A COMPARATIVE STUDY OF INDUSTRIAL HEAT SUPPLY BASED ON SECOND-LAW ANALYSIS AND OPERATING COSTS

by

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In this paper, the thermodynamic and economic efficiency of three different heat supply processes are compared, based on exergy flows and costs of heat. A gas turbine process with a heat recovery boiler, a gas and steam turbine combined cycle process and a high temperature heat pump system recovering waste heat are analysed. The aim is to provide heat 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 results show that the heat pump system has higher exergetic efficiency than the gas turbine or the gas turbine combined cycle process. For the consumption related costs, the economic calculation shows that the operation of a heat pump, working with a coefficient of performance of four and for a natural gas price of 25 €/MWh, is the cheapest way of heat production as long as the electricity price is lower than 45 €/MWh. For the period from January 2013 until June 2016 the total costs of heat, based on real gas and electricity prices from the European Energy Exchange, are calculated and analysed. The results show that the share of heat provided by the heat pump system varies between 45% and 76%. 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 which favours industrial heat supply with combined heat and power systems.

Key words: *heat pump, gas turbine, combined heat and power, pulp and paper, industry, economic factors*

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 (CHP) plant. 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

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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 pump systems provided waste heat is available at a reasonable temperature level. As another potential benefit for industrial operators in view of future restrictions of GHG emissions, heat pumps can be considered as CO_2-free heat-supply systems if they are operated with green electricity [1]. Heat pumps for industrial application have the potential to increase energy efficiency and to reduce CO_2 emissions [2]. 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.* [3] the latest developments in the market for high temperature heat pump (HTHP) technology allow for heat sink temperatures up to 140 °C, although further developments are foreseen. Chamoun *et al.* [4] introduced a dynamic model for a heat pump using water as refrigerant and designed a prototype, which was tested under laboratory conditions [5]. Several works focus on the optimization of heat and power production through cogeneration plants but comparing CHP with HTHP for industrial heat supply has not yet been examined in detail. Soltani *et al.* [6] addresses the exergetic efficiency increase of combined cycles by using co-firing. Sahoo *et al.* [7] focusses on exergoeconomic analysis to optimize a cogeneration system. Kaviri *et al.* [8] focusses on a thermo-economic approach to minimize the total operation costs of a CHP plant. Atmaca and Yumrutas [9] presents results based on thermo-economic calculations, which can serve as decision whether co-generation or non-cogeneration for wood-processing company is sensible. Phillip *et al.* [10] focuses on analyzing energy supply systems in food processing industry including gas fired steam boiler and ammonia chillers. Hartel and Sandau [11] developed two aggregation methods for representing heat supply systems (hybrid boilers, heat pumps, and CHP) in an adequate but computationally efficient way. Miah *et al.* [12] presents a novel heat integration framework to evaluate all possible heat integration opportunities including low grade and waste heat. Becker *et al.* [13] analyzed the potentials for heat pump integration in industrial processes. Staine and Favrat [14] developed an approach to introduce heat pumps and cogeneration units by taking complete heat transfer exergy losses into account. Schafer *et al.* [15] characterized heat pump heating systems and optimized potentials for implementing in existing procedures. It is shown, that heat pumps are suitable for integration into energy generation planning. Based on this literature, this paper addresses the question of the exergetic performances of typical heat production processes in the industry – gas turbine (GT), gas and steam turbine combined cycle (GT-CC), and HTHP 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. The CHP systems are common heat production technologies in the whole field of wood processing industry [16], 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.

Methods

The methodological approach of this paper contains process simulation, economic comparison, and optimization. In this chapter, the basic methods are described. The following calculations bases on the process simulation tool IPSEpro, which is described in detail below.

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 [17], which has been recommended by Baehr and Kabelac [18]) for the process streams. For the simulation of the heat supply processes, some assumptions are necessary, which are shown in tab. 1. Heat exchanger pressure drops are not considered in the calculations. This is due to a simplified consideration of the observed technologies to get an overview about possible potentials for each technology. To get precise information for an application case, specific data are necessary. The parameters of the GT depend on the performance data of a Siemens SGT-800 (53.0 MW) GT [19]. In general, the work of Bejan [20] describes basic heat transfer topics, like heat trans augmentation techniques, heat exchanger design, and thermal insulation systems. The analytical methods for evaluating and minimizing the irreversibility is basic literature in Second law analysis.

