INTEGRATED CHP CONCEPTS FOR ORC AND THEIR BENEFITS COMPARED TO CONVENTIONAL CONCEPTS

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ABSTRACT

The present study investigates the flexibility and suitability of different Combined Heat and Power concepts. An integrated concept for heat decoupling with a two-stage ORC concept and turbine bleeding is introduced and compared with other state-of-the-art concepts. The flexibility of the integrated system is determined for different isentropic fluids and siloxanes. Under general circumstances siloxanes are not suitable for turbine bleeding, due to their dry expansion behavior. However, this picture changes in this CHP context. A comparison is made for different temperature levels of heat transfer fluid. Based on OMTS as the working fluid other CHP concepts are compared with this integrated concept. Its benefits are determined by calculating the produced electricity per year. Therefore, the integration of the CHP concept into a virtual district heating network based on annual load duration curves is investigated and the annual electricity revenues are calculated. Based on these electricity revenues per year higher manufacturing costs due to a higher system complexity are compared.

1. INTRODUCTION

The Organic Rankine Cycle (ORC) is an established technique for waste heat recovery, as well as for the utilization of biomass, geothermal energy and solar thermal energy (Schuster *et al.*, 2009). Several reviews on technological aspects and applications can be found in literature (Schuster *et al.*, 2009, Quoillin *et al.*, 2013 and Tchanche *et al.*, 2011). Its application is economically limited to the small to medium size range (<1kW_e up to >1MW_e), but it enables the utilization of low temperature heat sources and its conversion to electricity.
The combined production of heat and power (CHP) is highly favorable for an operator from the economic point of view, since he is able to increase full load operational hours per year and has two different energetic products to sell. It is important to note, that the utilization of heat requires either a district heating network or an industrial process, where the heat can be used with minimal losses. In specific cases, the separate generation of electricity and heat can be more efficient from the primary energy point of view (Karl, 2009). In case of renewable energy sources and waste heat, where no additional CO_2 emissions are associated, CHP is always the better choice.
While medium scale CHP processes (>1MW_e) are already realized in existing plants by manufacturers (Bini and Manchiana, 1996, Knapek and Kittl, 2007), small scale CHP systems (<10 kW_e) for residential applications have been addressed in scientific literature (Schuster *et al.*, 2009, Mago *et al.*, 2010).
It is the aim of this work to focus on flexible CHP systems, which are suitable for fluctuating heat sources and capable of achieving a significant coverage of the mid load heat demand. The latter minimizes the utilization of fossil fuel fired peak load boilers. The work is based on state of the art CHP concepts and innovative ORC cycle layouts. It is the objective of this paper to present an integrated CHP concept with a high flexibility and efficiency, which is derived from conventional power plants. This concept is based on a two-stage ORC with turbine bleeding, which has already

been discussed thoroughly in Meinel *et. al.* (2014). It will be shown, that under these circumstances turbine bleeding can also be favorable for dry fluids, such as siloxanes.

2. COMBINED HEAT AND POWER (CHP)

2.1 CHP Concepts

Several configurations for CHP with an Organic Rankine Cycle can be found in literature (Karl, 2014, Mago *et al.*, 2010, Quoillin *et al.*, 2013). These concepts are shown in figure 1 and can be specified as follows:

a) Serial concept: Heat extraction to district heating from the heat source and after ORC.
b) Parallel concept: Heat from the heat source either to ORC or to district heating system.
c) Serial/parallel concept: Heat extraction to district heating after ORC and, in order to increase the temperature, parallel to the ORC.
d) Condensation concept (fixed σ): The district heat is supplied by the heat sink of the ORC in the condenser.
e) Condensation concept (flexible σ): The district heat is supplied by the heat sink of the ORC in the condenser. Since a cooling tower is added in parallel to the district heating system, the heat extraction is decoupled from the power generation in the ORC
f) Serial/condensation concept: These concepts are analogue to concepts d) and e), but they make use of excess heat from the waste heat source and increase the overall heat utilization.

The applicability and suitability of the above described concepts are strongly dependent on the temperature level of the (waste) heat source t_{WHS} and the temperature level of the district heating system t_{DHS}. In case of similar temperature levels for waste heat source and district heating system, with the waste heat source temperature being slightly higher ($t_{WHS} \geq t_{DHS}$) the parallel (a) or the

