptance of this sophisticated technology, a further step would be the consideration of compressor stations as a potential waste heat source in the so-called "Wärmeatlas" which was launched by Kommunalkredit Public Consulting GmbH (2012) and the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) in 2012. The map is displaying the theoretical potential of available industrial heat sources, which could be utilised, in DHS in example.

5 Waste heat recovery in the CS Weitendorf

Trans Austria Gasleitung is a natural gas pipeline, which transports Russian natural gas form the Austrian Slovak border at the intake station Baumgarten all the way down to the border between Italy and Austria to Arnoldstein in three lines. With a technical capacity up to 5,3 Million Nm³/h (Baumgarten) and a pressure range up to 71 barg the pipeline is an important primary energy provider in Europe. The 380km pipeline itself is operated and owned by the Trans Austria Gasleitung Gmbh, headquartered in Vienna, Austria. Shareholders in 2015 are two TSOs, the Austrian GCA and the Italian SNAM. Along the pipeline 5 CS and 3 MS are operated. The total load of all CS stations equals 475 MW_{peak}.

Figure 9: Trans Austria Gasleitung (TAG Gmbh, s.a.)

After a detailed market survey by TAG Gmbh for the period from 2015-2024 no expansion of the existing TS is planned. With booked capacities of 5,2 Million Nm³/h (intake station Baumgarten), the pipeline is nearly booked out until 2022. (TAG Gmbh, 2014)

The biggest energy saving potential through WHR along the TAG occurs within the CS because each one is equipped with three natural gas turbines, one per gas string. One of the 5 CS is located in Ruden, 8km away from Völkermarkt, a city with 10.953 inhabitants (Statistik Austria, 2015). From a resource oriented and environmental point of view the 2015 installed DH biomass fired boiler with a capacity of 4 $MW_{thermal}$ could have been compensated. Technically feasible, WHRU in the CS Ruden in combination with a TES facilty. The manufacturer of the biomass boiler URBAS Maschinenfabrik Gesellschaft m.b.H. is headquarter in Ruden. (URBAS Maschinenfabrik Gesellschaft m.b.H., 2015)

Figure 10: CS and WHRU in Weitendorf (Digital Globe Inc, 2015)

The above displayed CS Weitendorf in figure 10, is the newest CS and located close to Weitendorf. Technically, the site is subdivided into two parts. One section is the gas compressor station including the pigging station, and the compressor facility, which is connected to the WHRU, the offices and chillers and heaters. The second part is the WHRU, which was initially operated by external company, the OMV Gas & Power Gmbh. The position of the CS was chosen, in-between the railways and the “Phyrn Autobahn” highway, because no residential homes are located close by. Natural gas compressor stations are generally built in safe and abounded areas because of noise and emissions.

The three gas operated PGT25 GE Nuovo Pignone GTs are the core units of the facility. Each of them is air-cooled, divided in two stages (two shaft gearing) and operates with a sixteen stage axial compressor with a pressure ratio of 18:1. With an ISO capacity of 23,3 MW / GT and a stand alone energy conversion efficiency of 37,7% per GT it is using a mixture of compressed air and natural gas for even better performance results and and a higher conversion efficiency. Further, a stable injection performance of the fuel into is the annular combustion chamber can be ensured. In general, additional H_2O injection systems are common and reduce the overall NO_x emissions significantly. (Nuovo Pignone S.p.A., 2006)

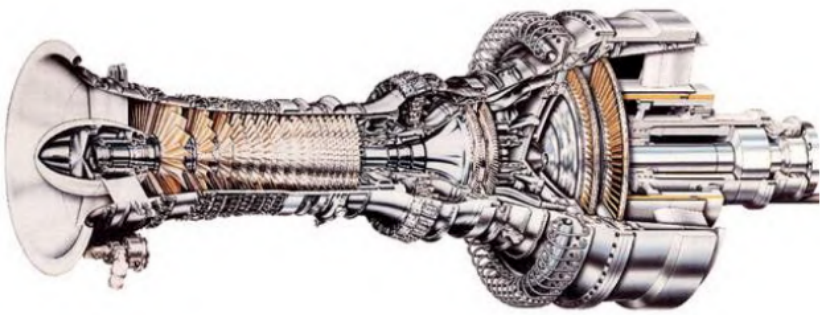

Figure 11: Gas turbine GE Nuovo Pignone PG25+ (Meher-Homji et al., 2008)

The GT are connected with the waste heat boiler and operates similarly to a HRSG with the small difference that the off gas is not burned within the facility but used. This unit consists of the LP and HP evaporator, a LP and HP economiser, a LP and HP superheater, a vent silencer and a chimney. LP and HP cycles are used in order to increase efficiencies by guaranteeing stable pressure. The cycles are fed with the exhausted gas with an average temperature of 540°C and water and release steam which is converted into electricity in the steam generator only if the bypass is opened by the supervisory system in advance. The below displayed facility in figure 12 outlines the WHRU which was engineered and constructed by Küttner Energy & Enviornment Gmbh, a subsidiary of the Küttner group in 2011. The exhausted off gas enters where the black arrows is pointing into the facility.

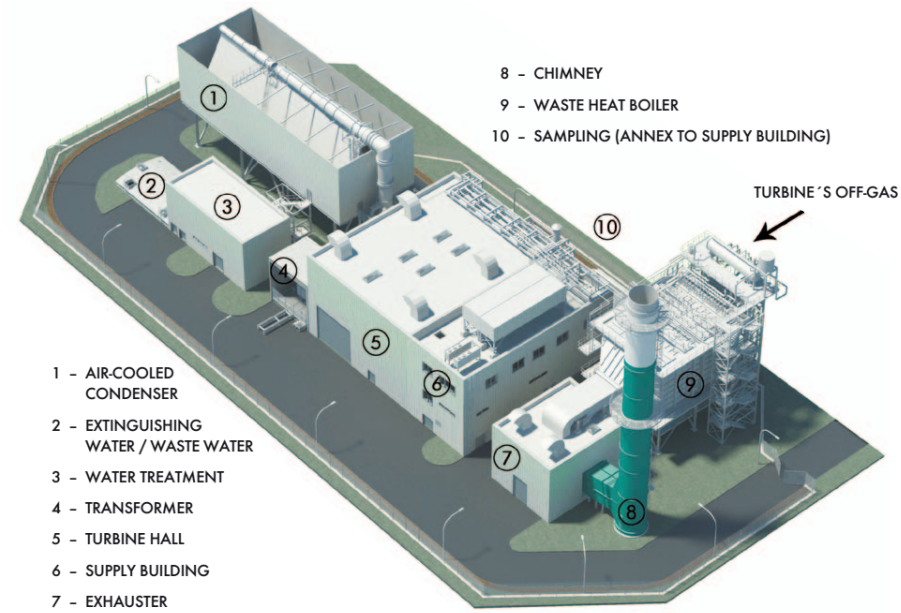

Figure 12: WHRU in Weitendorf (Küttner Energy & Enviornment Gmbh, 2011)

In line with the project documentation from Küttner the overall self conversion efficiency of the waste recovery unit in Weitendorf equals 58%. This refers to the electricity generation up to 14MW_{peak}. In comparison to this figure, state of the art WHRU with steam cycles are operated with overall self conversion efficiency up 80%. The numbers of steam turbine operating hours, dated on the 22.06.2015, equals 10324h. The overall percentage of bypassed operating hours of all three GTs is stated with 22,01%, which indicates that less than quarter of operated hours was used for electricity generation. This can be caused due to gas flow and gas pressure ratio within the whole pipeline system, which means that pressure can be increased also in other CS along the pipeline. Further the TSO decides if and when the WHRU can be operated.

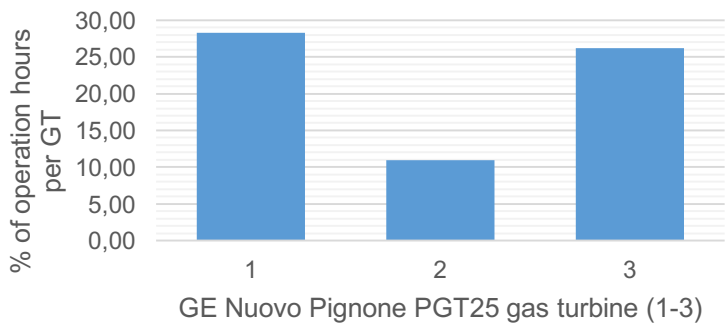

Figure 13: Percentage of bypassed operating hours per gas turbine (1-3) from 2011-2015 (Miljević, 2015)

5.1 Waste heat utilisation scenarios

The town of Weitendorf is located in the south of Graz, which is the capital city of Styria. The CS is situated in south between the villages of Lichendorf and Komberg. The Verbund AG operates 2 heating plants, which are fired mostly with heating oil and natural gas in Neudorf-Werndorf. Closed by in Mellach the power producer Verbund AG operates a CHP gas power plant in addition. Due to recent close down notifications by Verbund AG new heat sources should be connected to the DH.

