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Research Article

A comparative study of sustainable industrial heat supply based on economic and thermodynamic factors

Thermodynamischer und ökonomischer Vergleich nachhaltiger industrieller Prozesswärmebereitstellungsmethoden

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Summary

Three different process types of heat supply for industrial production processes requiring low temperature heat at 140°C are analyzed and compared with each other. The thermodynamic and economic efficiency of a gas turbine process with a heat recovery boiler (GT), a gas and steam turbine combined cycle process with a back-pressure turbine (GT-CC) and a high temperature heat pump (HTHP) system recovering waste heat from humid exhaust air between 90°C and 50°C are assessed based on energy flows, exergy flows and costs of heat provided as 4 bar (abs) saturated steam. The economic analysis bases on the comparison of the consumption-related costs of heat, the capital-related costs of heat and the operation-related costs of heat. The payback-times are calculated for different HTHP investment cost levels (1000 EUR/kW_Q, 750 EUR/kW_Q, 500 EUR/kW_Q and 250 EUR/kW_Q). To evaluate the effects of fluctuating energy costs, a sensitivity analysis with varying gas and electricity prices has been carried out.

The results show that the HTHP system, even with modest performance assumptions, has a higher exergetic efficiency than the GT or the GT-CC process. For the consumption-related costs, the economic calculation shows that the operation of a HTHP, working with a coefficient of performance (COP) of four and for a natural gas price of 25 EUR/MWh, is the cheapest way of heat production as long as the electricity price is lower than 45 EUR/MWh. An electricity price above 45 EUR/MWh makes a GT-CC process more favorable. For the period from January 2013 until June 2016, the total costs of heat and the payback times, based on real gas and electricity prices from the EEX, are calculated and analyzed. For overall cost-optimized heat supply, the results show that the share of heat provided by the HTHP system varies between 45% and 76% between January 2013 and June 2016. Especially in 2013 and 2014, the economic conditions for operating heat pumps were very good. Since October 2015, the natural gas prices have seen a decrease and the economic conditions shifted again favoring the industrial heat supply with combined heat and power systems.

Keywords: heat pump, gas turbine, combined heat and power, pulp and paper industry

Zusammenfassung

In dieser Studie werden drei unterschiedliche industrielle Prozesswärmebereitungsmethoden (Gasturbine, Gas- und Dampfturbine und Hochtemperaturwärmepumpe) anhand exergetischer und ökonomischer Parameter verglichen. Die ökonomische Analyse erfolgt auf Basis der verbrauchsbezogenen Energiekosten, den Kapitalkosten und den Servicekosten.

Die Ergebnisse zeigen, dass der exergetische Wirkungsgrad der Hochtemperaturwärmepumpe, auch bei unvorteilhaften Konditionen, höher als für die gasbetriebenen Systeme ist. In der untersuchten Periode von Januar 2013 bis Juni 2016 lag der Erzeugungsanteil der Wärmepumpe zwischen 45 % und 76 % in Abhängigkeit der Investitionskosten. Diese Studie soll als Entscheidungshilfe für Anlagenbetreiber dienen, in Zeiten von niedrigen Strompreisen die Prozesswärme elektrisch mittels Wärmepumpe, oder in Zeiten mit hohen Strompreisen mittels Kraft-Wärmekopplung Strom und Wärme zu produzieren, und damit auch zur Glättung von Fluktuationen im Stromnetz beizutragen.

Schlagworte: Wärmepumpe, Gasturbine, Kraft-Wärme-Kopplung, Papierindustrie

1. Introduction

The EU climate change goals are ambitious and represent a major challenge for the European economy. The reduction of CO_2 emissions, without constricting industry, requires an increase in energy-efficiency along with a shift to energy supply from renewable sources. A well-established and economically advantageous way for producing industrial heat is the combined heat and power plant (CHP). On the background of decreasing electricity prices on the liberalized electricity market, the question arises, how process heat should be produced, if CHP plants get uneconomic because using gas to produce power, even with a high efficiency, is more expensive than direct production of heat from (fossil) fuels. Since heat-driven CHP units effectively provide electricity with boiler efficiency, that is, about 90% based on the heating value of the additionally consumed fuel, this means that electricity from the grid is also cheaper than heat from fossil fuel in such a situation. Practically, during the periods of low electricity market prices, operators have already switched to heat-only production from industrial CHP plants recently in central Europe. However, low-temperature process heat can potentially be produced more cost-efficiently in times of low electricity prices using heat-pumps provided waste heat is available at a reasonable temperature level. As another potential benefit for industrial operators in view of future restrictions of greenhouse gas emissions, heat pumps can be considered as CO_2-free heat-supply systems if they are operated with green electricity (Lambauer et al., 2008) (IEA Heat Pump Centre, 2014). Since there is a high temperature demand in industry in the range 100°C to 150°C, the CO_2 emission reduction potential is high in this field. According to (Wolf et al., 2014) the latest developments in the market for high temperature heat pump technology (HTHP) allow for heat sink temperatures up to 140°C, although further developments are foreseen (Chamoun et al., 2012; 2014). Several works focus on the optimization of heat and power production through cogeneration plants (Kaviri et al., 2013; Sahoo et al., 2013; Soltani et al., 2013; Atmaca and Yumrutaş, 2014), but comparing CHP with HTHP for industrial heat supply has not yet been examined in detail. This paper addresses the question of the exergetic performances of typical heat production processes in the industry (gas turbine, gas and steam turbine combined cycle and high temperature heat pump systems) as well as on the economic performance of such systems considering energy prices and investment costs. For a tentative industrial setup including all three heat generation options, an optimization calculation has been carried out with the target function of minimized heat supply costs for the period between January 2013 and June 2016. Based on real energy price data. The industrial case study has been placed in the pulp and paper industry. Combined heat and power systems are common heat production technologies in the whole field of wood processing industry (Uran, 2006), and the requested process temperatures can be produced with HTHP systems. The outcome of the present study gives indications whether investing in a flexible heat generation setup may make sense in the framework of volatile electricity markets.

