University of Natural Resources and Life Sciences

Master thesis

ECONOMIC ANALYSES OF A HIGH TEMPERATURE HEAT PUMP IN AN AUSTRIAN PULP AND PAPER COMPANY

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Abstract

The potential of high temperature heat pumps (HTHP) for industrial applications has received increasing attention in recent years. Not only from an economic point of view, but also for CO_2 emissions reduction through efficiency increase, there is some interest to promote this technology and to use it for process heat supply in industry. Based on a specific drying process in an Austrian paper company, the present work examines how a HTHP with a coefficient of performance (COP) of 4 performs economically besides an on-site operating gas turbine and steam combined cycle (GT-CC). The economic comparison is executed on the basis of spot market prices and industrial gas prices over a period from 2004-2017. The results show that HTHP can have cost advantage over GT-CC, depending on the energy price constellation. In recent years the HTHP was the preferable heat supply system, since CoH stayed significantly below CoH for GT-CC. Earlier from 2004 to 2011, CoH for both heat supply systems where closer together in 2005, 2006 and 2008 the GT-CC was the preferable heat supply system. The reason is that gas prices were rather low in combination with rather high electricity prices. Due to volatile character of spot market prices, CoH can vary so that the preferable heat supply system can change hourly. In a coupled driving mode these price fluctuations can be used by the operator to switch between the heat supply modes. This would allow him to circumvent cost peaks for electricity and obtain savings compared to a single supply mode. At hourly peaks, heat production costs can rise up to 222 EUR/MWh for HTHP and 113 EUR/MWh for GT-CC. In both cases, CoH for the alternative heat supply system are very low. Thereby, in some price constellations the operator can also make profits by producing electricity in times of high prices or operate the HTHP when electricity price drops below 0 EUR/MWh.
What is also considered within this work are investment costs for a newly installed HTHP. The acquisition costs are chosen between 250 EUR/MWh and 1 000 EUR/MWh and additionally include interest, service and salary costs. Due to a high the share of production in a coupled driving mode, which can be up to 90% over a whole year, payback times below 6 years are possible.
The work is complemented by a comparison of the CO_2-footprint for both heat supply systems. The results show, that carbon dioxide savings are possible, if the CO_2 emission footprint of the used electricity for operating the HTHP is less than 480 kg/MWh. With the present electricity mix in Austria, savings up to 59 000 tons of CO_2 would be possible in the considered paper company. This is a strong motivation to intensify R&D in the technology of HTHP in order to achieve carbon dioxide reduction in industry and reach EU climate action targets.

Kurzfassung

Das Potential von Hochtemperaturwärmepumpen (HTWP) für industrielle Anwendungen rückte in den letzten Jahren immer mehr in den Fokus von Forschung und Entwicklung. Nicht nur aus wirtschaftlicher Sicht, sondern auch vor dem Hintergrund möglicher CO_2-Emissionsreduktion durch den Einsatz in industriellen Prozessen bietet diese Technologie ein vielversprechendes Potenzial.
In der vorliegenden Arbeit wird die wirtschaftliche Performance einer HTWP mit einem COP von 4 genauer unter die Lupe genommen. Dabei wird sie in einem Trocknungsprozess eines österreichischen Papierherstellers mit einer vor Ort betriebenen GuD-Anlage (Gas- und Dampfkraftwerk), welche dort derzeit als Wärmebereitstellungssystem dient, verglichen. Der Vergleich erfolgt auf Basis von vergangenen Spotmarktpreisen für elektrische Energie und Industriegaspreisen über einen Zeitraum von 2004 bis 2017. Die Ergebnisse zeigen, dass eine HTWP in Abhängigkeit der Energiepreiskonstellation, Kostenvorteile gegenüber einer GuD-Anlage haben kann. In den letzten Jahren waren die WGK (Wärmegestehungskosten) für HTWP deutlich unter jenen der GuD-Anlage. In den Jahren zuvor von 2004 bis 2011 zeigte sich ein anderes Bild. Die WGK beider Systeme lagen näher beieinander wodurch 2005, 2006 und 2008 die GuD-Anlage das zu bevorzugende Wärmebereitstellungssystem gewesen wäre. Der Grund liegt darin, dass die Gaspreise niedrig und die Strompreise hoch waren. Aufgrund des volatilen Preises für elektrischen Strom am Spotmarkt können die WGK sehr stark variieren. Unter der Annahme eines gekoppelten Betriebes beider Systeme am Produktionsstandort, könnten diese Preisfluktuationen vom Betreiber genutzt werden, indem dieser zwischen den verschieden Systemen wählen kann, je nach Kosten der Wärmebereitstellung. Daurch wäre es möglich, Peak-Preise zu umgehen und dabei Einsparungen im Vergleich zum Betrieb mit nur einem System zu erzielen. WGK können je nach Energiepreissituation auf 222 EUR/MWh für HTWP und 113 EUR/MWh für GuD ansteigen. In beiden Fällen sind die WGK der jeweils anderen Technologie sehr niedrig, wodurch phasenweise auch Gewinne erzielt werden könnten indem der Betreiber den selbst produzierten Strom aus der GuD-Anlage ins öffentliche Netz einspeist, bzw. bei Strompreisen unter 0 EUR/MWh die HTWP betreibt.
Um Investitionskosten in die wirtschaftliche Betrachtung mit einzubeziehen wurde weiters eine Amortisationsrechnung durchgeführt, bei der von Anschaffungskosten zwischen 250 EUR/MWh und 1000 EUR/MWh ausgegangen wurde. Im gekoppelten Betrieb und einen Produktionsanteil von 90% in den letzten Jahren wären sehr hohe Ersparnisse möglich gewesen, wodurch siche eine Investition in unter 6 Jahren amortisiert hätte.
Die Arbeit wird ergänzt durch einen Vergleich des CO_2-Fußabdruckes beider Wärmebereitstellungssysteme. Die Ergebnisse zeigen, dass Emissionseinsparungen möglich sind, solange der Fußabdruck des verwendeten Stroms zum Betrieb der HTWP niedriger ist als 480 kg/MWh. Mit dem derzeitigen Strommix in Österreich wären bei dem betrachteten Papierhersteller Einsparungen von 59 000 Tonnen CO_2 möglich. In Anbetracht der EU-Klimaziele, die CO_2-Einsparung vor allem im industriellen Sektor einfordern, liefern HTWP ein vielversprechendes Potenzial um dies zu erreichen. Die weitere Intensivierung von Forschung und Entwicklung in diesem Bereich ist deshalb zu empfehlen.

Danksagung

Ich habe dieses Thema für meine Masterarbeit gewählt, weil ich davon überzeugt bin, dass Hochtemperaturwärmepumpen im industriellen Einsatz positiv zur Lösung der Klimawandelproblematik beitragen können. Dabei ist die wirtschaftliche Betrachtung eines solchen Systems für potenzielle Investoren ein wichtiger Faktor. Diese Arbeit soll herausheben, was es zu beachten gilt, damit ein wirtschaftlicher Betrieb auf industrieller Ebene garantiert ist. Ich hoffe, dass ich hiermit einen Beitrag dazu leisten kann, die Weiterentwicklung dieser Technologie voranzutreiben.
Die Fertigstellung dieser Arbeit beschließt mein Studium an der Universität für Bodenkultur, daher ist es mir wichtig an dieser Stelle allen zu danken, ohne deren Unterstützung dies nicht möglich gewesen wäre.

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Nomenclature

Abbreviations	
GT	gas turbine
ST	steam turbine
GT-CC	gas turbine and steam combined cycle
HTHP	high temperature heat pump
HP	heat pump
COP	coefficient of performance
HSPF	heating seasonal performance factor
R718	Water
R-1234Ze(Z)	cis-1,3,3,3,-Tetrafluorprop-1-en
R-600	Butane
R-245fa	1,1,3,3,3-Pentafluorpropane
R-1233zd(E)	Tetrafluorpropen
R-1336mzz(Z)	1,1,1,4,4,4,-Hexafluorbut-2-en
R-245ca	1,1,2,2,3-Pentafluorpropane
SES36	Pentafluorbutane
R-365mfc	1,1,1,3,3-Pentafluorbutane
R-601	Pentane
R-113	1,1,2,-Trichlor-1,2,2,-trifluorethane
R-717	Ammonia
R-718	Water

Formula symbols		
CoH	costs of heat	[EUR/MWh]
$\mathrm{CoH}_{\mathrm{GT\text{-}CC}}$	costs of heat for the GT-CC process	[EUR/MWh]
$\mathrm{CoH}_{\mathrm{ST}}$	costs of heat ST-mode	[EUR/MWh]
$\mathrm{CoH}_{\mathrm{HTHP}}$	costs of heat for the HTHP process	[EUR/MWh]
$\mathrm{CoH}_{\mathrm{f,HTHP}}$	fixed costs of heat for HTHP	[EUR/MWh]
$\mathrm{CoH}_{\mathrm{v,HTHP}}$	(variable) consumption related costs of heat for HTHP	[EUR/MWh]
C_{el}	electricity price	[EUR/MWh]
C_{gas}	gas price	[EUR/MWh]
$C_{Capital}$	capital costs	[EUR/a]
C_{Salary}	salary costs	[EUR/a]
$C_{Service}$	service costs	[EUR/a]
I	specific investment costs	[EUR/kWh]
I_0	investment costs	[EUR]
R_w	residual value	[EUR]
C_D	depreciation costs	[EUR]
C_I	interest costs	[EUR]
$\mathrm{C}_{\mathrm{HTHP}}$	absolute costs of heat for HTHP	[EUR]
$\mathrm{C}_{\mathrm{GT\text{-}CC}}$	absolute costs of heat for GT-CC	[EUR]
C_{ST}	absolute costs of heat for ST-mode	[EUR]

n	life expectancy	[a]
i	interst rate	[%]
p	pressure	[bar]
T	temperature	[°C]
T_0	environmental temperature	[K]
T_1	outlet temperature	[K]
$\triangle$T	temperature difference	[K]
S	entropy	[J/K]
$\triangle$S	change of entropy	[J/K]
W	work	[J]
P_{fuel}	energy input	[MW]
P_{GT}	nominal power of the GT	[MW]
P_{ST}	nominal power of the ST	[MW]
P_{el}	electric power for the HP	[MW]
$P_{el,GT}$	electric power generation of the GT	[MW]
$P_{el,ST}$	electric power generation of the ST	[MW]
$P_{el,GT-CC}$	electricity production of the GT-CC over a year	[MWh/a]
$P_{el,HTHP}$	electricity demand of the HTHP over a year	[MWh/a]
$T_{ST,HP}$	steam temperature at high pressure level of the ST	[°C]
$p_{ST,HP}$	steam pressure at high pressure level of the ST	[bar]
$T_{ST,LP}$	steam temperature at low pressure level of the ST	[°C]
$p_{ST,LP}$	steam pressure at low pressure level of the ST	[bar]
T_{WHB}	steam temperature in the waste heat boiler	[°C]
p_{WHB}	steam pressure in the waste heat boiler	[bar]
$\dot{V}_{in,gas}$	average gas flow rate per hour	[Nm^3/h]
$V_{in,gas}$	yearly gas flow rate	[Nm^3/a]
$\dot{Q}_1$	heat output of a HP	[MW]
$\dot{Q}_{process}$	process heat	[MW]
Q_{source}	source heat per paper ton	[kWh/t]
$T_{exh,hood}$	temperature of the hood exhaust	[°C]
$\varepsilon_{c,HP}$	ideal Carnot factor	[-]
ε_{real}	real Carnot factor	[-]
ζ	exergetic efficiency of a HP-process	[-]
η_c	efficiency factor for thermal engines	[-]
η_{GT}	single cycle efficiency	[-]
$\eta_{el,GT-CC}$	electric efficiency of GT-CC	[-]
$\eta_{heat,GT-CC}$	heating efficiency of GT-CC	[-]
η_{total}	total electric efficiency	[-]

Contents

1 Introduction **9**
1.1 State of knowledge 10
1.2 Research questions 11

2 Thermodynamic and technical explanations to HTHP **13**
2.1 Basic working scheme of a heat pump 13
2.2 The Carnot cycle and performance factor 13
2.3 Definition of HTHP 17
2.4 State of the art of HTHP 17
2.4.1 Compressors for HTHP 17
2.4.2 Refrigerants for HTHP 20
2.4.3 HTHP R&D projects 22

3 Possible field of application of HTHP in industrial processes **25**
3.1 Heat demand in industrial processes 25
3.2 Pulp and paper industry 28
3.2.1 Energy portfolio in pulp and paper process 30
3.2.2 Waste heat in paper making processes 32
3.2.3 Manufacturers data 33

4 Methodological approach and assumptions for economical comparison **35**
4.1 Initial data for modeling and simulation 35
4.1.1 IPSEpro 36
4.1.2 MATLAB 37
4.2 GT-CC model and assumptions 37
4.3 HTHP model and assumptions 40
4.4 Assumptions for dynamic simulation of the GT-CC 41
4.4.1 MATLAB-IPSEpro interface 42
4.4.2 Calculation of energy input for economic comparison 42
4.5 Economic calculation method for heat supply 43
4.5.1 Levelized costs of heat production 43
4.5.2 Investment costs and operational costs for HTHP 44
4.5.3 Absolute costs of heat 45
4.6 Resulting set up of heat supply and process requirements 45
4.7 Calculation of carbon dioxide footprint for HTHP and GT-CC 47

5 Results **49**
5.1 Dynamic simulation of the GT-CC-process 49
5.2 Required energy input of HTHP and GT-CC for covering heat demand 51
5.3 Operational costs for GT-CC and HTHP 52
5.4 Production share between GT-CC and HTHP 54

5.5 Cost report, payback time and savings 56
5.6 Comparison of carbon dioxide footprint of HTHP and GT-CC 59

6 Discussion and Conclusion 61
6.1 Discussion 61
6.2 Conclusion 63

7 Appendix 73

1 Introduction

"Heat pumps have become increasingly important in the world as a technology to improve energy efficiency and reduce CO_2 emissions. In particular industrial heat pumps [...] offer various opportunities to all types of manufacturing processes and operations [...]. They can significantly reduce fossil fuel consumption and greenhouse gas emissions in drying, washing, evaporation and distillation processes in a variety of applications [...]. The introduction of heat pumps with operating temperature below 100° C is in many cases considered to be easy, however, higher temperature application still require additional R&D activities for the development of high temperature heat pumps, integration of heat pumps into industrial processes and development of high temperature, environmentally sound refrigerants", IEA (2014) [1].

EU climate action targets are ambitious and pose a major challenge to the European economy. Industry, as one of the main contributors to carbon dioxide emissions, requires increased energy efficiency and conversion to energy from renewable sources, in order to be not constricted in its economic interests. By looking more closely at Austria's energetic end-use portfolio in Figure 1, the supply of process heat is identified as the main driver for energy consumption. Final energy use was 1 121 PJ in 2016, with an industrial share of about 31%. According to Rieberer et al. 2015 [2] about 23% can be further distinguished as process heat demand.

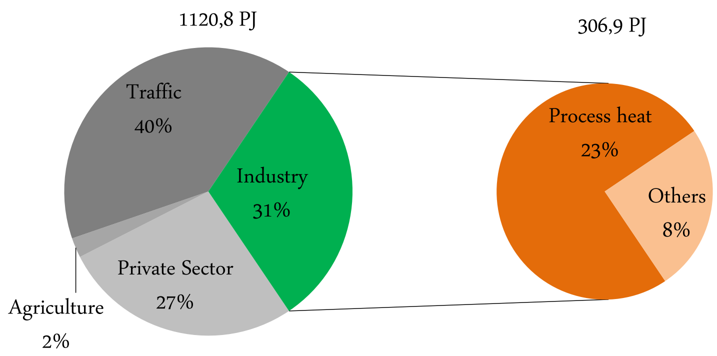


Figure 1: Industrial share of energetic end use in Austria and estimated process heat demand in 2016, according to Rieberer et al. and Bundesministerium für Wissenschaft Forschung und Wirtschaft [2, 3]

A very energy-intensive industry in Austria is the pulp and paper industry. There are currently 24 mills in operation, which consumed around 72 PJ of fuel and electricity in 2016. In 2014, CO_2 emissions in the Austrian paper industry amounted to 5.3 million tons, of which 1.5 million tons derived from burning fossil fuels [4]. Compared to total CO_2 emissions in Austria of 64.3 million tons, the share lays around 6%, so that a closer look into the branch is of interest. Energy consumption is a major cost driver in paper production and accounts for approximately 15% of the total costs [5]. A common energetic concept of most pulp and paper industries is the operation of demand-oriented combined heat and power plants (CHP) to generate heat for production processes on the one hand and to supply electricity on the other hand. The necessary fuel is provided in the form of fossil fuels (40.2%) and biogenic fuels (59.8%). According to Posch et al. 2015 [5], the use of natural gas had been increased and was around 32% in 2016. Electricity and gas prices are thus an important factor for operators. With falling electricity prices since the liberalization of the Austrian electricity market, CHP plants have suffered a loss of profitability in recent years. In order to remain competitive, it is of interest for operators to discover alternative ways for generating heat [5–7]. High temperature heat pumps (HTHP) are a potential heat supply technology for this purpose and experience intensified R&D in recent years. The potential temperature range for HTHP increased under laboratory conditions to 160°C, which would allow a supply of various industrial processes. Several branches operate processes in a temperature range between 100 and 200°C, such as cooling, distilling, drying and others. Besides increasing effort in developing this promising technology, for operators it is of interest to shed light on the possible economical output of a HTHP in such a process. Paper production for example affords a high amount of energy for drying process, which is supplied by heat at a temperature range of about 140°C [8–10].
The prevailing master thesis presupposes the idea of a technologically mature HTHP, which is applied in a drying process of a paper mill. The assumption is that the HTHP works on-site as an additional heat supply system next to a predominant GT-CC-system. In such a case, the operator would have the opportunity to generate heat in times of low electricity prices with the HTHP and to switch to GT-CC in times of high electricity prices and low gas prices. This could mean that heat can periodically be produced CO_2-free under the circumstance of green electricity that drives the HTHP. This scenario can have a few advantages. On the one hand, the operator can yield savings, due to a switch from the one energy cost factor to another. On the other hand he could reduce his $\mathrm{CO_2}$ foot print. The aim of this work is, therefore, to prove the economic viability of such an on-site HTHP and to discover defining parameters that influence the economic behaviour. In order to obtain meaningful results, data from an existing GT-CC system (gas turbine and steam turbine combined cycle power plant), which come from an Austrian paper mill, are used. In combination with real energy price data, a cost comparison of GT-CC and HTHP was carried out for the period from 2004 to 2017.