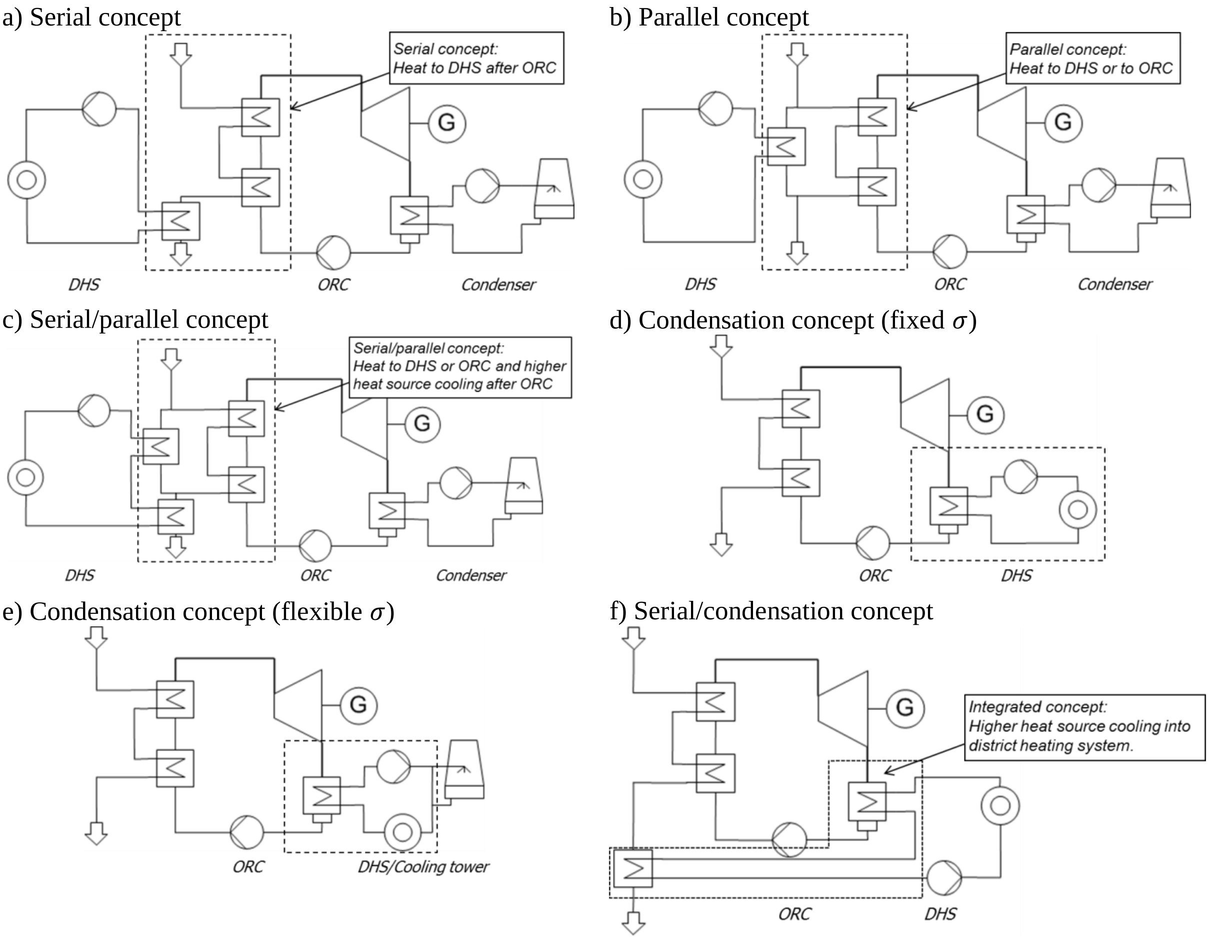


Figure 1: Qualitative schematics of common CHP concepts based on ORC systems.

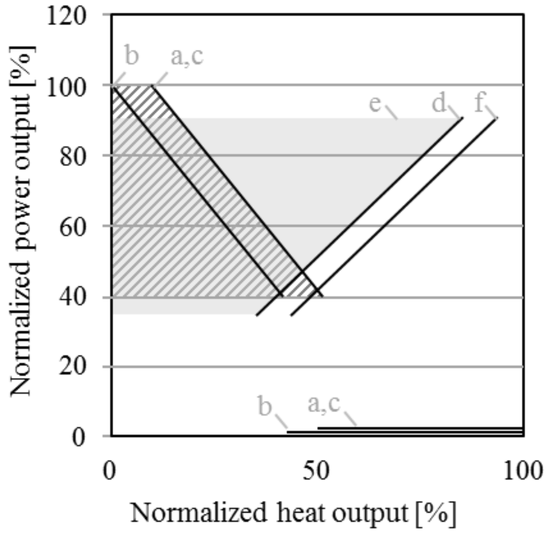


Figure 2: Qualitative $\dot{Q}_{DHS} - P_e$-diagram for different CHP-concepts

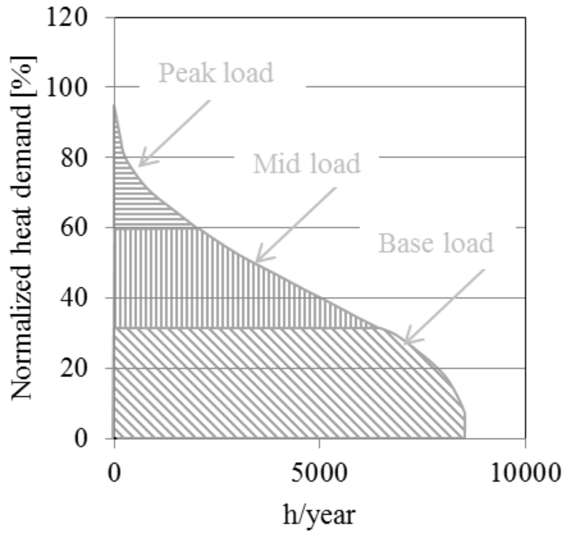


Figure 3: Annual load duration curve for an industrial consumer with different load zones