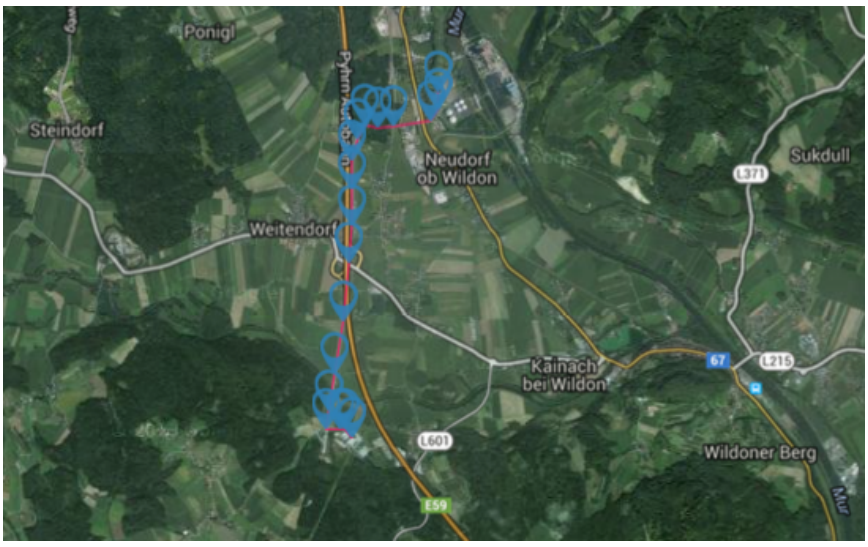

Figure 14: Estimated distance between the WHRU and the DHS connexion point (Digital Globe Inc, 2015)

The connexion to the DHS could be realised by Wärme Gmbh, headquartered in Graz. Only the heat exchanger (+ OM) and the transfer station should be constructed by TAG Gmbh. Wärme Gmbh, the local DHS operator for the city of Graz and the surrounding suburbs and villages.

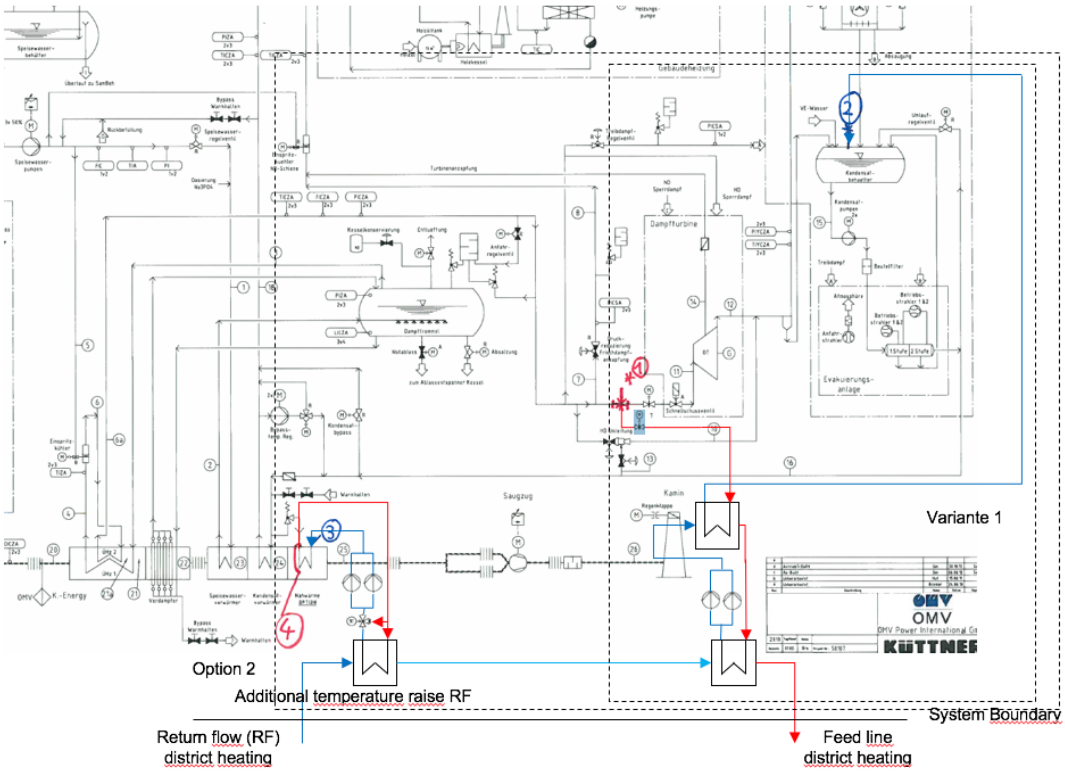

Figure 15: Scheme of the heat exchanger connexion for DH (TAG Gmbh, 2015)

According to Energie Steiermark Wärme GmbH (2015), the pre-insulated district heating steel pipes would be connected to the closest existing DH network which is 3500-4200m away, just in-between the highway Phyrn Autobahn and the plant group in Werndorf. Due to the close connexion point instalment costs are significantly low. DN400/560 or DN400/630 pre-insulated pipes shall be connected via a new constructed pumping station. Including property costs, transformer station, digging works, connexion costs, permissions and other labour work, the pumping station and the pipe would cost approximately 8,5 Million €. This costs would be coverd by Energie Steiermark Wärme GmbH.

As in figure 15 displayed (feed-in line), and under the cirumstances that 2 GT are operated constantly gas flow of approximately 138 kg/s with an temperature of 528°C could be realised. With an output of 110°C and a backflow of 65°C from the DHS ($\Delta T = 10°C$) approximately 62 MW could be utilised for DH purposes.

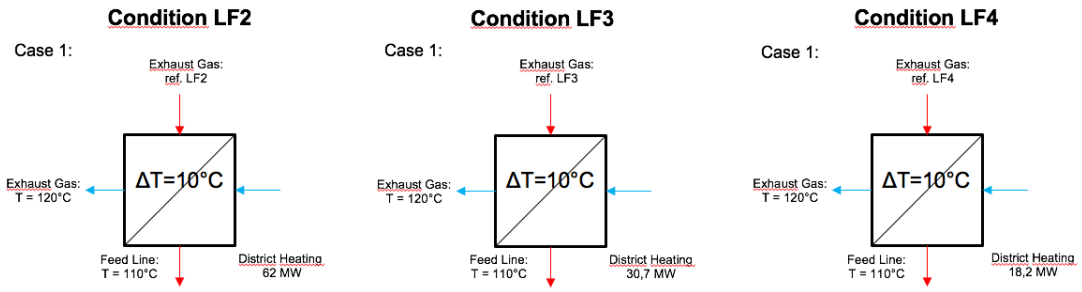

Figure 16: Load scenarios for DH utilisation (Miljević after TAG Gmbh, 2015)

A key factor is the operating hour / full load hour, which is stated on an annual base. This assumption is necessary in order to calculate the net output of the certain facility. As a result, generated power or provided heat will give the TSO the possibility to check if the project realisation would be feasible, not only from a technical and environmental point of view but also form a financial point of view. In the period between 2014 and 2015 the CS was operated most during January and February The CS was operated 285 (+/- 5%) hours per month on average. The station is presumed to operate more than 3400 hours per year. The assumed FLH of the WHRU are calculated with 1528 FLH per year.

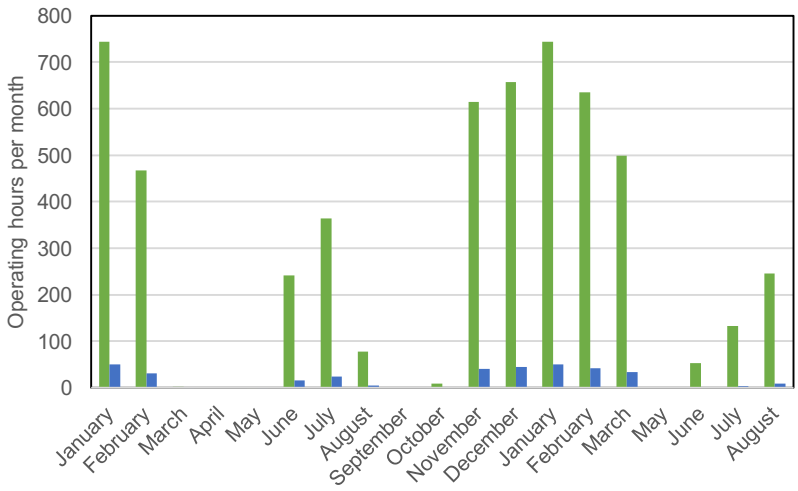

Figure 17: Operating hours' comparison CS/ WHRU for the period January 2014 until August 2015 (Miljević after TAG, 2015)

Based on the technical investigations 3 out of 5 LF (load cases) have been taken into consideration. For the calculation only the realistic LF2 scenario will be used. In

addition, two scenarios, based on the designed capacities from project documentation are presumed for the utilisation options. Altogether, the heat only scenario is stated with 62MW_{peak}, the CHP scenario is assumed with 11,1 MW_{peak} + 14MW_{peak}, and the electricity scenario is based on a capacity of 14 MW_{peak}. The letter P indicates different price scenarios, L is highlighting different load scenarios and M different CHP mix scenarios (different share of electricity and heat production). Based on results and figures current and assumed future energy prices are used for each scenario. Finally, as in the table below displayed, the pay off time should be estimated in order to ensure O&M budgets in future.