1.1 State of knowledge

The present work is inspired and based on investigations from Wolf 2017 [11], who addresses the optimization and application potential of HTHP in industrial processes.

Besides significant optimization potential for HTHP-systems, she points out that HTHP can operate economically in industrial processes, compared to conventional heat supply systems. In her work, she considers the paper drying process as a potential field of application in which the HTHP can have a cost advantage, compared to GT-CC. She states *"[...] that for the recent European situation of natural gas and electricity prices, the operating costs optimum is clearly on the heat-pump side. Based on consumption related costs, the HTHP system (working with a COP of 4) is the most economic heat production technology, if a gas price of 25 EUR/MWh [...] is asumed and the elctricity price is lower than 45 EUR/MWh$_{el}$"*, Wolf 2017 [11].
The findings of her work serve as basis for the present work in which a more detailed investigation is conducted on this subject.

1.2 Research questions

The outcome of this thesis should deliver insight into the economic competitiveness of HTHP against GT-CC, respectively the potential savings for the operator in a combined operating mode of both heat supply systems in a paper drying process. The economic comparison is first made by investigating operational CoH for both heat supply systems. They are used to calculate the potential production share over a certain year for HTHP in order to calculate savings. Further, additional investment costs allow statements about payback times for a newly installed HTHP. The investigation is made under consideration of volatile parameters, which could have an impact on the delivered results. In the framework of this thesis, the following research questions are answered:

1. How does a HTHP-system perform economically compared to a GT-CC-system in an industrial process?
2. How high are operational costs for for HTHP and GT-CC?
3. How high are costs for heat supply for HTHP under consideration of investment costs?
4. Which share of production would have been reachable for a HTHP-system compared to GT-CC-system in an heat supply process during the time range from 2004 until 2017?
5. Which pay-back times would have been achievable for a HTHP at different intvestment costs from 2004 until 2017?
6. Which parameters influence the economic feasabliity of HTHP and GT-CC?

The present work begins with explanations to thermodynamic and technical foundations to HTHP in Chapter 2. A summary of the present state of the art is presented in which ongoing R&D projects and barriers for application are introduced. In a further step, the possible field of industrial applications is presented in Chapter 3. Thereby, the pulp and paper industry in Austria is investigated more in detail. After these theoretic explanations the chosen methodological approach for performing the economical calculation is presented in Chapter 4. In Chapter 5 and Chapter 6 the calculated results are shown and further interpreted and discussed before they are concluded.

2 Thermodynamic and technical explanations to HTHP

2.1 Basic working scheme of a heat pump

Originally, the technical concept of a heat pump (HP) derives from refrigeration technique. A refrigerator is designed for gaining refrigeration capacity at lower temperature, by simultaneously emitting heat at higher temperature. A heat pump though, is meant to supply heat capacity at higher temperature, while absorbing heat at lower temperature. Still, both systems are technically refrigeration machines.
What is crucial for HP to function properly is a suitable heat reservoir from which heat can be absorbed. The absorbing medium is a refrigerant, which evaporates at the prevailing source temperature. An evaporator serves as technical component in order to increase surface of the refrigerant and takes care of efficient heat absorption. In the ongoing cyclic process the gaseous refrigerant derives an increase of pressure by a mechanically driven compressor, which causes a complementary increase of temperature. The higher temperature can be released in the condenser in order to serve as a certain process e.g. space heating, water heating, drying processes, process heating in pulp and paper industry, etc. This causes the refrigerant to condense and after pressure release at the expansion valve, the cyclic process starts again with evaporation of the refrigerant. An examplified process of a heat pump with its four main technical ingredients is shown in Figure 2. Briefly summarzied one can say that the refrigerent runs through a cyclic process by constantly changing its state of aggregation due to varying temperature and pressure conditions. By doing so, it functions as transport medium of heat energy [12–14].

2.2 The Carnot cycle and performance factor

The theoretical foundation of a HP can be explained by a left-handed Carnot cycle, which depicts an ideal thermodynamic process of a refrigerant machine. The left-handed Carnot cycle evolved from the right-handed Carnot cycle, which is an idealistic idea of a working heat engine. The difference between those two theoretical models is that the right handed Carnot cycle describes the ideal way of converting heat to mechanical work, whereas the left-handed cycle stands for the opposite function, which is converting mechanical work into heat. For doing so, an ideal gas is assumed that functions as working medium. It runs through a cyclic process by transporting heat from one place to another. Thereby its state of aggregation stays gaseous, since ideal gases do not condense. A useful method to depict this thermodynamic processes of the working gas is the T,S-Diagram in Figure 3.

Temperature T is shown on the y-axis and entropy S on the x-axis. These two quantities of state describe the thermodynamic condition of the ideal gas in the process.

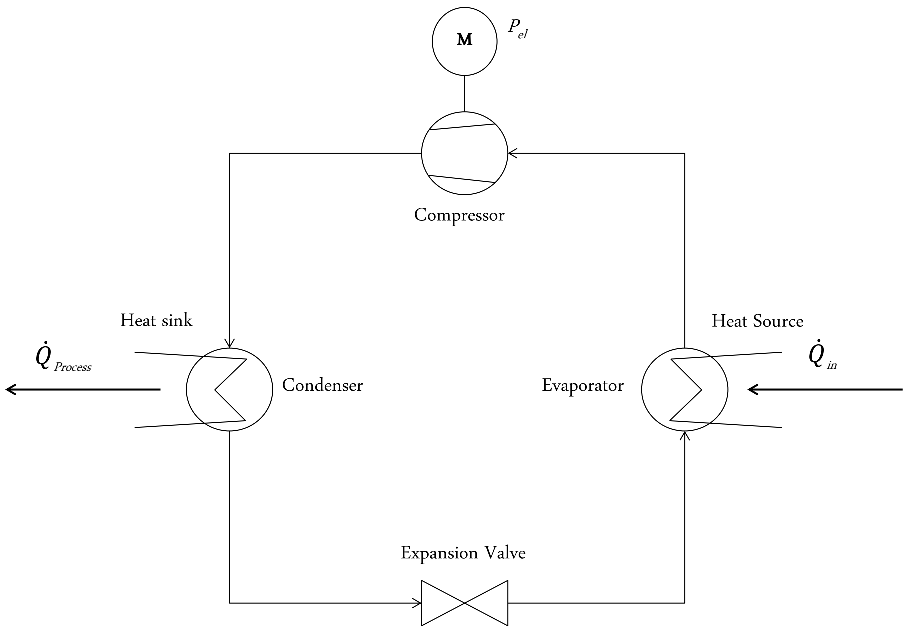


Figure 2: Simplified HP process with its four main ingredients: evaporator, compressor, condensor and expansion valve [14]

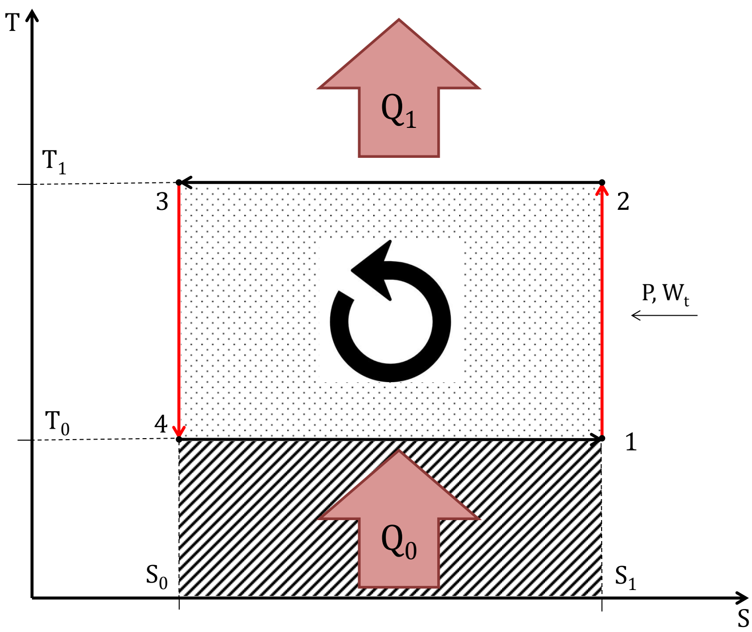


Figure 3: T,s-Diagram of an left-handed ideal carnot process [13].

Whereas entropy changes by absorbing or emitting heat, temperature increases by adding external work. The consecutive change causes two isentropic and two isothermal shifts of the ideal gas. In detail, the process works as follows:

- Isothermal evaporation (4,1): the gas derives heat Q_0 on the source side. Entropy rises at constant temperature: S_0 - S_1, T_1=const.
- Isentropic compression (1,2): due to the compression, temperature rises at constant entropy: T_0 - T_1, S_1=const.
- Isothermal condensation (2,3): the gas condensates on the sink side. Entropy drops at constant temperature: S_1 - S_0, T_1=const. Heat Q_1 is released.
- Isentropic expansion (3,4): due to the expansion of the gas, temperature drops at constant entropy: T_1 - T_0, S_0=const.

Following Reisner 2013 [13] the lift of temperature multiplied with the change of entropy equals work W (Eq. (1)) and represents energetic effort that goes into the cycle. The output is represented by Q_1 and stands for the produced heat. It can be defined by the the sum of absorbed heat Q_0 plus afforded work W, deriving from a compressor (Eq. (2)). Accordingly, Equation (3) is a more detailed breakdown, which describes the refrigerant process by the two parameters S and T. Q_1 can therefore be seen equal to the product of $\triangle$S and T_1.

$$W = \triangle S * (T_1 - T_0) \tag{1}$$

$$Q_1 = Q_0 + W \tag{2}$$

$$\triangle S * T_1 = \triangle S * T_0 + \triangle S * (T_1 - T_0) \tag{3}$$

In ideal thermal engines, the factor of efficiency is described by η_c and is defined by the two temperature values T_1 and T_0 (Eq. (4)).

$$\eta_c = \frac{T_1 - T_0}{T_1} \tag{4}$$

In an ideal refrigerant machine though, the factor of efficiency is described by the Carnot factor $\varepsilon_{c,HP}$, which is the reciprocal to η_c. It is defined by sink temperature T_1 divided by the difference of sink and source temperature T_0 (Eq. (5)). The performance of a real HP-process is calculated by the ratio of the heat output $\dot{Q}_1$ and electric power P_{el} as in Equation (6) described. A common used parameter, which describes the efficiency of a HP is the COP (coefficient of performance), which is equal to ε_{real}.

$$\varepsilon_{c,HP} = \frac{1}{\eta_c} = \frac{T_1}{T_1 - T_0} \tag{5}$$

$$\varepsilon_{real} = \frac{\dot{Q}_1}{P_{el}} = COP \tag{6}$$

The ratio of $\varepsilon_{c,HP}$ and ε_{real} defines the exergetic efficiency ζ of the HP-process (Eq. (7). In practice, technical losses limit the exergetic efficiency to approximately 60%

$$\zeta = \frac{\varepsilon_{real}}{\varepsilon_{c,HP}} \tag{7}$$

A comparison of real and ideal performance factors is shown in a graphical account by Figure 4. The ideal Carnot factor of performance is represented by the dashed line and the real performance factor is shown by the continuous line. The ambient temperature T_0 is chosen with 295.15 K. It is visible that a higher temperature lift results in a lower efficiency factor.

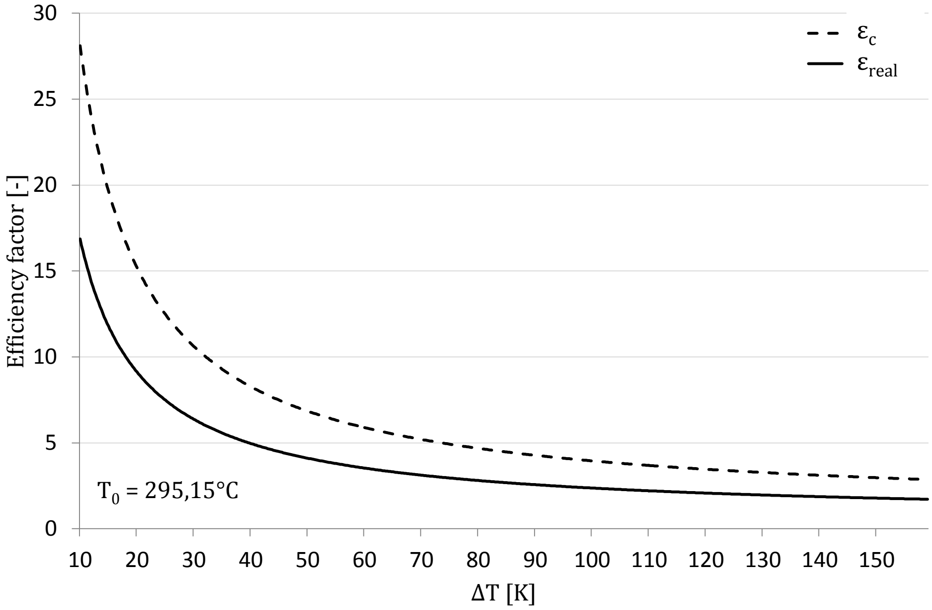


Figure 4: Ideal Carnot factor ($\varepsilon_{c,HP}$) of an ideal Carnot cycle and realistic efficiency factor (ε_{real}) of a heat pump cycle depending on the difference between T_1 and T_0, for a heat source temperature T_0=295.15 K

A high COP stands for a high level of efficiency and is therefore an important factor for operators. For example a COP of five would mean, that the added power multiplied with five is the result of delivered heat capacity $\dot{Q}_{process}$. It is important to understand, that the COP is just a snapshot for exactly defined conditions. Over a period of time, these conditions may change like for example $\triangle$T, which could be caused by a change of the temperature of the waste heat stream or the temperature condition on the sink side. A factor, which takes this changes into account is the "heating seasonal performance factor" (HSPF). For determining the HSPF, the energy consumption over the year represents the basis for calculation and is therefore a even more meaningful factor to operators (Eq. (8)).

$$HSPF = \frac{\int \dot{Q}_{process} * dt}{\int P_{in} * dt} \tag{8}$$

2.3 Definition of HTHP

The definition of "High Temperature Heat Pump" is neither explicitely determined in literature nor it is by producers, like Lambauer 2008 [15] explains. A literature overview concerning HTHP from Arpagaus 2017 [10] summarises several explanations concerning the definition of HTHP. He points out that there is no common sense about the lowest temperature limit for HTHP. Data reach from 60°C up to 100°C. Heat pumps which are used for industrial heat supply, are also named "Industrial Heat Pumps", as Rieberer 2015 [2] points out. Very often, industrial processes require heat in a temperature range above 80°C or 90°C, which means that HTHP and industrial heat pumps can be used synonymously. France established an explicit definition for heat pumps and distinguishes along temperature ranges. HP supplying temperatures from 40°C to 80°C are called "High Temperature Heat Pumps" and for 100°C - 140°C the term "Very High Temperature Heat Pumps" applies. Nevertheless, there is no common definition for HTHP in general, which means that for the framework of this thesis the term HTHP will stand for HP which are capable of producing heat above 100°C.

2.4 State of the art of HTHP

Generally, mechanically driven HTHP based on the vapor compression cycle work according to the same technical and thermodynamic principles as conventional HP. Higher temperatures and higher capacity requirements, however, require much more technical effort and complexity. While materials must withstand higher temperatures and be durable at the same time, the efficiency should be as high as possible for them to operate cost-effectively. In order to meet these challenges, research and development has intensified in recent years as awareness of the potential scope of HTHP in the industrial sector has become more prominent. The symbiosis between compressor and refrigerant plays a major role in the HTHP process. The following summary presents firstly the major tasks to fulfill of those two technical components and secondly the present state of art concerning high temperature applications (sections Section 2.4.1 and Section 2.4.2). In a further step, ongoing *R&D* projects are introduced to give an overview and outlook about the technical possibilities of prevailing and future technology (section Section 2.4.3). The illustrations take technical and market-related problems and barriers into account which overcome [9, 10, 16].

2.4.1 Compressors for HTHP

One can distinguish different types of HP, which differ in their constructional design. The following categorization in figure Figure 5 according to Cube et al. (1997) can be made.

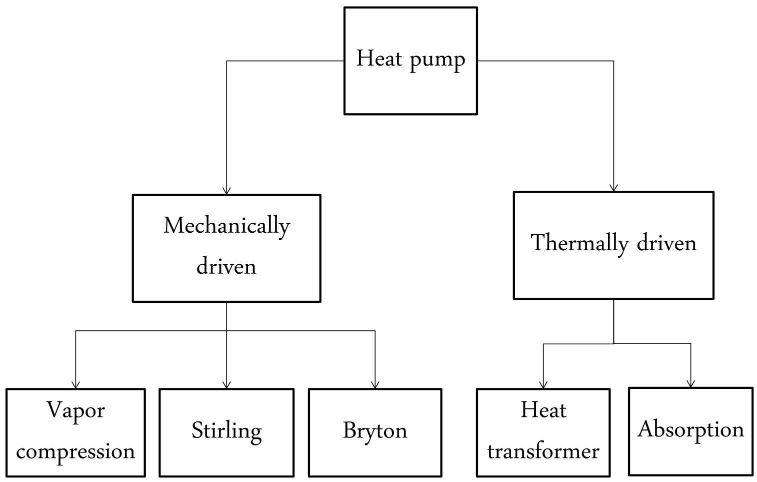


Figure 5: Classification of Heat Pumps by their different driving force [17]

In this thesis, thermally driven HP are not in the matter of concern, since the mechanical HP-technology is more sophisticated. The HTHP in concern of this thesis is a vapor compression HP and is also the most advanced and applied HP-technology world wide [17]. The commonly used compressors for HTHP are driven by electric energy. Their efficiency is essential for the HP to operate economically. Further characteristics such as temperature limits, longevity and low noise emissions do also determine the quality of a compressor. What a compressor basically does from molecular point of few is to suck in the refrigerant gas and compress the same amount of molecules into smaller space. This causes temperature and pressure of the gas to rise. There are different ways in which this can be accomplished which is why there exist several types of mechanical vapor compressors that follow a different style of compressing the refrigerant gas. The four main types are:

- Reciprocating piston compressor
  The piston compressor works according to the principle of positive displacement by repressing gas in a cyclic movement. It is a very robust and service-friendly compressor, and is universally applicable. One can distinguish this construction further into open systems, hermetic systems and semi-hermetic systems.