2. Methodology

The methodology of this paper contains process simulation, economic comparison and optimization. In a first step, the process models of different heat supply approaches are developed. These simulations allow for a comparison on a thermodynamic basis. In a second step, economic parameters like the specific consumption related costs of heat, the costs of heat dependent on different acquisition costs of the HTHP and the pay-back times of the HTHP are calculated. The total costs of heat generation (CoH) are calculated for each generation scenario based on real world natural gas and electricity prices for the 2013-2016 period. A simple comparison-based optimization shows the relative share of the heat generation technologies in the investigated period.

2.1 Process modelling and simulation

In the first step, a process model of the chosen heat supply processes is set up using the process simulation software IPSEpro. Based on mass and energy balances, a system of equations is generated and solved using a Newton-Raphson-type root-finder. The process simulation allows for concise calculation of all needed specific thermodynamic data, like the specific thermo-chemical energy (based on lower heating value and temperature-dependent heat capacity) and the specific exergy (based on an equilibrium reference environment by (Ahrendts, 1979), which has been recommended by Baehr and Kabelac (2012) of the process streams). For the simulation of the heat supply processes, some assumptions are necessary, which are shown in Table 1. Heat exchanger pressure drops are not considered in the calculations. The parameters of the gas

Table 1. General performance assumptions for key process components
Tabelle 1. Leistungsangaben und Wirkungsgrade wichtiger Prozesskomponenten

Parameter	Value	Unit
η_{Compr}	0.80	-
η_{motor}	0.97	-
$\eta_{SGT\text{-}800}$	0.39	-
$p_{ratio\ SGT\text{-}800}$	21.4 : 1	-
$T_{SGT\text{-}800,out}$	551	°C

Table 2. Technological setting for the heat supply processes for a paper mill
Tabelle 2. Technische Parameter zur Prozesswärmebereitung in der Papierindustrie

Parameter	Value	Unit
$T_{Feedwater}$	120	°C
$T_{Steam,\ Out}$	142	°C
$p_{Steam,\ out}$	3.8	bar(abs)
Δh	2232	kJ/kg
$\dot{m}_{Steam}$	44.8	kg/s
$\dot{Q}_{Process}$	100	MW

turbine depend on the performance data of the Siemens SGT-800 (53.0 MW) gas turbine (Siemens, 2016).
The process and working parameters are fixed according to Table 2 in order to compare the alternative technologies on a fair basis. The scope of all technologies is to produce heat for a typical industrial production process in the paper industry. The minimum outlet temperature to the heat sink is assumed with 141.8°C and a pressure level of 3.8 bar.

2.2 Process types for industrial heat supply

The following chapter explains the considered process types of thermodynamically efficient low-temperature heat generation, which will be further analyzed in the present study. A broad used technology for process heat supply are boiler systems, but because of high exergy losses, this technology is not examined in detail. For the basic comparisons, a boiler efficiency of 90% for calculating the costs of heat is assumed.

2.2.1 Gas turbine process with heat recovery boiler

The open gas turbine process (GT) converts the chemical energy of fuel into electricity and heat. With combined heat and power (CHP) units, the waste heat in the exhaust gas of the gas turbine may be used to supply industrial processes. The process consists of a compressor, a combustion chamber, a gas turbine, a waste heat boiler, a pump and a heat sink. In the first step, air is compressed, then, fuel is combusted in the pressurized air stream to increase the temperature and the hot exhaust gas is expanded in a gas turbine. The exergy in the exhaust gas is partly converted into electric power and the remaining enthalpy in the turbine of gas can be used to produce steam in a heat recovery boiler. The low-pressure heat recovery boiler comprises an evaporator, a steam drum and an economizer. The produced saturated steam is used to supply heat to industrial processes. The efficiency of the gas turbine process is evaluated with some key figures, especially the electric efficiency, the thermal efficiency and the exergetic efficiency. The electric efficiency (1) describes the conversion efficiency of the used fuel into electricity. For all calculations, complete combustion is assumed.

$$\eta_{el} = \frac{P_{el}}{\dot{m}_{Fuel}\, H_L} \tag{1}$$

The heat utilization efficiency (2) relates the heat, produced with the exhaust gas of the gas turbine process, which is used to supply heat to other processes.

$$\eta_{heat} = \frac{\dot{Q}_{Process}}{\dot{m}_{Fuel}\, H_L} \tag{2}$$

$$\eta_{total} = \frac{P_{el} + \dot{Q}_{Process}}{\dot{m}_{Fuel}\, H_L} \tag{3}$$

The total fuel utilization efficiency is shown in equation (3). Because mixing up heat and electricity as in equation (3) neglects the thermodynamic value of the energy forms, we introduce an exergy-based comparison in the following. The exergetic efficiency describes the conversion of input exergy into useful exergy. For combined heat and power plants, the exergetic efficiency includes, apart from the produced electric power, also the exergy stream of the usable process heat. Equation (5) shows the exergetic efficiency definition for the gas turbine process. Work and electricity have got 100% exergetic value. The exergy flow of the heat (4) is calculated as described below.

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_Q}\right) \dot{Q} \tag{4}$$

$$\zeta = \frac{P_{el} + \dot{E}_Q}{\dot{m}_{Fuel}\, e_{Fuel}} \tag{5}$$

The specific exergy at standard conditions (e_{Fuel}) is calculated based on the chemical exergy formulation according to (Baehr and Kabelac, 2012) based on the equilibrium environment by (Ahrendts, 1979).