Table 6: Depreciation scenario for the WHRU (Miljević, 2015)

Event	Year	Depreciated amount [€]
Construction	2008	37.000.000
Status quo	2015	17.700.000
Depreciation	20xx	0

Based on Q1 and Q2 (2015) results from 2015 OM costs for the existing WHRU are assumed approximately with 750.000 € excluding HR costs. In total the amount of 1.000.000 € will be used for the OM cost escalation, assumed only for scenario electricity production. For solely heat production, CC and OM are only considered for the heat exchanger operation. Because OM are variable and difficult to predict a variation of up to 15% will be considered in the sensitivity analysis. (TAG Gmbh, 2015)

Table 7: Load scenario P1 – heat production only (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	62,00	[MW_{peak}]
FLH	1.528,00	[h/a]
Investment Costs	30.000,00	[€/MW]
O&M	2,40	[€/MWh]
FIT for heat	30,00-42,12	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	94.736,00	[MWh]
Long Run generation costs	4,34	[€/MWh]
O&M	227.366,40	[€/year]
O&M	4.547.328,00	[€/20 years]

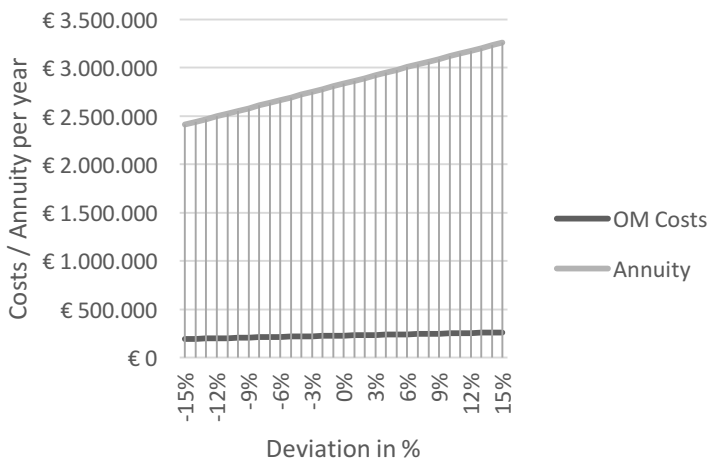

Figure 18: Sensitivity of the annuity in variation to the OM costs per year according to P1 Scenario (Miljević, 2015)

The assumed sales prices for this scenario for the period from 2016-2036 is yearly increased by 2% which results in 30,00 €/MWh (2016) and 42,12 €/MWh (2036). Similar escalations according to the so-called VPI or EPI are used for business plans for CHP biomass plants in Austria. Such price indices are weighted averages based on overall prices from the whole last year which are published yearly by the Austrian Energy Agency (AEA). In 2013 the DH prices per kWh increased by 4,3%, while in 2014% the price increased only by 2,6%. Due to current market price development in 2015 it is expected that prices will not increase. (AEA, 2015)

The investment costs for the heat exchanger, and the transfer station to DHS, approval and commissioning costs and a suitable supervisory system are assumed to be 30.000 € per installed MW. For the assumed 62 MW investment costs equal 1.860.000 €. As displayed in table 7, 1.528.000 have been assumed. This costs cover also HR, which must be TAG Gmbh personnel.

Table 8: Load scenario P2 – heat production only (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	62,00	[MW_{peak}]
FLH	1.528,00	[h/a]
Investment Costs	30.000,00	[€/MW]
O&M	2,40	[€/MWh]
FIT for heat	40,00	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	94.736,00	[MWh]
Long Run generation costs	4,34	[€/MWh]
O&M	227.366,40	[€/year]
O&M	4.547.328,00	[€/20 years]

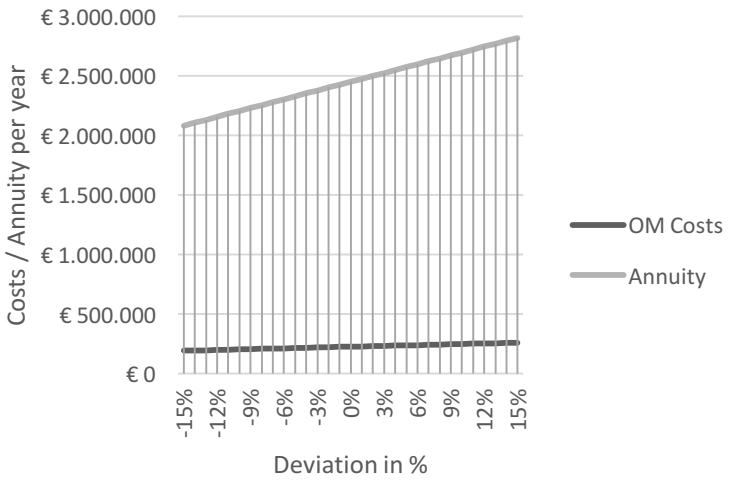

Figure 19: Sensitivity of the annuity in variation to the O&M costs per year according to P2 Scenario (Miljević, 2015)

Assumed sales prices for heat for this scenario (Figure 19) for the period from 2016-2036 is stable and equals 30,00 €/MWh. In comparison to scenario P1 the CF in P2 is lower. The OM expenditures are equal to the previous P1 Scenario. The third P3 scenario (Table 8) is based on a worst case assumption, which means declined prices by 75% until 2036. Even in that scenario the business case in definitely positive with an annuity of 2 Million €/ year.

Table 9: Load scenario P3 – heat production only (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	62,00	[MW_{peak}]
FLH	1.528,00	[h/a]
Investment Costs	30.000,00	[€/MW]
O&M	2,40	[€/MWh]
FIT for heat	45,00-10,80	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	94.736,00	[MWh]
Long Run generation costs	4,34	[€/MWh]
O&M	227.366,40	[€/year]
O&M	4.547.328,00	[€/20 years]

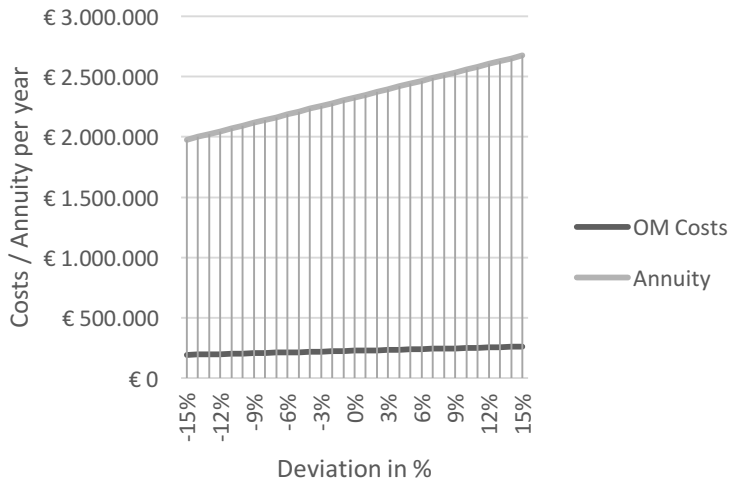

Figure 20: Sensitivity of the annuity in variation to the O&M costs per year according to P3 Scenario (Miljević, 2015)

The rated capacity for electricity generated (14$MW_{electric}$) is linked to very high operations costs as above described. According to E-Control the current electricity market price equals 31,5 €/MWh. It is expected that the price will be decline down to 28 €/MWh by 2016. (E-Control, 2015)

Table 10: Load scenario P1 – electricity production only (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	14,00	[MWpeak]
FLH	1.528,00	[h/a]
Investment Costs	0,00	[€/MW]
O&M	45,00	[€/MWh]
FIT (electrcity)	54,00	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	21.392,00	[MWh]
LRGC (Long Run generation costs)	54,35	[€/MWh]
O&M	962.640,00	[€/year]
O&M	19.252.800,00	[€/20 years]

The stated FIT of 54 €/MWh, as assumed for the scenario in figure 20, results in a positive annuity, which is very close to zero. Taking the E-Control predictions for 2016 into account the price difference between market price and necessary FIT is 24 €/MWh.