serial/parallel (b) concepts are favorable. Possible applications for these concepts cover geothermal, solar thermal and low temperature industrial waste heat in conjunction with district heating systems. Besides that, high temperature (waste) heat sources such as biomass in conjunction with high temperature process heat are suitable for these designs as well. Contrary to that, if the temperature level of the (waste) heat source is significantly higher than the temperature of the district heating system $t_{WHS} \gg t_{DHS}$ the serial concept (a) or one of the condensation concepts (d-f) are of better choice.

By comparing these concepts with each other, it has to be noted additional, that the concepts (a-c) can be used for any kind of heat sources, while the concepts (d-f) are chosen for applications where the heat source can be controlled and is on a high temperature level, e.g. biomass applications. Main reason for this is the flexibility of the concepts and the heat source utilization of these concepts, which is generally high. Therefore, the flexibility will be described more thoroughly in the next section.

2.2 Flexibility of CHP Concepts

The flexibility can be described in terms of the CHP coefficient σ, which is defined as the ratio between generated electrical power P_e and the heat flow to the district heating network $\dot{Q}_{DHS}$.

$$\sigma = \frac{P_e}{\dot{Q}_{DHS}} \tag{1}$$

While concepts (d) and (f) from figure 1 have a fixed CHP coefficient, the other concepts are characterized with a certain flexibility in this parameter. A qualitative characterization of the flexibility in a $\dot{Q}_{DHS} - P_e$-diagram is shown in figure 2. The concept (e) is highlighted with the grey area. It shows a more flexible heat provision than the concepts (d) and (f). This flexibility is associated with a lower overall utilization efficiency of the heat source – one of the main advantages of this concept. The concepts (a-c) are all flexible concerning the CHP coefficient, which is denoted by the hatched area. The diagonal curves of (a-c) denote the full load operation for the concepts with the highest heat source utilization. The horizontal lines of (a-c) at the bottom of the diagram show the heat only mode, which is able to provide maximal heat to the district heating system. Note, that the above considerations neglect heat losses and assume a minimal part load for the ORC of $P_{min} = 0.4P_{max}$. Note also, that operation in the hatched area is associated with heat losses.

Based on this characterization, the concepts can be allocated to cover specific heat loads. For this purpose an annual load duration curve is exemplarily shown in figure 3. In this figure base load, mid load and peak load are shown qualitatively. While base load is supposed to lead to high full load operation hours (>7000 h/year), peak load has fairly small operational hours (< 2000 h/year). The more flexible a CHP system is, the more suitable it is for a high coverage of the heat demand (a-c, e). In all cases peak load is covered by a fossil fuel fired peak load boiler.

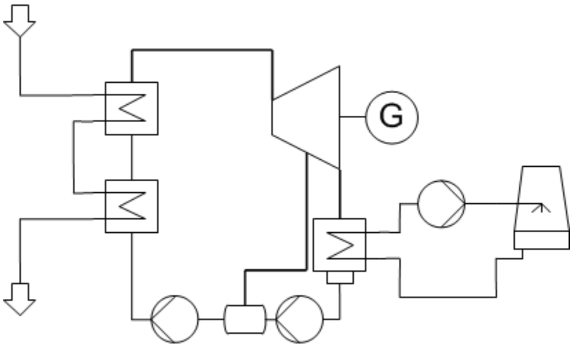


Figure 4: Two-stage ORC concept with turbine bleeding for regenerative pre-heating