2.2.2 Gas and steam turbine combined cycle with back-pressure steam turbine

Compared to a GT process, a gas and steam turbine combined cycle (GT-CC) works with a gas turbine and an additional steam turbine (ST) cycle as a second power cycle. The hot exhaust gas leaving the gas turbine operates a heat recovery steam generator, which runs a steam turbine. The GT-CC is operated in heat-demand driven mode. So, a back-pressure steam turbine is chosen where the turbine off-steam is condensed in the heat sink at a suitable pressure level to supply the required heat at the required temperature level to the industrial processes. In this paper, a two-pressure stage heat recovery system with a high-pressure turbine and an intermediate pressure turbine with additional enthalpy utilization of the exhaust gas is analyzed. The system is composed of two sets of superheaters, evaporators and economizers, one for each pressure stage. The thermodynamic key parameters are calculated similarly to those of the GT process with (1) – (5). The electric power of the GT-CC process is the sum of the electric power of the gas turbine and the steam turbine.

2.2.3 High temperature heat pump process

In this work, an electrically driven compression heat pump system is analyzed working with a polytrope (intercooled) compression system and water as refrigerant. The process works with two heat exchangers for heat source and heat sink, a compressor and a valve to expand the refrigerant. The efficiency of electrically driven heat pump systems is determined by the quotient of produced heating power to applied electrical power, called the coefficient of performance (COP) as shown in equation (6). The exergetic efficiency includes the exergy stream of the heat sink, the incoming exergy stream of the heat source and the electric power (equation (7)).

$$COP = \frac{Q_{Process}}{P_{el}} \tag{6}$$

$$\zeta_{HP} = \frac{\dot{E}_Q}{P_{el} + \dot{E}_{in}} \tag{7}$$

2.3 Economic calculation

The economic calculations were made to compare the economic performance of the heat supply processes. The calculations include, firstly, the consumption related costs of the three systems. The formulation in equation (8) holds for the pre-existing gas-turbine based systems and equation (9) reflects the consumption related costs of the HTHP system. Secondly, investment costs for a newly installed HTHP are to be considered, because in our methodological approach, we assume that either a GT or a GT-CC system is already in operation while the HTHP system requires installation of additional technology. For consumption related costs of heat for GT and GT-CC systems, the costs for fuel and the revenue for the produced electricity are considered. As electricity price, the purchase price for electricity based on the day ahead data from EEX is assumed. Taxes are not considered. The resulting setup comprises two parallel heat generation options and the operator can flexibly choose between a gas-powered and an electricity-powered heat supply system dependent on the energy price situation. GT and GT-CC systems are state of the art to produce process heat, so it is assumed that one of these systems is still installed. So, only acquisition costs for a heat pump system has to be considered.

$$CoH_{GT\&GT-CC} = \frac{P_{Fuel}\, C_{Gas} - P_{el}\, C_{El}}{\dot{Q}_{Process}} \tag{8}$$

$$CoH_{v,HTHP} = \frac{C_{El}}{COP} \tag{9}$$

The collected industrial energy prices for both, electricity and gas prices, refer to E-Control and serve as foundation for the calculated consumption related costs. In order to get a precise picture of the economic performance of an HTHP, the investment costs are converted into EUR/kW$_Q$ and include capital costs as well as service and personal costs. When it comes to investment, capital costs $C_{Capital}$ are to be considered as well. The approach therefore considers costs for depreciation D_C, shown in equation (10) and interest costs I_C shown in equation (11). Costs for annual interests are calculated with the average cost method according to Schneider (Schneider, 2006). Since the costs for investment are very high, we assume total debt financing and chose an interest rate of 5% p.a.

$$D_C = \frac{I_0 - R_W}{n} \quad (10)$$

$$I_C = \frac{I_0 + R_W}{2} \quad (11)$$

$$C_{Capital} = D_C + I_C \quad (12)$$

For allocating the total costs into EUR per MWh, additional costs for capital, salary and service are to be summed up and divided by $Q_{Process}$, as shown in equation (13). Because either the GT/ GT-CC or the heat pump is running, the service costs are assumed as fixed. Finally, total costs for heat production in EUR per MWh can be calculated for the HTHP system (equation (14)).

$$CoH_{f,HTHP} = \frac{C_{Capital} + C_{Personnel} + C_{Service}}{Q_{Process}} \quad (13)$$

$$CoH_{HTHP} = CoH_{v,HTHP} + CoH_{f,HTHP} \quad (14)$$

Table 3 gives an overview of the included parameters. With respect to uncertainties about precise investment costs, we consider four levels of specific investment costs and study the impact of HTHP system erection costs on the total CoH.
According to (Zhang et al., 2016) and data from several manufacturers, the estimated installation costs of HTHP range between 250 EUR/kW$_Q$ and 750 EUR/kW$_Q$, although further decline in the future due to serial production is expected.

3. Results

With respect to our chosen methodological approach described above, the following results have been obtained. Firstly, the outcome of the modeled heat supply systems is presented and, secondly, followed by economic analyses using real-life European energy market prices 2013–2016 (see Figure 3).

3.1 Thermodynamic results

Table 4 and Table 5 summarize the energetic and exergetic parameters. The results show that the exergetic efficiency of the HTHP, even if a moderate COP of 3 is assumed, is higher than for the GT and the GT-CC process. In practice, the COP will depend on the temperature level of the waste heat reservoir used as heat source by the HTHP system. In paper industry, for instance, humid exhaust air is available from drying and can be used as heat source. If such a stream is available at 90°C, a three-stage HTHP system can be operated using 90°C/75°C, 75°C/60°C and 50°C/35°C, and resulting in COPs of approximately 5, 4 and 3, respectively. In average, a COP of 4 can be obtained in such a case.