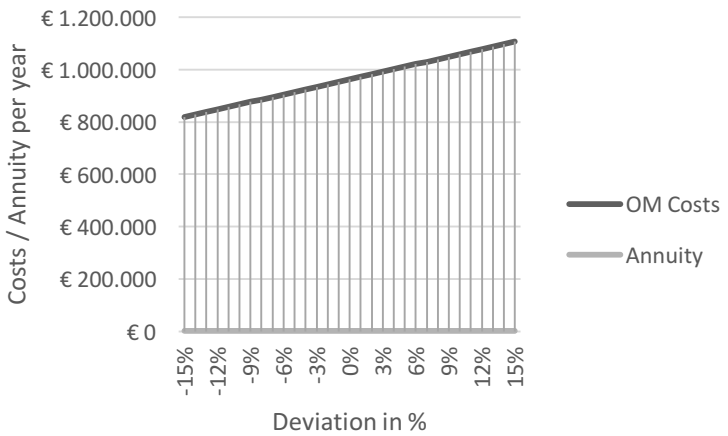

Figure 21: Sensitivity of the annuity in variation to the O&M costs per year according to P1 Scenario (Miljević, 2015)

Table 11: Load scenario P2 – electricity production only (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	14,00	[MWpeak]
FLH	1.528,00	[h/a]
Investment Costs	0,00	[€/MW]
O&M	45,00	[€/MWh]
FIT (electrcity)	31,50	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	21.392,00	[MWh]
LRGC (Long Run generation costs)	54,35	[€/MWh]
O&M	962.640,00	[€/year]
O&M	19.252.800,00	[€/20 years]

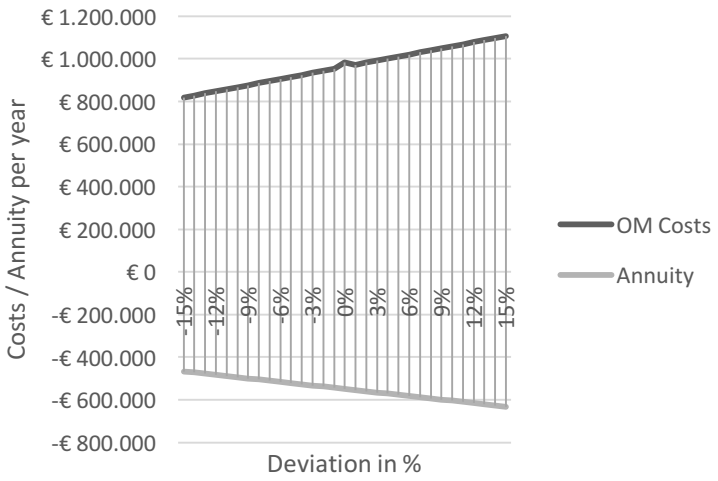

Figure 22: Sensitivity of the annuity in variation to the O&M costs per year according to P2 Scenario (Miljević, 2015)

A downscaling the market price of 31,50 €/MWh in 2016 by yearly 2% down to 22,10 €/MWh in 2036 clearly confirms that the WHRU, as it is operated currently is not operated profitable at all. To be exact, it has to be supposed that even OM costs cannot be covered. Considering the CHP application, OM costs per year increase even more. In order to cover gross margins a target FIT of 82 €/MWh has to be achieved. There are KPC funds available, though it is not clear if the CHP option is feasible.

Table 12: Load scenario P1 – CHP (Miljević, 2015)

Position	Value	Unit
Investment horizon	20,00	[years]
Discounted rate/cost of Capital	4,00	[%/year]
Rated peak capacity	25,10	[MWpeak]
FLH	1.528,00	[h/a]
Investment Costs	30.000,00	[€/MW]
O&M	54,60	[€/MWh]
FIT (heat+elect)	82,00	[€/MWh]
Escalation of O&M	2,00	[%/year]
Yearly heat production	38.352,80	[MWh]
LRGC (Long Run generation costs)	67,39	[€/MWh]
O&M	2.094.062,88	[€/year]
O&M	41.881.257,60	[€/20year]

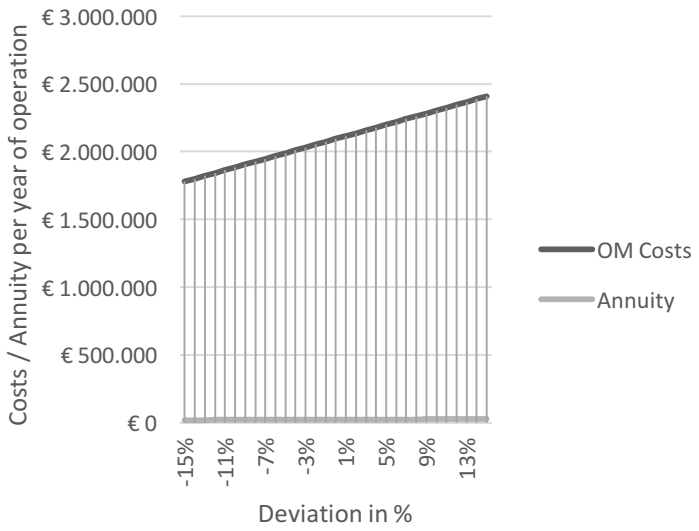

Figure 23: Sensitivity of the annuity in variation to the O&M costs per year according to P1 CHP (Miljević, 2015)

The result of the scenario analysis is depending on the OM costs escalation. A comparison of the data in table 8 and table 9 shows, that heat exchanger OM costs for the direct heat utilisation in the DHS are more or less 4 times lower. Addressing the planned operation of 20 years, this reduces the financing model by 14,7 Million €. Experts claim that a operation time of 30-50 years is realistic, if significantly high OM cost and repair works are considered in the calculations. (TAG Gmbh, 2014)

5.2 Risk assessment

In the below displayed chart, generated MWh per quarter are listed for the period in between 2014-2015. The blue line displays the average value for the total net output of generated electricity per quarter (=4 months) and equals 4028 MWh.

This diagram outlines, that the electricity consumption for the station itself is very low. Though, the security of supply argument should not be a reason to put the electricity generation in favour. In Austria, electricity became so cheap, that the WHRU could be applied on other CS with similar types of gas turbines. This option refers to countries where purchasing of electricity costs a lot and where pollution issues occurs.

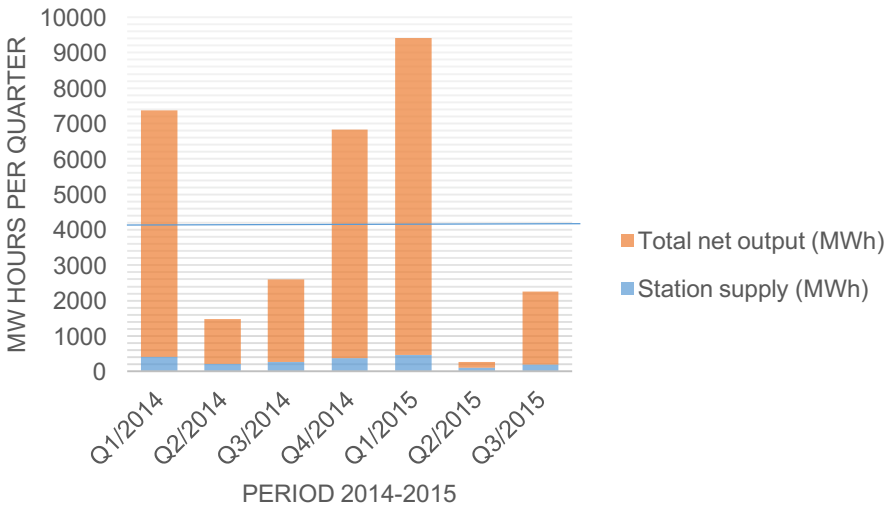

Figure 24: Generated $MWh_{electric}$ per quarter in from Q1/2014 until Q3/2015 (Miljević after TAG, 2015)

The risks analysis process detected internal and external risks for this project. External risks are based on on the supply side and on legal and political frameworks. With more than 6000 costumers the DH demand in the area of Graz is stable and future variations in demand are not recognisable. The DHS Graz is operated on 365 days per year and with a capacity of 380km DH grid the buffer capacity can compensate shocks in supply at full load operation easily. (Energie Graz GmbH & Co KG, s.a)

Gas pipeline operation is a proven business since over more than hundred years and undies very high requirements regarding safety operation. As above in 5.1. highlighted, TAG Gmbh booked capacities until 2022 (TAG, 2014) and according to experts the natural gas supply in Austria will be stable within the next 100 years.

External political and legal risks are based on national legal regulations. The Austrian Gas Act (GWG-2011), §108 (2) implies that the TSO are not allowed to directly or indirectly exercise control over an undertaking performing any of the functions of energy production. This also includes the generation of electricity.
(TAG Gmbh, 2015)

5.3 Waste heat for the district heating system in Graz

Recovered heat is utilised in various industrial and non-industrial applications. In areas where compressor stations along pipelines exist, waste heat can be utilised for example for / within

- DHS for heating purposes of individual and commercial buildings
- Warm water supply and space heating for schools and hospitals
- Warm water supply and space heating for airports
- Space heating and farming in greenhouses
- Heating supply for aqua farms
- Light manufacturing
- Paper production and printing
- Chemical and petrochemical industry
- TES

(IEA, 2015)

On long term perspectives waste heat utilisation can significantly help to lower down heating costs because waste heat application compensate heat plants, which are fired mostly with fossil fuels. In general, up to 30% of total heat demand can be covered by WHRU. Minister of Natural Resources Canada (2005).