- Scroll compressor
  A scroll compressor works with two spirals, a static and a mobile one of which the latter moves in an eccentric way. This movement causes the space between both helices, which is filled with refrigerant gas, to decrease constantly. The gas is thereby moved towards the higher pressurized side of the compressor.

- Rotary screw compressor
  In a compact construction design, two interlocked screws are arranged in a way that the space between both decreases by rotation. These compressors can be constructed in semi-hermetic or open form and can be used for larger capacity ranges.

- Turbo compressor
  This construction design works with a reverse turbine that accelerates the gaseous molecules to high speed and transfer it into a bigger cross section, what causes the pressure to increase. They have the advantage to be very compact and work very efficiently and silently.

For high temperature and high performance applications, rotary screw compressors and turbo compressors can be found more frequently. There are still very few compressors with high power and temperature levels in operation. Table 1 is a collection of compressors for industrial applications, manufactured by different companies. The actual benchmark for highest temperature is 165°C, accomplished by the SGH 165, a product of the japanese company Kobelco. HTHP with high amount of heating capacity can be found in district heating processes. Russia, Sweden and Norway operate HTHP with heating capacities up to 100 MW which can supply around 100°C sink temperature. [9, 10, 13, 18].

Table 1: Collection of the presently implemented compressors for high temperature use and high performance level [10, 18].

Compressor	$\mathbf{T}_{supply}$ °C	$\dot{Q}_{supply}$ [MW]	**Producer**
Double rotary scew	165	0.07-0.66	Kobelco
Double rotary scew	120	0.070 - 0.37	Kobelco
Reciprocating	120	0.25 - 2.5	Hybrid Energy
Rotary screw	120	0.065 - 0.09	Mayekawa
Reciprocating, Rotary Screw	110	0.045 - 2.2	Dürr Thermea
-	90	14	Norway
-	80	27	Sweden
-	100	100	Russia

The COP values of the presently installed applications vary from 2.4 up to 5.8 at a temperature lift from 40K to 95K. The compression is accomplished in different ways. Most of the HTHP are designed in single stage mode, some are constructed in a two stage compression style. What can also be found are several parallel compressors in order to heighten the capacity range. For reaching a higher COP some further technical devices are used:

- **Recuperator** Before the refrigerant gas reaches the compressor, an integrated internal recuperator takes care of overheating the gas so condensation is prevented. This could cause technical problems in the compressor.

- **Sub cooler** A sub cooler is a technical feature for the purpose of heightening the COP. It takes care of cooling down the refrigerant under evaporating temperature before it is expanded through the expansion valve. Therefore, a higher percentage of liquid refrigerant is recaptured and efficiency of the HTHP rises.

2.4.2 Refrigerants for HTHP

The basic requirement of a refrigerant is to evaporate at prevailing source temperature level and condensate at required sink temperature level by transforming a big amount of heat capacity within the cyclic process of the HP. In case of a HTHP, the refrigerant evaporates and condenses at higher temperatures and withstands higher temperature lifts. Beside these main issues, further standards concerning safety and environmental compatibility need to be satisfied. Reisner 2013 [13] distinguishes between four properties, which are relevant for refrigerants:

- Thermodynamic properties
  High critical temperature T_{crit} and high critical pressure p_{crit} in order to have a gap between operating conditions and critical point of a refrigerant.

- Chemical properties
  The refrigerant must not decompose while operating under extreme conditions. Further, compatibleness with other chemical substances like lubricants inside the HP processes needs to be secured.

- Physiological properties
  In this concern, refrigerants need to fulfil criteria concerning toxicity and flammability, to guaranty safety for people who are handling them. Refrigerants can be classified into six different safety groups. A1 would stand for the safest refrigerant, while B3 would include the unsafest refrigerants. The letters A and B stand for low respectively higher toxicity. The numbers 1 to 3 indicate the flammability. 1 would imply low flammability whereas 3 would imply high flammability (Table 2).

Table 2: Classification of refrigernats into six safety groups

	toxicity	
	low	high
no flame propagation	A I	B I
lower flammability	A II	B II
higher flammability	A III	B III

- Ecological properties
  Ecological impacts should be as little as possible when it comes to leakage in a refrigerant machine. There are several factors like for example Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) which lay focus on contemplating ecological concerns. A GWP of 2 for example would mean that green house gas potential of the refrigerant is two times higher compared to CO_2. The new regulation about green hous gases (F-Gas-Verordnung) determines that after 2022 newly installed HP are only allowed to be driven with refrigerants that have GWP below 150 [19].

- Volumetric heating capacity (VHC)
  The VHC [kJ/m^3] describes the heat output per sucked volume of vaporized refrigerant in the compressor. The higher the VHC is, the smaller the size of

the compressor needed. Smaller VHC require therefore bigger compressors that need more power and have a higher loss of heat. This has impact on the COP. Typical VHC in HP-technology are in a range between 3 000 and 6 000 kJ/m^3 [10, 13].

These criteria are crucial for refrigerants to be fulfilled, especially in HTHP, where mostly a high amount of refrigerant fluid is afforded. Intensified R&D developed new refrigerants especially for high temperature use. Table 3 is a collection of developed refrigerants which either are already in use or tested in various R&D projects. What is also included are refrigerants that only partly fulfil the given criteria. Some of them are restricted for usage by law or due to other criterias. The collection comprises thermodynamic, chemical, physiological and ecological properties of the refrigerants.

Table 3: Potential refrigerants for high temperature use.

Refrigerant	**T_{crit}** [°C]	**P_{crit}**	**GWP**	**T$_{evap}$** 2 [°C]	**Safety group**
R-1234ze(Z) 1	150	35.3	<1	9.8	A2
R-600	152	38.0	20	-0.5	A3
R-245fa	154	36.5	1 030	15.1	B1
R-1233zd(E) 1	166	36.0	1	18.0	A1
R-1336mzz(Z) 1	171	29.0	2	33.4	A1
R-245ca	174	39.3	693	25.1	-
SES36	178	28.5	3 126	35.6	A2
R-365mfc	187	32.7	825	41.3	A2
R-601	197	34.0	20	36.1	A3
R-113	214	33.9	4 800	47.6	A1
R-717	132	113.3	0	-33.3	B2
R-718	374	220.6	0	100	A1

1 Applicable of the Refrigerants for use in HTHP systems,
according to Arpagaus 2017 [10] .
2 T$_{evap}$ at a pressure of 1.013 bar

Following highlighted and further described refrigerants are the most promising refrigerants for HTHP applications. Other refrigerants listed in table Table 3 are not applicable either due to a worse GWP, bad safety classification or because of other specific reasons which are not considered here. Organic refrigerants such as R-600 or R-600a are restricted for applying them in HTHP, due to bad safety properties [10]. **R-1234ze(Z)** is a quite new refrigerant with promising properties for HTHP-systems and a GWP below 1, although there is less information about its availability yet. Critical temperature and pressure lie at 150.1°C and 35.3 bar, which allows to be driven at high temperature but in the sub-critical range.

R-1233zd(E) has its critical temperature and pressure at 165.5°C and 35.7 bar. It is classified as A1 refrigerant with a GWP of 1 and therefore brings a good basis for high temperature applications. There are still a few aspects, which are to be thought of. One for example is that its steam pressure is below the steam pressure of air at 20°C, what could cause infiltration of air into the HTHP-circle.

R1336mzz(Z) is also a rather new refrigerant available on the market. It has critical temperature and pressure at 171.3°C and 29 bar at a GWP of below 2 and good safety properties. Experimental results show that a super heating is affordable due to a re-entrant saturation line in the log(p)-h-diagram.

R-718 (Water) has a rather high boiling temperature (100°C), which affords the system to be below atmospheric pressure. Critical temperature and pressure lay at 373.9°C and 220.6 bar. Water has the advantage to be nontoxic, nonflammable and its thermodynamic properties are suitable for HTHP-use. For enabling high temperatures such as 150°C, a rather low pressure of 5 bar is enough. What is problematic though is that water has a quite low vapor density, which causes low VHC. Also, water is highly superheated at compressor outlet, due to the shape of the condensation line. This property causes for HTHP to be built in a multistage compression system with intercooling [20]. Water was selected as refrigerant for the model of a HTHP (Chapter 4).

The number of HTHP operating in the industrial field still are very few and temperature range is rarely above 120°C as Table 1 introduces. There are not only technical barriers to overcome, as Sections 2.4.1 and 2.4.2 summarize, also market barriers are to be considered. Less experience and a lack of suppliers in this particular branch cause possible investors to face a not assessable risk, which hinders investment. Furthermore, prices of fossil energy determine the demand for alternative technology. Since they were rather low in the last years, the driving force was too weak to give this technology a break through. As far as compressors and refrigerants are concerned, the market increases, although there are still technical issues to overcome. Further development for HTHP is needed to be able for creating market-ready products [10].

2.4.3 HTHP R&D projects

The state of the art in R&D is more sophisticated and shows that higher temperatures are reachable. The actual benchmark for maximum temperature lays around 160°C, which is reached by two HTHP. The first one is a research project from Helminger et al. 2016 [8], who worked with a reciprocating compressor and R1336mzzz-Z as refrigerant. They were able to reach 160°C under laboratory conditions. The same constellation of compressor and refrigerant is used by the firm Viking Heat Engines, a manufacturer from Norway. They advertise a HTHP with a temperature range of 160°C with "a good COP", Viking Heat Engines (2018). The prevailing maximum heat capacity range is stated with 200kW. Their goal is to provide market-ready HTHP solutions in MW-range until 2019 [21]. ECOP is an Austrian start-up company that focuses on development and production of rotational HP for industrial use. They choose a different way for compressing the refrigerant gas, by using a centrifugal field. In difference to conventional HP-cycles, this single-stage cycle is designed in a way that the refrigerant stays in gaseous condition through out the whole cycle. This causes a higher possible COP, and high reachable temperatures up to 150°C [22, 23]. The Energy research Centre of the Netherlands (ECN) presently coordinates a project

(STEPS), in which HTHP-technology for industrial use is developed. Their aim is to utilize geothermal heat or waste heat for generating steam up to 200°C. Per email contact, they informed to use a two-stage compression heat pump and deliver heat up to a steam pressure of 6 bar. They see their developing technology to be applied in chemical industry, refining, paper and food industry [24].
A collection of recent and ongoing R&D projects as HTHP-providers is collected in Table 4. Technical components such as compressor and refrigerant are taken into consideration.

Table 4: HTHP collection of producers and R&D projects.

Institution	**Compressor**	**Refrigerant**	**T**max °C]	$\dot{Q}_{supply}$ [MW]	**Year**
STEPS, ESN Netherlands	-	-	120-200	-	since 2016
Austrian Institute of Technology [8]	R	R1336mzzz-Z	160	0.012	2016
Viking Heat Engines [21]	R	R1336mzzz-Z	160	0.05-0.2	2016
ECOP, Austria	RC	-	150	0.7	2016
PACO, University Lyon [10]	DS	H_2O	145	0.3	2014
Institut für Kältetechnik (ILK), Dresden	R	LG6	140	0.012	2016
Alter ECO	DS	ECO3	140	0.15-0.4	2012
Austrian Institut of Technology, Ochsner	RS	ÖKO1	130	0.25-0.4	2016

R = Reciprocating compressor
RC = Rotary compressor
RS = Rotary screw compressor
DS = Double screw compressor

Summarizing, HTHP for industrial applications experience increasing progress. Although the HTHP market is rarely supplied with products for high capacity applications yet, R&D delivers promising results for the future. In the next step, the industrial field of application is investigated and possible processes for HTHP-supply are highlighted.

3 Possible field of application of HTHP in industrial processes

After introducing the technology of HTHP above in Chapter 2, this chapter takes a closer look into the industry in order to highlight the possible field of application for HTHP. What is important for HTHP in general is that afforded process temperatures are reachable with prevailing technology and that an appropriate amount of waste heat is available.
First, general heat demand in the D-A-CH industry (Germany, Austria and Switzerland) is introduced, then possible processes which could be appropriate for HTHP-use are highlighted. Since this master thesis attends especially the pulp and paper industry, the completing section of this chapter sheds light on this particular branch. A closer look into the manufacturing of pulp and paper briefly introduces particular process steps and presents an energetic production portfolio in general and in further consequence of the Austrian pulp and paper branch.

3.1 Heat demand in industrial processes

Industrial heat demand has a significant share in the final energy demand. In order to get a picture of the dimensions about the energy amount that is used for heating purposes, following numbers about the D-A-CH-industry are alleged:

- In Switzerland the industrial heat demand in 2011 was about 87 PJ, which were 53% of its final industrial energy consumption.
- The final industrial energy consumption in Germany accounted 2 576 PJ in 2015, of which 1 917 PJ went into heat supply. In other words, heat supply has a share of 74% of the final industrial energy consumption in Germany.
- Austrias industry claimed 336 PJ final energy consumption in 2013. The rate for process heating is around 74%, which equals a heat demand of around 250 PJ (22%), domestic heating excluded [2, 10, 25–27].

What is not distinguishable in this numbers is the temperature range in which the heat is demanded. Beside residual and warm water heating, a big amount of heat is afforded to supply particular processes, which require different temperatures. A typical classification is:

- low temperature range: lower than 100°C
- mid temperature range: 100 - 400°C
- high temperature range: higher than 400°C

High temperature levels for example are required for glass- and steel-making, whereas the mid temperature level includes for example cooking, drying, or distilling processes, that occur in various branches. The lower temperature range is mainly covered by domestic heating. In Figure 6 this temperature classification is quantified by their share of total heat deamand in Austria according to IEA (2014). Almost the half of the heat demand occurs in temperature ranges higher than 400°C. Heat demand from 100°C to 400°C requires 27% and heat demand under 100°C rates 26% [1, 2].

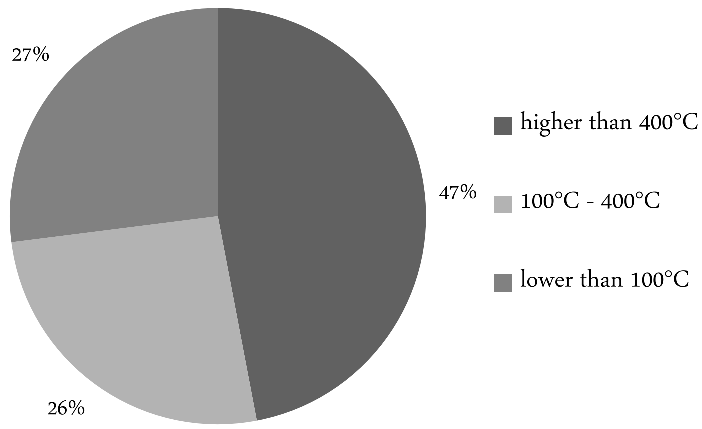


Figure 6: Heat demand in Austria devided into three temperature ranges, [2]

Wolf et al. (2014) [9] made an even more precise breakdown for Germanys heat demand in the mid and low temperature range. They point out that the theoretic potential for heat supply in industrial processes below 140°C amounts to 611 PJ. More precisely, it can be distinguished between 211 PJ for processes under 70°C, 226 PJ in between 70°C and 100°C and another 174 PJ in the range from 100°C to 140°C. This is correspondent to one third of the total industrial heat demand in 2012, which could be covered theoretically by HTHP-technology.
For discovering possible processes for HTHP-supply Table 5 exemplifies common industrial processes in mid temperature range, complemented by the technical potential in the particular branch in Germany 2012 [2, 9, 28, 29]. Evaporation, cooking and drying processes are quite common and can be found in various branches. Their required process temperatures vary between the different production sites and would require a closer on-site investigation weather HTHP can be applied or not.

Table 5: Common industral processes with reachable temperature ranges for HTHP and technical potential in Germany [2, 9, 28, 29].

Branch	**Process**	**Temperature** [°C]	**Technical Potential** [PJ]
Food	Pasteurization and Sterilization	70-120	145
	Cooking	100-240	
	Distillation	40-100	
	Drying	40-250	
	Evaporation	40-170	
	Baking	160-260	
Pulp and Paper	Cooking	160	151
	Drying	110-240	
Chemistry	Cooking	95-105	131
	Distillation	110-300	
	Thermal converting	130-160	
	Concentrating	125-130	
Wood	Glue	120-180	8

To briefly conclude this, one can say that in the D-A-CH industry high potential for HTHP use can be estimated. Regarding the possible temperature benchmark for HTHP, a significant heat demand at process temperatures below 160°C can be recognized, especially against the background of quite common industrial processes in mid temperature range.
In order to get insight into the applicability of HTHP in one particular branch, the pulp and paper industry is now introduced further. The following section deals with the manufacturing processes of pulp and paper for the purpose of considering possible

process integration for HTHP.

3.2 Pulp and paper industry

Manufacturing of pulp and paper needs high amounts of thermal and electrical energy, which is mostly acquired by combustion technologies. For the purpose of allocating the potential application of HTHP, the pulp and paper process is illustrated briefly followed by energetic considerations of the described processes. In addition, possible waste heat sources are highlighted. Kramer et al. 2009 [6] distinguish between six major processes:

Preparation of raw materials Paper consists of fiber, which either can be extracted from wood or recycled from waste paper and paperboard. About 45% of the manufactured paper and paperboard include reused waste paper. It is mostly utilized for newsprint paper, printing paper, toilet paper, packaging paper and paperboard products. The main fiber source for paper production is wood, which expenditure lays around 8 Mill cubic meters every year. In order to prepare wood for the further pulping process, it needs to be freed from bark and in a further step cut into wood chips. This processes are driven mechanically and do not afford higher temperatures [6, 30].

Pulping process In the pulping process wood gets divided into its basic components, which is cellulose, hemi-cellulose and lignin in order to extract fibers from lignin. Strong and long aging papers are more elaboratve and afford higher energy input. Long fibers and less lignin in the pulp enable production of higher quality papers. There are several methods for pulping which differ in their energy intensity:

- Mechanical pulping
  The mechanical pulping process can be further divided into stone groundwood pulping, refiner mechanical pulping, thermomechanical pulping and chemithermomechanical pulping. The latter two require steam around 130°C. Characteristic for mechanical pulping is that lignin is hardly removed from the pulp, which has the advantage of higher yields but produces rather short and weak fibers, which lowers the quality of the paper [6, 31].

- Chemical pulping
  In an higher temperated and pressurized process the chemical bonds of lignin are opened up and fiber is separated from the feedstock. In this process a higher percentage of lignin can be removed which allows prodcution of stronger and more stable paper products. One can distinguish between the Kraft pulping process (sulfate pulping process) and the sulfite pulping process, of which the first one is the most common used method. 98% of the U.S. chemical pulping operators use Kraft pulping processes. Similarly, Germany produces 85% of the yield fiber through the sulfate process. In the Kraft pulping process, hot steam is used for softening the wood chips. In a further step, the wood chips are cooked in an highly alkaline solution at 160-170°C over a few hours. [6, 32].

