Seasonal heat storage as an optimization tool for the operation of CHP plants

Dan Bauer, Roman Marx
University of Stuttgart, Institute of Thermodynamics and Thermal Engineering (ITW)
Research and Testing Centre for Thermal Solar Systems (TZS)
Pfaffenwaldring 6, 70550 Stuttgart, Germany
Phone: 0049-711-685-69445, Fax: 0049-711-685-63503
Email: bauer@itw.uni-stuttgart.de

Abstract: *The economical and ecological optimization of a combined heat and power (CHP) plant by seasonal heat storage has been investigated in a simulation study. An innovative concept of the CHP plant has been developed. The CHP plant consists of four main components: a bio fuel combustion engine driving an electric generator, an electric driven heat pump, a seasonal borehole thermal energy store and a hot water buffer store. Due to the seasonal heat storage, the combustion engine can run continuously at nominal power. Furthermore, the CHP plant is able to supply 100 % of the yearly heat demand of a residential area by district heating. The generated electric power is sold to the public grid. The CHP plant emits less CO_2 compared to a gas fired condensing boiler. In addition, it offers a high level of economic efficiency due to the guaranteed high feed-in tariff in Germany.*

1 Introduction

In 2010, the fraction of renewable energy of Germany's end energy consumption was smaller for heat (9.8 %) than for electricity (16.8 %) /1/. The total fraction of renewable energy of Germany's total end energy consumption is planned to be increased from 11 % in 2010 /1/ to 18 % in 2020 and to 60 % in 2050 /2/. Due to the high overall efficiency, bio fuel driven combined heat and power (CHP) generation can make a crucial contribution to achieve theses ambitious goals in the heat and electricity sector. As a consequence, bio fuel driven CHP generation is highly government-funded by the Renewable Energy Law (Erneuerbare-Energien-Gesetz - EEG) §27 /3/.

However, one major problem of the concurrent combined heat and power generation is the different time profile of heat and electric energy demand. The demand of electric energy mainly varies during the day. By contrast, the heat demand of a residential area varies very much during the year. Hence, combined heat and power generation can be more efficient by either heat or electric energy storage. Considering the same storage efficiency, heat storage can be performed at lower costs than the storage of electric energy.

2 Materials and method

The optimization of a CHP plant by adding a seasonal heat store has been investigated in a simulation study. The seasonal heat storage shall allow a continuous power generation during the whole year at nominal power while supplying a residential area with 100 % of its yearly heat demand without the necessity of additional heat generation by a gas fired condensing boiler. The following basic conditions have been considered:

- Complete heat supply for hot water preparation and space heating of a southern German residential area by a district heating network (6 932 MWh/a annual heat demand with supply temperature of 70 °C and average return temperature of 42 °C); The heat demand profile was measured at a district heating network in southern Germany in 2007, see Fig. 2.

- Bio fuel driven CHP generation for low CO_2 emission and guaranteed high feed-in tariff for electric energy
- Continuous power generation during the whole year
- Seasonal heat storage by a borehole thermal energy store (BTES); A BTES consists of a large number of borehole heat exchangers with a depth in the range of 30 to 100 m installed next to each other and uses the underground as storage medium.
- Integration of an electric driven compression heat pump

The simulations led to a technically reasonable system concept as depicted in Fig.1: A hot water buffer store with a volume of 600 m^3 is needed for compensating the peak heat demand of the residential area and for the distribution of thermal energy. The district heating network is connected to the buffer store. A constant supply temperature of 70 °C is achieved by adding water from the return flow if the temperature of the buffer store is higher than 70 °C. The combined heat and power generation (750 kW_{th}, 500 kW_{el}, η_{total} = 90 %) by a combustion engine driving an electric generator is running continuously at nominal power. The water for cooling the combustion engine is taken from the buffer store at its bottom. This water firstly flows through the condenser of the heat pump, no matter if the heat pump is running or not. The water subsequently flows through the combustion engine where it is heated up. It is reinjected into the buffer store at its top. The mass flow rate is controlled in such a way that the outlet temperature of the combustion engine is always 80 °C.