A continuous waste heat supply for industrial and greenhouse farming can help to boost economic growth in remote areas because cheap heat could be directly sold to commercial customers. If the heat, such as in the example Weitendorf, cannot be supplied continuously, a TES could be used as a buffer in order to offer steady heat input on the costumer side. TES facilities can significantly help to balance necessary capacities within a DHS with overtaking a buffer functionality. Secondly, DSO can profit of being less dependent from fluctuating fuel prices. The Austrian DSO, EVN Wärme Gmbh, proofed successfully that operation of a 50.000 m^3 storage facility is operated successfully. One main advantage is that the DHS is filled with warm water out of the TES even when the connected power plant (460 $MW_{electric}$) is shut down. (Oberhammer and Prawits, 2012)

The so-called KEK2020 is climate preservation plan for 2020, implemented by the city of Graz. Beside the integration of solar energy into the local DHS, industrial waste heat is playing a major role in order to meet future demand and to increase the diversification of heat supply. By the same time, industrial waste heat utilisation can prevent the increase of CO, CO_2 and NO_x emissions locally. Further energy efficiency would be increased. (Umweltamt Stadt Graz, 2011b)

The city of Graz (Umweltamt Stadt Graz, 2011a) published a statement on the energy concept for the city of Graz in 2011. In this report, potential CHP heat sources for DH were Werndorf 1 (160 MW), Werndorf 2 (200 MW), Mellach (230 MW), GDK Mellach (250-400 MW). Current available sources for the DHS were stated with capacity of HKW Graz (250 MW), Gas turbine (250 MW) and HKW Graz Zusatzkessel (400 MW). In total 900$MW_{thermal}$ energy have been available for Graz.

This situation changed in 2014, because the mentioned capacities are not available anymore due to high costs of electricity generation and renewable and alternative energy sources were put in favour. According to Statistik Austria (2015a), in the city of Graz in Styria/ Austria live 270.000 inhabitants. Between 2014 and 2034 there will be increase of 59.000 persons, which means a rise of 22%. As a result in 2034 heat supply shall be guaranteed for 329.000 in the city of Graz. In 2014, Grazer Energieagentur GmbH 2014 presented planned capacities for 2020-2030. Correspondent to DH demands of the city of Graz as displayed in figure XY, the WHRU in Weitendorf with a capacity of 11-65$MW_{thermal}$ could play an essential role for future heat supply of Graz.

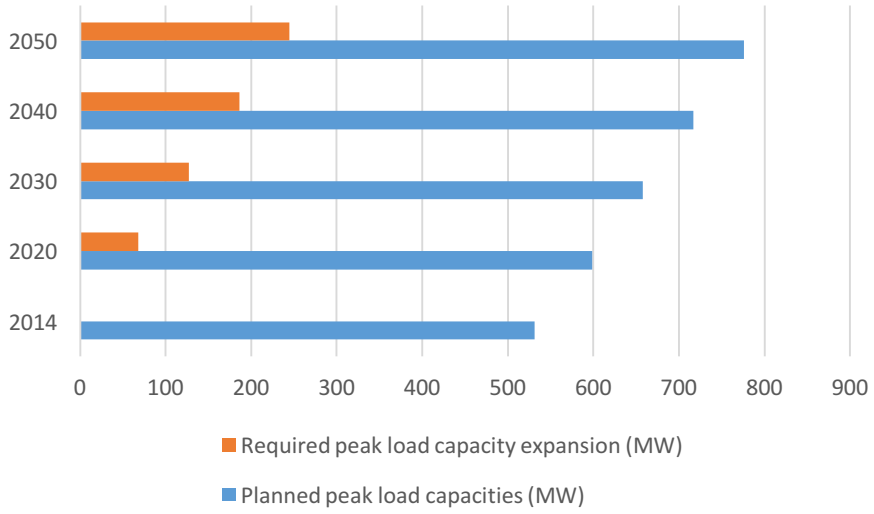

Figure 25: Peak load capacity assumption for DHS of Graz on cold winter days, 2014-2050 (Miljević after Grazer Energieagentur GmbH, 2014)

According to the calculation in the action plan from 2010 for 2025 of the community of Graz, the so-called "Kommunales Energiekonzept", an annual expansion of 20-30MW thermal energy is realistic if the DH connexion potential is going to be utilised. For the production of 15$MW_{thermal}$ an asset of 75 Million € was predicted. (Energie Steiermark, AG)

In fact, the construction of a WHRU at the CS Weitendorf in the community of Wildon should be possible from an environmental and legal point of view. In communities where air pollutants such as SO_2, NOx, CO, CO_2, PM10 occur more frequently measures such as the DH expansion have to be implemented. This should ensure a decrease of mentioned emission into the atmosphere locally. (Umweltamt Stadt Graz, 2011a).

Finally, through the project realisation up to 12,5 tCO_2e (peak load according to the heat scenario of 62MW) could be saved because the most feasible alternative are natural gas operated heat boilers (Kranzl et al., 2014).

5.4 Best practice

As a proof of feasibility, the WHRU in the CS Ruswil in Switzerland is analysed from a technical and economical point of view.

Already more than 15 years ago in 1999 the Swiss gas association claimed that WHR with off gas from gas turbines with temperatures above 450° Celsius can be operated economically (Verband der Schweizerischen Gasindustrie, 1999). Switzerland became forerunner in Europe and in the period between 2000 and 2002 the GE Nuovo Pignone PGT25 GT TKC and TKD were installed at the CS Ruswil. By that time the company Innovative Steam Technologies applied a OTSG for the very time in combination with a CS. This is ensured of one LP with 3,5bar which is used for hot water supply and a HP cycle with 30,9bar which is producing steam for the electricity generator. As below stated, the exhausted gas at full capacity is rated with 537,1°C, which equals with the condition in Weitendorf.

Table 13: Relevant parameters of the WHRU in CS Ruswil
(Miljević after Transitgas AG , 2015)

Technical parameters of the CS Ruswil	Unit
Gas turbine off gas at full load	62.66 kg/s, 537 °C
Off gas temperature to the ambient	110 °C
Capacity of the high pressure steam cycle	39 bar, 500 °C
Operation of the high pressure steam cycle	30 bar abs, 456 °C, 8.25 kg/s
Condenser capacity	-0.45 bar, 110 °C
Condenser in operation	0.1 bar abs
Electricity production at full load of the GT	7,06 MW
Capacity of the low pressure steam cycle	2.5 bar, 185 °C
Capacity of sanitary water production	24 kg/s, 95 °C

The water which is constantly fed (100 m^3/h) in into the forerun with 95 °C and comes back from the clients such as a close by hospital and greenhouse with 65 °C has a maximum peak load of 3 $MW_{thermal}$.

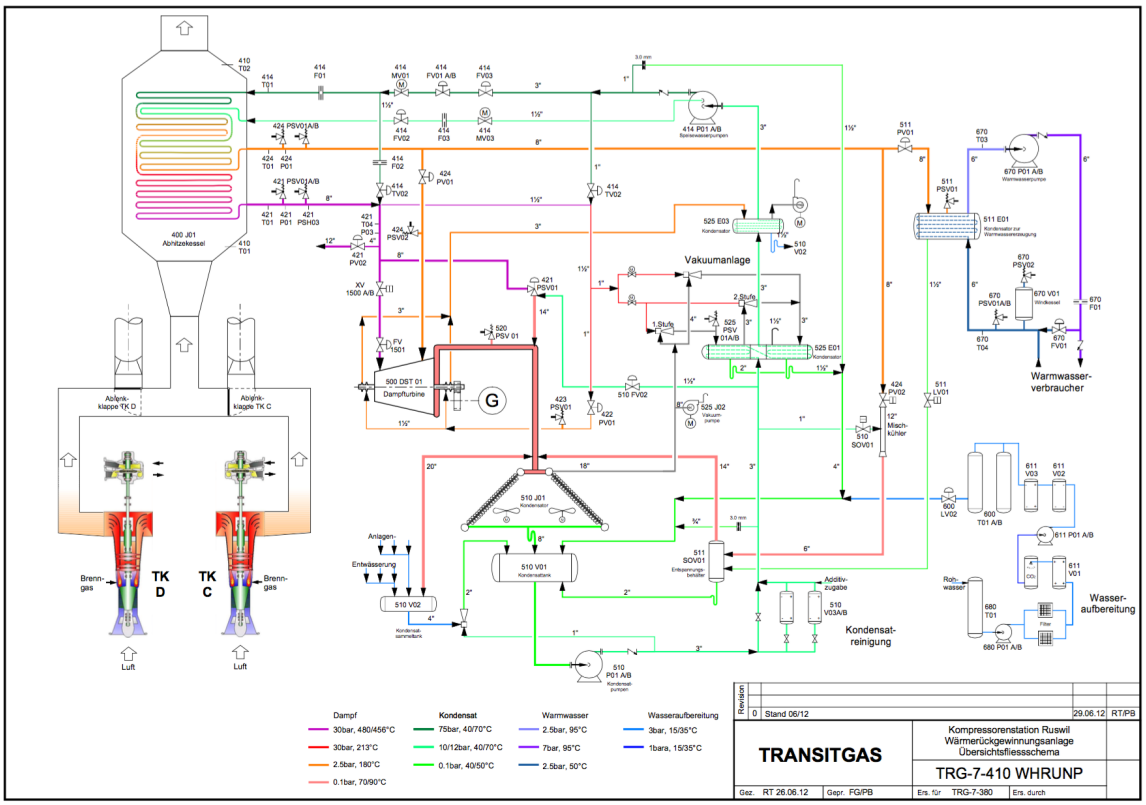

Figure 26: WHR plant scheme of the facility in Ruswil (Transitgas AG, 2015)

