Performance Analysis of a Biomass ORC Poly-generation System

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Abstract

This paper shows monitoring results of the operation of a biomass fuelled combined heat and power (CHP) plant using the Organic-Rankine-Cycle (ORC) technology and a district heating network as a heat sink. Furthermore a decentralised thermal cooling system, connected to the district heating is being described. Annual analyses focus on the performance of the facilities and the optimisation potential.
Monitoring data from the control system and various sensors in the cycle are assessed over several annual periods. The results give an overview of the economic and ecologic performance of the facility. Auxiliary energies are discussed in detail. Economical and ecological aspects of the system are discussed.

Keywords

Cogeneration, ORC, district heating, thermal cooling, auxiliary energy

Introduction

Facing the challenges for de-centralised and highly efficient power supply, more than 150 ORC-plants have been installed all over Central Europe. The majority of modules have been produced by the market leader Turboden of Italy. The vast majority (140) is based on biomass combustion systems. More than 50 of those biomass cogeneration plants feed their sink heat into district heating systems [6]/[7]. Detailed pieces of information on the annual and long term performance of this kind of facilities are rare. Therefore this paper will take on that subject.
The POLYCITY project is examining the ORC-technology within the project site of "Scharnhauser Park" a quarter of the city of Ostfildern, near Stuttgart. Being taken into operation in the year 2003 the plant supplies the heat demand of a growing quarter with an actual population of 7300 (as of December 2010 [1]). The power plant is designed for a maximum annual heat production of 35000 MWh. The 8 MW_{th} biomass furnace burns wood chips and landscape preservation material with widely varying qualities. Thus the quarter achieves a remarkable ratio of over 80% of CO_2 neutral heating energy. Approximately 50% of the electric energy consumption in the area can be covered through the combined heat and power system.

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Methodology

Over a period of 6 years all relevant data of the system have been acquired to give a comprehensive and precise overview of the operation.

The energy flows inside the power plant are measured by heat meters of Kamstrup. According to its size the district heating is monitored with a MAXICAL III type. The manufacturer states an accuracy class of 0.2% [11] for temperature spreads larger than 20 K.
In the transfer system the thermal oil is measured utilising a MAXICAL401. All heat meters fulfil the requirements of an EN 1434-1 Class A device. Therefore less than ±2% deviation can be expected taking the sensors, gauge and calculators accuracy into account.
All heat meters are connected to m-bus systems. From there data are transferred to the main control of the power plant. Measured values are written via a script the into four files containing a dBase table. Exhaust system, transfer cycle, district heating network and ORC-module are saved in separate files with a time step of 1 minute. In this way all energy flows from the combustion process to the transfer system into the generating cycle and from there into the district heating system can be monitored. The files are transferred from the power plant server to a database server in the research institute via FTP. After the automated unification of the various data sources monthly and annual reports for the period have been generated.

Results

Biomass conversion

The core of the Scharnhauser Park CHP plant is a state of the art biomass grate furnace, which serves as the thermal energy source for the ORC module, where electricity is generated. In fact, the biomass boiler can be seen as the heart of the conversion system as its efficiency influences substantially the overall system efficiency.