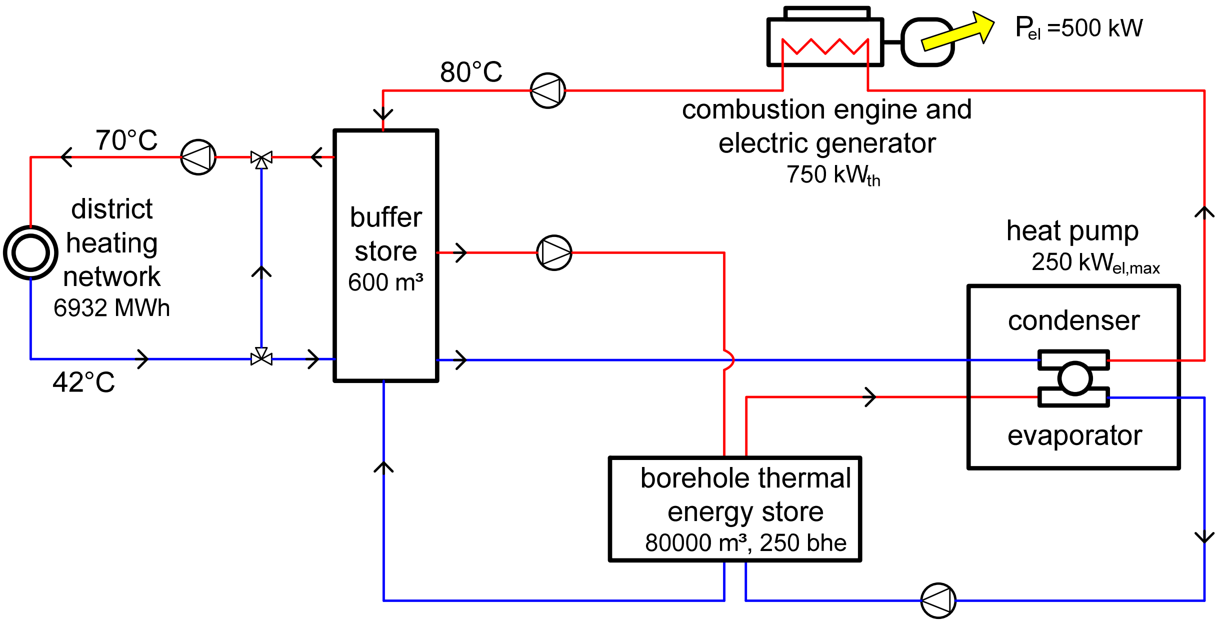

Fig. 1: System concept of the CHP plant with seasonal heat store

In summer, when the combustion engine generates more heat than needed by the residential area and if the buffer store is completely charged, heat from the buffer store is shifted to the BTES with an effective volume of 80 000 m^3 and consisting of 250 borehole heat exchangers. In wintertime, heat is extracted from the BTES by the heat pump (250 $kW_{el,max}$, 1920 $kW_{th,max}$). Depending on the temperature of the buffer store, the heat pump runs with 50 % or 100 % nominal electrical power. The condenser of the heat pump and the combustion engine are connected in parallel. The heat pump preheats the cooling water of the combustion engine before it is heated up to 80 °C by the combustion engine. This concept allows both, a high storage utilization ratio of the BTES and a high seasonal performance factor (SPF) of the heat pump. The electric power demand of the heat pump is much smaller than the electric power generation by the generator. Hence, the CHP plant is able to deliver the total electricity demand of the heat pump at any time.

3 Results of the simulation study

The results of the simulation study show that the complete heat supply of the southern German residential area including the peak demand can be managed by the system. Either the combustion engine or the heat pump can be switched off for maintenance work. The security of supply can be ensured for a sufficiently long period by only one of these components in combination with the buffer store. A back-up heat generation system (e.g. a gas boiler) is not necessary.