- Semi-chemical pulping
  This process combines both chemical and mechanical pulping and is often used

for hardwoods in order to produce paper that has a smoother property with higher density. For this process, lower temperatures than for chemical pulping are needed [6].

- Recycled pulping
  In this process waste paper is mixed with water in a tank. In mechanical and chemical processes dirt, inks and other contaminants can be extracted from the pulp. The recycling of waste paper usually affords a lower energy input than the above mentioned processes, although it can not be used for high quality grades [6].

Chemical recovery In the chemical recovery processes, chemicals that were used for prior pulping can be recaptured from the cooking liquor in order to serve the ongoing pulping process again. An established method for recovery after the Kraft pulping process, can be introduced in four stages:

- black liquor concentration
- black liquor combustion
- recausticizing
- calcining

Shortly summarized, water from the black liquor is evaporated so that the remaining solids can be used energetically. In a recovery boiler they are combusted in order to produce steam for further purposes. In the recausticizing and calcining processes, the used chemicals can be recaptured and reused in the pulping processes [6].

Bleaching Bleaching is done in case of paper products which afford a higher grade of brightness such as printing and office paper. In this processes, the brown tainted pulp is either treated in an chemical-intensive process to decolorize remaining lignin or in a less chemical-intensive process in which the remaining lignin is extracted from the pulp [6].

Pulp drying Pulp drying as a step before papermaking can be affordable, if pulping and papermaking does not take place in one facility. Pulp drying is a very energy intensive processes in which pulp is dried to 10wt% water content. The afforded energy is around 1.2 MWh steam per ton of pulp [6].

Paper making In the paper making procesess, the pulp runs through following three stages:

- stock preparation
- wet end processing
- dry end processing

During these manufacturing steps, the pulp is first prepared for the final paper product and is rehashed as a homogenous mass before being fed into the paper machine. After the paper web is formed it moves further to the press section, which strengthens and dewaters the paper sheet. In an ongoing step the paper is dried in the drying section of the paper machine. In this process, the paper is drawn over a row of cylindric rolls, which are heated by 2-4 bar saturated steam. This causes the remaining water to evaporate from the paper until a certain degree of humidty is reached, which is usually below 10%. In this section, the largest amount of thermal energy is consumed [6, 33].

3.2.1 Energy portfolio in pulp and paper process

Austria's pulp and paper industry comprises 24 producers, which have a yearly output of 5 Mill tons of paper and paperboard products and approximately 2 Mill tons of pulp. The manufacturing process itself consumes high energy amounts. In 2016 the industry afforded around 64 PJ in form of fuel and 17 PJ electrical and has an approximate share of about 6% of Austria's final energy use in the regarded year. The related carbon footprint in 2016 accounted 6.1 Mill tons CO_2 of which 1.7 Mill tons were from fossil source and 4.4 Mill tons from biogenic sources. Table 6 is a more detailed break down and shows fuel and electricity consumption and the particualr carbon dioxide emissions of the whole branch in the years 2000, 2010 and 2014 to 2016. Black liquor as a byproduct in pulp production depicts the biggest energy source, follwed by natural gas. The utilization of electricity from back pressure turbines is about in the same range as external power consumption from the grid and has the third biggest consumption share. Besides coal, oil and biomass, sludge is also utilized for combustion. Gas turbines as well as hydropower and vapor condensation are used for electricity production. What can be seen as well in the considered table is that gas turbines had a much higher share in the electricity production up to 2010 than they had in the last years. While in the years 2000 and 2010 the production of electricity was above 1 000 GWh, in recent years it has fallen below 500 GWh. Simultaneous behavior can be observed with consumption of natural gas [4, 5, 27, 30].

Figures 7 and 8 show the energetic consumption of the different processes in pulp and paper making in the U.S. industry. What can be drawn from these graphs are the predominant energy consumers in pulp and paper making processes as well as the form of energy which is utilized. Evaporation, cooking and chemical preparation are the biggest energy consumers in pulping. As it is stated above, there are many different forms of pulping. In U.S. the Kraft pulping process is the most applied technique and is mostly supplied by steam around 150°C. Generally, most processes in pulp making refer to steam supply, direct fuel combustion is only used for chemical preparation. In each process electrical driven motors cause considerable amount of electric energy consumption. In the paper making process, the drying process represents the biggest energy consumer and is mostly fed by hot steam. The forming of paper web in the wet end process represents also a quite energy intensive process, halfway supported by electricity and halfwaa supported by hot steam [6, 34].

Table 6: Fuel and electricity consumption in Austria's pulp and paper industry in the years 2000, 2010 and from 2014 until 2016 [4, 30].

Energy source	**2000**	**2010**	**2014**	**2015**	**2016**
		Fuel [GWh]			
Coal	1 276	978	1 168	1 162	1 224
Fuel oil	552	268	60	48	30
Natural gas	8 488	8 026	5 583	5 920	5 874
Black liquor	6 358	7 498	7 426	6 775	8 867
Biomass	921	672	648	541	1 089
Sludge	326	693	689	713	408
Others	-	358	318	319	347
Total consumption	17 919	18 501	15 892	15 478	17 839
		Electricity [GWh]			
Gas turbine	1 069	1 276	400	484	402
Back pressure turbine	2 027	2 178	2 082	1 917	1 999
Vapor condensation	263	171	60	54	336
Hydro power	201	217	169	148	165
Others	0	0	0	0	2
Feed into grid	119	364	220	222	303
External power	1 139	1 283	2 113	2 090	2 128
Total consumption	4589	4761	4 604	4 471	4 729
		Carbon dioxide emissions [Mill tons]			
CO_2 (fossil)	2 157	2 053	1 501	1 580	1 677
CO_2 (biogenic)	3 431	4 158	3 770	3 537	4 396

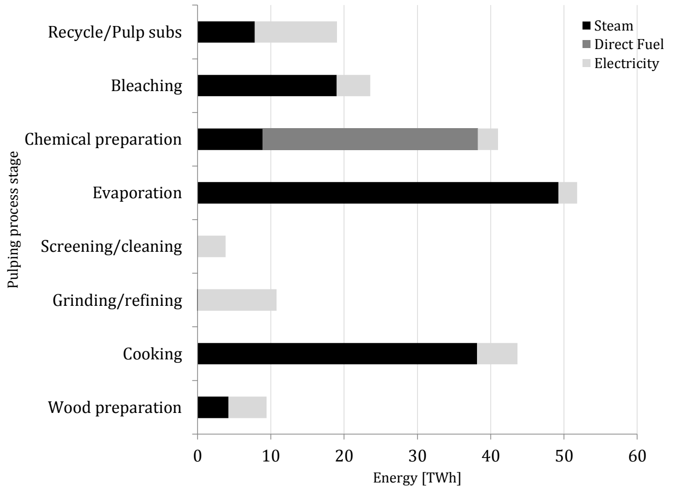


Figure 7: Energy use of U.S. pulp manufacturing by end use energy type in 2002, according to Kramer et al. (2009) and Jacobs and IPST (2006) [6, 34]

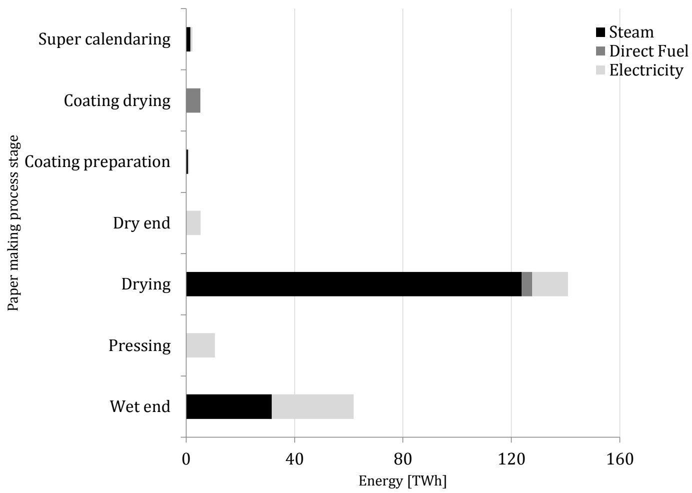


Figure 8: Energy use of U.S. paper manufacturing by end use energy type in 2002, according to Kramer et al. (2009) and Jacobs and IPST (2006) [6, 34]

3.2.2 Waste heat in paper making processes

HTHP depend on constant waste heat streams, in order to guarantee consistent working conditions. The first and most important issue before planning a HTHP on site, is to identify waste heat streams that could function as heat source. Table 7 summarizes typical waste heat streams in paper production complemented by their temperature range.

Table 7: Temperature range of typical waste heat streams in paper industry, [35, 36]

Waste heat stream	**T** [°C]
waste water paper maschine	20-40
waste water pulp preparation with deinking	40-60
wast water pulp preparation without deinking	30-50
waste water grinding/TMP plant	60-70
exhaust air production facility	30-40
exhaust air vacuum pump	40-50
exhaust air vacuum fan	130-160
exhaust air drying stage	60-80
exhaust air coating machine	100 - 140
heat radiation	-

3.2.3 Manufacturers data

The considered company is focused on paper production, so the whole pulping process is outsourced and pulp is externally purchased. As summarized in Table 8, the firm has two paper machines operating on site, which produce around 800 000 tons of paper yearly. The related CO_2 emissions amount to around 350 000 tons per year. The two paper mills produce two different types of papers, namely super calendered papers (SC-papers) and bogus paper [37].

Table 8: Two paper machines in an Austrian pulp and paper mill.

Paper machine I	**Paper machine II**	**Unit**
1987	2002	date built
bogus paper	SC-paper	type
450 000	350 000	t/year
70-140	40-65	g/m^2
1 600	1 800	m/min
7 500	8 950	mm

The energetic supply is accomplished by an combined heat and power plant (CHP), fed by natural gas, which produces thermal heat and electricity. Whereas the CHP covers the whole heat demand on site, a hydro power plant and the public grid supply the remaining electric demand. Further information about the heat supply mode is introduced in Chapter 4.

Summarizing these findings about the pulp and paper making process and Austria's pulp and paper industry, one can say that there are various pulping techniques that require different amounts and forms of energy. Two types of mechanical pulping require steam around 130°C. Chemical pulping process is done in a higher temperature range above 150°C. The Kraft pulping process, as a very far spread pulping methodology is driven in a temperature range between 160-170°C. Within this process, lignin is separated from cellulose. After evaporation, the remaining solids are combusted and heat can be used for steam production. In Austria 5 manufacturers produce pulp and operate a paper mill in one place. Other companies focus on paper making only, which means that possible waste heat from pulping is not usable for recycling. The residual heat from paper making though, presented in Table 7, shows that a potential source heat for HTHP is available.

4 Methodological approach and assumptions for economical comparison

4.1 Initial data for modeling and simulation

The methodological approach for an economical comparison of GT-CC and HTHP is based on received real world data from an Austrian paper mill, which operates a GT-CC as heat supply system for the drying process in their paper machine. The received data are summarized in table Table 9 and contain information about the dimension of the installed plant, which were used for modelling the GT-CC. Further, information about the quantity of consumed gas that has been fed into the operating GT-CC-system was passed on. The gas flow rate was received in hourly resolution in Nm^3 over a whole year, from 01.01.2013 until 31.12.2013 and is used for a dynamic simulation of the GT-CC-system, in order to gain information about the demanded process heat of the paper mill. As a benchmark, the operator stated a heat demand for the year of 2014 of 462 GWh and an electric output of the GT-CC of 96 GWh.

Table 9: Summary of received data about a GT-CC in an Austrian paper mill

Parameter	**Value**	**Unit**
P_{GT}	39.3	[MW]
P_{ST}	20.3	[MW]
$T_{ST,HP}$	495	[°C]
$p_{ST,HP}$	63	[bar]
T_{WHB}	520	[°C]
p_{WHB}	65	[bar]
	Process steam	
$T_{ST,LP}$	217	[°C]
$p_{ST,LP}$	6	[bar]
$\varnothing\dot{V}_{in,gas\ 01.-12.\ 2013}$	9 270	[Nm^3/h]
working hours	8 752	[h/a]
heat demand 2014	463	[GWh]
electric output 2014	94.6	[GWh]
$T_{exh,hood}$	120 - 150	[°C]
exhaust gas oxygen	13-15	[%]

In a first step, the GT-CC-system is modeled similar to the received data in the stationary process simulation program IPSEpro. Information concerning this program can be looked up in upcoming Section 4.1.1. The following dynamic simulation based

on the received gas flow rate is accomplished by the mathematical program MATLAB (further information in Section 4.1.2) and delivers results about heat demand and electrical output of the GT-CC in the year 2013. These results are further used for dimensioning the HTHP, as well as for calculating levelized and absolute costs of heat production for both heat supply systems which are compared along a time range from 2004 until 2017.
The model assumptions for both heat supply systems are described in Sections 4.2 and 4.3. The approach for the dynamic simulation is explained in Section 4.4 followed by the methodology for the economic calculations in Section 4.5. The resulting frame in which the heat supply systems are compared with each other on an economical basis is described in Section 4.6.

4.1.1 IPSEpro

The "IPSEpro" program is a process simulation environment (PSE) which was developed by the company "SimTech". The program is designed for calculating heat balances and simulating processes, and design of process plants. For doing so, the program reverts to a range of modules in order to create numerous processes that can be utilized for different applications. The modules are used for calculation of heat balances, verify and validate measurements, monitoring and optimizing of plant performances and for modification of existing plants. A special feature for users is to be able to adapt existing or design new model libraries, which allows creation of proprietary solutions. The system architecture is designed in two levels, namely the component level and the process level. At the component level, all properties of every particular component is defined in mathematical equations and allows the user to combine and integrate the components into a complete process model. The component models are built and organized in model libraries of which every library is designed for different applications. At the process level, the user has the possibility to create and model processes that revert to a particular process library. For structuring a process the surface of the program is design as a collections of the preedefined technical components that are depicted as icons. On a graphic display the user has the possibility to build up a process structure, which means that all equations of the component models are connected into a single system of equations. The program allows, therefore, to fastly build complex process models [38]. A graphical account of the system architecture of IPSEpro is presented in Figure 9.

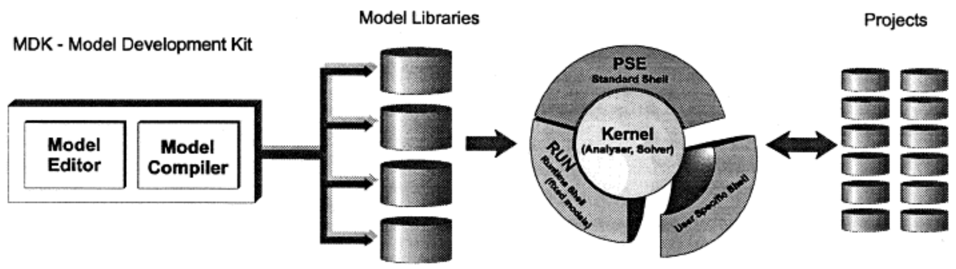


Figure 9: IPSEpro system architecture.

In the framework of this thesis, IPSEpro served to model both heat supply systems, HTHP and GT-CC. For doing so, the following process libraries were used:

- **Advanced Power Plant Library - APP** The Advanced Power Plant Library can be utilized for a broad range of thermal power systems such as conventional power plants, cogeneration plants and combined cycle plants. The user has the possibility tho design new plants as well as analyse and optimize existing plants. In the framework of this thesis, this library was used for modeling the GT-CC plant.

- **Pyrolyis and Gasification Process Library - PGP** The Pyrolysis and Gasification Process Library can be used for creation and analyses of Biomass Gasification Plants. The library includes items such as gasifiers, fuel dryers, compressors, condensers, gas engines, heat exchangers pipes and other features. The user can model biomass conversion systems and technologies, including combustion, pyrolysis, gasification and gas cleanup applications. For modeling the observed HTHP in this thesis, the PGP library was used.

4.1.2 MATLAB

MATLAB is a software from the company MathWorks which is used for finding solutions of mathematical problems as well as the graphical representation of the results. It primarily is designed for numerical computations using matrices from which the name derives: MATrix LABoratory. The software is mainly used in numerical simulation as well as in data collection, data analysis and analysis in industry and universities. For this thesis, the program was used for implementing a dynamic simulation of the modeled GT-CC in order to get results of the demanded heat as well as the produced electric energy, [39].

4.2 GT-CC model and assumptions

Generally, a GT-CC process functions as an energy conversion process, where the energy content of the fuel gas (P_{fuel}) is set free by combustion and converted into heat energy ($\dot{Q}_{process}$) and electric energy ($P_{net,el}$). The modeled GT-CC is laid out for covering the operators heat demand and works with a gas turbine (GT) and a back pressure steam turbine (ST) in a combined cycle, which both produce electric power. The operator has the possibility for two different operating modes, namely GT-CC-mode (with GT in operation, Figure 10) and ST-mode (without GT in operation, only the ST produces electricity, Figure 11). In GT-CC-mode, high pressure air from the compressor is combusted together with natural gas at 1 140°C in the combustion chamber before it gets expanded in the GT. The exhaust gas leaves the turbine at about 600°C and is used to produce process steam. This is accomplished by a waste heat boiler comprising economizer, evaporator and superheater. Within this process, the feed water is preheated, evaporates at 63 bar and gets superheated up to 495°C. The live steam gets expanded in a back-pressure turbine. The expanded steam leaves the turbine at 6 bar and 213°C and serves as heat source for the drying process in the paper machine. Additional natural gas burners are used in the exhaust duct upstream of the boiler to increase the steam production duty. Does the operator choose, not to operate with the GT (ST-mode), he has the possibility to produce the afforded process steam at 63 bar and 495°C only by using the additional gas burners.