According to Transitgas AG, the operation and maintenance have been covered with stable heat sales and electricity generation. Until 2015 this was financial feasible because the electricity was subsidised by Swiss government. This changed with 2015 and after 13 years of operation the CS has to participate within the day-ahead electricity market. This means that nominated quantities must be delivered, and if nominations were wrong, penalties have to be paid to the grid operator. Concluding, heat sales only would guarantee higher sales due to a better efficiency and a stable operation would ensure green energy supply in the region. Alternative business cases of necessary technical changes within the facility, such as the instalment of a heat exchanger, shall be generally done on a very early stage of the project.

Through more proofed best practise such as Ruswil other TSO's could be pushed to invest more efforts in order to use their full grid capacities in the most efficient way. Lessons learned from the CS Weitendorf and CS Ruswil other TSO's such as the Austrian GCA Gmbh could use existing know how for current projects. Waste recovery units could be also applied at:

- the construction of a new CS in Rainbach (DN1200) at the WAG in between (Project BOG 2014/02) between Oberkappel and Baumgarten

- the construction of some of the 3 CS which are planned for the planned “BACI” pipeline, a bidirectional Austrian-Czech interconnexion (European Commission, 2015b)

Another European TSO, which is investigating in waste heat recovery technologies along CS is the Polish company GAZ - SYSTEM S.A. from Warsaw. Together with the Polish Institute of Thermal Technology, Silesian University of Technology, part load and full load scenarios were considered for WHRU operation in paper, which was recently published in the Energy conversion and management journal published by Elsevier B.V. In 2014, the paper on the same subject, submitted from Wojciech Kostowski, was nominated as the best paper at the SEE SDEWES Conference in Macedonia. (Kostowski, 2015)

If WHRUs are implemented on an early stage of the project development process, the added value for the pipeline operation can be considered in the investment calculation and legal requirements can be checked with National energy authorities. Definitely, it has to be considered as an alternative or RE source for energy generation. Moreover, HR could help to improve public awareness towards natural gas pipelines significantly. Legal support regarding unbundling issues at the project implementation stage is provided by the national authority body. On European level special interest group such as ENTSOG should work on constructive solutions for TSOs in order to make WHR possible from legal perspectives. On one hand ENTSOG is promoting CO_2 reductions because of WHR (Ruswil CS) in the annual report of 2014, but on the other hand TSOs are missing framework conditions for further developments.

6 Conclusions

The scientific outputs of this thesis are based on calculations and comparisons of utilisation scenarios of waste heat streams of the compressor station in Weitendorf /Austria. In fact, these very specific project conditions cannot be compared with other natural gas compressor stations.

Not considering legal frameworks, which forbid transmission system operators to produce energy, the scenarios consider power generation, combined heat and power generation, as well as heat production only. Before considering a certain project realisation, the current legal situation referring to the Third Gas Directive and Regulation 715 from the European Commission should change. Otherwise, it would not be possible to utilise the waste heat streams of the natural gas turbines.

As a general rule operation and maintenance (OM) costs, which include labour costs, of gas compressor stations and WHRU are very high. This applies also to heat and electricity production applications. Highly qualified and long experienced labour force is a key feature for safe and professional operation of compressor stations and WHRUs. In line with the heat production only scenarios, OM costs are considered as significantly low due to minor equipment and repair work costs. Additionally personnel costs are lower because already employed stuff at the compressor station would be in charge for this additional application.

Therefore, referring to results of the applied scenarios, only the heat supply to the district heating systems via a heat exchanger has to be considered as feasible from a financial point of view. Nevertheless, in order to guarantee the security of heat supply, an additional natural gas boiler has to be built and to be operated in order to compensate heat supply from the CS in case of not being in operation. This situation occurs quite often when the natural gas flow conditions within the pipeline have no necessity to operate the CS, which is connected to the WHRU. The current gas supply situation within the European Union could lead to a reduction of operating hours of the gas compressors along the TAG pipeline. This could definitely effect the feasibility of WHR in general.

The increased overall energy conversion efficiency and the indirect energy savings potentially support a reduction CO, CO_2 and NO_x emissions. An applied CHP solution, is made by considering electricity and heat supply. Focusing on the electricity production only, Saavedra et al. (2010) emphasise that a FIT of 65,81 €/ MWh is necessary for a profitable ORC WHRU operation. The results proofed that 54 €/ MWh are sufficient with the steam cycle based WHRU in Weitendorf.

Addressing the general potential in Austria, detailed feasibility studies for WHR for other CS could definitely help to quantify the technical potential of energy savings on an annual basis. State of the art technologies such as TES could help to promote a local utilisation because of fluctuating heat demand curves.

Further, from a global perspective the USA, Russia and Europe have the biggest potential for utilisation of WHR in compressor stations. The Power Siberia II pipeline project is considered as a project of high potential for WHR utilisation because of the neighbourhood of the cities of Tomsk and Novosibirsk in Russia.

Moreover, a lack of support from European interest groups was detected in line with so-called unbundling issues. Legal obstacles harm recent developments of WHR along natural gas compressor stations. There is hardly any communication strategy between European TSO on the WHR subject. Conferences or panels could definitely help to exchange valuable experience.

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Appendix

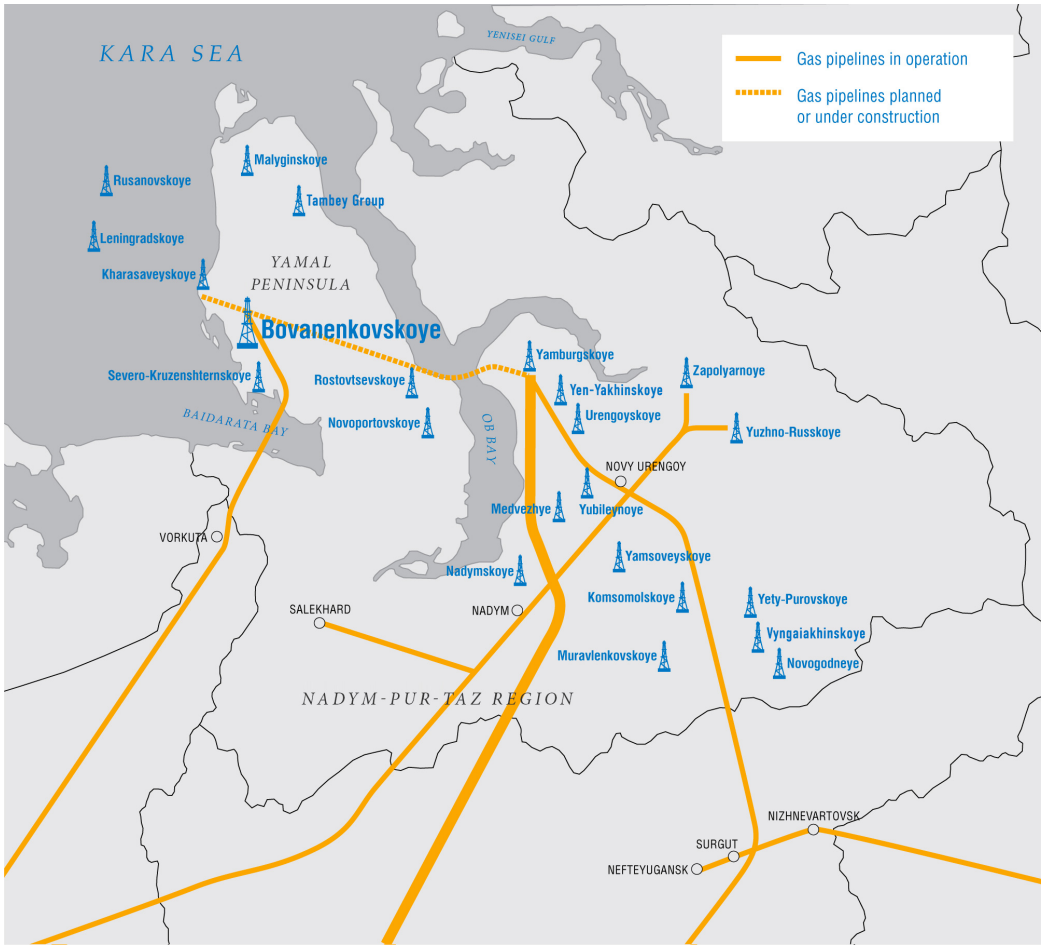


Figure: Overview on the Yamal gas fields, Nadym-Pur-Taz-region (Gazprom)