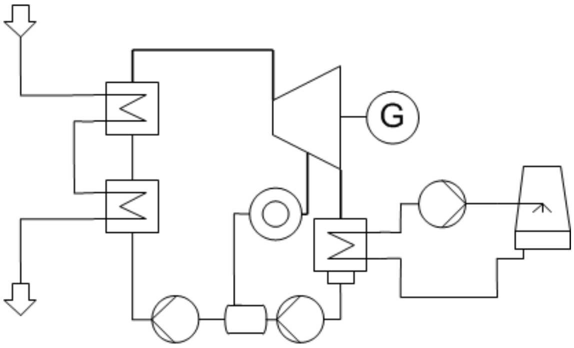


Figure 5: Integrated CHP concept with regenerative pre-heating

2.3 Operational strategies of CHP systems

In Vatopoulos *et al.* (2012) four major operation modes for CHP plants are distinguished: (1) Matching the electrical base load, additional power is purchased from the grid and heat is covered either by CHP or additional boilers; (2) Matching the thermal base load by meeting the base load in conjunction with a peak load boiler; (3) Matching the electrical load. For heat decoupling an additional boiler is used; (4) Matching thermal loads. Operation modes (3) and (4) can be considered as the classical electricity-driven and heat-driven operation.
A least cost strategy has been investigated by Hawkes and Leach (2007), which is not necessarily in line with the above mentioned ones. Hawkes and Leach (2007) investigated that least cost operational strategies can be a mix of the above mentioned operational strategies. It is apparent, that this operation mode is depending on the season and the overall coverage of the heat demand. Nevertheless, the heat-led operation leads always to minimal CO_2-emissions and to smallest primary energy consumption. In order to obtain a high coverage of the heat demand, flexible CHP systems are desired.

3. CONCEPT AND SIMULATION

3.1 Integrated CHP concept

In the literature a two-stage ORC with turbine bleeding has been investigated (Meinel *et al.*, 2014) This concept is shown schematically in figure 4, where the vapor from the turbine is extracted at an intermediate pressure level and used to saturate the working fluid in the liquid state in a direct contact heat exchanger. This measure increases the thermal efficiency of the ORC. It has been shown, that this concept is especially suitable for wet and isentropic organic fluids and that the performance increase is significantly better compared to a recuperator concept operated with the same fluid. The condensation temperature of the extracted fluid was in the range of 80 °C for R245fa. These findings suggested the investigation of heat extraction to a district heating system, which is integrated into the vapor extraction from the turbine. This concept is shown in figure 5.
It has to be noted, that this concept is associated with a higher system complexity due to the necessity of a multistage turbine and additional components (e.g. heat exchanger and pump). This results in higher investment costs. A further drawback of the system is the temperature level of the district heating system, which needs to be smaller than the evaporation temperature.

Table 1: Global specifications in the simulations

Parameter	Value	Parameter	Value
Mechanical efficiency	0.98	Supply temperature in heating network	80 °C
Generator efficiency	0.95	Return temperature in heating network	50 °C
Pump isentropic efficiency	0.90	Condensation temperature	30 °C
Turbine isentropic efficiency	0.80	Cooling water inlet temperature	20 °C
Pinch point specification	10 K	Temperature heat transfer media	240 °C/340 °C
Heat source scale	5 MW_t	Heat source temperature	490 °C

3.2 Simulation and boundary conditions

Simulations are carried out in Aspen V7.3, which is a well-known simulation tool for process engineering and offers a lot of component libraries, modules as well as fluid data bases.

The Peng Robinson equation of state is used to calculate fluid properties for these simulations. An overview of the applied boundary conditions, parameters and constraints is given in Table 1. The pressure level of the turbine bleeding was adjusted in order to meet the boundary conditions from the district heating and a given pinch point of 10 K. Furthermore, a pinch point of 10 K has been applied to all other heat exchangers. The temperatures for the district heating are in line with literature values found e.g. in Paar (2013) and Duminil *et al.* (2003). The heat source is assumed to originate from an internal combustion engine at a temperature level of $t_{WHS} = 490$ °C and ambient pressure (Karellas and Schuster, 2008). For simplification the gas composition is assumed to be equal to air. The energy content of the (waste) heat source is scaled to $\dot{Q}_{WHS} = 5$ MW_t and a thermal oil loop transfers this heat to the ORC. In the present study thermal oil temperatures of 240 °C (Karellas and Schuster, 2008) and 340 °C (Drescher and Brüggemann, 2007) are used, which are typical for waste heat recovery and biomass, respectively.

The working fluids in this study focus on isentropic fluids, but also include siloxanes, which are state-of-the-art for biomass applications. The next paragraphs explain the working fluid selection.

Among others, fluorinated alkanes such as 1,1,1,3,3-pentafluoropopane (R245fa) and the related 1,1,2,2,3-pentafluoropropane (R245ca) are considered, which are so called HFC. In particular R245fa is an often applied and investigated fluid and is used in experimental test rigs and operating plants nowadays.

In order to circumvent environmental-related issues, like high global warming potential, new molecules with lower impact on the climate are available. Thus, representatives of so-called fourth generation fluids (HFO) are included in the analysis, which are promising replacements for currently applied fluids. Namely cis-1,3,3,3-tetrafluoropropene (R1234zeZ) and trans-1-chloro-3,3,3-trifluoro-1-propene (R1233zd) are considered.

Cyclobutane, cyclopentene, furan and 2,5-dihydrofuran are selected from the group of cyclic molecules due to suitable critical parameters in the range of the chosen heat source temperatures.