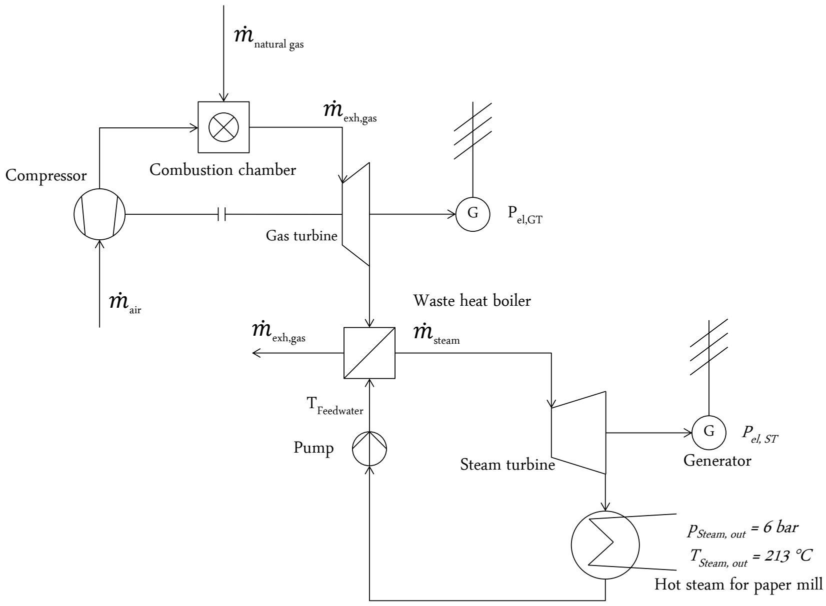


Figure 10: Simplified scheme of a GT-CC with heat recovery boiler and back-pressure steam turbine, (GT-CC-mode).

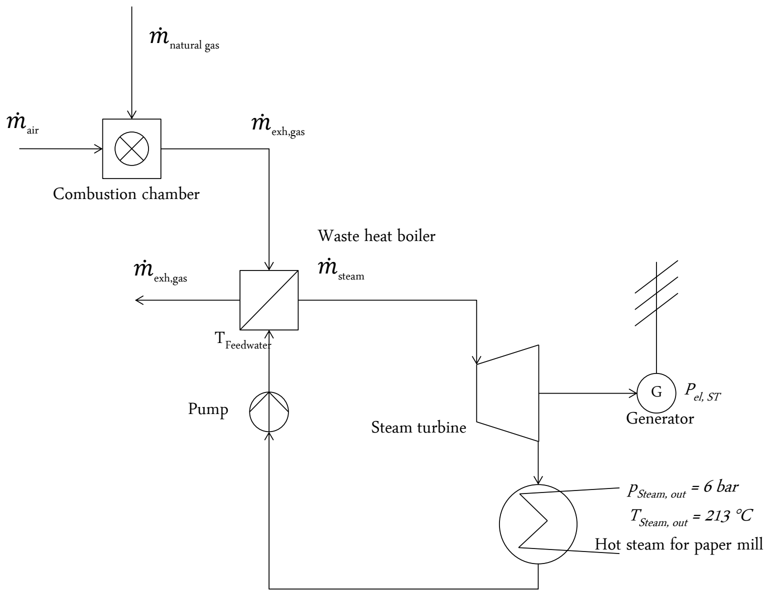


Figure 11: Simplified scheme of a heat recovery boiler and back-pressure steam turbine, (ST-mode).

Since not every technical detail has been disclosed by the operator, the GT and the ST are modelled according to product datasheets from turbines which have the same dimensions as those of the operator. The selected GT is a GE 6B 03, a product from GE Oil & Gas with 44 MW_{el} nominal electric power. The chosen ST is a Siemens SST-150 which has a nominal electric power of 20 MW_{el}. Further technical details concerning the GT-CC are summarized in Table 10. The following equations explain different efficiency parameters, which are calculated. The single cycle efficiency according to Equation (9) is a characteristic factor for GT. In order to distinguish electric and heat utilization of the GT-CC systems, Equations (10) and (11) are brought into play. The sum of both parameters equals in the total fuel utilization efficiency of the GT-CC, described by Equation (12).

$$\eta_{GT} = \frac{P_{el,GT}}{P_{fuel}} \tag{9}$$

$$\eta_{el,GT-CC} = \frac{P_{el,GT} + P_{el,ST}}{P_{fuel}} \tag{10}$$

$$\eta_{heat,GT-CC} = \frac{\dot{Q}_{heat}}{P_{fuel}} \tag{11}$$

$$\eta_{total} = \eta_{heat,GT-CC} + \eta_{el,GT-CC} \tag{12}$$

The resulting efficiency factor of the GT-CC accounts 82.37% with operating GT and 82.87% without GT. The operator indicated a total fuel utilization efficiency of around 85%, which is rather low compared to modern GT-CC systems. Higher efficient GT and a comprehensive waste heat use could allow efficiency factors around 90%. Furhtermore, standard GT nowadays can achieve single cycle efficiency above 40% [40].

Table 10: Technical parameters of the modeled GT-CC

Parameter	**GT-CC**	**ST**	**Unit**
P_{GT}	44		[MW]
$pressure\ ratio_{GT}$	12.2:1		[-]
η_{GT}	30.27		[%]
η_{compr}	0.85		[-]
η_{heat}	43.91		[%]
$\eta_{net,el}$	38.46		[%]
η_{total}	82.37		[%]
η_{heat}		69.82	[%]
$\eta_{net,el}$		13.05	[%]
η_{total}		82.87	[%]
P_{ST}	20		[MW]
$\eta_{ST^{\mathrm{MS6001B}}}$	0.86		[-]
$T_{ST,HP}$	495		[°C]
$p_{ST,HP}$	63		[bar]
$T_{ST,LP}$	213		[°C]
$p_{ST,LP}$	6		[bar]
$\triangle\ h$	2 880		[kJ/kg]
$\triangle\ m$	85 787		[kg/h]
T_{exh}	600		[°C]
p_{exh}	1		[bar]

4.3 HTHP model and assumptions

The modelled HTHP system basically follows the described set up in Section 2.1 with two heat exchangers (evaporator and condenser), an expansion valve for the refrigerant and an electrically driven compressor (Figure 12). The compressor is constructed with an inter cooling system, which withdraws heat from the comperssor. The chosen refrigerant is water (R718), which functions similarly as process steam for the drying process. There is no absolute certainty about the amount of waste heat at the production site, it is assumed within this thesis, though to be sufficiently available. After the evaporation at a temperature of 80°C (at 0.47 bar), the refrigerant is compressed in a polytrope compression system. Due to the compression of the refrigerant to a level of 6 bar, the condensation temperature increases to 160°C. The superheated process steam serves now for the drying process in the paper machine. After condensation and pressure release in the expansion valve, the cyclic process is completed and starts again. Various parameter concerning the modelled HTHP process are collected in table Table 11. The added capacity is accomplished by an electrical driven compressor with an η_s of 0.8. The COP of 4 is calculated according to Equation (13) and is leaned onto explanations in Section 2.2.

$$COP = \frac{\dot{Q}_{process}}{P_{el}} \tag{13}$$

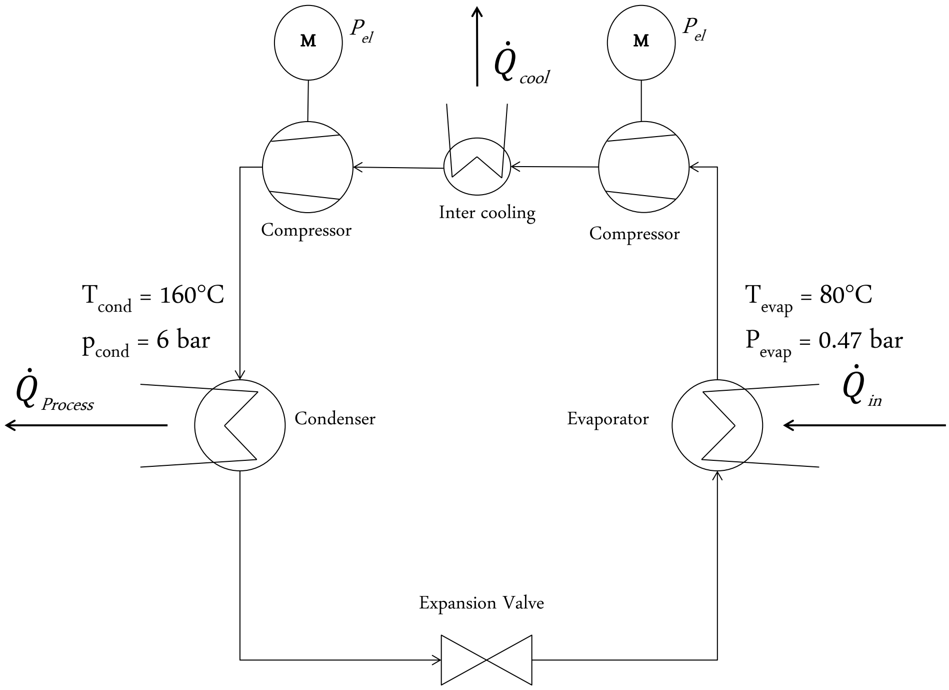


Figure 12: Simplified drawing of the modeled HTHP process with polytropic inter cooling in IPSEpro

Table 11: Technical parameters of the modeled HTHP

Parameter	**Value**	**Unit**
η_{Compr}	0.80	[-]
η_{Motor}	0.97	[-]
T_{evap}	80	[°C]
p_{evap}	0.47	[bar]
T_{cond}	160	[°C]
p_{cond}	6	[bar]
p_{cond}/p_{evap}	12.7	[-]
$\dot{m}$	2756	[kg/h]
$\triangle\ h$	2760	[kJ/kg]
COP	4	[-]

4.4 Assumptions for dynamic simulation of the GT-CC

In order to get heat demand as well as energy output in a hourly resolution of the modelled GT-CC for the year 2013, a loop in MATLAB is programmed with overall 8 752 calculated data sets, thus for every hour. The fact that the GT-CC can be driven in two modes is reflected in the received gas flow rate and therefore considered in the simulation. What can not be distinguished from the data is the amount of supplemental firing for regulating the heat demand. Since the operator does not know about the exact amount of additional firing as well, it is not considered in the simulation. The differentiation is only made regarding the GT. The assumption is that, if the gas flow is beyond 10 000 Nm^3/h, GT-CC driving mode is assumed, so the GT is in operation. If it is below 10 000 Nm^3/h, ST-mode is assumed, so the GT is switched off. Therefore, the data record was split into those two operational modes before executing the simulation. In case of GT-CC-mode, the GT is included in the simulation. On the contrary case of the ST-mode the GT is excluded from the simulation. Overall, in 2013 there are 2 931 hours in GT-CC-mode at an average gas flow rate of 13 365 Nm^3/h and 5 821 hours in ST-mode with an average gas flow rate of 7 202 Nm^3/h, as Table 12 summarizes. The operator had a 10 hours maintenance break on the 15th of January, and switched 7 times between the two operational modes over the whole year.

Table 12: Combined heat and power (CHP) operation through 2013.

driving mode	**∅ operating hours [h]**	**gas flow rate [Nm^3/h]**
GT-CC-mode	2 931	13 365
ST-mode	5 821	7 202

4.4.1 MATLAB-IPSEpro interface

For the simulation, the designed program in MATLAB built the connection between MATLAB and IPSEpro. In a loop with overall 8 752 data sets the hourly gas flow rate $\dot{V}$(i) in Nm^3/h was loaded into the IPSEpro-model. For every value, the model calculated electric output of the ST P_{ST} and the GT-CC P_{GT}, as well as the hourly produced heat capacity $\dot{Q}_{process}$. These values were saved in a CSV file and served for further calculation. Further details concerning the used program code can be read in Appendix.

4.4.2 Calculation of energy input for economic comparison

In order to make an economic comparison for each heat supply mode over the years, the resulting heat demand of the dynamic simulation of the GT-CC serves as basis for calculating the afforded energy input for every particular heat supply mode. The three modes are:

- HTHP-mode at a COP of 4
- GT-CC-mode with GT in operation
- ST-mode without GT in operation

For doing so, the hourly heat demand during 8752 hours is used to recalculate the energy input per hour. In addition, corresponding electric output of the GT-CC for every hour can be calculated as well, according to Equations (9) to (11). The efficiency factors are used, similarly to Table 10 for the GT-CC and for the HTHP the calculation for P_{el} is done as described in Equation (13). The resulting energy input and output of the three heat supply modes are further used for the economic calculation. A graphic account of the procedure is shown in Figure 13.

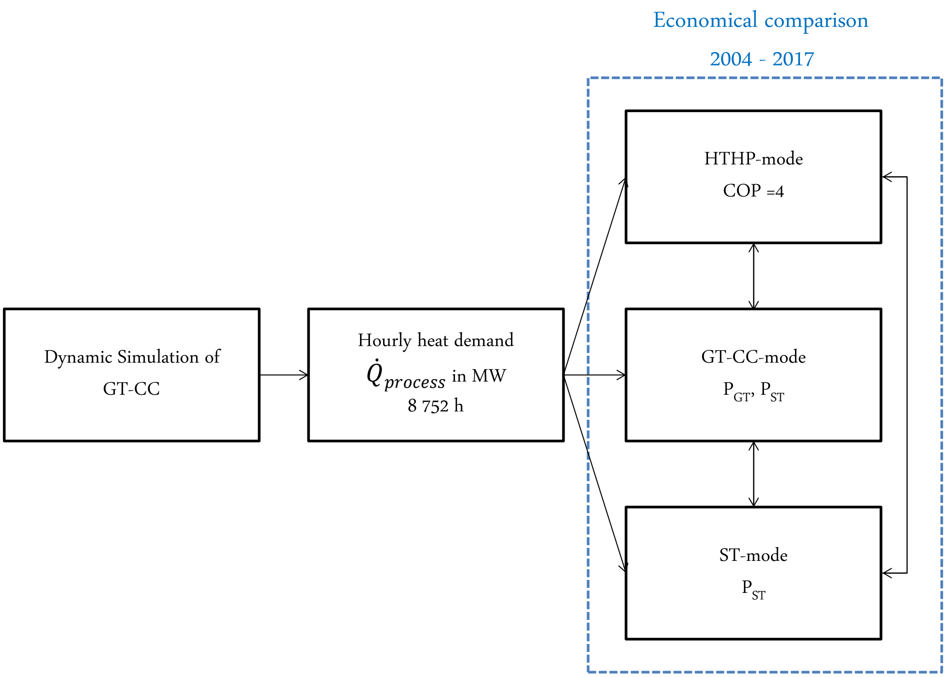


Figure 13: Schematic account of methodological approach for economic comparison

4.5 Economic calculation method for heat supply

The results from the dynamic simulation are used for the economic calculations. The hourly heatload of the year 2013 which results from the dynamic simulation is thereby assumed to occur likewise in the years 2004 - 2017. Due to the fact that both heat supply systems are influenced by different parameters, the method of calculation differs as well. The costs of heat generated by the HTHP depend on electricity prices, whereas the GT-CC depends on both, electricity- and gas prices. For the GT-CC, annual gas prices in EUR/MWh from 2004 until 2017, that refer to data from e-control 2017 [41] are used. The electricity prices are chosen from the spot market in hourly resolution from 2004 - 2017 and refer to data from EXAA 2017 [42]. The economic analysis is made by comparing cost of heat supply of the GT-CC and HTHP.

4.5.1 Levelized costs of heat production

In order to make different heat supply systems comparable, consumption related costs for each system are considered on a levelized basis in EUR/MWh over a particular year. The assumptions behind these calculations are summarized in Table 13. For HTHP the variable ($COH_{v,HTHP}$) and fixed CoH ($COH_{f,HTHP}$ in Section 4.5.2) are calcualated. Since a pre-existent and fully discounted GT-CC is assumed, only the

variable CoH are considered for the GT-CC.
For the GT-CC, the calculation of CoH is done by dividing the costs of heat production on the input-side by the amount of produced heat on the output-side. The costs need to be corrected for the discounts through electricity yields. The CoH for HTHP are calculated differently, namely the electricity price divided by the COP. The calculation of CoH is done for the three different operating modes, since the operator has the possibility to choose between them. HTHP-mode Equation (14), GT-CC-mode Equation (15) and ST-mode Equation (16).

$$CoH_{v,HTHP} = \frac{C_{el}}{COP} \tag{14}$$

$$CoH_{GT-CC} = \frac{P_{fuel} * C_{Gas} - (P_{el,GT} + P_{el,ST}) * C_{el}}{\dot{Q}_{Process}} \tag{15}$$

$$CoH_{ST} = \frac{P_{fuel} * C_{Gas} - P_{el,ST} * C_{el}}{\dot{Q}_{Process}} \tag{16}$$

4.5.2 Investment costs and operational costs for HTHP

For the purpose of comparing the heat supply systems with each other, under the given fact of a newly installed HTHP, acquisition costs for a HTHP need to be broken down onto a EUR/MWh-basis as well. For doing so, capital costs $C_{Capital}$, personal costs C_{Salary} as well as service costs $C_{Service}$ are taken into account. The latter two are based on assumptions according to Table 13. Costs for capital also underlie several assumptions and are built by the sum of depreciation costs C_D and interest costs C_I (Eq. (19)). For the calculation of depreciation (Eq. (17)), a life expectancy of 20 years and a residual value of zero, after the end of its useful life is assumed. The costs for interest (Eq. (18)) are calculated after the residual value methodology and under the assumption of complete external financing with a chosen annual interest rate of 5%.

$$C_D = \frac{I_0 - R_W}{n} \tag{17}$$

$$C_I = \frac{I_0 + R_W}{2} * i \tag{18}$$

$$C_{Capital} = C_D + C_I \tag{19}$$

The summarised costs per year devided by the annual heat demand yields the CoH as in eq. 20. The total CoH are built by the sum of variable and fixed CoH (Eq. (21)).

$$COH_{f,HTHP} = C_{Capital} + C_{Salary} + C_{Service} \tag{20}$$

$$COH_{HTHP} = LCOH_{f,HTHP} + LCOH_{v,HTHP} \tag{21}$$

Since no HTHP in this dimension has been implemented yet, the degree of uncertainty concerning the investment costs is limited by looking at different specific investment cost scenarios. The assumptions refer on the one hand to received manufacturers data, on the other hand to literature, and are accordingly chosen inbetween

Table 13: Assumptions for calculating CH for a newly installed HTHP with four different heights of investment costs.

Parameter	Invest A	Invest B	Invest C	Invest D	Unit
I	1000[1]	750[2]	500[3]	250[4]	[EUR/kWh]
R_w		0			[EUR]
n		20			[a]
t		8 752			[h]
i		5.0			%
C_{Salary}		40 000			[EUR/a]
$C_{Service}$		10 000			[EUR/a]

1 assumption

2 Viking Heat Engines [21]

3 Viking Heat Engines [21], Wolf 2014 [9]

4 Zhang et al. 2016 [43]

250 EUR/kWh and 750 EUR/kWh. In order to account for uncertainty the assumption of 1000 EUR/kWh is made additionally by the author.Table 13 summarzies the chosen assumptions [9, 21, 43].