Table: Overview on Russian Gazprom CS

Name of the TSO	Number of CS
Gazprom Moscow	48
Gazprom Yugorsk	220
Gazprom Tomsk	10
Gazprom Saint Petersburg	32
Gazprom Ekaterinburg	18
Gazprom Uhta	54
Gazprom Ufa	17
Gazprom Saratov	37
Gazprom Total	**436**

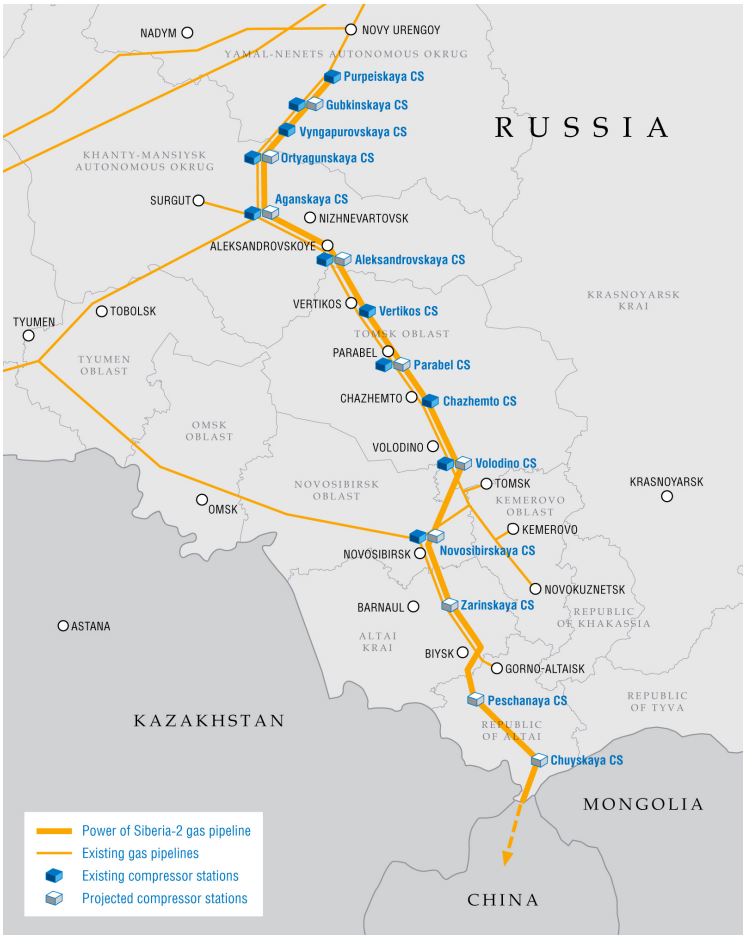


Figure: Power of Sibiria 2 pipeline project and planned CS

Figure: Natural gas pipelines which transport Russian quantities into the EU

Overview on the amount of CS per pipeline:

Soyuz pipeline:

Per 132km one CS, in total in UKR 1568,5km, total in UKR 12 CS

Yamal Evropa pipline

2000km, 14 CS in total, per 142km one CS

TAG pipeline, 380km 5 CS, per 76km one CS

Urengoy–Pomary–Uzhgorod (Bratsvo) pipeline

4500km, 42 compressor stations, per 107km one

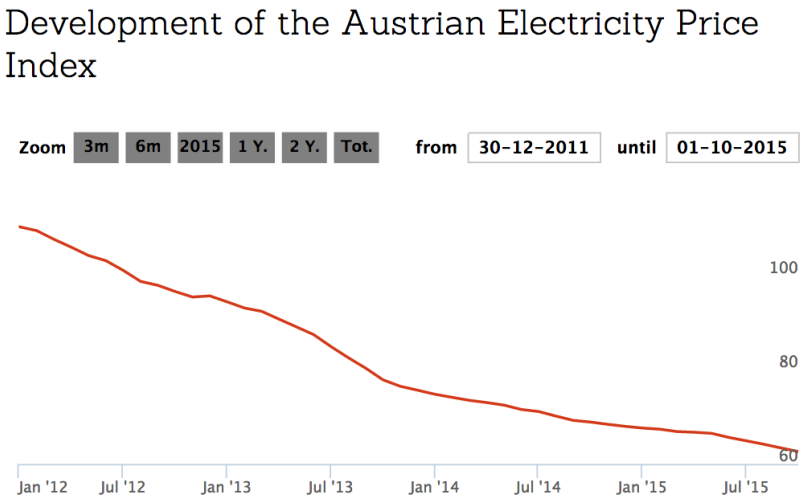
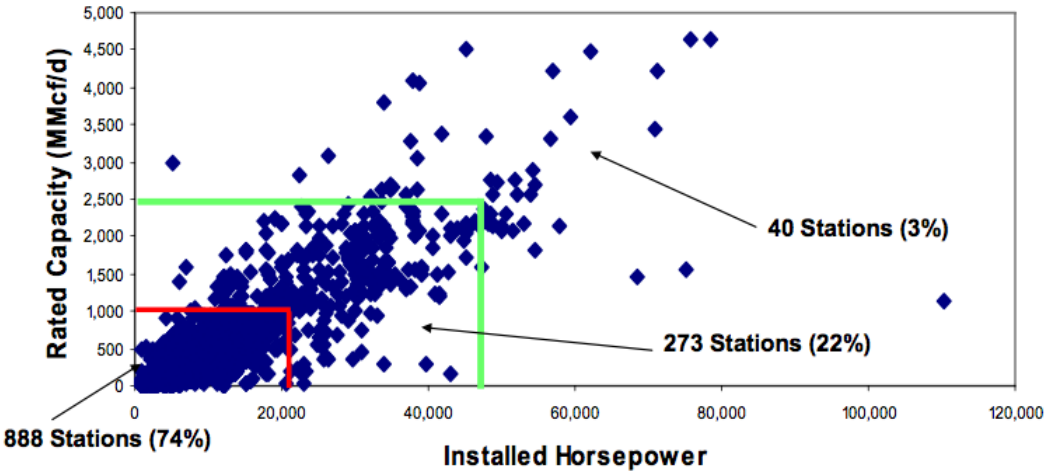


Figure: Development of Austrian electricity price index (AEA)