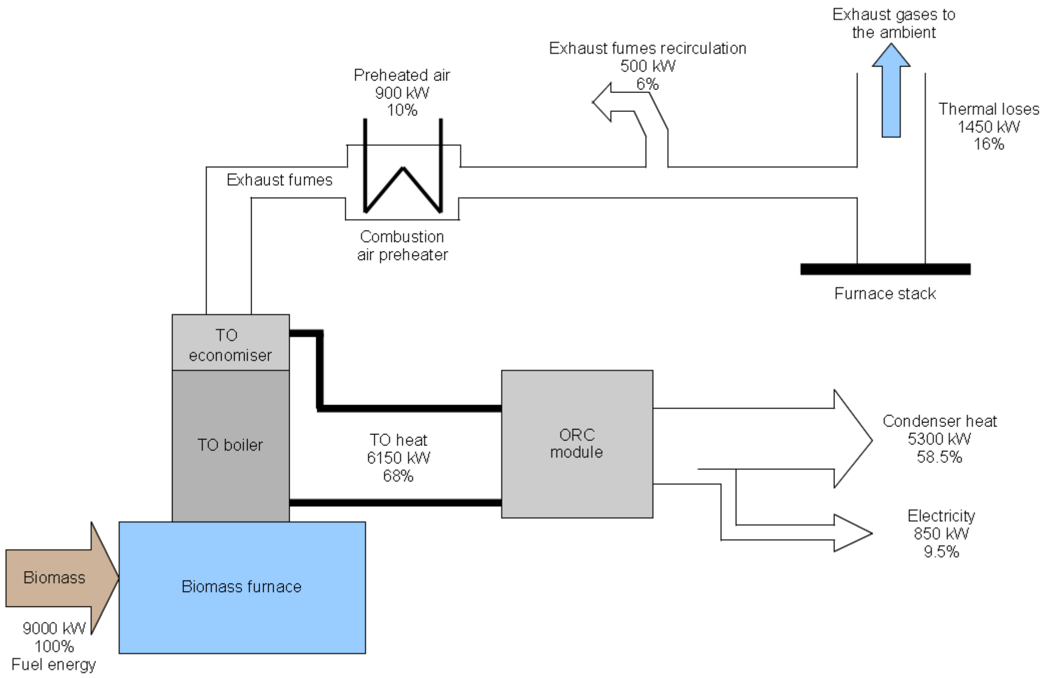

Figure 1: Biomass combustion based cogeneration at the CHP Scharnhauser Park – energy balance at nominal load

In recent years great effort in development of biomass combustion technologies can be observed, which is still on-going. The primary aim of this development is to maximise the combustion efficiency and thus the profitability of bio-energy projects. The conversion

efficiency of biomass combustion plants depends mainly on the amount of unburned fuel components and thermal losses by sensible heat of the flue gas.
The combustion efficiency of the furnace at the CHP plant can be calculated using an indirect method. In the indirect method the combustion efficiency is obtained from the estimation of energy losses related to incomplete combustion and thermal losses of the hot flue gases. The calculation results of the combustion efficiency are presented in Figure 2.

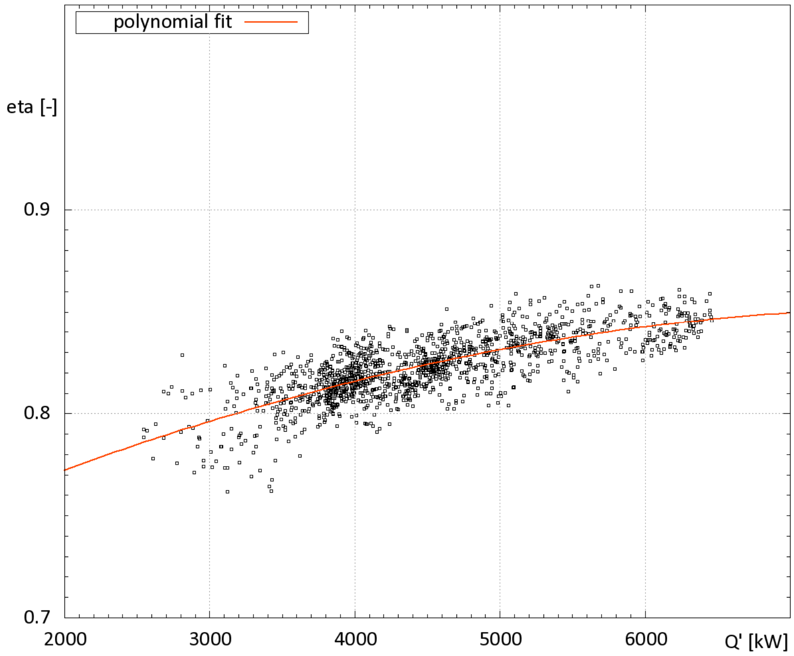

Figure 2: combustion efficiency vs. thermal heat output of furnace

According to the information provided by the furnace manufacturer, the combustion plant should achieve efficiencies of about 91%. The calculated values did not reach this level. In the case of the analysed furnace combustion efficiencies of above 90% can only be achieved if good quality fuel with a high calorific value of about 19 MJ/kg (dry basis) and relatively low water content (w < 45%) is burned. Due to cost reasons park waste wood and landscape management residues with relatively low quality ($LCV_{DryFuel}$ = 16 MJ/kg = 1.56 MWh/m³) are used as combustible at the CHP plant Scharnhauser Park. Another disadvantage of the utilised wood chips is the relatively low ash melting temperature. In order to avoid exceeding of the ash melting temperature fresh cut woodchips with a water content of w≈50% are burned.