3.2 Economic results

Figure 1 shows the consumption related costs of heat production ($CoH_{GT\&GT\text{-}CC}$ and $CoH_{v,HTHP}$) depending on the electricity price. For electricity prices below 45 EUR/MWh$_{el}$ and a gas price of 25 EUR/MWh (based on lower heating value), the HTHP is the economically best way of heat production. Higher electricity prices favor the GT-CC and the GT process. Additionally, a boiler system with a boiler efficiency of 90% is shown. So, the costs of heat production of the boiler system amount 28 EUR/MWh, if a gas price of 25 EUR/MWh is assumed.
Figure 2 shows the total costs of heat production of a newly installed HTHP in comparison to other available heat supply systems for a period from January 2013 to June 2016 (with energy prices as shown in Figure 3). The graphs of the conventional systems are based on equation (8). Furthermore, a boiler system (boiler efficiency = 90%) is shown. The graph of the HTHP is calculated at a COP of 4 and investment costs of 500 EUR/kW$_Q$ are assumed. The results show that in the period between February 2013 and May 2014, as well as in the period between August 2014 and September 2015, economic conditions

Table 3. Assumptions and calculations for modelling the economic model of the capital related costs of heat production
Tabelle 3. Annahmen und Kalkulationen für das ökonomische Model zur Berechnung der Kapitalkosten der Prozesswärmebereitung

Parameter	A	B	C	D	Unit
Specific acquisition costs	1 000	750	500	250	EUR/kW$_Q$
I_0	100 000 000	75 000 000	50 000 000	25 000 000	EUR
R_W	0				EUR
n	20*				A
t	6 000				H
i	5.0				%
$Q_{Process}$	600 000				MWh/a
$C_{Personnel}$	40 000				EUR/a
$C_{Service}$	10 000				EUR/a
D_C	5 000 000	3 750 000	2 500 000	1 250 000	EUR/a
I_C	2 500 000	1 875 000	1 250 000	625 000	EUR/a
$CoH_{f,HTHP}$	12.58	9.46	6.33	3.21	EUR/MWh

* (Verein deutscher Ingenieure, 2003)

for replacing conventional heat supply systems would have been favorable. From October 2015 onwards, CHP-based CoH decrease as a result of decreasing natural gas prices and increasing electricity prices. The CoH of HTHP range in the considered time window between 12 EUR/MWh and 18 EUR/MWh.

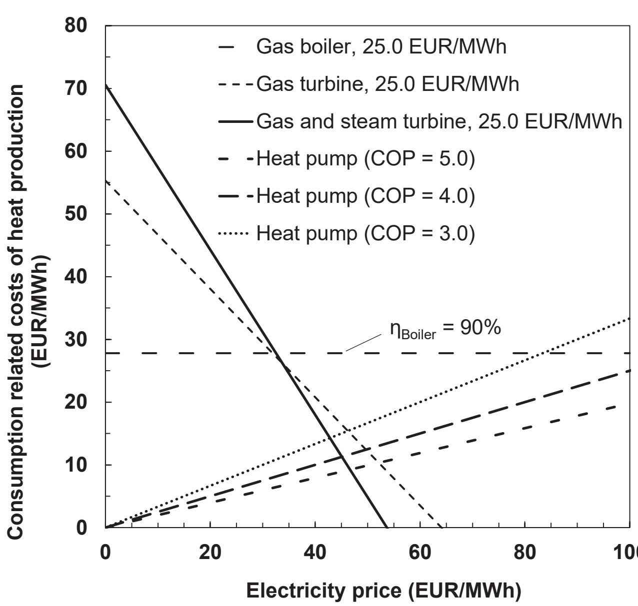

Figure 1. Consumption related costs of heat production depending on the electricity price. The graph shows the consumptions related costs for electricity and fuels, the gas price is assumed with 25.0 EUR/MWh (basis lower heating value).
Abbildung 1. Verbrauchsbezogenen Kosten der Wärmeproduktion in Abhängigkeit des Strompreises. Der Graph zeigt die verbrauchsbezogenen Wärmegestehungskosten bei einem Gaspreis von 25.0 EUR/MWh (bezogen auf den Heizwert).

It is evident from Figure 2 that the GT-CC system is in direct competition to the HTHP system. In price situations where the GT system would be superior to the GT-CC system, the HTHP system is always more economic than GT. Figure 4 shows the switching schedule between GTCC and HTHP operation in a tentative plant where both technologies are available in the investigated time window. Since the CoH of the HTHP system depend on operational costs as well as investment costs, the calculation is done for the four different levels of specific erection costs of the HTHP system.

The share of the heat production technologies, based on the examination of Figure 4, is shown in Table 6. The results obtained again show that the HTHP and the GT-CC process are most economic. The share of the heat pump system on heat production varies from 45% to 76% depending on the specific investment costs. Lower investment costs favor the operation of the HTHP, and the share of heat production for HTHP with specific investments of 750 EUR/kW$_Q$, 500 EUR/kW$_Q$, and 250 EUR/ kW$_Q$, is higher than 50%. A switch of between the systems increase the fixed costs per unit, but these results give the first overview about the economic operation range of HTHP.