Trade movements 2014 as liquefied natural gas

Billion cubic metres	From																					
To	US*	Brazil*	Trinidad & Tobago	Peru	Norway	Other Europe*	Russian Federation	Oman	Qatar	United Arab Emirates	Yemen	Algeria	Angola	Egypt	Equatorial Guinea	Nigeria	Australia	Brunei	Indonesia	Malaysia	Papua New Guinea	South Korea*	Total imports
US	–	–	1.2	–	0.2	0.1	–	–	–	–	0.2	–	–	–	–	–	–	–	–	–	–	–	**1.7**
Canada	†	–	0.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.6**
Mexico	†	–	0.4	4.3	0.2	0.2	–	–	1.4	–	–	–	–	–	–	2.5	–	–	0.3	–	–	–	**9.3**
North America	†	–	2.2	4.3	0.3	0.3	–	–	1.4	–	0.2	–	–	–	–	2.5	–	–	0.3	–	–	–	**11.6**
Argentina	–	0.1	3.4	–	0.2	1.1	–	–	0.9	–	–	–	–	–	–	0.9	–	–	–	–	–	–	**6.5**
Brazil	0.1	–	1.9	–	1.1	1.7	–	–	0.6	–	–	0.1	0.1	–	0.5	1.9	–	–	–	–	–	–	**7.9**
Chile	–	–	3.7	–	–	–	–	–	0.1	–	–	–	–	–	0.1	–	–	–	–	–	–	–	**3.8**
Other S. & Cent. America	–	–	2.6	–	0.1	0.1	–	–	0.1	–	–	–	–	–	–	0.2	–	–	–	–	–	–	**3.0**
S. & Cent. America	0.1	0.1	11.5	–	1.3	2.9	–	–	1.7	–	–	0.1	0.1	–	0.5	3.0	–	–	–	–	–	–	**21.4**
Belgium	–	–	–	–	–	–	–	–	2.9	–	–	†	–	–	–	–	–	–	–	–	–	–	**2.9**
France	–	–	0.1	0.1	0.2	0.1	–	–	1.0	–	–	4.4	–	–	0.1	1.2	–	–	–	–	–	–	**7.1**
Italy	–	–	0.1	–	–	0.1	–	–	4.3	–	–	0.1	–	–	–	–	–	–	–	–	–	–	**4.5**
Spain	–	–	2.0	1.2	1.2	0.2	–	0.2	3.0	–	–	4.9	–	–	–	2.7	–	–	–	–	–	–	**15.5**
Turkey	–	–	0.1	–	0.3	0.2	–	–	1.1	–	–	4.1	–	–	–	1.5	–	–	–	–	–	–	**7.3**
United Kingdom	–	–	0.4	–	–	–	–	–	10.4	–	–	0.5	–	–	–	†	–	–	–	–	–	–	**11.3**
Other Europe & Eurasia	–	–	0.5	–	1.0	0.2	–	–	0.9	–	–	0.6	–	–	–	0.4	–	–	–	–	–	–	**3.5**
Europe and Eurasia	–	–	3.1	1.3	2.7	0.8	–	0.2	23.6	–	–	14.6	–	–	0.1	5.8	–	–	–	–	–	–	**52.1**
Middle East	–	–	1.2	–	–	0.4	–	0.1	2.3	–	0.4	–	–	–	–	0.7	0.1	–	–	0.3	–	–	**5.4**
China	–	–	0.2	–	0.2	0.3	0.2	0.2	9.2	–	1.4	0.3	0.2	0.2	1.0	0.6	5.2	0.2	3.5	4.1	0.4	0.1	**27.1**
India	–	–	0.1	–	0.1	0.3	–	0.1	16.2	0.1	0.6	0.2	–	–	–	1.2	–	–	–	0.1	–	0.1	**18.9**
Japan	0.3	–	0.2	0.1	0.5	1.3	11.5	4.7	21.9	7.7	1.3	1.0	0.1	0.1	1.2	6.5	25.0	5.9	7.8	20.3	3.0	–	**120.6**
Malaysia	–	–	–	–	0.1	0.2	–	–	0.1	–	0.4	0.5	–	0.1	–	0.4	0.1	0.4	–	0.2	–	–	**2.4**
Singapore	–	–	0.4	–	–	0.2	–	–	–	–	–	–	–	–	1.9	–	–	–	0.1	–	–	–	**2.6**
South Korea	–	–	0.2	–	0.1	1.5	2.6	5.1	17.7	0.1	4.2	0.5	0.1	0.1	0.1	4.4	1.2	1.0	7.1	5.1	–	–	**51.1**
Taiwan	–	–	0.1	–	–	0.1	0.1	0.2	8.0	–	0.3	0.1	–	–	0.2	0.2	0.1	0.8	2.8	3.9	1.3	–	**18.1**
Thailand	–	–	0.1	–	–	–	0.1	0.1	1.3	–	0.1	–	–	–	–	0.2	–	–	–	0.1	–	–	**1.9**
Asia Pacific	0.3	–	1.2	0.1	0.9	3.8	14.5	10.4	74.4	8.0	8.3	2.6	0.4	0.4	4.4	13.3	31.6	8.3	21.4	33.7	4.7	0.2	**242.7**
Total exports	**0.4**	**0.1**	**19.3**	**5.7**	**5.3**	**8.2**	**14.5**	**10.6**	**103.4**	**8.0**	**8.9**	**17.3**	**0.5**	**0.4**	**5.0**	**25.3**	**31.6**	**8.3**	**21.7**	**33.9**	**4.7**	**0.2**	**333.3**

Figure: Overview on LNG trade movements in 2014 (BP, 2015)



MMcf/d = million cubic feet per day.
Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division Gas, Gas Transportation Information System

Figure: Relationship of Installed Horsepower and Throughput Rating (Capacity) in the US gas grid

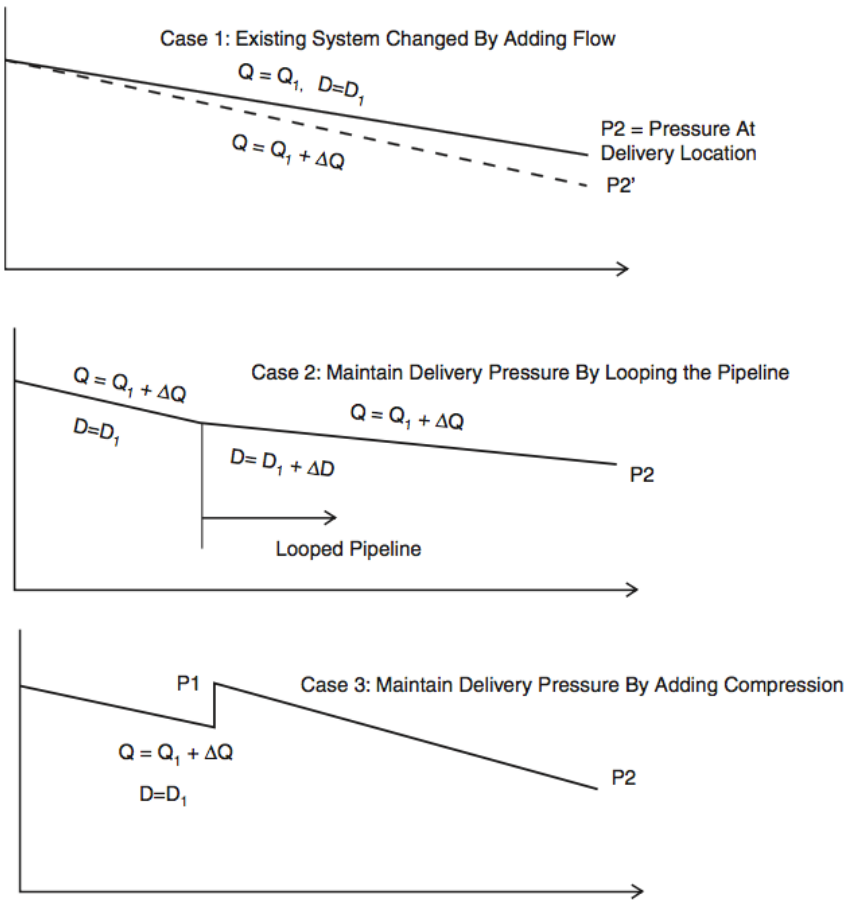


Figure: Pipeline looping systems vs. Compression systems

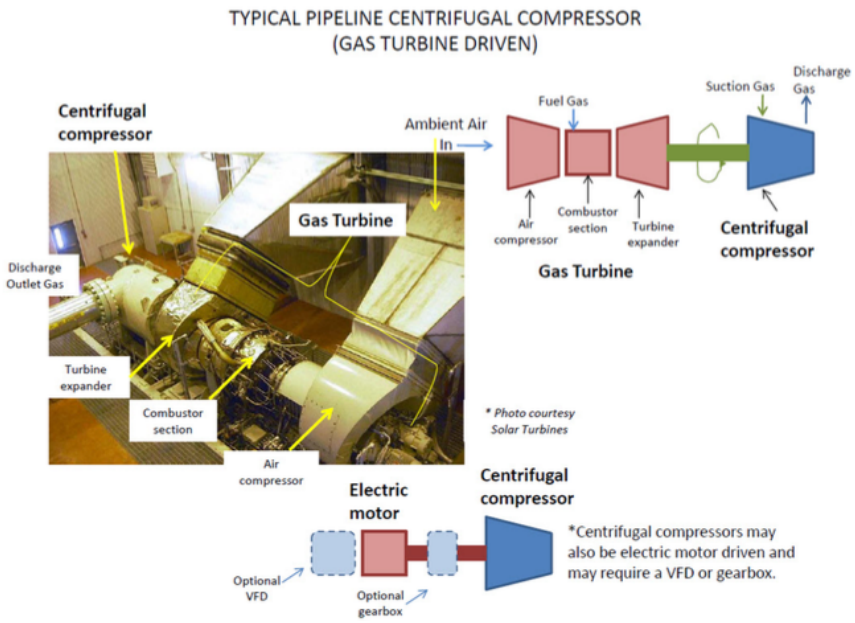


Figure: Centrifugal compressor driven by gas turbines

Table: NO_2 Emissions of the city of Graz (2010-2014)

Tabelle 18: NO_x-Jahresmittelwerte an den Grazer Messstellen 2010 bis 2014, angegeben in $\mu g NO_2/m^3$..

	Graz Don Bosco	Graz Mitte Gries	Graz Nord	Graz Ost	Graz Süd	Graz West
1995			57,0			76,0
1996			51,3			72,2
1997			56,6			66,4
1998			54,5			69,7
1999			55,4			66,2
2000	221,5		53,5			68,7
2001	198,9		50,1			64,3
2002	158,0		53,7			69,8
2003	174,8		56,0			77,6
2004	161,4		51,4		97,8	67,1
2005	159,9		48,7		99,8	70,7
2006	167,0		55,4	81,9	104,1	76,4
2007	144,5		48,0	72,3	92,5	65,5
2008	147,6		47,5	69,9	88,6	66,5
2009	133,1		43,1	64,4	75,9	57,9
2010	135,7		43,4	66,9	80,8	61,2
2011	143,0	69,3	47,0	70,0	86,8	63,6
2012	132,5	61,3	40,3	66,9	77,8	52,8
2013	128,0	57,2	40,6	62,4	68,9	54,6
2014	118,7	57,1	36,5	66,4	66,9	51,6