4.5.3 Absolute costs of heat

The calculation of absolute costs of heat production is done for every hour and depends on the energy input and energy prices. In order to calculate savings per year (Eq. (25)), the hourly costs of both heat supply systems, respectively the three operational modes are summed up so they can be compared. The absolute hourly costs for GT-CC in both operating modes and HTHP are calculated by Equations (22) to (24).

$$C_{GT-CC} = P_{fuel} * C_{Gas} - P_{el,GT-CC} * C_{el} \tag{22}$$

$$C_{ST} = P_{fuel} * C_{Gas} - P_{el,ST} * C_{el} \tag{23}$$

$$C_{HTHP} = P_{el,HTHP} * C_{el} \tag{24}$$

$$Savings\ per\ year = \sum_{n=1}^{8752} C_{GT-CC} - \sum_{n=1}^{8752} C_{HTHP} \tag{25}$$

4.6 Resulting set up of heat supply and process requirements

As a summary of the explanations above, the resulting set up is taken into a graphical account in Figure 14. The operator has the theoretical possibility to choose between GT-CC and HTHP, whereas the GT-CC can be operated in two ways. Either in GT-CC-mode or in ST-mode, in which both the ST is continuously in operation, whereas the GT only operates in GT-CC-mode. In order to underline the initial thought of this thesis, the potential of less CO_2 emissions by the HTHP in times of a high share of renewable power stands against the GT-CC as a CO_2 producing heat supply technology. The electrical output will be predominantly used for own consumption but could also be fed into the electric grid. The waste heat after the drying process is typically lost to the environment with a humid hot air stream around 60 to 80°C [35, 36]. The HTHP requires source heat, which can be withdrawn from waste heat after the drying process. By adding electric energy, the waste heat can be brought to a temperature level of about 160°C and 6 bar and supply the drying process.

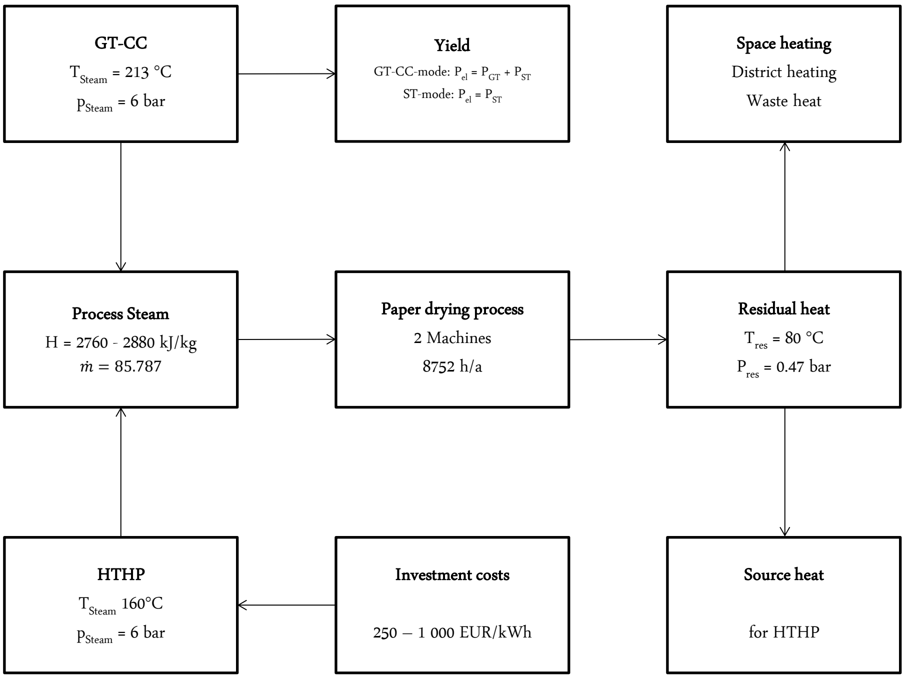


Figure 14: Graphical account of the resulting set up of operational modes to supply the heat demand of an austrian paper mill, in reliance on possible influencing parameters.

In a log(p)-h-diagram, like Figure 15 introduces, one can read out the characteristics of the process steam for the declared process parameters. The enthalpy of process steam produced by the GT-CC-system is superheated and accounts about 2 880 kJ/kg. The HTHP is modeled for 160 °C and 6 bar. The enthalpy of this steam accounts to 2 760 kJ/kg and would be almost equal to the superheated steam from the GT-CC. Following the statements of the operator, the GT-CC produces its heat about 200 meters off the actual paper production site, which he mentions as a reason for producing superheated steam. Hereby can be ensured, that the steam does not condense on the way to the drying process. A newly installed HTHP is assumed to be closer to the paper machines, which is why a condensation temperature of 160 °C is enough to supply the process.

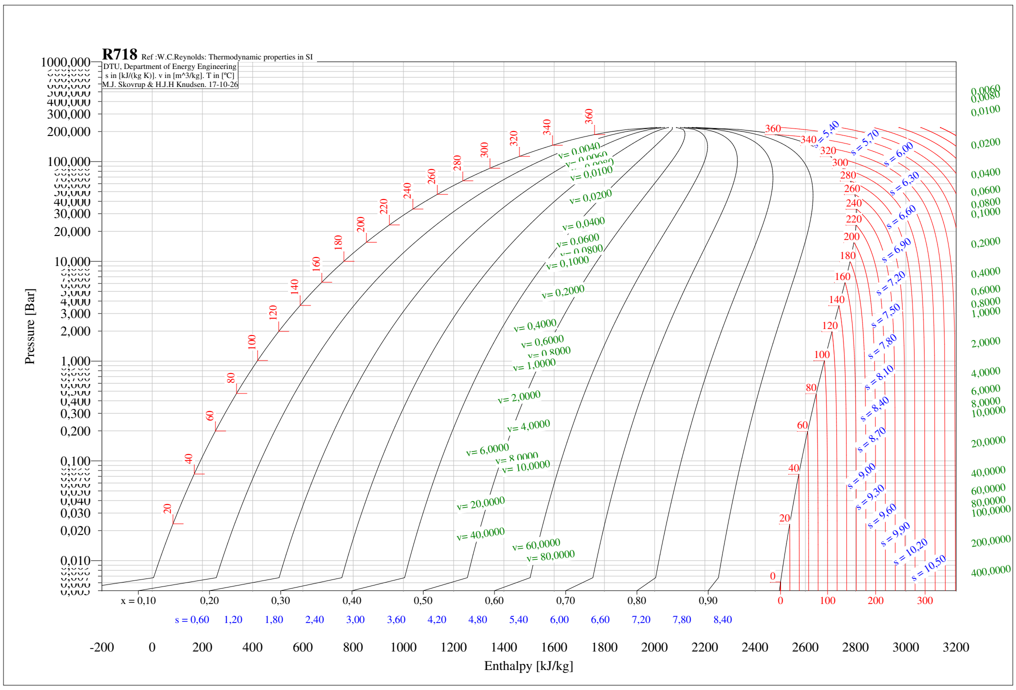


Figure 15: log(p)-h-Diagram of R718

4.7 Calculation of carbon dioxide footprint for HTHP and GT-CC

In order to get a valid comparison of CO_2 emissions for both heat supply systems, the following Equations (26) and (27) are applied.

$$Carbon\ footprint_{GT-CC} = V_{in,gas} * CO_{2,gas} \tag{26}$$

$$Carbon\ footprint_{HTHP} = P_{el,HTHP} * CO_{2,el} + P_{el,GT-CC} * CO_{2,el} \tag{27}$$

The value $V_{in,gas}$ stands for the consumed gas of the paper company over a whole year, whereas $CO_{2,gas}$ is the specific emission of CO_2 per MWh. The specific emissions are calculated with a lower heating value (LHV) of 10 kWh/Nm^3 for natural gas (CH_4) and a density for CO_2 of 1.96 kg/Nm^3. The resulting specific carbon footprint accounts 196 kg CO_2/MWh$_{LHV}$. The CO_2 footprint for electricity to operate the HTHP is chosen with 300 kg CO_2/MWh according to Umweltbundesamt (2017) [44]. Multiplied with the consumed electricity of the HTHP plus electricity from the grid over a year, the carbon footprint of the HTHP can be calculated. The comparison of both heat supply systems is made in single driving mode, which means, that every heat supply system is assumed to produce heat for whole 8 752 hours.

5 Results

The following explanations address the posed research questions and result from the executed calculations. The first Section (5.1) describes the simulation of the GT-CC, which serves as basis for further comparison of heat supply modes. The actual comparison of CoH, in order to go into the research question two and three, is made in Section 5.3. The issue concerning production share as well as pay back time for a HTHP, which is thematized in research question four and five, is addressed by Sections 5.4 and 5.5. Finally, the carbon dioxide footprint of both heat supply systems is instructed in Section 5.6.

5.1 Dynamic simulation of the GT-CC-process

The introductory results come from the dynamic simulation of the GT-CC for the year 2013. The delivered heat demand is the most important output of this simulation in order to serve further calculations. For the first 2 800 hours, the GT is continuously driven at an average capacity of 40 MW, in which the whole GT-CC consumes about 13 500 Nm^3 average gas flow per hour. The rest of the year, the GT produces temporarily for short periods of time and the electric output derives mostly from the ST with an average output of around 10 MW. The gas consumption plateaus at about 7 500 Nm^3 in the operation mode without GT. There is one point in which all lines drop to zero, which is the mentioned maintenance break of 10 hours in January.
The heat duty curve shows a slight reaction to the turn off of the GT. At the beginning it lies around 58 MW in average with GT, and after the switch-off, it drops to 50 MW in average. The difference in heat load between both driving modes can also be seen in Table 14, which takes the results in numerical account. Over the whole year, the average process heat capacity lays at 52.81 MW and heat demand over the whole year amounts to 463 GWh, which is exactly the stated demand of the operator for the year 2014. Accordingly, the average electrical capacity, which depends on the driving mode, is at 49.13 MW in GT-CC-mode and 9.33 MW in ST-mode. The electrical output over the whole year is 228 GWh, whereby about 100 GWh are produced by the ST and the rest is produced by the GT. The peak values of the simulation are a one-time occurrence for two hours in the month may and account 69.41 MW in heat capacity and 56.67 MW in GT-CC-mode, respectively 11.67 MW in ST-mode. The corresponding graphic account of the simulation is shown in Figure 16. It shows the heat capacity as well as the electric capacity of ST and GT for the year 2013 in an hourly resolution and also includes the natural gas input in Nm^3. It is well visible, when the GT is in operation and when it is not.

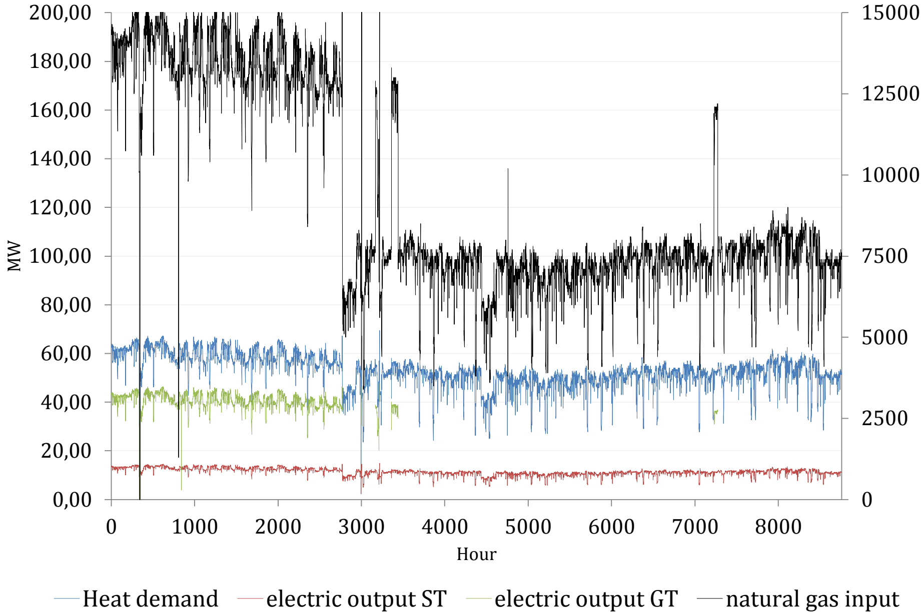


Figure 16: Graphic account of heat demand as well as electrical output of an Austrian paper mill in 2013

Table 14: Results of the dynamic simulation of the GT-CC with two different driving modes: GT-CC-mode and ST-mode.

Parameter	**GT-CC-mode** [MW]	**ST-mode** [MW]
$\varnothing\dot{Q}_{heat}$	58.45	49.98
$\varnothing P_{fuel}$	120.28	75.64
$\varnothing P_{el,GT-CC}$	49.13	9.33
$max.\dot{Q}_{heat}$	69.41	62.48
$max.P_{fuel}$	158.07	89.48
$max.P_{el,GT-CC}$	56.76	11.67

The results of the dynamic simulation gives indication about the heat demand of the paper mill. The ongoing calculations are built on these results and are described in following sections.

5.2 Required energy input of HTHP and GT-CC for covering heat demand

As an intermediate step between dynamic simulation (Section 5.1) and economical explanations (Section 5.3), the particular required energy input for the three driving modes to cover the heat demand over a whole year is calculated and presented in this section. The results are relevant in order to make an economic comparison on an hourly basis. What the results of the calculation show is that, if:

- heat is produced with a HTHP with a COP of 4, the consumed electric power would account 13.20 MW in average by simultaneously absorbing about 39.61 MW from the heat source. For covering the peak demand, the HTHP would afford an electrical input of 17.70 MW. The required source heat (Q_{source}) over a whole year amounts to 346 GWh. Table 7 shows that there are several waste heat streams at different temperature levels in the paper industry. More detailed information about the amount and humidity would allow statements, if the HTHP could be supplied sufficiently.
- the GT-CC operates without GT, the required natural gas would be 75.46 MW in average per hour for covering the heat demand. The additional electric power would mean 9.87 MW on average, produced by the ST.
- the GT-CC operates with GT, the amount of natural gas would plateau at 120.28 MW in average per hour. This would go along with an electric power of 54.62 MW, whereas 44.75 MW fall upon GT and 9.87 upon ST.

Numeric details are presented in Table 15.

Table 15: Energy input and output of HTHP and GT-CC based on hourly heat output, resulting from a dynamic simulation of an operating GT-CC in an austrain paper mill with gas flow data from 2013.

Parameter	**GT-CC-mode** [MW]	**ST-mode** [MW]	**HTHP** [MW]
$\varnothing\dot{Q}_{heat}$	52.81	52.81	52.81
$\varnothing P_{fuel}$	120.28	75.64	-
$\varnothing P_{el,HTHP}$	-	-	13.20
$\varnothing\dot{Q}_{source}$	-	-	39.61
$\varnothing P_{el,GT-CC}$	44.75	9.87	-
$max.\dot{Q}_{heat}$	69.41	69.41	69.41
$max.P_{fuel}$	158.07	99.41	-
$max.P_{el,HTHP}$	-	-	17.70
$max.P_{el,GT-CC}$	60.00	13.23	-

To take this into graphic account Figure 17 is introduced. The five lines show the required energy input, respectively the output of the three driving modes. Again, one recognizes the cut in demand after 2 800 hours as well as the 10 hours maintenance break in January.

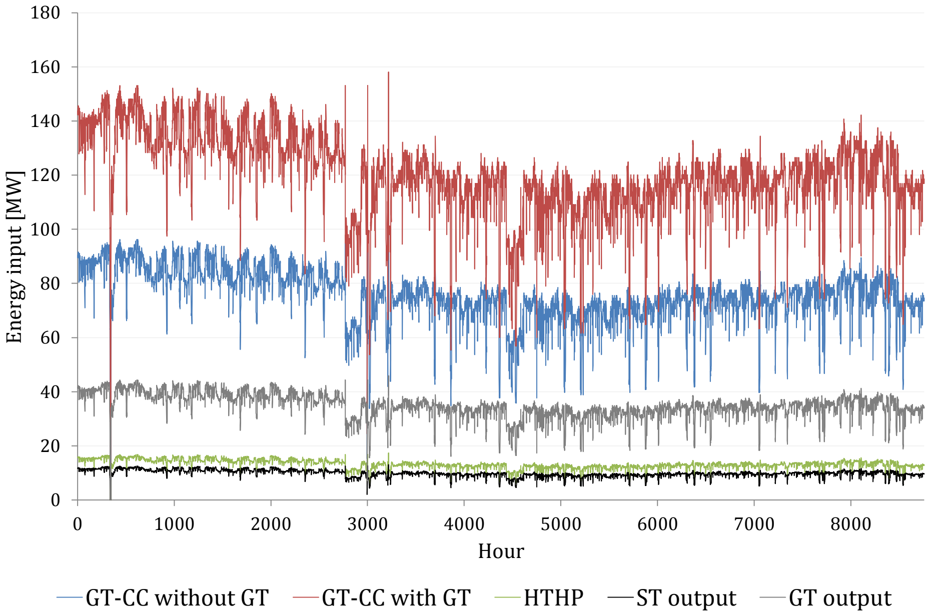


Figure 17: Energy input of GT-CC with GT, GT-CC without GT and HTHP in MW for 8752 hours to cover the heat demand of an Austrian paper mill.

5.3 Operational costs for GT-CC and HTHP

The calculated energy input for the three operating modes is used for obtaining CoH according to explanations in Section 4.5. First, the resulting CoH for a newly installed HTHP are introduced in order to compare CoH for both heat supply systems with each other. The assumed costs range from 13.2 Mill EUR up to 52.9 Mill EUR under the given assumptions. By considering depreciation, interest, salary and service costs, CoH range from 2.25 EUR/MWh for low investment costs up to 6.68 EUR/MWh for high investment costs, based on a yearly heat demand of 463 GWh. At an interest rate of 5%, interest costs vary, depending on the specific investment costs between 330 000 EUR and 1.3 Mill EUR. A more detailed insight into the calculated results is given by Table 16.

Table 16: Results of calculating CoH for a newly installed HTHP with four different heights of investment costs.