A sensitivity analysis of the consumption related costs is done for these two technologies. Figure 5 depicts the effects of changing electricity and gas prices on the costs. The first picture (a) shows the correlation of COH of a GT-CC and a HTHP process by varying the gas price +/- 10%. In the second picture (b), the electricity price is varied +/- 10%. The change of the consumption related costs for the GT-CC process in connection with changing energy prices

Table 4. Thermodynamic results of the simulation of the industrial heat supply for gas turbine and gas and steam turbine combined cycle processes
Tabelle 4. Thermodynamische Ergebnisse der Simulation der industriellen Prozesswärmebereitung mit Gasturbine und Gas-und Dampfturbine

	Gas turbine	
η_{el}	39.01	%
η_{heat}	45.21	%
η_{total}	84.22	%
ζ	49.82	%
P_{Fuel}	221	MW
P_{el}	86	MW
$\dot{Q}_{Process}$	100	MW
	Gas and steam turbine combined cycle	
η_{el}	46.49	%
η_{heat}	35.44	%
η_{total}	81.93	%
ζ	53.44	%
P_{Fuel}	282	MW
P_{el}	131	MW
$\dot{Q}_{Process}$	100	MW

Table 5. Simulation results for the industrial heat pump system assuming three different COP situations
Tabelle 5. Simulationsergebnisse für die industrielle Wärmepumpe bei drei unterschiedlichen COP´s

	Heat pump	
T_{evap}	50.0	°C
$\dot{Q}_{in}$	69	MW
P_{el}	33	MW
$\dot{Q}_{Process}$	100	MW
COP	3.0	-
ζ_{HP}	59.57	%
T_{evap}	75.0	°C
$\dot{Q}_{in}$	77	MW
P_{el}	25	MW
$\dot{Q}_{Process}$	100	MW
COP	4.0	-
ζ_{HP}	70.15	%
T_{evap}	90.0	°C
$\dot{Q}_{in}$	82	MW
P_{el}	20	MW
$\dot{Q}_{Process}$	100	MW
COP	5.0	-
ζ_{HP}	78.35	%

is more distinct than for the HTHP. The diagrams for the gas-fired systems show that changing gas prices have more impact on the costs of heat production than changing electricity prices. For HTHP systems changing gas prices are not relevant.

Since economic considerations in industry always include the factor pay-back time, a breakdown of it for the four considered heights of investment is brought into play and illustrated in Figure 6. The payback time for every case of investment heights is shown for every month and refer to the left axis. It is calculated under the assumption of the given price conditions and are expected to be constant,

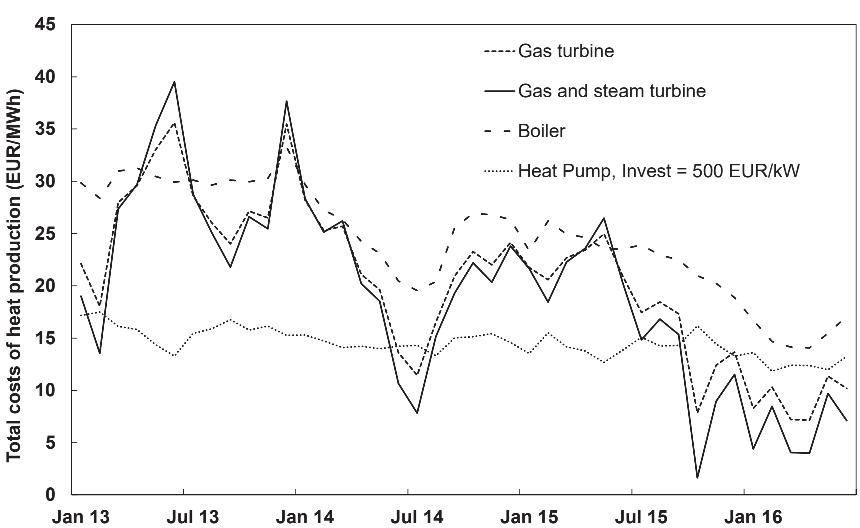

Figure 2. Cumulative costs of heat for a gas turbine, a gas and steam turbine, a boiler and a heat pump system working with a COP of 4 from January 2013 until June 2016. The costs of heat of the heat pump system includes the investment costs, assumed with 500 EUR/kWQ and the consumption related costs.
Abbildung 2. Kumulativen Wärmegestehungskosten einer Gasturbine, einer Gas-und Dampfturbine, einem Boiler und einer Hochtemperaturwärmepumpe mit einem COP von 4 in der Periode von Januar 2013 bis Juni 2016. Die Wärmegestehungskosten der Wärmepumpe setzen sich aus den verbrauchsbezogenen Kosten und den Kapitalkosten bei spezifischen Investitionskosten von 500 EUR/kWQ zusammen.

Table 6. Share of each heat production technology depending on the specific investment costs for the HTHP system in the period January 2013 to June 2016
Tabelle 6. Erzeugungsrate der einzelnen Wärmebereitstellungsmethoden in Abhängigkeit unterschiedlicher spezifischen Investitionskosten der Wärmepumpe von Jänner 2013 bis Juni 2016

Specific investment	1 000	750	500	250	EUR/kW$_Q$
B	0.0	0.0	0.0	0.0	%
GT	0.0	0.0	0.0	0.0	%
GT-CC	54.8	42.9	31.0	23.8	%
HTHP	45.2	57.1	69.0	76.2	%

which of course is not accurate for reality. The outcome of the graph shows that in case of low investment costs, thus 250 EUR/kW$_Q$ or 500 EUR/kW$_Q$, payback time would have been clearly below ten years most of the time.

Figure 6 also depicts the monthly savings for substituting a GT-CC with a HTHP system. For the calculation of monthly savings, it is assumed, that the annual process heat $Q_{Process}$ is distributed equally for all twelve months. This graph should give an overview about the possible payback times, if in past years an HTHP would have been installed on site. Over the whole period, the trend shows decreased savings. From March 2013 until June 2013, the payback times would have been below 10 years. In contrast, from October 2015 until June 2016, no savings could be achieved, which is a sign that the best times for investing into HTHP technology were from January 2013 until August 2015. After this period, the economic benefits are reduced and the future development of energy markets needs to be evaluated in order to decide about potential investment in HTHP systems.