Table 1. General performance assumptions for key process components

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

Table 2. Process parameters for the heat supply processes for a paper mill

Parameter	Value	Unit
$T_{\mathrm{feedwater}}$	120	°C
$T_{\mathrm{steam,out}}$	142	°C
$P_{\mathrm{steam,out}}$	3.8	bar(abs)
Δh	2,232	kJ/kg
$\dot{m}_{\mathrm{steam}}$	44.8	kg/s
$\dot{Q}_{\mathrm{process}}$	100	MW

The process and working parameters are fixed according to tab. 2 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.

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. The most important technologies for producing low temperature steam, about 4 bar (abs) and 140 °C, in a considering power range (40-100 $\mathrm{MW_{therm}}$) are examined in detail. However, the described technologies can also be applied in food, biotechnology, pharmaceutical and textile industry. The described analysis can be extended to these branches in further examinations. For the basic comparisons, a boiler efficiency of 90% for calculating the costs of heat is assumed.

Gas turbine process with heat recovery boiler

The open GT process converts the chemical energy of fuel into electricity and heat. With CHP units, the waste heat in the exhaust gas of the GT may be used to supply industrial processes. The exergy in the exhaust gas is partly converted into electric power and the remaining enthalpy in the turbine off gas can be used to produce steam in a heat recovery boiler.

The efficiency of the GT process is evaluated with some key figures, especially the electric efficiency, the thermal efficiency, and the exergetic efficiency. The electric efficiency, as shown in eq. (1), describes the conversion efficiency of the used fuel into electricity. For all calculations, complete combustion is assumed:

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{el}}}{\dot{m}_{\mathrm{fuel}} H_{\mathrm{L}}} \tag{1}$$

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

$$\eta_{\mathrm{heat}} = \frac{\dot{Q}_{\mathrm{process}}}{\dot{m}_{\mathrm{fuel}} H_{\mathrm{L}}} \tag{2}$$

$$\eta_{\mathrm{total}} = \frac{P_{\mathrm{el}} + \dot{Q}_{\mathrm{process}}}{\dot{m}_{\mathrm{fuel}} H_{\mathrm{L}}} \tag{3}$$

The total fuel utilization efficiency, eq. (3), describes the conversion efficiency of fuel power to electric and thermal power. Because mixing up heat and electricity 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 CHP plants, the exergetic efficiency includes, apart from the produced electric power, also the exergy stream of the usable process heat. The following correlation shows the exergetic efficiency definition for the GT process, eq. (5). Work and electricity have got 100% exergetic value. The exergy flow of the heat is calculated as described in eq. (4):

$$\dot{E}_{\mathrm{Q}} = \left(1 - \frac{T_0}{T_{\mathrm{Q}}}\right)\dot{Q} \tag{4}$$

$$\zeta = \frac{P_{\mathrm{el}} + \dot{E}_{\mathrm{Q}}}{\dot{m}_{\mathrm{fuel}} e_{\mathrm{fuel}}} \tag{5}$$

The specific exergy at standard conditions, e_{fuel}, is calculated based on the chemical exergy formulation according to Baehr and Kabelac [18] based on the equilibrium environment by Ahrendts [17].

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

Compared to a GT process, a gas and GT-CC works with a steam turbine (ST) cycle as a second power cycle. The GT-CC is operated in heat-demand driven mode. So, a back-pressure ST is chosen where the turbine off-steam is condensed in the heat sink at a suitable pressure level to supply the required heat to the industrial processes. The thermodynamic key parameters are calculated similarly to those of the GT process with eqs. (1)-(5). The electric power of the GT-CC process is the sum of the electric power of the GT and the ST.

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 efficiency of electrically driven heat pump system is determined by the quotient of produced heating power to applied electrical power, called the coefficient of performance (COP), as shown in eq. (6). The exergetic efficiency, eq. (7), includes the exergy stream of the heat sink, the incoming exergy stream of the heat source and the electric power:

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{process}}}{P_{\mathrm{el}}} \tag{6}$$

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

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 eq. (8) holds for the pre-existing GT based systems and eq. (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 European Energy Exchange are 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:

$$CoH_{\mathrm{GT\&GT\text{-}CC}} = \frac{P_{\mathrm{fuel}} C_{\mathrm{gas}} - P_{\mathrm{el}} C_{\mathrm{el}}}{\dot{Q}_{\mathrm{process}}} \tag{8}$$