Overall degree of efficiency
The measurements results archived at the CHP plant contain the amounts of generated energy as well as the amounts of combusted wood chips. The comparison between the amount of generated energy and the fuel energy can be used to evaluate the overall degree of efficiency of the combustion system. The calculation is based on data gathered since the beginning of the plant operation and enables the determination of the quality of the combustion system while operating under non stable working conditions.
The fuel energy can be calculated on the basis of the amount of fuel burned and the calorific value of the combustible. The fuel value of wood chips depends clearly on their humidity and can be estimated as a function of humidity for a given wood type (see Figure 3). For fresh cut woodchips with approximately 55% of water content the LHV achieves 0.65 MWh/m^3.

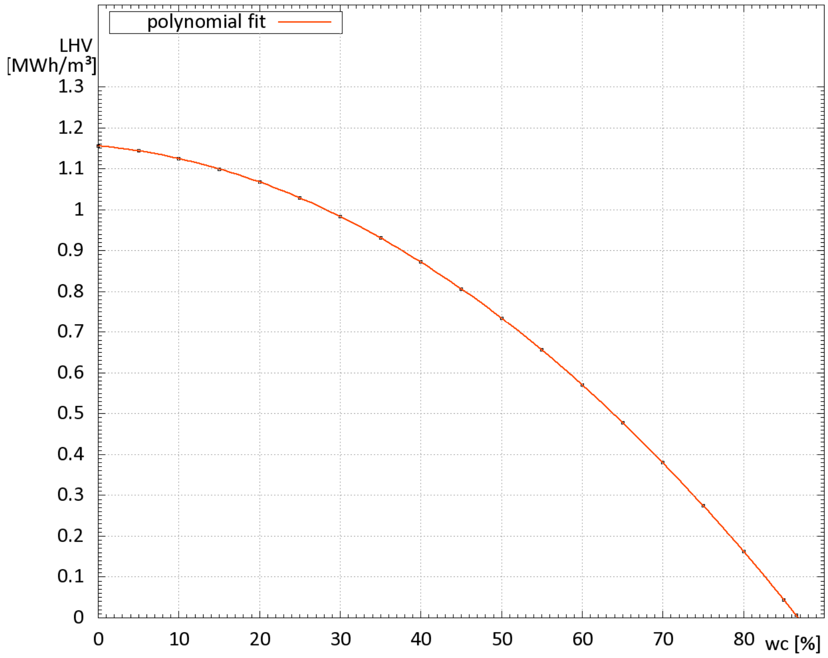

Figure 3: Net calorific value (NCV/LHV) as a function of fuel water content.

The results of the calculation of the overall degree of efficiency for the biomass combustion system are presented in Table 1.

Table 1: Combustion plant efficiency (2004-2010)

	value	unit
combusted wood chips	286373	m^3
LHV	0.65	MWh/m^3
fuel energy	186142	MWh
excess heat	26350	MWh
biomass heat to network	113158	MWh
electricity generated	12385	MWh
converted energy (heat+electricity)	151893	MWh
mean overall efficiency	81.60%	-

The overall degree of efficiency can be quantified using reference values given in the literature. In [5] the overall degrees of efficiency were calculated for 30 biomass heating systems in Switzerland. Most of the systems achieved degrees of efficiency of between 70 and 80%. The calculated overall degree of efficiency of 81.6% for the biomass furnace at the CHP plant Scharnhauser Park can be considered as relatively high in respect of those reference values.

Electric generation

The plot in Figure 4 shows mean hourly values of the electric feed-in derived from minute values. Over the whole operational range from 2.5 MW to 6.3 MW the values increase steadily. Points scattered underneath and above the fit curve are mainly start-up and shut-down procedures of the cycle. In these cases unsteady states are displayed.