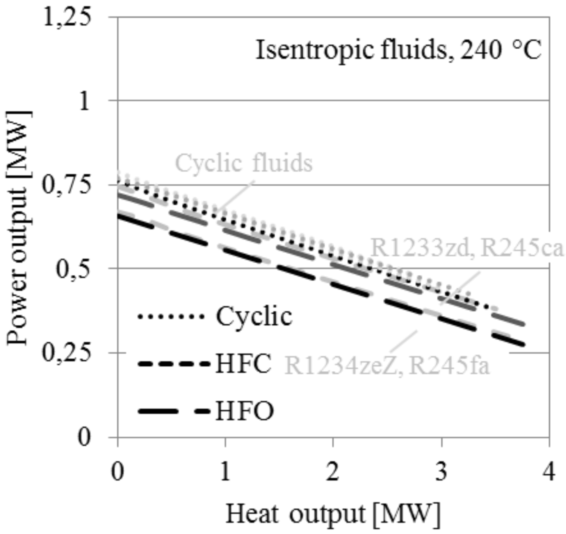
Commercially available systems for high temperature biomass and industrial waste heat applications are mainly operated by siloxanes. Siloxanes feature high critical temperatures in conjunction with good safety and environment-related properties. Thus in the present study several siloxanes are considered in the analyses as references. Depending on the heat source temperature hexamethyldisiloxane (MM), octamethylcyclotetrasiloxane (OMTS) and octamethyltrisiloxane (MDM) are simulated.

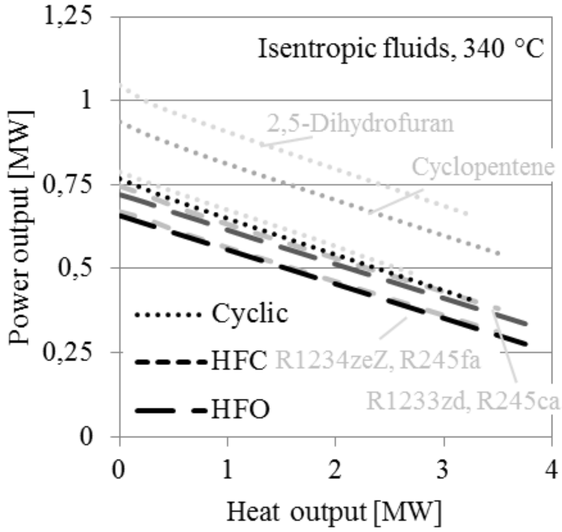
To conclude, representatives of hydrofluorocarbons (HFC), hydrofluoroolefins (HFO), cyclic compounds (Cyclic) and siloxanes (Siloxane) are investigated. Table 2 lists the considered working fluids and corresponding critical parameters as well as fluid type and characteristic.

Table 2: Investigated working fluids in the simulations including fluid type and critical parameters

Working fluid	Fluid type	t_{crit}	p_{crit}
cis-1,3,3,3-Tetrafluoropropene (R1234zeZ)	isentropic	150.08	35.30
1,1,1,3,3-Pentafluoropropane (R245fa)	isentropic	154.29	36.50
trans-1-Chloro-3,3,3-trifluoro-1-propene (R1233zd)	isentropic	165.56	35.70
Cyclobutane	isentropic	187.05	49.88

1,1,2,2,3-Pentafluoropropane (R245ca)	isentropic/dry	174.58	39.30
Furan	isentropic/dry	217.26	55.13
Cyclopentene	isentropic/dry	234.11	48.05
2,5-Dihydrofuran	isentropic/dry	269.10	55.13
Hexamethyldisiloxan (MM)	dry	245.68	19.13
Octamethyltrisiloxan (MDM)	dry	290.94	14.15
Octamethylcyclotetrasiloxan (OMTS)	dry	313.49	13.38





4. RESULTS

Since Meinel *et al.*, 2014 has shown that the efficiency of the two-stage concept with turbine bleeding performs best with isentropic working fluids, the first section focuses on these isentropic working fluids and the integrated CHP concept as shown in figure 5. For siloxanes the recuperation of the sensible heat becomes more and more favorable, due to the dry expansion behavior and the sensible heat content after the turbine outlet. Therefore a second section deals with siloxanes and a comparison of three different concepts. A final section presents a method to estimate annual electricity generation based on annual load duration curves.

4.1 Comparison of isentropic working fluids

In figure 6 results of the CHP simulations with the integrated concept for isentropic and wet working fluids are shown. Two different temperature levels of the thermal oil are investigated, which represent waste heat from internatl combustion engines (240 °C) and biomass application (340 °C). For the 240 °C case all the fluids perform similar and only minor changes can be obeserved. Among the fluids Furan performs best generating up to 787.6 kW_e. The next ranked fluids in terms of electric power output are cyclopentene (-2.2 %) and 2,5-dihydrofuran (-2.3 %) with slightly less power output compared to furan. Note that at a condensation temperature of 30 °C cyclopentene, furan and 2,5-dihydrofuran expand into vacuum (Table 3), which causes higher investment costs for turbine and consenser. Noteworthy alternatives are cyclobutane (-3.0%) and R1233zd (-8.5%). Where especially R1233zd represents a good trade-off between environmental-related (low global warming potential, no ozone depletion potential), thermodynamic (relativ high power output) and economic aspects (no vacuum expansion).