The continuous power generation at nominal power can be effectively achieved by storing the not used excess heat in the seasonal heat store. This allows the maximum possible generation of electric energy and so a maximum possible economic efficiency because of the high feed-in tariff for electric energy. Unlike other renewable electric power generation technologies like wind power stations or photovoltaic systems, the bio fuel fed CHP plant with seasonal heat storage is able to generate renewable electric power at base load conditions during the whole year.

Fig. 2 depicts the computed monthly energy balance of the entire system. Fig. 3 depicts the computed energy balance of a year.

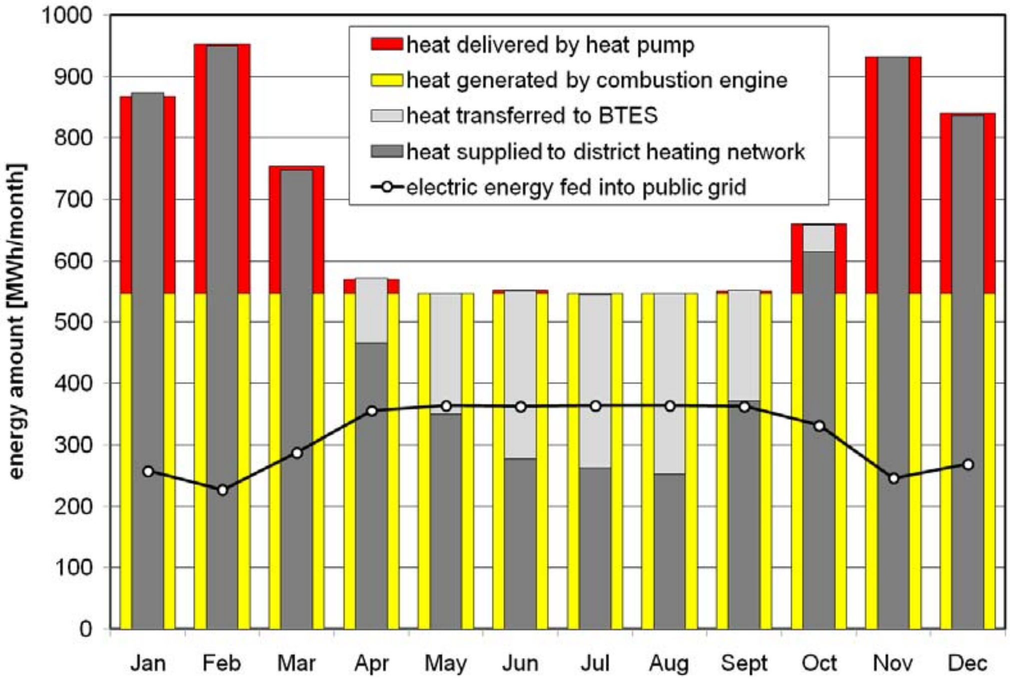

Fig. 2: Computed monthly energy balance of the CHP plant with heat pump and seasonal heat storage; the wide bars in the background are showing the heat sources, the small bars in the foreground are showing the heat sinks

Only 21 % of the heat generated by the combustion engine needs to be stored seasonally. This corresponds to 11.4 % of the fuel consumption. The BTES reaches a maximum temperature of 45 °C in autumn and a minimal temperature of 15 °C in spring. The amplitude and the medium temperature level of the BTES can be influenced by the variation of the store volume and the capacity of the heat pump. This in turn has an influence on the storage utilization ratio of the BTES and the SPF of the heat pump. In this study, the power of the heat pump has been chosen in such a way, that the storage utilization ratio of the BTES is 90 %. The SPF of the heat pump then is 3.0. Hence, in relation to the fuel consumption, only 1.2 % of the energy is lost by the seasonal heat storage.

The amount of electric energy fed into the public grid is smaller during the winter months than during the summer months. The reason for this is the electric energy consumption of the heat pump. The monthly energy balance shows an untypical large heat demand of the district heating network in November, which can be explained by the use of real measured data of a district heating network in 2007.