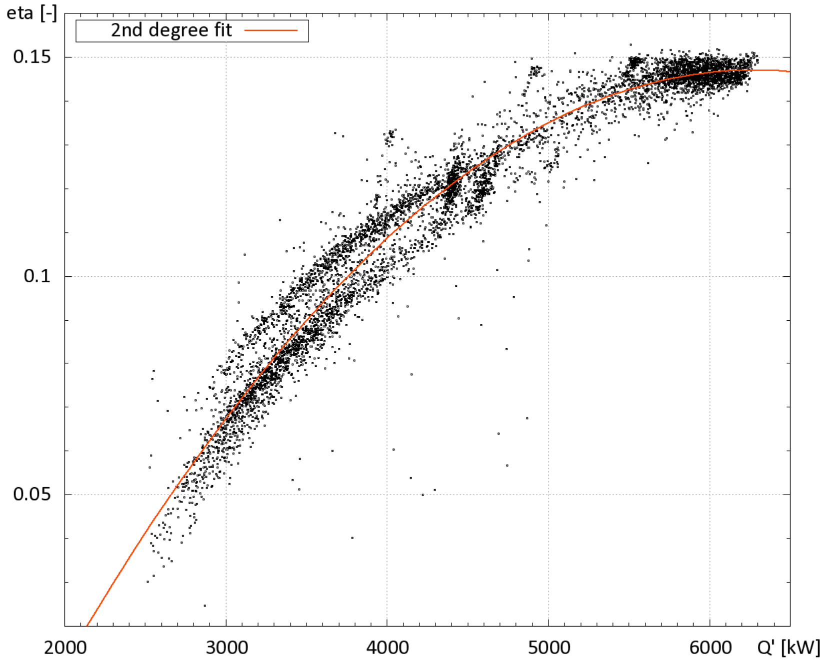

Figure 4: electric gross efficiency vs. thermal input (2008)

Maximum values of 14% to 15% of electric efficiency can be expected between 5.5 MW and 6.3 MW. The design efficiency of the cycle, predicted with 16.37% (at 5.8 MW) by the manufacturer could not be reached [1]. In the low operational range the point form two parallel clouds. These accumulations of states represent winter operation (upper) and summer operation (lower). In the summer mode even lower thermal inputs are recorded as the system is run including the re-cooling unit which assures safe continuous operation.

District heating

The demand within the urban quarter is mainly determined by two factors; the total number of inhabitants and the climate conditions. The plot of the annual degree days in Figure 5 shows that in the monitored period only one year was colder than the 20 years' mean. The demand was therefore lower than expected.

Figure 6 shows the overall performance of the cogeneration facility. Heating energy delivered by the biomass furnace and natural gas boilers and the electric yield are plotted for seven years. In the winter period 2005 to 2006 the OR-Cycle was offline due to an evaporator leakage. After several month of revision and the replacement of the plate heat exchanger by a shell tube type the system went back to the grid in November 2007. The winter period of 2007 to 2008 has been the so far most successful operating time in terms of electric generation. In the winter period 2008 to 2009 a fire incident in the main building near to the biomass furnace caused severe damage to the system. Besides the thermal oil system, the heating coils of the boiler, several secondary systems and the PV-inverters have been destroyed. Thus in the following year only emergency operation with 100% gas was possible. After a major revision the facility was taken back into standard operation in November 2009.