Parameter	**Invest A**	**Invest B**	**Invest C**	**Invest D**	**Unit**
Investment costs	52 869 257	39 651 943	26 434 628	13 217 314	[EUR/kWh]
R_w		0			[EUR]
n		20			[a]
t		8 752			[h]
heat demand		462 711			[EUR/MWh]
i		5.0			%
C_D	2 643 463	1 982 597	1 321 731	660 866	[EUR]
C_I	1 321 731	991 299	660 866	330 433	[EUR]
C_{Salary}		40 000			[EUR/a]
$C_{Service}$		10 000			[EUR/a]
CoH	8.68	6.54	4.28	2.25	[EUR/MWh]

Before using these results in order to compare CoH including investment for HTHP, the comparison is first made without investment costs for both heat supply systems, as shown in Figure 18. Considering both energy prices, one can see that electricity prices show a more volatile character than gas prices. The lowest electricity prices occurred in 2004 at 28 EUR/MWh, whereas the peak was in 2008, at 66 EUR/MWh. The gas price varies between 13 EUR/MWh in 2004 and 29 EUR/MWh in 2013. The constellation of both energy prices influences operational costs of both heat supply systems, although GT-CC depends on both prices and HTHP is attached to electricity price.

By first comparing both red lines with each other, one can see that the operational costs for driving mode with GT is favorable for the operator as long as electricity prices are high. Lower electricity prices cause an approach between both lines. An electricity price of about 37 EUR/MWh is the point, where costs for both driving modes are almost equal. A slight advantage for the operating GT can be identified, though. Since the GT-CC with GT in operation is at least as cheap as without GT, the further comparison is only made between GT-CC-mode and HTHP. By comparing these two lines, namely the red GT-CC with the blue HTHP, one can see, that the operational costs for the HTHP are below those of the GT-CC since 2009, which is caused by a heavy price decline for electricity. Therefore, the GT-CC's revenue for electricity and the operational costs for HTHP fall. The biggest gap between both lines accounts about 18 EUR/MWh and can be identified in 2013, when gas price had a peak. Since 2013, the gas price shows a steady downwards trend, whereas electricity price increase since 2016, by causing costs for both systems to move towards each other again in the recent past, although HTHP still operates with a cost advantage. From 2004 until 2006 as well as in 2008, the GT-CC had lower operational costs due to high electricity prices. 2005 the GT-CC made profit over the whole year at a price level of 4 EUR/MWh.

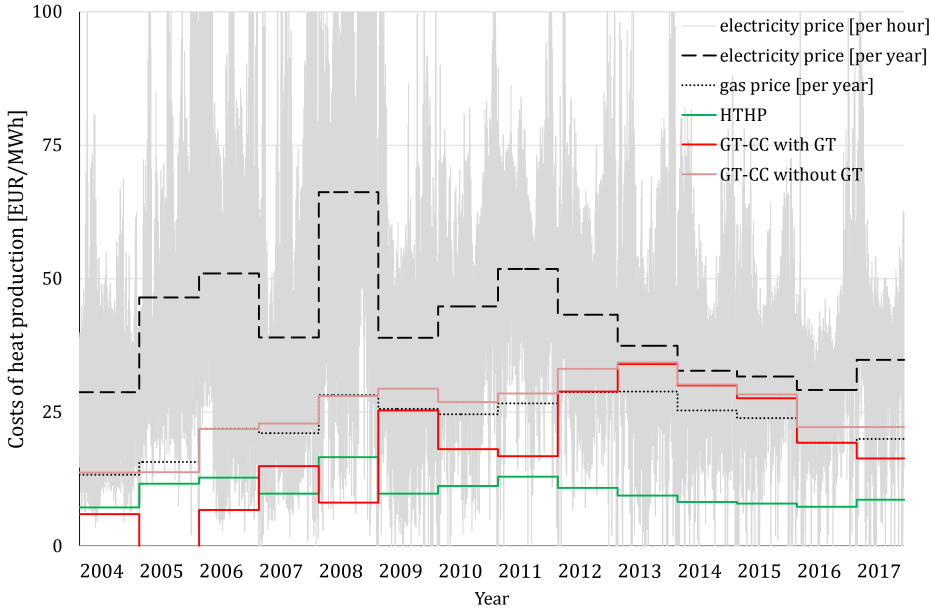


Figure 18: Operational costs of heat for GT-CC with GT and without GT as well as HTHP, depending on electricity and gas prices from 2004-2017.

If investment costs are included in the analysis, the results are slightly different. Figure 19 shows again costs of heat production for the GT-CC in contrast to HTHP, including investment for a newly installed HTHP according to Table 16. The four green lines for the HTHP stand for investment costs A,B,C and D and the graph is again considering a time window from 2004 until 2017. In 2007, 2010, 2011 and 2017 the height of investment change the outcome, weather GT-CC or HTHP would be cheaper over the whole year.

5.4 Production share between GT-CC and HTHP

For answering the fourth research question about the production share, Figure 20 is introduced. Both depicted bars show the production share in percent of HTHP and GT-CC, whereas the red one stands for the GT-CC, and the green one for the HTHP. A high production share for HTHP can be distinguished when gas prices are relatively high and electricity prices are relatively low. There were two years in which GT-CC proved to be the predominant heat supply system, which was in 2005 and 2008, when gas and electricity price where far apart from each other. The other years, HTHP had at least a production share of 45 percent and was the favorable heat supply system most of the time. Since 2009 production share of HTHP did not fall below 70 percent and mostly was around 90 percent, especially in the last years. A closer look into the gas and electricity price history shows, that gas prices steadily increased over the

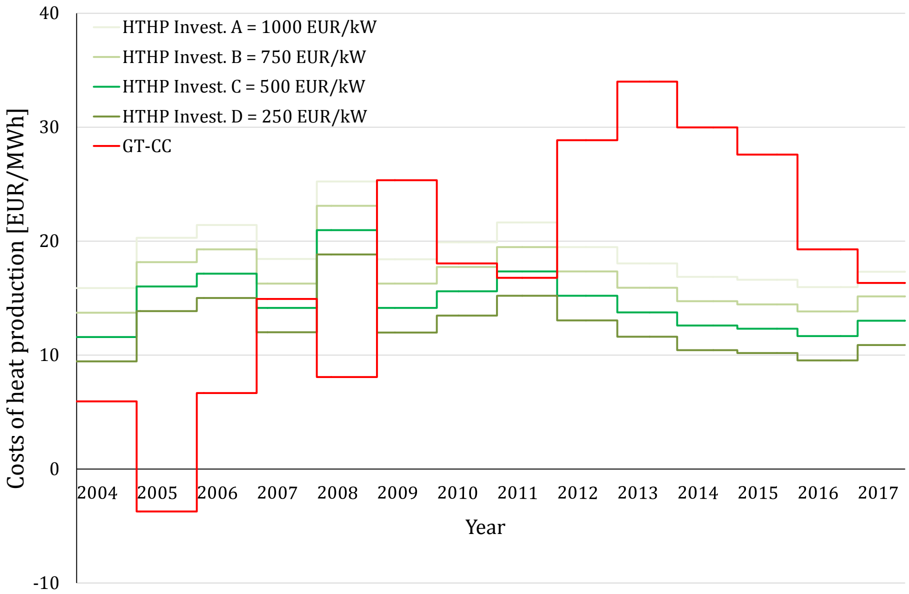


Figure 19: Comparison of the costs of heat for GT-CC and HTHP from 2004 to 2017. The costs of the HTHP include investment costs of 500 EUR/kWh as well as internal fix costs

chosen time window in a quite constant manner, whereas electricity prices were more volatile and show a steady decline from 2011 since 2016. Due to the fact that gas prices did also fall since 2013, the share of production for HTHP did not increase. The development since 2015 shows that GT-CC production share grows, because both energy prices diverge from each other.

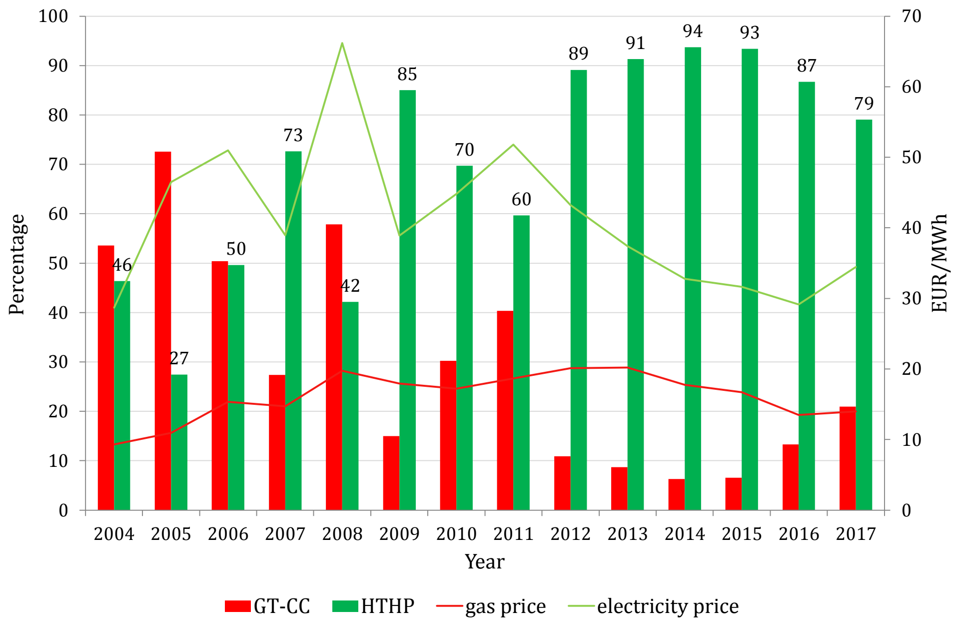


Figure 20: Theoretical share of production of HTHP an GT-CC in a coupled heat supply set up for an Austrian paper mill.

5.5 Cost report, payback time and savings

In order to create awareness about the range of costs for heat supply in this dimension, operational costs for HTHP and GT-CC are introduced in Table 17 on a levelized basis as well as in absolute numbers. The combined driving mode allows the operator to circumvent very high hourly CoH for GT-CC or HTHP and can decide for the given situation, which supply system should perform. Hourly costs for GT-CC can range up to 113 EUR/MWh, but also drop to -703 EUR/MWh, which would allow very high hourly profits. CoH for HTHP can be higher per hour up to 222 EUR/MWh and on the other hand drop to -16 EUR/MWh. If the operator is able to switch between the heat supply systems, very high savings can be gained. The potential savings due to a combined set up in comparison to a single heat production by GT-CC range from 0.9 Mill EUR to 11.6 Mill EUR and would result in heat supply costs between -2.6 Mill EUR and 4.5 Mill EUR. The yearly costs of heat supply for GT-CC range thereby from a revenue of 1.7 Mill EUR in 2005 up to 15.6 Mill EUR actual costs in 2013. Costs for HTHP vary between 3.3 and 7.7 Mill EUR. The potential savings are used to calculate pay back times for a new HTHP, if it is used in a coupled driving mode with a GT-CC. Depending on investment costs, pay back times according to Figure 21 are reachable in a time range from 2004 until 2015. Investments after 2015 would not pay off in the considered time frame, and therefore are not depicted. High investment costs (Invest. A) cause payback times over 7 years, depending on the year of investment. It is conspicuous that pay back times drop over the time range, which is caused by increasing savings over the years. Due to the high acquisition costs of Invest. A, high savings from 2011 to 2015 would not last for pay back in the considered time frame. Invest. B shows similar payback times which range from 5 years in 2011 to 9 years in 2004. A later investment would not pay back in the considered time frame. Invest. C and D allow payback times less than 5 years after 2008. Invest D drops down to payback times of 2 years, due to high savings since 2012.

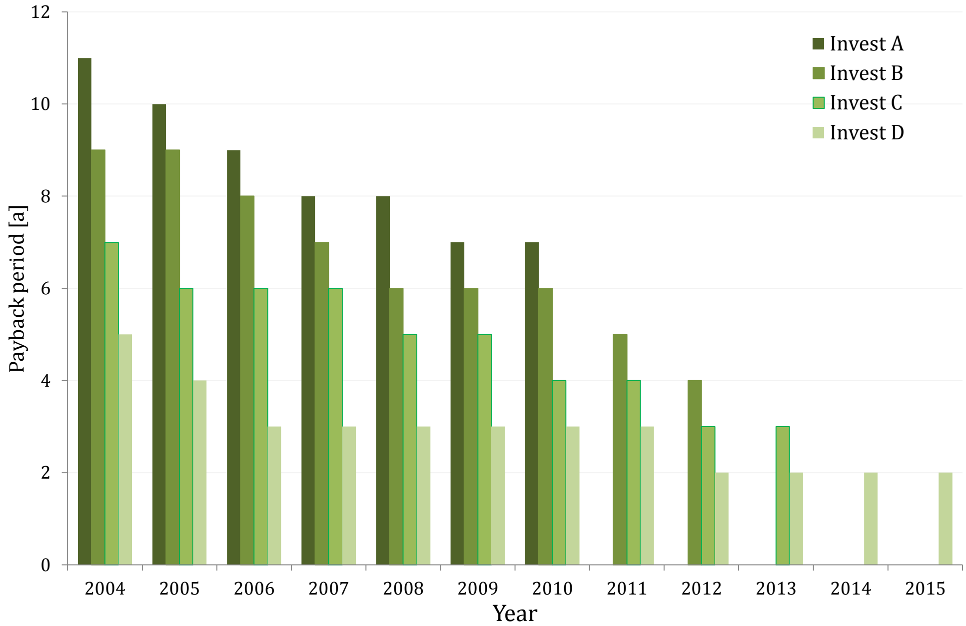


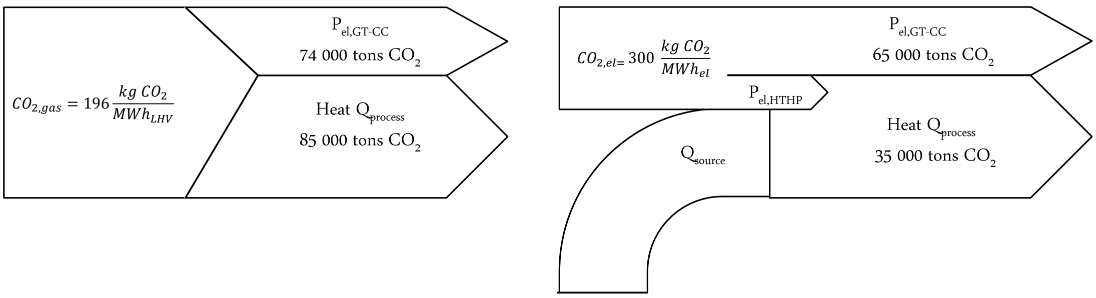
Figure 21: Pay-back times in years of an HTHP operating in an Austrian paper mill form 2004 - 2017.

Table 17: Cost report for heat supply of HTHP and GT-CC as well as electricity price from 2004 - 2017

	2004	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
hourly maximum and minimum electricity price [EUR/MWh]														
min.	0	0	0	0	0	0	0	0	0	-33	-65	-23	-51	-43
max.	100	425	888	520	248	123	124	124	176	120	88	78	101	143
hourly maximum and minimum operational costs [thousand EUR]														
max. GT-CC	1.6	2.2	3.2	3.1	4.0	3.7	3.6	3.9	4.2	4.9	6.3	4.8	4.8	3.8
max. HTHP	1.1	5.8	11.1	7.3	3.2	1.8	1.6	1.7	2.7	1.8	1.3	1.1	1.6	2.3
min. GT-CC	-2.3	-17.8	-35.1	-22.1	-7.6	-2.5	-2.6	-2.5	-5.1	-2.1	-720	-688	-2.6	-4.8
min. HTHP	0	0	0	0	0	0	0	0	0	-417	-875	-371	-698	-493
hourly maximum and minimum operational costs [EUR/MWh]														
max. GT-CC	30	36	50	48	64	58	56	61	66	93	113	73	87	82
max. HTHP	25	106	222	130	62	31	31	31	44	30	22	20	25	36
min. GT-CC	-55	-325	-703	-393	-146	-46	-49	- 44	-83	-36	-17	-12	-41	-76
min. HTHP	0	0	0	0	0	0	0	0	0	-8	-16	-6	-13	-11
Costs and Savings per year [million EUR]														
GT-CC	2.7	-1.7	2.8	6.9	3.77	11.6	8.4	7.7	13.2	15.6	13.8	12.8	9.0	10.2
HTHP	3.3	5.4	6.0	4.5	7.7	4.5	5.2	6.00	5.0	4.4	3.8	3.7	3.4	3.2
Combi	0.9	-2.6	-0.6	0.6	0.2	3.4	3.8	4.3	4.5	4.0	3.6	3.5	2.7	2.1
Savings	1.8	0.9	3.4	6.3	3.6	8.2	4.6	3.5	8.8	11.6	10.2	9.3	6.2	3.8

5.6 Comparison of carbon dioxide footprint of HTHP and GT-CC

The comparison of the yearly carbon dioxide emissions of HTHP and GT-CC operating in the paper company is shown in Fig. 22. One can see that HTHP has advantage over the GT-CC. Despite lower specific CO_2 emissions for natural gas, the high amount of gas consumption causes a larger CO_2 footprint of the GT-CC. Overall, the yearly natural gas consumption ($V_{in,gas}$) of the company accounts approximately 82 Mill Nm^3, which goes with a carbon footprint of 159 000 tons CO_2. A HTHP would consume 116 GWh ($P_{el,HTHP}$) over a whole year, which would cause a carbon footprint of 35 000 tons of CO_2. Additional 65 000 tons CO_2 are caused by drawing electricity from the grid ($P_{el,GT-CC}$=218 GWh), since the GT-CC is not operating. Hence, according to these calculations, heat production with GT-CC at the considered paper company causes 159 000 tons of CO_2 and heat production with HTHP causes 100 000 tons of CO_2 over a year. As long as the CO_2 emission footprint of the used electricity is less than 480 kg/MWh, the HTHP has a smaller CO_2 foot print than GT-CC. The calculations are based on Equations (26) and (27).