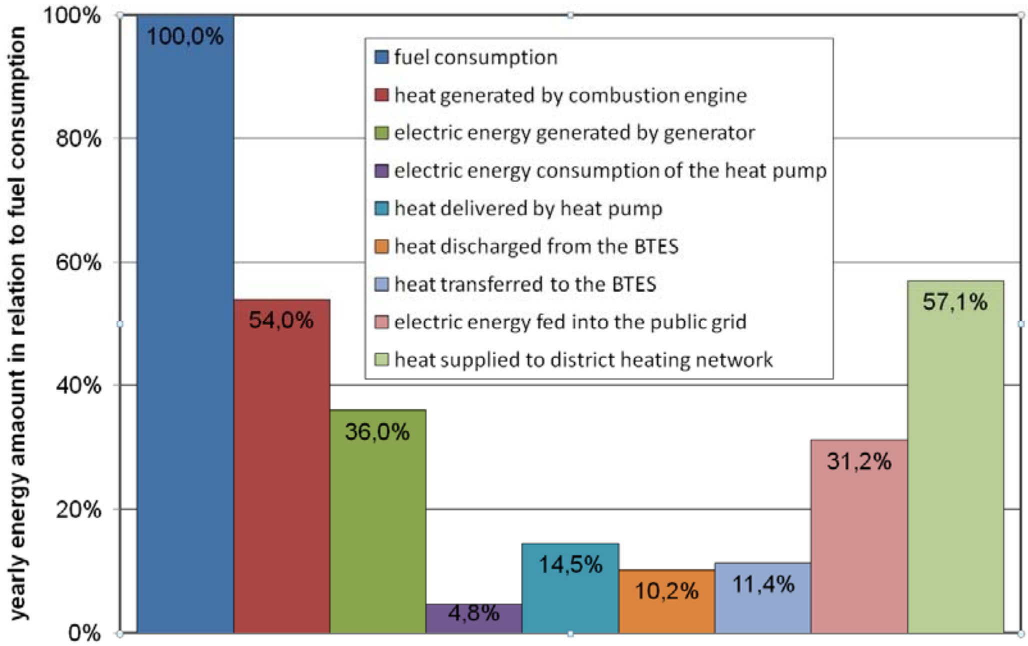

Fig. 3: Computed yearly energy balance of the CHP plant with heat pump and seasonal heat storage

4 Ecological and economic assessment

The CO_2 emission of the combined heat and power generation has been calculated according to the global emission model for integrated systems (GEMIS) /4/. The GEMIS calculates with separate specific emission values for heat and for power and it includes emissions during the production and the transport of the fuel. It even accounts for negative specific emission values if the emissions avoided due to the replacement of conventional heat or electric energy generation by renewable CHP generation are higher than the local emissions of the CHP plant /5/.

A reduction of the CO_2 emissions of 85 % compared to the conventional, separate generation of heat and power can be achieved, if rapeseed oil is used as bio fuel for the CHP plant. The conventional reference system is based on a gas fired condensing boiler for heat generation and on the German electricity mix in 2010 for electric energy generation. Table 1 shows the CO_2 emissions of both systems calculated according to the GEMIS.

An economic analysis based on the annuity method (interest rate: 5 %, period of depreciation: 20 years) has been carried out. It shows the fundamental cost effectiveness of the CHP plant with heat pump and seasonal heat storage. The investment costs are higher compared to a heat generation system based on a gas condensing boiler. However, the revenues are higher, too. The feed-in tariff for electric energy which is defined by the German EEG consists of a basic remuneration of 9.18 Cent/kWh$_{el}$ for a maximum power of 500 kW$_{el}$ and a bonus for combined heat and power generation of 3.0 Cent/kWh$_{el}$. Depending on the technology of combined heat and power generation and on the kind of bio fuel, an additional technology bonus of 2.0 Cent/kWh$_{el}$ and a bonus for renewable raw materials of 6.0 Cent/kWh$_{el}$ are paid. The basic remuneration increases to 11.67 Cent/kWh$_{el}$ for a maximum power of 150 kW$_{el}$. Table 2 shows the economic analysis of the CHP plant with heat pump and seasonal heat storage and of the system based on a gas fired condensing boiler.