Figure 6: Performance of isentropic fluids at different thermal oil temperatures

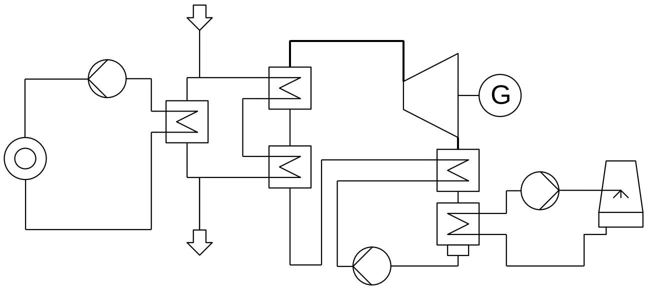


Figure 7: Parallel concept with recuperator concept for dry fluids (siloxanes)

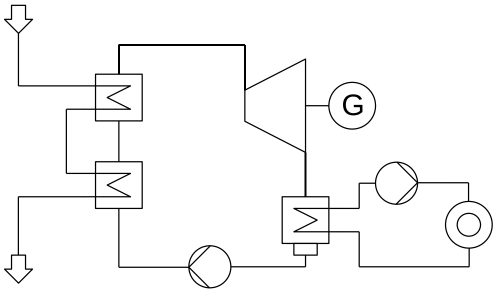


Figure 8: Parallel concept with recuperator concept for dry fluids (siloxanes)

For a thermal oil temperature of 340 °C only 2,5-dihydrofuran and cyclopentene as working fluids offer higher power outputs compared to the 240 °C-case. This increased power output is based on the fact, that the pinch point location changes from pre-heater outlet (240 °C) to the pre-heater inlet (350 °C) and no pinch point limitiation occurs anymore. For the other fluids no significant increase in the power output is observed. With 2,5-dihydrofuran as the working fluid 1045.79 kW_e are generated followed by cyclopentene with 937 kW_e (-10.5%) and furan (-24.7%). Similar to the simulations at 240 °C cyclobutane (-26.6%) and R1233zd (-31.1%) are alternatives but seem more suitable for lower temperatures.

4.2 Comparison of siloxanes

Since siloxanes are suitable for high temperatures and mainly used for biomass applications, the comparison of these working fluids focuses only on the high temperature case of the thermal oil (340 °C). In order to evaluate siloxanes three different concepts are compared in terms of a $P_e - \dot{Q}_{DHS}$-diagram:

1. Parallel concept with a recuperator to increase the thermodynamic efficiency (Figure 7). This concept is state-of-the-art for biomass fired power plants and process heat.
2. Condensation concept without a recuperator (Figure 8). This concept is state-of-the-art for biomass fired power plants and residential heating purposes.
3. Integrated CHP concept as shown in figure 5. This concept is beyond state-of-the-art for CHP applications.

Figure 9 shows the results for the three concepts and OMTS as working fluid. It can be seen, that the integrated concept offers a significantly higher power output compared to the parallel concept, if the capacity to the district heating system exceeds 1.25 MW_t. The condenser concept shows a lower electricity output for all operational conditions and becomes equal to the integrated concept with maximal heat decoupling. Note, that the CHP coefficients of the parallel concept and the integrated concept are variable, as was already described in section 2.2. The shaded triangle in figure 9 denotes operational points, where the proposed integrated CHP concept is more beneficial compared to the other designs.

For the other investigated siloxanes, MM and MDM the results are almost identical, which means, that a similar power and district heat output can be achieved. A comparison of the different siloxanes is shown in figure 10.

The recuperator cycle in general needs additional investments for the recuperator, which is an expensive component due to its size. The heat transfer from superheated vapor demands large surfaces. On the other hand side, the integrated concepts need additional components, as it was mentioned earlier, which causes additional costs as well. It is not the scope of this work to quantify

Table 3: Condensation pressures at a temperature of 30 °C

Working Fluid	p_{cond} @ 30 °C [bar]	Working Fluid	p_{cond} @ 30 °C [bar]
R245fa	1.77	Cyclobutane	1.83
R245ca	1.21	Cyclopentene	0.61
R1234zeZ	2.10	Furan	1.00
R1233zd	1.55	2,5-Dihydrofuran	0.29
MM	0.07	OMTS	0.03

these costs for the investigated concepts due to high uncertainties of available cost functions. In order to estimate benefits the power sales for the different concepts and different district heating systems will be compared. The procedure as well as the results will be described in the next section.