(a) GT-CC (b) HTHP

Figure 22: Yearly carbon dioxide emissions of a GT-CC (a) and a HTHP (b) in an Austrian paper mill

6 Discussion and Conclusion

6.1 Discussion

In the course of the discussion of the results from Chapter 5, the posed research questions are answered. Thereby, a critical reappraisal of the stated assumptions is made in order to pay attention to potential instability factors which could cause different outcomes in the results. The 1^{st} and the 2^{nd} research question concerning economic performance of a HTHP beside a GT-CC can be answered by recapitulating the results in Figure 18. In the years 2012 until 2015, the CoH for HTHP amounted to 8-11 EUR/MWh and were below CoH for GT-CC, which varied in a range of 28 to 34 EUR/MWh. It is important to understand though, that this constellation of costs is due to energy prices. The gap between gas and electricity price decides, which heat supply system is preferable. Since both prices behaved almost complementary between 2013 and 2016, CoH for HTHP stayed below those of GT-CC. In 2016 electricity price did not drop as much as gas prices and in 2017, electricity prices increased more than gas prices, which caused both cost lines to approach each other. Costs for GT-CC dropped to 19 and 16 EUR/MWh whereas costs for HTHP were at 7 respectively 9 EUR/MWh. CoH for HTHP react more inelastic to a change of electricity prices than GT-CC do. This can be explained by the characteristic of a HTHP, which derives most of its consumed energy from waste heat. Thus, it can happen that a strong increase in electricity price cause heat supply costs for GT-CC to drop below the costs of HTHP and in case of 2005 be profitably over the whole year. In summary, one can say that in the considered time frame from 2004 to 2017, the HTHP had cost advantages in comparison to GT-CC. Nevertheless, due to the more volatile character of the CoH for GT-CC, it can occur, that CoH for GT-CC drop below those of HTHP. Subsequently, the 3^{rd} research question comes into the focus, which takes investment costs into consideration. Considering Table 16, one can see that CoH for HTHP could increase between 2.3 and 8.7 EUR/MWh, depending on the height of acquisition costs. This means for the comparison of CoH for both heat supply systems that they can be so close together that the height of investment costs decides, which system produces the cheapest heat (Figure 19). The so far delivered achievements show that HTHP periodically can operate less cost intensive than a GT-CC. Figure 20 lays focus on the issue of production share of a HTHP in a coupled driving mode with GT-CC, which is adressed by research question 4. As it is explained above, production share for GT-CC was predominant especially in 2005 and 2008. The rest of the considered time frame shows the HTHP has at least a share of 45% and did not drop below 70% since 2009. The share was around 90% between 2012 and 2015, and experienced a slight decline since 2016. The production share allows savings in comparison to single supply mode of a GT-CC (Table 17) and leads to calculation of pay-back times, what is addressed by research question 5. Figure 21 shows that payback times below 5 years are possible, but depend on the specific investment costs for HTHP. Higher investment costs can cause amortization periods of around 11 years and make the HTHP to be economically less attractive. In case of low investment cost, payback times below 5 years are possible and in times of high savings even 2 years are enough for the HTHP to be repaid. What can also be concluded is that 2012 was the best time for investment, due to very high savings in the following years, according to Table 17.

In order to answer research question 6, the results are rolled up from a critical point of view by simultaneously distinguishing parameters of uncertainty that could cause different economical outcome for the HTHP.

A main issue to consider are the modelled heat supply systems, which are based on several assumptions. The modeled GT-CC has an efficiency factor of about 82.37%, which is rather inefficient in comparison to modern GT-CC systems that are able to reach efficiency factors around 90%. A possible reason can be distinguished, by considering the single cycle efficiency of the assumed GT, which is rather low at 30%. Modern GT are able to reach around 40% single cycle efficiency and would cause higher electricity yields. In further consequence, a reduction of afforded natural gas would be possible and result in lower operational costs for the GT-CC. However, the considered system is energetically not state of the art, possibly due to its heat-oriented operating mode. Furthermore, the system was built in 1993 and technology has developed since then. Another factor to mention is supplemental firing, which is not considered in the model. If it would be possible to take it into account as well, the heat demand curve (Figure 16) may show a slightly different outcome along the considered time frame.

Concerning the modeled HTHP, several assumed parameters could possibly vary and cause a change in operational costs of heat production. The assumed COP of 4 for the HTHP requires on the one hand constant heat delivery from the heat source, and on the other hand a technically optimized HTHP in a very high temperature range, which has never been technically realized on an industrial level. Yet, in the light of the latest development in R&D in the field of HTHP, the chosen assumptions seem to be achievable in the future. An important issue for HTHP is a sufficient amount of source heat in order to function efficiently. The collected data about the waste heat streams in paper industry do not ensure, that the HTHP can be supplied sufficiently, although they indicate that enough waste heat could be available. It is therefore advisable to make a closer investigation at the paper production site.

The CoH for investment include rather conservative assumptions and could possibly be different. The chosen investment costs for HTHP are based on a mixture of literature and manufacturers data plus an estimation from the author. Which costs would really occur for an installation of a HTHP at this capacity range still includes a factor of uncertainty. What is hard to estimate are for example costs that are related to the location of implementation, as well as costs of interest. Furthermore, life expectancy of 20 years is not verified and would influence costs for depreciation. The outcome of lower life expectancy would be higher CoH and therefore less economic advantage for a HTHP.

Since hourly electricity prices can vary very strongly on the spot market (Figure 18), a coupled heat supply set up bears a lot of potential for saving money. The operator would have the advantage to choose the way of cheapest costs by comparing both energy prices with each other. This could enable him to bypass very high hourly costs and yield hourly revenue due to negative, or very high electricity prices. Even if the

resulted costs, introduced in Table 17, should not be taken literally, it is the scale of costs though, which is worthy of remark. What is to mention is that stated costs do not include start-up and shut-down times.
A final issue that needs to be addressed is the initial motivation of this thesis, which is to investigate the economical feasibility of a heat supply system that has the potential for less carbon emissions. This aim is also under the need of critical consideration. Since the emission foot print of electricity in Austria presently lays at 300 kg CO_2/MWh, savings up to about 59 000 tons of CO_2 per year in the paper company are possible. Due to a lack of electricity from the GT-CC, the operator needs to draw electricity from the grid, which enlarges the carbon emission foot print of the HTHP. As long as the CO_2 footprint of the used electricity for the HTHP is less than 480 kg/MWh, savings are guaranteed. What is to mention though is that for GT-CC only chimney emissions are considered. Prior preparation of the natural gas are not considered in these calculations, but would possibly cause a larger CO_2 emission foot print for the GT-CC. An important factor to consider in this concern is the used refrigerant. In this thesis, water is assumed, which has a GWP of 0. If conditions for heat supply would be different, it might be that a refrigerant with a higher GWP is chosen what in turn would affect the CO_2 footprint of the HTHP system.

6.2 Conclusion

The present work gives insight into the economic performance of a HTHP at a COP of 4 besides a GT-CC in an industrial process, namely a drying process in an Austrian pulp and paper mill with a yearly heat demand of 463 GWh. The outcome of the research shows that HTHP can perform economically compared to the GT-CC. What is to mention though is that HTHP benefited from low electricity prices on the spot market in the last years since 2012, which caused a cost advantage towards HTHP-supply. Due to the volatile character of electricity prices CoH for HTHP can rise very fast and cause the GT-CC to be the preferable heat supply system. In order to use such price fluctuations, an operator could combine both heat supply systems in a coupled driving mode to supply heat with HTHP in case of low electricity prices, and supply with GT-CC in case of high electricity prices. This would allow him to bypass cost peaks and therefore obtain savings compared to single supply mode. Hourly production costs can rise up to 222 EUR/MWh for HTHP, respectively 113 EUR/MWh for GT-CC. On the other hand they can also fall below zero, which would allow the operator to make profits. According to research results investment costs are assumed between 250 EUR/MWh to 1 000 EUR/MWh and would cause total investment costs between 13 million and 53 million EUR in this certain case. In such a coupled driving mode, acquisition for HTHP would have amortize in a time range between 2-5 years since 2012, depending on the investment cost. The energy price constellation towards HTHP in the last years resulted in a production share for HTHP around 90% from 2012 until 2016.
Concluding these explanations, HTHP in industrial processes such as a pulp and paper mill have economic potential to compete with GT-CC, which is a wide-spread heat supply technology. As an economically attractive possibility for operators participating at the electricity spot market, a coupled driving mode can create high savings in order to repay acquisition costs for HTHP within reasonable time frames of 2-5 years. A

positive effect from ecological point of view would be possible CO_2 savings that are reachable as long as the CO_2 emission foot print of the used electricity, to operate the HTHP, is below 480 kg/MWh. Therefore, implementing this technology at industrial scale has the potential to positively contribute to reach the announced climate goals.

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List of Figures

1 Industrial share of energetic end use in Austria and estimated process heat demand in 2016, according to Rieberer et al. and Bundesministerium für Wissenschaft Forschung und Wirtschaft [2, 3] 9

2 Simplified HP process with its four main ingredients: evaporator, compressor, condensor and expansion valve [14] 14
3 T,s-Diagram of an left-handed ideal carnot process [13]. 14
4 Ideal Carnot factor ($\varepsilon_{c,HP}$) of an ideal Carnot cycle and realistic efficiency factor (ε_{real}) of a heat pump cycle depending on the difference between T_1 and T_0, for a heat source temperature T_0=295.15 K 16
5 Classification of Heat Pumps by their different driving force [17] . . . 18

6 Heat demand in Austria devided into three temperature ranges, [2] . . 26
7 Energy use of U.S. pulp manufacturing by end use energy type in 2002, according to Kramer et al. (2009) and Jacobs and IPST (2006) [6, 34] 32
8 Energy use of U.S. paper manufacturing by end use energy type in 2002, according to Kramer et al. (2009) and Jacobs and IPST (2006) [6, 34] 32

9 IPSEpro system architecture. 36
10 Simplified scheme of a GT-CC with heat recovery boiler and back-pressure steam turbine, (GT-CC-mode). 38
11 Simplified scheme of a heat recovery boiler and back-pressure steam turbine, (ST-mode). 38
12 Simplified drawing of the modeled HTHP process with polytropic inter cooling in IPSEpro 41
13 Schematic account of methodological approach for economic comparison 43
14 Graphical account of the resulting set up of operational modes to supply the heat demand of an austrian paper mill, in reliance on possible influencing parameters. 46
15 log(p)-h-Diagram of R718 47

16 Graphic account of heat demand as well as electrical output of an Austrian paper mill in 2013 50
17 Energy input of GT-CC with GT, GT-CC without GT and HTHP in MW for 8752 hours to cover the heat demand of an Austrian paper mill. 52
18 Operational costs of heat for GT-CC with GT and without GT as well as HTHP, depending on electricity and gas prices from 2004-2017. . . 54
19 Comparison of the costs of heat for GT-CC and HTHP from 2004 to 2017. The costs of the HTHP include investment costs of 500 EUR/kWh as well as internal fix costs 55

20 Theoretical share of production of HTHP an GT-CC in a coupled heat supply set up for an Austrian paper mill. 56
21 Pay-back times in years of an HTHP operating in an Austrian paper mill form 2004 - 2017. 57
22 Yearly carbon dioxide emissions of a GT-CC (a) and a HTHP (b) in an Austrian paper mill 59

23 Email conversation with Dr. Tim Hamacher, General Manager R&D at Viking Heat Engines. 74
24 Screenshot of received data from an austrian pulp and paper mill. . . 75

List of Tables

1 Collection of the presently implemented compressors for high temperature use and high performance level [10, 18]. 19
2 Classification of refrigernats into six safety groups 20
3 Potential refrigerants for high temperature use. 21
4 HTHP collection of producers and R&D projects. 23

5 Common industral processes with reachable temperature ranges for HTHP and technical potential in Germany [2, 9, 28, 29]. 27
6 Fuel and electricity consumption in Austria's pulp and paper industry in the years 2000, 2010 and from 2014 until 2016 [4, 30]. 31
7 Temperature range of typical waste heat streams in paper industry, [35, 36] 33
8 Two paper machines in an Austrian pulp and paper mill. 33

9 Summary of received data about a GT-CC in an Austrian paper mill . 35
10 Technical parameters of the modeled GT-CC 40
11 Technical parameters of the modeled HTHP 41
12 Combined heat and power (CHP) operation through 2013. 42
13 Assumptions for calculating CH for a newly installed HTHP with four different heights of investment costs. 45

14 Results of the dynamic simulation of the GT-CC with two different driving modes: GT-CC-mode and ST-mode. 50
15 Energy input and output of HTHP and GT-CC based on hourly heat output, resulting from a dynamic simulation of an operating GT-CC in an austrain paper mill with gas flow data from 2013. 51
16 Results of calculating CoH for a newly installed HTHP with four different heights of investment costs. 53
17 Cost report for heat supply of HTHP and GT-CC as well as electricity price from 2004 - 2017 58

7 Appendix

Gmail - Infos zum HeatBooster https://mail.google.com/mail/u/0/?ui=2&ik=c1bf33903a&jsver=Rh8ki...

Gmail **Thomas Detzlhofer <thomas.detzlhofer@gmail.com>**

Infos zum HeatBooster

Dr. Tim Hamacher <Tim.Hamacher@vikingheatengines.com> 27. Februar 2017 um 11:08
An: Thomas Detzlhofer <thomas.detzlhofer@gmail.com>
Cc: Andreas Mück <andreas.mueck@vikingheatengines.com>

Guten Tag Herr Detzlhofer,

ein sehr interessantes Thema haben sie sich da für ihre Masterarbeit ausgesucht. Unser Heatbooster ist noch in der Entwicklung und deswegen kann ich ihnen noch keine detaillierten Angaben zu den Investitionskosten machen. Auf Grund unseres flexiblen Kolbenkompressors, der eine Ableitung unseres ORC Expanders ist, sind wir sehr frei in der Wahl unserer Arbeitsmedien. Je nach Temperaturniveau nutzen wir z.B. R245fa, R1336mzz oder auch R1233zd.

Im Herbst dieses Jahres werden wir mit unserem System HBS4 in die Erprobungsphase mit verschiedenen Industriepartnern gehen. Das System hat eine elektrische Anschlussleistung von 40kW und liefert je nach Anwendung bis zu knapp 200kW thermische Energie. Hierfür liegt aktuell der Endkundenpreis in der Demonstrationsphase zwischen 100.000€ und 150.000€. In der Serienfertigung wird dieser Preis noch sinken. Weiterhin sind größere Anlagen mit elektrischer Leistung zwischen 100 und 400 kW in der Planung, die im spezifischen Invest noch einmal deutlich darunterliegen werden.

Gerne würden wir mehr über die Resultate ihrer Arbeit erfahren, wenn sie dann vorliegen.

Mit freundlichen Grüßen

Best regards

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1 von 2 31.10.2017, 23:49

Figure 23: Email conversation with Dr. Tim Hamacher, General Manager R&D at Viking Heat Engines.

B	C	D	G	H	I	J
			bezogen		Abweichung	
Datum	von	bis	MWh	Nm^3/h	[%]	MWh/h
01.01.2013	00:00	01:00	158	14310	-0,01 %	-2,32
	01:00	02:00	159	14400	-0,03 %	-4,43
	02:00	03:00	160	14480	-0,03 %	-5,31
	03:00	04:00	160	14420	-0,03 %	-4,65
	04:00	05:00	160	14460	-0,03 %	-3,99
	05:00	06:00	161	14570	-0,04 %	-6,31
	06:00	07:00	162	14650	-0,05 %	-7,20
	07:00	08:00	159	14320	-0,02 %	-3,54
	08:00	09:00	162	14630	-0,05 %	-8,08
	09:00	10:00	160	14430	-0,04 %	-5,87
	10:00	11:00	161	14530	-0,05 %	-6,97
	11:00	12:00	159	14330	-0,03 %	-4,76
	12:00	13:00	158	14270	-0,02 %	-2,99
	13:00	14:00	157	14200	-0,01 %	-2,21
	14:00	15:00	149	13440	-0,07 %	-9,30
	15:00	16:00	142	12860	-0,02 %	-2,88
	16:00	17:00	144	13040	-0,04 %	-5,98
	17:00	18:00	144	12970	-0,04 %	-5,20
	18:00	19:00	143	12930	-0,03 %	-4,76
	19:00	20:00	143	12940	-0,04 %	-4,87
	20:00	21:00	161	14560	-0,06 %	-9,52
	21:00	22:00	155	13980	-0,01 %	-1,99
	22:00	23:00	160	14440	-0,05 %	-7,08
	23:00	00:00	159	14380	-0,04 %	-6,42
02.01.2013	00:00	01:00	158	14310	-0,02 %	-3,43

Figure 24: Screenshot of received data from an austrian pulp and paper mill.

MATLAB-IPSEpro interface

```
app=actxserver('PSE.application');

proj=invoke(app,'openProject', 'C:\Users\admin\[...]);
j=0;

%% Input and Output for Ipse

KESSEL_INP=invoke(proj, 'findObject', 'u_source_g_001'); % combustion chamber
WUE_OUT=invoke(proj, 'findObject', 'u_htex_gw_002'); % heat exchanger
Elec_OUT_ST=invoke(proj, 'findObject', 'u_gen_el_002'); % electric output steam turbine
Elec_OUT_GT=invoke(proj, 'findObject', 'u_gen_el_001'); % electric output gas turbine

%% Defining variables

LEISTUNG_WUE=invoke(WUE_OUT, 'finditem', 0 , 'Q_trans'); %heat output of heat exchanger
MASS_KESSEL=invoke(KESSEL_INP, 'finditem', 0 , 'nvolflow');%massflow heat exchanger
Leistung_Elec_ST=invoke(Elec_OUT_ST, 'finditem', 0 , 'power'); %safe in  file
Leistung_Elec_GT=invoke(Elec_OUT_GT, 'finditem', 0 , 'power'); %safe in file
LEISTUNG_MIT_GT = NaN(8752,1);
LEISTUNG_Elec_ST_MIT_GT = NaN(8752,1);
LEISTUNG_Elec_GT_MIT_GT = NaN(8752,1);

for i =1:2931 %GT-CC mode

   invoke(MASS_KESSEL,'setStatus',1,MASSFLOW_MIT_GT(i));

   run=invoke(proj, 'runSimulation',0);
   if run >1
      run;
      j=j+1;
      save=invoke(proj, 'save');

   else
   invoke(proj,'importEstimates',0);
   LEISTUNG_MIT_GT(i)= invoke(LEISTUNG_WUE, 'resultValue');
   LEISTUNG_Elec_ST_MIT_GT(i)= invoke(Leistung_Elec_ST, 'resultValue');
   LEISTUNG_Elec_GT_MIT_GT(i)= invoke(Leistung_Elec_GT, 'resultValue');
   end

end

for i =1:5821 %ST-mode

   invoke(MASS_KESSEL,'setStatus',1,MASSFLOW_MIT_GT(i));

   run=invoke(proj, 'runSimulation',0);
   if run >1
      run;
      j=j+1;
      save=invoke(proj, 'save');

   else
   invoke(proj,'importEstimates',0);
   LEISTUNG_MIT_GT(i)= invoke(LEISTUNG_WUE, 'resultValue');
   LEISTUNG_Elec_ST_MIT_GT(i)= invoke(Leistung_Elec_ST, 'resultValue');
   LEISTUNG_Elec_GT_MIT_GT(i)= invoke(Leistung_Elec_GT, 'resultValue');
   end

end
  app.release
```