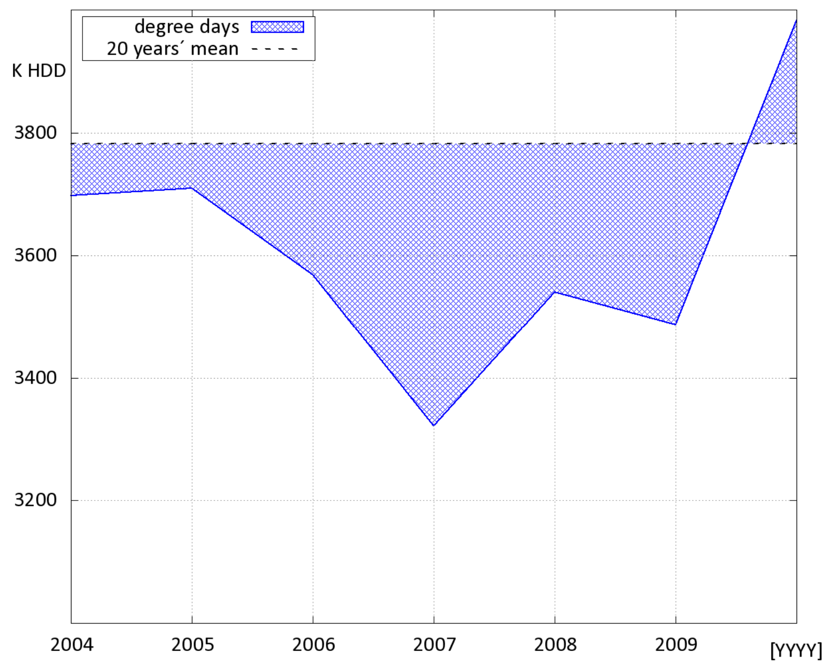

Figure 5: degree days 2004-2009, Stuttgart Airport [12]

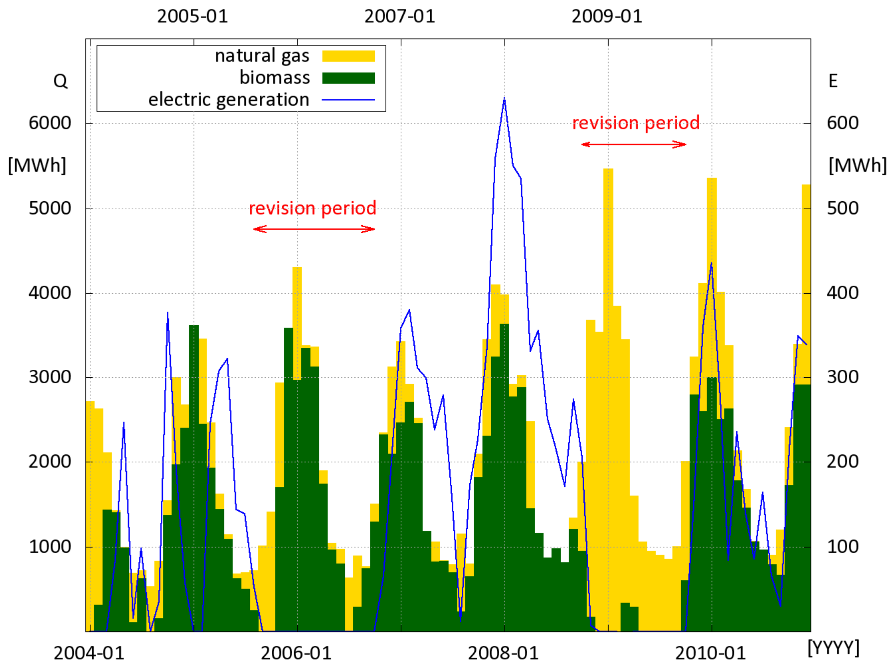

Figure 6: monthly heating energy produced from biomass and natural gas and ORC electric yield

Analysing the measured values from all heat meters between 2004 and 2010 the following results can be shown:

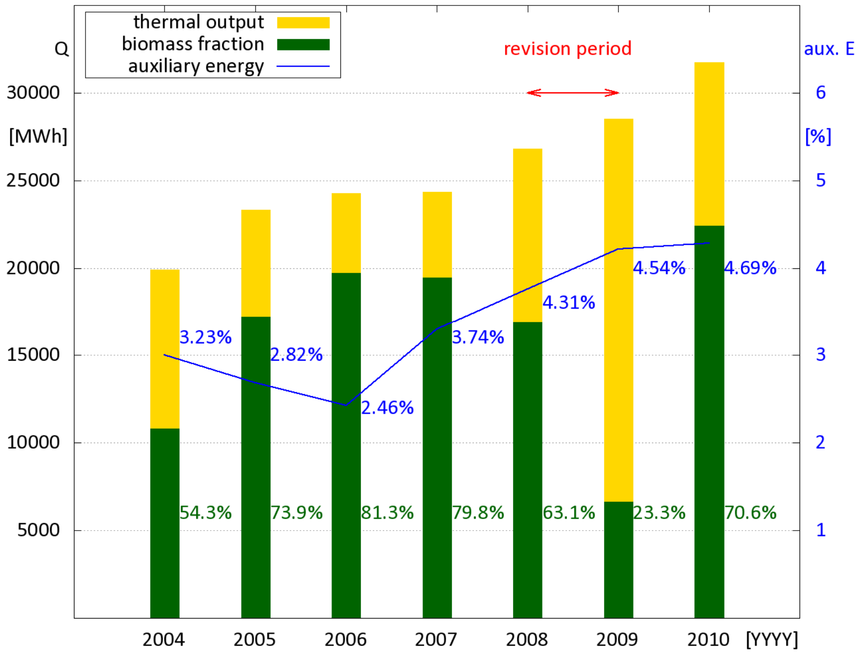

Figure 7: biomass fraction of total heating energy and auxiliary energy annual values (2004-2010)