4.3 Estimation of economic benefits

For the economic calculation procedure an annual load duration curve is needed. If no measurement data are available, models are available in literature to approximate such curves. One of these models is the Sochinsky model, which determines the time dependent heat demand $\dot{Q}(\tau)$ in dependence of specific parameters:

$$\dot{Q}(\tau) = \dot{Q}_{max}\left(1 - (1 - m_0) \cdot \tau^{\frac{m-m_0}{1-m}}\right) \tag{2}$$

In the above equation $\dot{Q}_{max}$ is the maximum heat demand of the district heating system and τ the hour of the year. The load factor m can be expressed as the ratio of full load operational hours per year z and the hours per year z_a:

$$m = \frac{z}{z_a} \sim \frac{z}{8760} \tag{3}$$

The uniformity factor m_0 is depending on the minimal $\dot{Q}_{min}$ and maximal heat demand $\dot{Q}_{max}$ in the district heating system and is determined through the following equation:

$$m_0 = \frac{\dot{Q}_{min}}{\dot{Q}_{max}} \tag{4}$$

The resulting normalized annual load duration curve is shown in figure 11 with $z = 2500$ and $\dot{Q}_{min} = 0.1\dot{Q}_{max}$. The grey curve represents data from a real district heating network in southern Germany. It can be seen, that both load profiles differ significantly. Note that real annual load duration curves differ in general, because they strongly depend on the type and number of consumers and are unique for each district heating system. In order to take these variations into account, both curves will be used in further investigations.

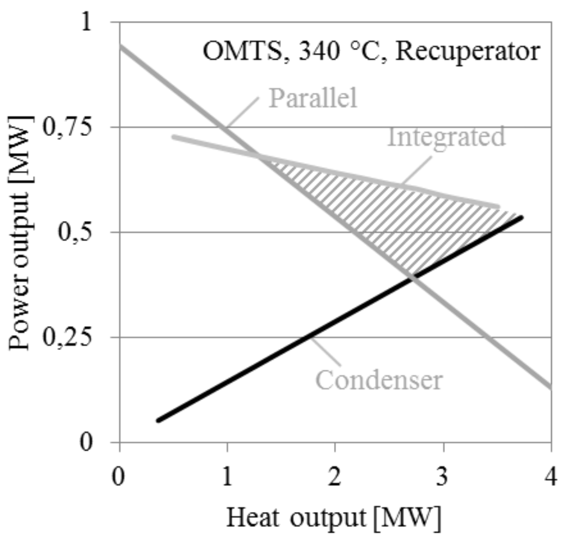


Figure 9: Comparison of CHP concepts with OMTS as a working fluid

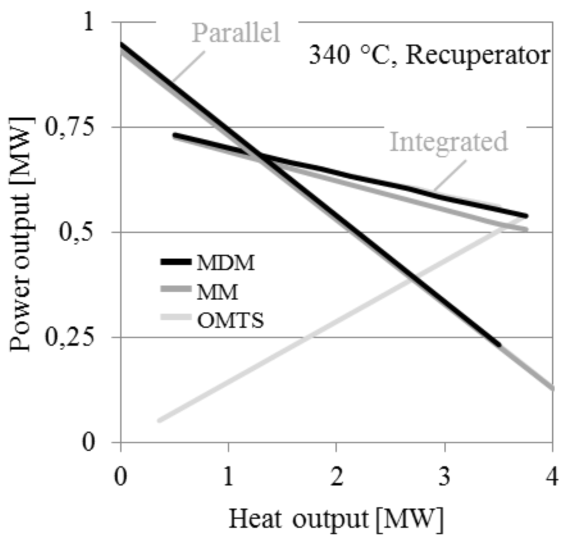


Figure 10: Comparison of different siloxanes

The integration of a CHP system into the district heating network is described by a cover ratio X_{CHP} which denotes the share of the maximal heat demand in the district heating system $\dot{Q}_{max}$ which can be covered by the CHP system at full load operation $\dot{Q}_{CHP,max}$:

$$X_{CHP} = \frac{\dot{Q}_{CHP,max}}{\dot{Q}_{max}} \quad (5)$$

This cover ratio is varied for the different CHP concepts and the cumulated power is evaluated. Note that the part load behavior of the cycle is also taken into account ($P_{min} = 0.4 \cdot P_{max}$). Figure 12 shows the cumulated electricity over the cover ratio for the different concepts as well as the different annual load duration curves. For high cover ratios the parallel concept approaches the integrated concept, while the integrated concept is similar to the condenser concept for low cover ratios. In between the electricity generation of the integrated concept is significantly higher than for the other two concepts. These findings are valid for the Sochinsky model (solid line) as well as the real data of a district heating system (dashed line). Therefore, it can be concluded that the integrated concept is suitable for the whole range of cover ratios, while the condenser concept and the parallel concept are limited in their application.