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

The collected industrial energy prices for both, gas prices [21] and electricity prices [22], refer to E-Control and serve as foundation for the calculated consumption related costs. To get a precise picture of the economic performance of an HTHP, the investment costs are converted into €/kW$_{\mathrm{Q}}$ and include capital costs as well as internal fixed 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}, and interest costs I_{C}. Costs for annual interests are calculated with the average cost method according to Schneider [23] and shown in eqs. (10)-(12). Since the costs for investment are very high, we assume total debt financing and chose an interest rate of 5% p. a.

$$D_{\mathrm{C}} = \frac{I_0 - R_{\mathrm{W}}}{n} \tag{10}$$

$$I_{\mathrm{C}} = \frac{I_0 - R_{\mathrm{W}}}{2} i \tag{11}$$

$$C_{\mathrm{capital}} = D_{\mathrm{C}} + I_{\mathrm{C}} \tag{12}$$

For allocating the total costs into € per MWh, additional costs for capital, salary and service are to be summed up and divided by Q_{process}, as shown in eq. (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 € per MWh can be calculated for the HTHP system, eq. (14):

$$CoH_{\text{f,HTHP}} = \frac{C_{\text{capital}} + C_{\text{personnel}} + C_{\text{service}}}{\dot{Q}_{\text{process}}} \tag{13}$$

$$CoH_{\text{HTHP}} = CoH_{\text{v,HTHP}} + CoH_{\text{f,HTHP}} \tag{14}$$

Table 3 gives an overview of the included parameters and calculations for the economic model. 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*.

Table 3. Assumptions and calculations for modelling the economic model of the capital related costs of heat production

Parameter	A	B	C	D	Unit
Specific acquisition costs	1000	750	500	250	€/kW$_Q$
I_0	100000000	75000000	50000000	25000000	€
R_W	0				€
n	20 *				a
t	6.000				h
i	5.0				%
Q_{process}	600000				MWh/a
$C_{\text{personnel}}$	40000				€/a
C_{service}	10000				€/a
D_C	5000000	3750000	2500000	1250000	€/a
I_C	2500000	1875000	1250000	625000	€/a
$CoH_{\text{f,HTHP}}$	12.58	9.46	6.33	3.21	€/MWh

* Verein deutscher Ingenieure, 2003 [24].

According to Zhang *et al.* [25] and data from several manufacturers, the estimated installation costs of HTHP range between 250 €/kW$_Q$ and 750 €/kW$_Q$, although further decline in the future due to serial production is expected.

Results and discussion

With respect to our chosen methodological approach previously described, 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.

Thermodynamic results

In tabs. 4 and 5 the energetic and exergetic parameters are summarized. Table 4 includes the results for GT and GT-CC, whereas tab. 5 includes the results for the industrial heat pump system considering three different temperature levels. 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, but also in other branches like food or textile, 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 90/75 °C, 75/60 °C, and 50/35 °C, and resulting in COP of approximately 5, 4, and 3, respectively. In average, a COP of 4 can be obtained in such a case.

Table 4. Thermodynamic results of the simulation of the industrial heat supply for GT and GT-CC

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 HTHP system

Heat pump		
$\dot{Q}_{in}$	69	MW
P_{el}	33	MW
$\dot{Q}_{process}$	100	MW
COP	3.0	–
ζ_{HP}	59.57	%
$\dot{Q}_{in}$	77	MW
P_{el}	25	MW
$\dot{Q}_{process}$	100	MW
COP	4.0	–
ζ_{HP}	70.15	%
$\dot{Q}_{in}$	82	MW
P_{el}	20	MW
$\dot{Q}_{process}$	100	MW
COP	5.0	–
ζ_{HP}	78.35	%

Economic results

Figure 1 shows the consumption related costs of heat ($CoH_{GT\&GT\text{-}CC}$ and $CoH_{v,HTHP}$) depending on the electricity price, which is assumed as the selling price for electricity on the spot market. The graph shows the consumptions related costs for electricity and fuels, the gas price is assumed with 25.0 €/MWh (basis on lower heating value). For electricity prices below 45 €/MWh$_{el}$ and a gas price of 25 €/MWh, the HTHP is the economically best way of heat production. Even for the gas prices the costs for transmission and distribution are not included. In general, higher electricity prices favour the GT-CC and the GT process. Based on this diagram it can be decided if heat is produced with the HTHP when the electricity price is low, or if electricity is produced with the CHP plant when the electricity price is high. Figure 1 shows a first overview about the coherences of energy prices and the costs of heat production of the different technologies. Following (see fig. 2), the costs of heat production based on real selling prices for energy on spot market, according to E-Control (gas price [21], electricity price [22]), from January 2013 to June 2016 are calculated. Spot market prices do not include costs for transmission and distribution but give a first trend. Further examinations must be done, including costs for transmission and distribution. Therefore, it is necessary to pick a concrete example to get specific information about contractual conditions.