With exception of the years 2008 and 2009 the overall trend shows a growing biomass heating energy production. The overall demand is steadily increasing. The population development in the quarter in the last years has been linear. Taking into account an extraordinarily warm winter (3321.8 Kelvin days [12]) of 2007 the overall demand is mainly depending on the number of inhabitants. The maximum annual energy in the district heating, as expected in the design phase with 35000 MWh, will be exceeded when the quarter reaches the final population of over 10000. The manufacturer of the furnace indicates an auxiliary electric energy consumption for this power plant of 25 kWh_{el}/MWh_{th}, respectively 2.5%. As the blue line in Figure 7 shows this threshold could not be reached except in the year 2006.

Thermal cooling

Since 2009 the company of Elektror is operating an absorption chiller in their office building fed by the district heating network.

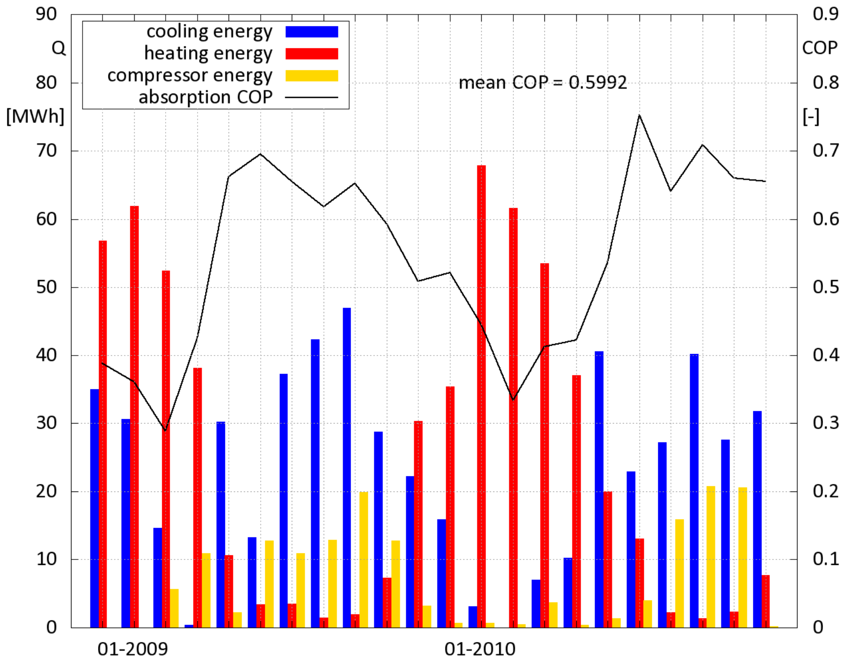

Figure 8: performance of the Elektror building (2009-2010)

The generator of the absorption chiller is connected as a by-pass in parallel to the main network feeding line.

The results of the Elektror building in Figure 8 show a rather balanced heat and cold distribution over the year. Compressor cooling is mainly used in summer. The COP curve indicated a linear part-load dependency as shown in Figure 9. The range of variation for this 105 kW absorption chiller is situated between 0.3 and 0.75.