According to Dötsch *et al.* 1998 cover ratios of $0.1 \leq X_{CHP} \leq 0.4$ are common for real CHP plants and offer best profitability due to high full load operation hours. Taking $X_{CHP} = 0.3$ and the annual load duration curve of Sochinsky, the integrated concept is able to generate almost 5200 MWh/a, while the condenser concept (3500 MWh/a) and the parallel concepts (1340 MWh/a) produce significantly less electricity.

Revenues can be calculated by taking electricity prices into account, which range around $c_e \approx 40$ €/MWh at the European stock exchange and c_e =105.50 €/MWh for biomass applications of the considered CHP capacity according to the renewable energy act (EEG, 2014). These prices lead to annual revenues of $R_e(EEX) = 208\,000$ €/a and $R_e(EEG) = 548\,600$ €/a for the integrated concept and the Sochinsky-like district heating system.

5. CONCLUSIONS

In this study an integrated CHP concept is presented, which is based on a two-stage turbine bleeding ORC. The demand of the heating network is covered by decoupling heat from the steam extraction prior to the direct-contact heat exchanger. This integrated concept features a high level of flexibility due to the simultaneous adaption of the intermediate pressure in conjunction with a higher system performance due to regenerative pre-heating in the direct-contact heat exchanger.

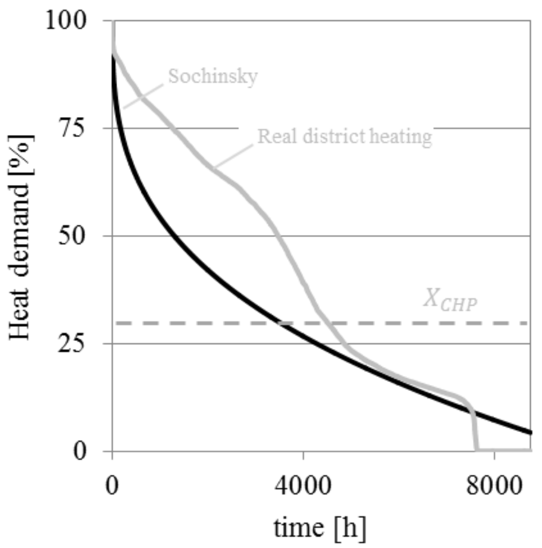


Figure 11: Annual load duration curve according to the Sochinsky model and real district heating data for southern Germany

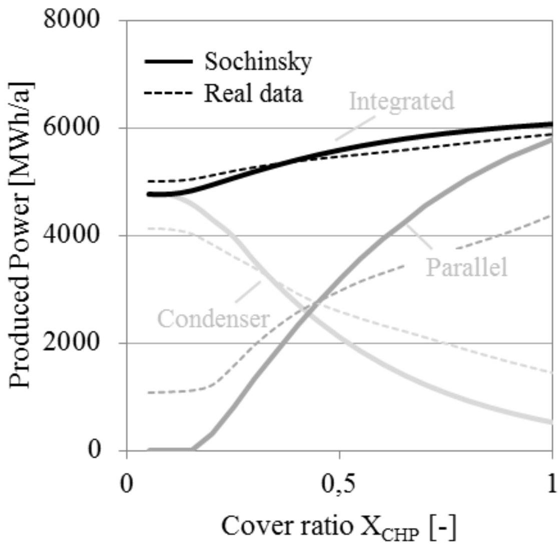


Figure 12: Annual cumulated power production for CHP integration in a district heating system in dependence of various cover ratios

First, the potential of the proposed system is characterized in terms of isentropic fluids. The investigated isentropic fluids are HFC, HFO and cyclic compounds. For waste heat applications R1233zd shows a good tradeoff between environment, thermodynamics and economics, although cyclic compounds have higher electricity output. For higher temperatures, similar to biomass applications, the cyclic compounds increase significantly in power output due to the absence of a pinch point limitation. Thus, this advantage might justify their application up to certain extent.
A comparison between different cycles for biomass applications with siloxanes as working fluids is presented, showing that the integrated concept has significant higher power output compared to other concepts.
The evaluation of the cumulated annual electricity production in dependence of the cover ratio within a district heating network shows, that the concept is flexible and applicable for the entire range of cover ratios.
In dependence of electricity prices the revenues per year are significantly higher and can justify also higher investments due to the higher system complexity of the presented integrated concept.

NOMENCLATURE

Parameter

c	prize	[€/MWh]
p	Pressure	[bar]
P	Power	[MW]
$\dot{Q}$	Heat	[MW]
R	Revenue	[€/a]
t	Temperature	[°C]
X	variable/ratio	[-]
z	time	[h/a]

Greek symbols

σ	CHP coefficient	[-]
η	efficiency	[-]
τ	time	h

Abbreviations

CHP	Combined heat and power	
HFC	Hydrofluorocarbons	
HFO	Hydrofluoroolefines	

Subscripts

$cond$	condensation
$crit$	critical
DHS	District heating system
e	electricity
max	maximum
min	minimum
t	thermal
WHS	Waste heat source

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