Figure 2 shows the total costs of heat production of a newly installed HTHP in comparison to a GT, a gas and steam turbine and a heat pump for a period from January 2013 to June 2016 including the gas and electricity prices in the observed period. The graph of the HTHP is calculated at a *COP* of 4. The cost of heat of the heat pump system includes the investment costs, assumed with 500 €/kW$_Q$ and the consumption related costs. 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 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. Generally, the *CoH* from the HTHP system are less influenced by volatile electricity prices than the *CoH* from the CHP systems. The *CoH* of HTHP range in the considered time window between 12 €/MWh and 18 €/MWh.

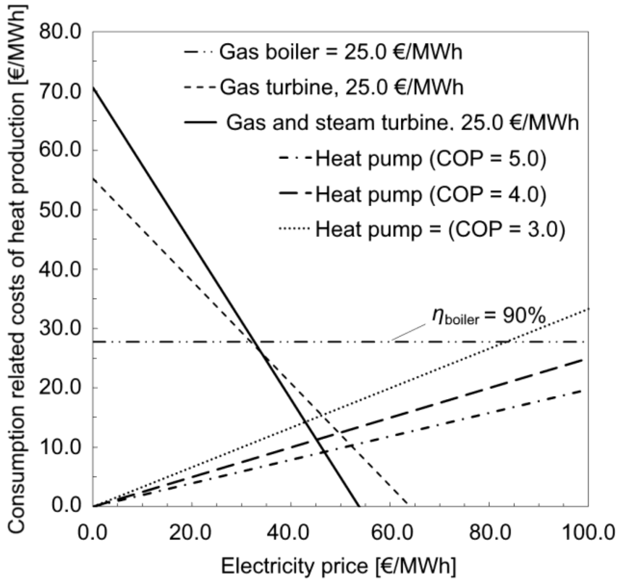

Figure 1. Consumption related costs of heat production depending on the electricity price

It is evident from fig. 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 3 shows the switching schedule between GT-CC and HTHP operation in a tentative plant where both technologies are available in the investigated time window. The graph shows the results for

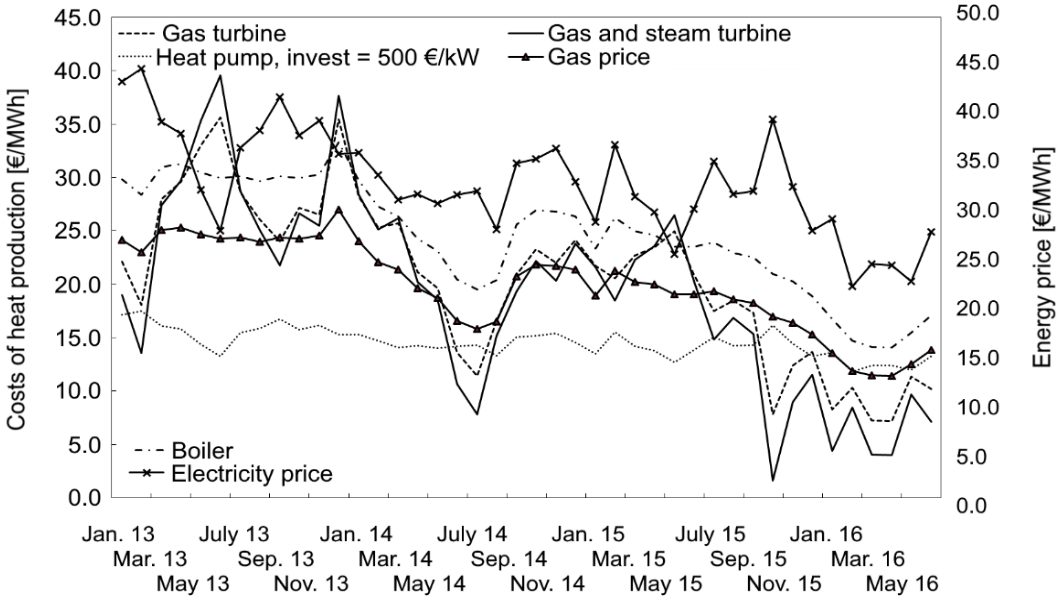

Figure 2. Cumulative costs of heat for a GT, a gas and steam turbine, a boiler and a heat pump system

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 GT and the boiler had higher costs in this period for heat production. Since the *CoH* of the HTHP system depend on operation costs as well as on investment costs. The calculation is done for four different levels of specific erection costs of the HTHP system.