Table 1: Anual CO_2 emissions calculated according to the GEMIS

	CHP plant with heat pump and seasonal heat storage	**conventional technology (separate generation of heat and power)**
generated energy	6932 MWh$_{th}$ (heat) 3795 MWh$_{el}$ (electric energy)	6932 MWh$_{th}$ (heat) 3795 MWh$_{el}$ (electric energy)
specific CO_2 emission	-92 g/kWh$_{th}$ (heat) /5/ 320 g/kWh$_{el}$ (electric energy) /5/	254 g/kWh$_{th}$ (gas condensing boiler) /5/ 563 g/kWh$_{el}$ (German electricity mix 2010)
absolute CO_2 emission	-638 t (heat) 1214 t (electric energy) 576 t (total)	1761 t (heat) 2137 t (electric energy) 3898 t (total)
Reduction of CO_2 emission	85 %	

Table 2: Economic analysis of the CHP plant with heat pump seasonal heat storage and of a system based on a gas fired condensing boiler

	CHP plant with heat pump and seasonal heat storage	**gas condensing boiler**
investment costs	1.685.500 €	825.000 €
yearly costs for capital	84.275 €/a	41.250 €/a
yearly costs for fuel	728.880 €/a	462.133 €/a
yearly costs for maintenance	40.800 €/a	12.000 €/a
yearly total costs	853.955 €/a	515.383 €/a
remuneration for heat	693.200 €/a*	693.200 €/a*
remuneration for electric energy	462.231 €/a** / 765.831 €/a***	-
total remuneration	1.155.431 €/a** / 1.459.031 €/a***	693.200 €/a
yearly earnings	301.476 €/a** / 605.076 €/a***	177.817 €/a
payback period	5.6 a** / 2.8 a***	4.6 a

* 0.1 €/kWh$_{th}$
** basic remuneration 9.18 Cent/kWh$_{el}$ + CHP bonus 3.0 Cent/ kWh$_{el}$
*** basic remuneration 9.18 Cent/kWh$_{el}$ + CHP bonus 3.0 Cent/ kWh$_{el}$ + bonus for renewable raw materials 6.0 Cent/ kWh$_{el}$ + technology bonus 2.0 Cent/ kWh$_{el}$

5 Conclusions

The developed system concept of a CHP plant with seasonal heat storage is an ecological and economical interesting way of heat and power supply for cities and communes. It is outstanding because it allows the generation of renewable electric power at base load conditions while completely supplying a residential area with heat for hot water preparation and space heating. The investment costs are higher compared to a conventional heat generation system based on a gas condensing boiler. However, the revenues are higher, too, because of the guaranteed high feed-in tariff for electric energy in Germany. Assuming the highest possible feed-in tariff a financial payback time of less than 3 years can be achieved.

Seasonal thermal energy storage with BTES is a proved and reliable technology with moderate costs. Only a small part (21 %) of the heat generated by the combustion engine needs to be stored seasonally. Furthermore, the BTES has a high storage utilization ratio of 90 % due to the heat extraction with a heat pump. Because of these facts, in relation to the fuel consumption, only 1.2 % of the energy is lost by the seasonal heat storage.

The efficiency of the seasonal thermal energy storage decreases with decreasing size of the BTES because of the increasing surface/volume ratio. However, a reduction of the plant size from 500 kW_{el} to 150 kW_{el} and 6932 MWh_{th}/a to 1029 MWh_{th}/a corresponding to the heat demand of about 40 single family houses, still leads to a storage utilization ration of 80 % and a SPF of the heat pump of 3.1. In this case, in relation to the fuel consumption, 2.7 % of the energy is lost by the seasonal heat storage.

In a next step, this interesting energy concept should be realized in the form of a pilot plant. At the moment, the authors are looking for project partners.

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