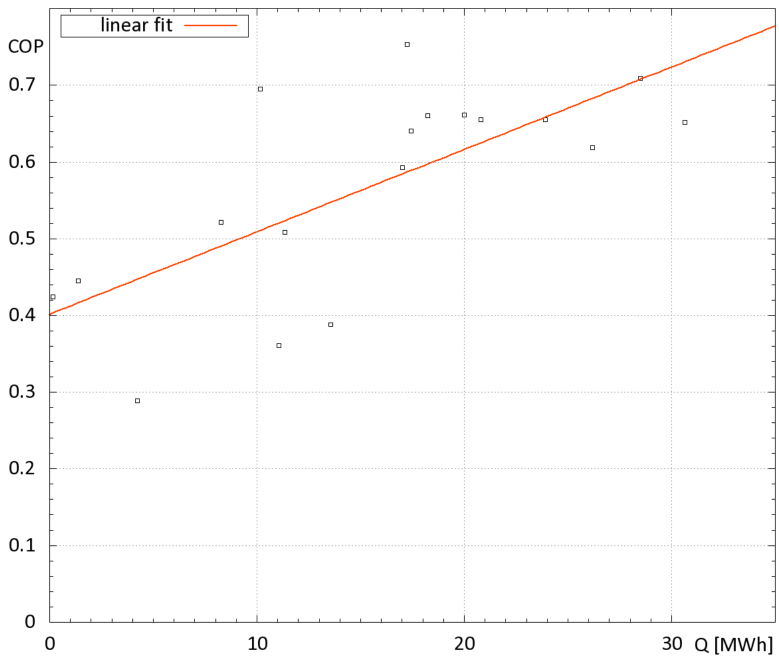

Figure 9: COP versus cold output (2009-2010)

Discussion

ORC systems are often chosen as a technology with low operational costs (low pressure systems, no permanent operational personnel) [2]/[3]/[4]. During the first years of operation, this goal was not yet achieved. In the beginning of the operation the local supplier SWE expected automatic operation periods of up to 72h. In fact the facility is run by several technicians with weekdays (8:00-18:00) attendance.

Main reasons for this are fuel and fuel system problems, such as crane errors or jams by frozen woodchips. The quality of the fuel is rather low. The high ash and water contents and the comparably low calorific value lead to a high fuel turnover, which leads to an increased wear on the system. Despite the challenges in daily operation the overall result for the combustion can be seen a positive. The comparably high conversion efficiency from biomass to thermal energy is a positive point to be mentioned. Aside from repair period the coverage by biomass for the demand of the quarter shows good results. Roughly 80% of the thermal energy, the biggest energy flow in urban system, is de facto CO_2-neutral.

The results show that the auxiliary energy for complex conversion processes might be underestimated. Compared to the design parameters the specific values of auxiliary energy exceed the expected consumption. The usage of low quality combustibles has to be compensated with an increased amount of combustion air. Thus higher primary air fan consumptions can be expected.

The results of the OR-cycle show clearly that the operation has not yet been optimal. The designed peak power could not be reached in daily operation. The upper pressure level of the cycle does not meet the specifications. Due to safety regulations the thermo oil cycle's temperature limit was set to 290°C instead of 300°C. Thus the resulting temperatures in the cycle are lower and the saturated pressure of 9.5 bars cannot be reached. The pressure losses in the control valve and the steam filter before the turbine have been underestimated in the beginning. During average operation these losses sum up to 0.7 bar. The turbine pressure drop is then lower than expected. In longer operational periods the performance of the cycle decreased. The reason for this behaviour can be found in the usage of the vacuum pump. To extract gaseous compounds from the condenser and to improve efficiency the vacuum pump is used frequently. By extracting gas from the cycle to the atmosphere small amounts of cycle fluid get lost as well. A low filling level of cycle fluid leads to lower pressures before the turbine.

The absorption cooling in the Elektror building is performing well. The COP meets the expected level. The overall energy balance of the building shows that the design size of compression as well as of the absorption chiller has been chosen appropriately. The low operating hours of the compressor support these findings.

Nomenclature

T	Temperature [K]
Q'	heat [MW_{th}], [kW_{th}]
MDM	Octamethyltrisiloxane
Q	MWh_{th} Megawatt hours thermal, [MWh_{el}] Megawatt hours electric
P	[kW_{el} / kVA] Kilowatts electric
MDM	Octamethyltrisiloxane, working fluid inside the Rankine-Cyle
T66	Therminol66© thermal oil used in the transfer cycle of the power plant
SWE	Stadtwerke Esslingen GmbH&Co.KG, local supply company
EEE	Department of Electrical and Electronical Engineering
P-Bus	PROFIBUS, Profi Field Bus
TCP/IP	Transmission Control Protocol/Internet Protocol
OPC UA	OPC Unified Architecture
FTP	File transfer protocol
LHV	energy released in complete combustion under standard conditions
HHV	LHV + condensing heat of water vapour
NCV	see LHV

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