The share of the heat production technologies, based on the examination of fig. 3, is shown in tab. 6. The results obtained again show that the HTHP and the GT-CC process are most economical in the observed period from January 2013-June 2016. The share of the heat pump system on heat production varies from 45%-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 €/kW$_Q$, 500 €/kW$_Q$, and 250 €/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.

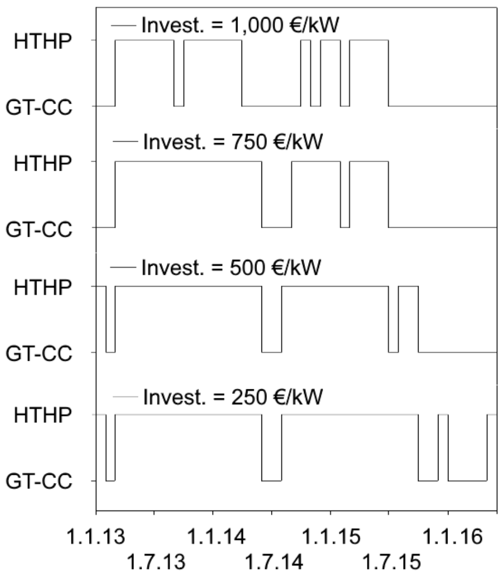

Figure 3. Economically best technology for industrial heat production depending on the cumulative costs of heat

Table 6. Share of each heat production technology depending on the specific investment costs for the HTHP system

Specific investment	1,000	750	500	250	€/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	%

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 €/MWh (basis lower heating value) is assumed and the electricity price is lower than 45.0 €/MWh$_{el}$. Considering capital, operation and service costs, the cumulative costs for the period from January 2013 until June 2016 are calculated monthly. The results showed 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 the 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. For the energy price situation between January 2013 and May 2014 and between September 2014 and August 2015 the HTHP system has the lowest operational costs. The recent development after September 2015 clearly discourages investment in HTHP systems. In general, the quantitative results of this paper are likely to 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, [€/a]
C_{el} – electricity price, [€/MWh]
C_{gas} – gas price, [€/a]
$C_{personnel}$ – personal costs for operating the HTHP, [€/a]
$C_{service}$ – service costs of the HTHP, [€/a]
$CoH_{GT\&GT\text{-}CC}$ – costs of heat for the GT and the GT-CC process, [€/MWh]
$CoH_{v,HTHP}$ – (variable) consumption related costs of heat for the HTHP, [€/MWh]
$CoH_{f,HTHP}$ – (fixed) capital and operation costs of heat for the HTHP, [€/MWh]
CoH_{HTHP} – cumulative costs of heat for the HTHP, [€/MWh]
COP – coefficient of performance, [–]
D_C – imputed depreciation, [€/a]
e_{fuel} – specific exergy of the fuel, [kJkg^{-1}]
$\dot{E}_{in}$ – exergy stream of the heat source of the heat pump, [MW]
$\dot{E}_Q$ – exergy stream of the (process) heat, [MW]
Δh – difference of specific enthalpy of the used process heat, [kJkg^{-1}]
H_L – lower heating value, [MJkg^{-1}]
I_0 – acquisition costs, [€]
I_C – imputed interests, [€/a]
i – required rate of return, [%]
$\dot{m}_{fuel}$ – mass-flow of the fuel, [kgs^{-1}]
$\dot{m}_{steam}$ – mass-flow of the steam used as process heat, [kgs^{-1}]
n – expected life time, [a]
P_{el} – electric power of the compressor, [MW]
P_{fuel} – power of used fuel (referred to the lower heating value), [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]
$Q_{process}$ – process heat, [MWh/a]
$\dot{Q}_{process}$ – heating power used as process heat, [MW]
R_W – liquidity receipts, [€]
T_0 – environmental temperature, [°C]
$T_{feedwater}$ – feed water 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]

Greek symbols

ζ – exergetic efficiency, [–]
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 (referred to the lower heating value), [–]
η_{heat} – heat utilization efficiency of the process (referred to the lower heating value), [–]
η_{motor} – conversion efficiency from the motor, [–]
$\eta_{SGT\text{-}800}$ – gross efficiency of the SGT-800 GT process (referred to the lower heating value), [–]
η_{total} – total fuel utilization efficiency, [–]

Subscripts

el – electric
Q – thermal energy

Acronyms

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
ST – steam turbine

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