4. Conclusion

This paper focuses on the performance of three different heat production processes for supplying industrial processes in pulp and paper industry. 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 25.0 EUR/MWh (basis lower heating value) is assumed and the electricity price is lower than 45.0 EUR/MWh$_{el}$. Considering capital, operation and service

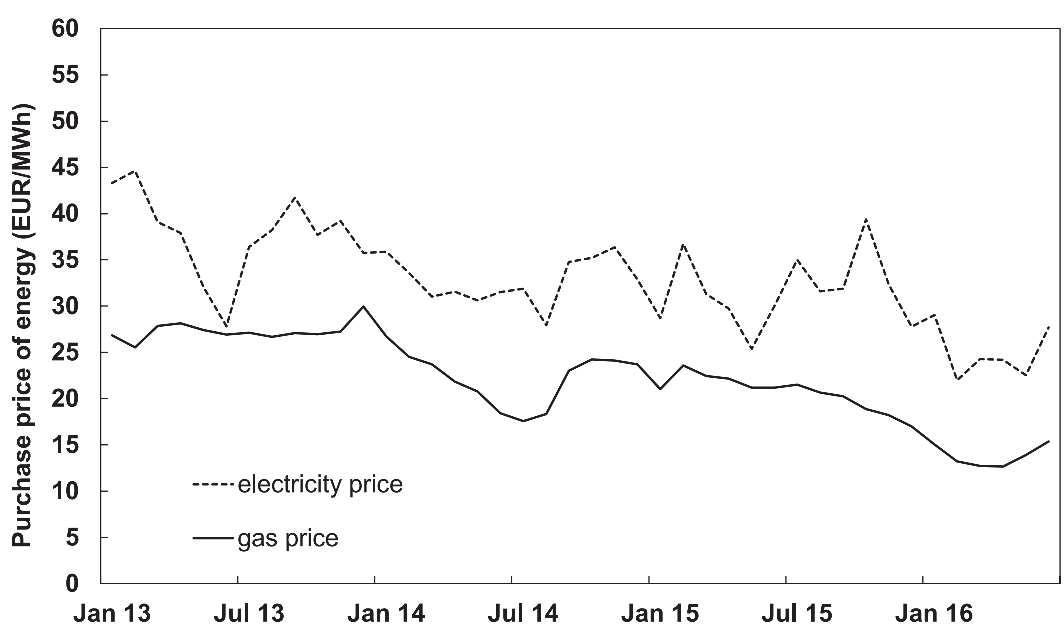

Figure 3. Electricity and gas prices from January 2013 until June 2016 according to E-control (E-Control, 2016a, b)
Abbildung 3. Strom- und Gaspreise von Jänner 2013 bis Juni 2016 (E-Control, 2016a, b)

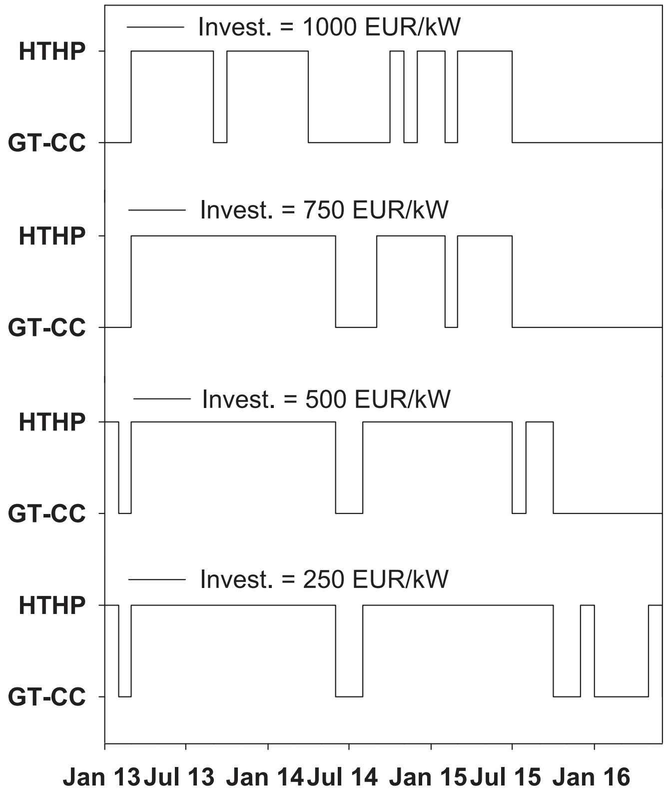

Figure 4. Economically best technology for industrial heat production depending on the cumulative costs of heat for the period from January 2013 until June 2016 according to different investment costs. The graph shows that HTHP and GT-CC were economic best, the gas turbine and the boiler had in this period higher costs for heat production.
Abbildung 4. Ökonomisch effizienteste Wärmebereitstellungsmethode in Abhängigkeit der kumulativen Wärmegestehungskosten von Jänner 2013 bis Juni 2016 bei unterschiedlichen spezifischen Investitionskosten. Das Diagramm zeigt, dass in der untersuchten Periode die Wärmepumpe und die Gas- und Dampfturbine die effizientesten industriellen Wärmebereitstellungsmethoden waren.

costs, the cumulative costs for the period from January 2013 until June 2016 are calculated on a monthly basis. The results show that, depending on the occurred energy prices, either the GT-CC or the HTHP system were most economic. Based on a monthly analysis, the share of heat supply for HTHP varies between 45% and 76%, and for GT-CC between 24% and 55%, depending on the assumed investment costs for the HTHP system. For the investigated period, the GT or gas boiler solutions were not economic compared to the combination of GT-CC and HTHP. The sensitivity analysis shows that the fuel-based heat production technologies depend more on gas price than on electricity price. This means, gas prices have a higher influence on the costs of heat than electricity prices. An overview of the theoretical amortization time shows that depending on real electricity prices, the expected pay-back time is subject to intense fluctuations. For investments of 250 EUR/kW$_Q$ or 500 EUR/kW$_Q$, pay-back times would have been below ten years for the energy price situation between January 2013 and May 2014 and between September 2014 and August 2015. The recent development after September 2015 clearly discourages investment in HTHP systems. It should be generally noted that the methodological approach for the economic calculation can be considered conservative with a high interest rate of 5% per annum. In general, the results of this paper can serve as decision aid for industrial plant and electricity grid operators, as electricity can be flexibly produced with CHP in times of high electricity prices, or electricity is purchased from the grid for heat supply using HTHP systems when electricity prices are low. This way, industrial players can contribute to balancing supply and demand mismatches in the electricity grid, both on a daily and on a seasonal basis.

Nomenclature

$C_{Capital}$	capital costs	EUR/a
C_{El}	electricity price	EUR/MWh
C_{Gas}	gas price	EUR/MWh
$C_{personnel}$	Personal costs for operating the HTHP	EUR/a
$C_{Service}$	service costs of the HTHP	EUR/a
$CoH_{GT\&GT\text{-}CC}$	costs of heat for the GT and the GT-CC process	EUR/MWh
$CoH_{v,HTHP}$	consumption related costs of heat for the HTHP	EUR/MWh
$CoH_{f,HTHP}$	(fixed) capital and operation costs of heat for the HTHP	EUR/MWh
CoH_{HTHP}	cumulative costs of heat for the HTHP	EUR/MWh
COP	coefficient of performance	-
D_C	imputed depreciation	EUR/a
e_{Fuel}	specific exergy of the fuel	kJ/kg
$\dot{E}_{Fuel}$	exergy stream of the fuel	MW
$\dot{E}_{in}$	exergy stream of the heat source of the heat pump	MW
$\dot{E}_Q$	exergy stream of the heat	MW
Δh	difference of specific enthalpy of the used process heat	kJ/kg
H_L	lower heating value	MJ/kg
i	required rate of return	%

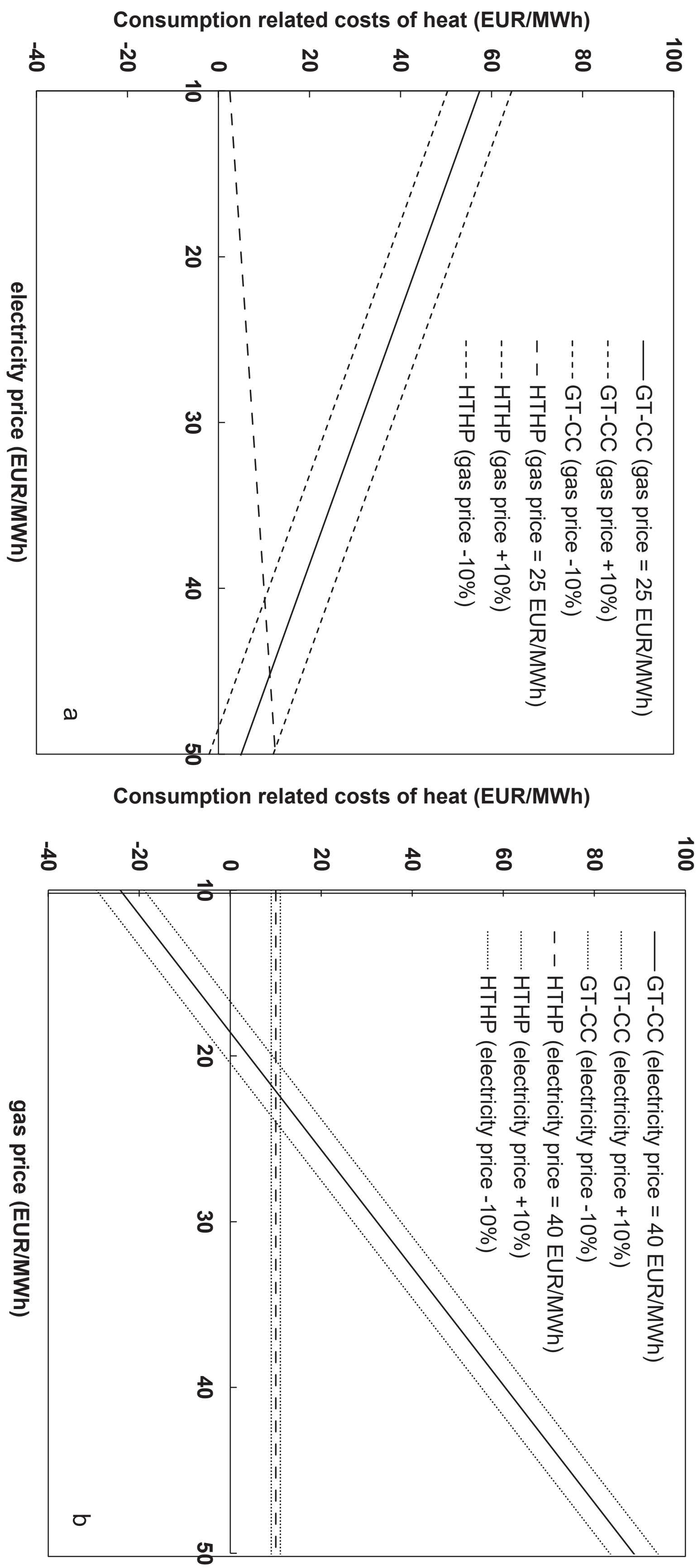

Figure 5. Sensitivity analysis of the consumption related costs of a GT-CC and the HTHP with a COP of 4 depending on different electricity and gas prices.
Abbildung 5. Sensitivitätsanalyse der verbrauchsbezogenen Kosten für eine Gas- und Dampfturbine und einer Wärmepumpe mit einem COP von 4 bei unterschiedlichen Energiekosten.

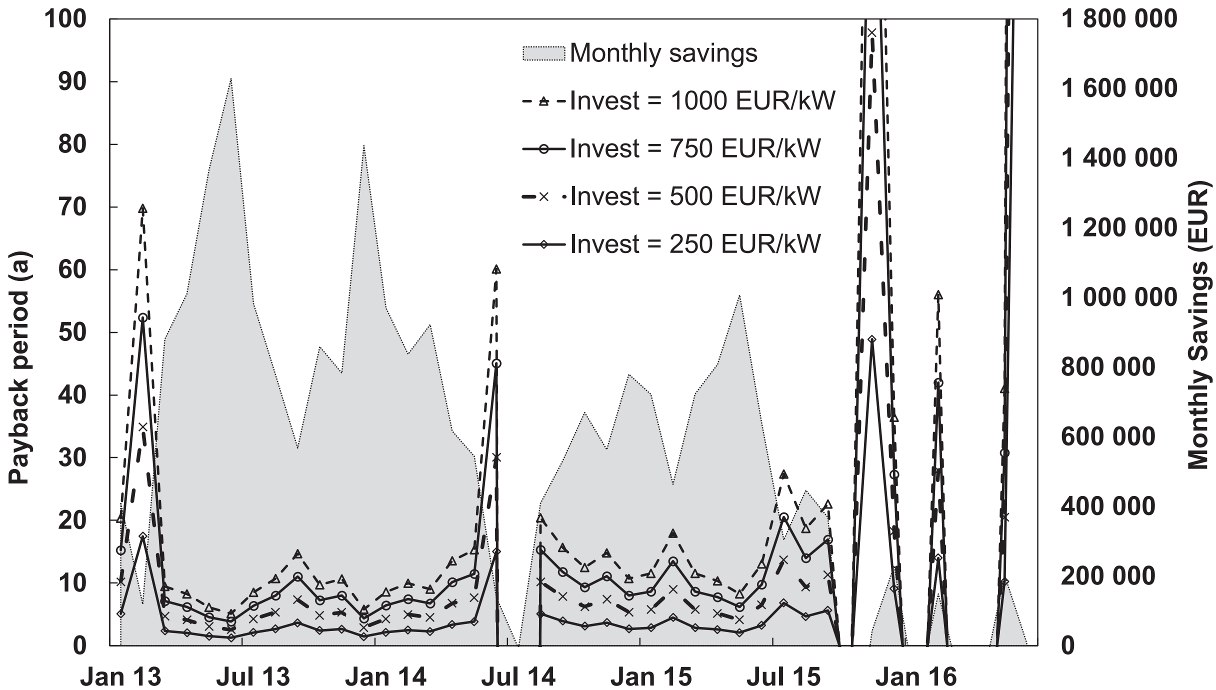

Figure 6. Pay-back time of a heat pump system working with a COP = 4 substituting a gas and steam turbine process according to different investment costs over a period from January 2013 until June 2016. The diagram also shows the monthly savings by using a HTHP for industrial heat production instead of a GT-CC.
Abbildung 6. Amortisationszeit eines Wärmepumpensystems mit einem COP von 4, wenn ein Gas- und Dampfturbinensystem substituiert wird. Der Graph zeigt die Amortisationszeiten und die monatlichen Einsparungen bei Einsatz einer Wärmepumpe bei unterschiedlichen spezifischen Investmentkosten in der Periode von Januar 2013 bis Juni 2016.

I_0	acquisition costs	EUR
I_C	imputed interests	EUR/a
$\dot{m}_{Fuel}$	mass flow of the fuel	kg/s
$\dot{m}_{Steam}$	mass flow of the steam used as process heat	kg/s
n	expected life time	a
P_{el}	electric power of the compressor	MW
P_{Fuel}	power of used fuel*	MW
$p_{ratio\ SGT\text{-}800}$	pressure ratio of the SGT-800 GT process	-
$p_{Steam,out}$	minimum pressure level of the process steam	bar(abs)
$\dot{Q}$	heat stream	MW
$\dot{Q}_{in}$	heat source stream of the heat pump	MW
$Q_{Process}$	process heat	MWh
$\dot{Q}_{Process}$	heating power used as process heat	MW
R_W	liquidity receipts	EUR
T_0	environmental temperature	°C
$T_{Feedwater}$	feedwater temperature of the used process steam	°C
T_Q	temperature of the heat	°C
$T_{SGT\text{-}800,out}$	turbine outlet temperature of the SGT-800 GT process	°C
$T_{Steam,out}$	outlet temperature of the used process steam	°C

*referred to the lower heating value (LHV)

Greek Letters

ζ	exergetic efficiency of the GT and GT-CC process	-
ζ_{HP}	exergetic efficiency of the heat pump system	-
η_{Compr}	isentropic efficiency of the compressor	-
η_{el}	net electric efficiency of the GT process*	-
η_{heat}	heat utilization efficiency of the process*	-
η_{motor}	conversion efficiency from the motor	-

$\eta_{SGT\text{-}800}$	gross efficiency of the SGT-800 GT process*	-
η_{total}	total fuel utilization efficiency	-

*referred to the lower heating value (LHV)

Abbreviations

CHP	combined heat and power
CoH	costs of heat
GT	gas turbine process
GT – CC	gas turbine and steam combined cycle
HTHP	high temperature heat pump process
LHV	lower heating value
ST	steam turbine
NPV	net present value

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