Optimising the Low Temperature Cooling Energy Supply: Experimental Performance of an Absorption Chiller, a Compression Refrigeration Machine and Direct Cooling – a Comparison

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Abstract:
A strategy to optimise the low temperature cooling energy supply of a newly build office building is discussed against the background of a changing energy system. It is focused on, what production way - Direct Cooling, the Compression Refrigeration Machine or the Absorption Chiller provided with heat from Combined Heat and Power Plants - has the lowest primary energy consumption at what load level. For low levels this is direct cooling. If demand exceeds the capacity of direct cooling, the absorption chiller is the option to choose. However, in future the compression refrigeration machine is more efficient at providing high load levels than the Absorption Chiller. The operation analysis shows that flow rates are often held constant and the re-cooling temperatures are often above the ambient temperature. By the integration of automatic flow rate control and lowering the re-cooling temperature of the chillers, electricity consumption of pumps can be reduced and energy efficiency enhanced.

Keywords:
Compression refrigeration chiller, direct cooling, primary energy optimisation, trigeneration

1. Introduction

In order to reduce the energy demand of a newly built office building 50% below the official requirements the buildings envelope was optimised. Therefore heating demand in winter and cooling demand in summer is decreased. Furthermore, it has a multivalent energy system with high and low temperature heat as well as cooling energy supply and the possibility to supply heat to existing buildings at the company's campus.

Recent results of the energy monitoring of this building show that low temperature cooling demand is at almost all times below 700kW and at most times below 100kW. At the same time there is a total installed capacity of about 1700kW for providing it.

Therefore this paper discusses the process of optimising the low temperature energy supply. The question in focus is what chiller needs the minimum of primary energy at what operating state. Furthermore it is analysed what circumstances must be given that the results hold true.

2. The Low Temperature Cooling Energy System

Figure 1 shows the three ways low temperature cooling energy can be provided in the building. The low temperature energy system is designed to provide cooling water at a temperature of 8°C and a spread of 6°C. So far the operation of the components is bound to fixed levels of ambient temperature:

Direct Cooling (DC): Three re-cooling plants each with a capacity of 800 kW are installed on the roof of the building. For DC a capacity of 350kW can be used. So far DC is planned to be operated if the ambient temperature is below 10°C.

Compression Refrigeration Machine (CRM): The CRM has a capacity of 665kW. It is re-cooled by the re-cooling plant on the roof. The temperature of the re-cooling water is planned to be 27°C with a spread of 6°C. So far it is planned to be operated, if the ambient temperature is above 10°C and below 30°C.

Absorption Chiller (AC): The AC has capacity of 710kW. The high temperature heat buffer storage provides it with heat. The inlet temperature level at the AC is planned to be 95°C with a spread of 15°C. The buffer storage is served by the two on-site combined heat and power plants (CHPs). It is re-cooled in the same way like the CRM. So far the AC is planned to be operated if the ambient temperature is above 30°C.

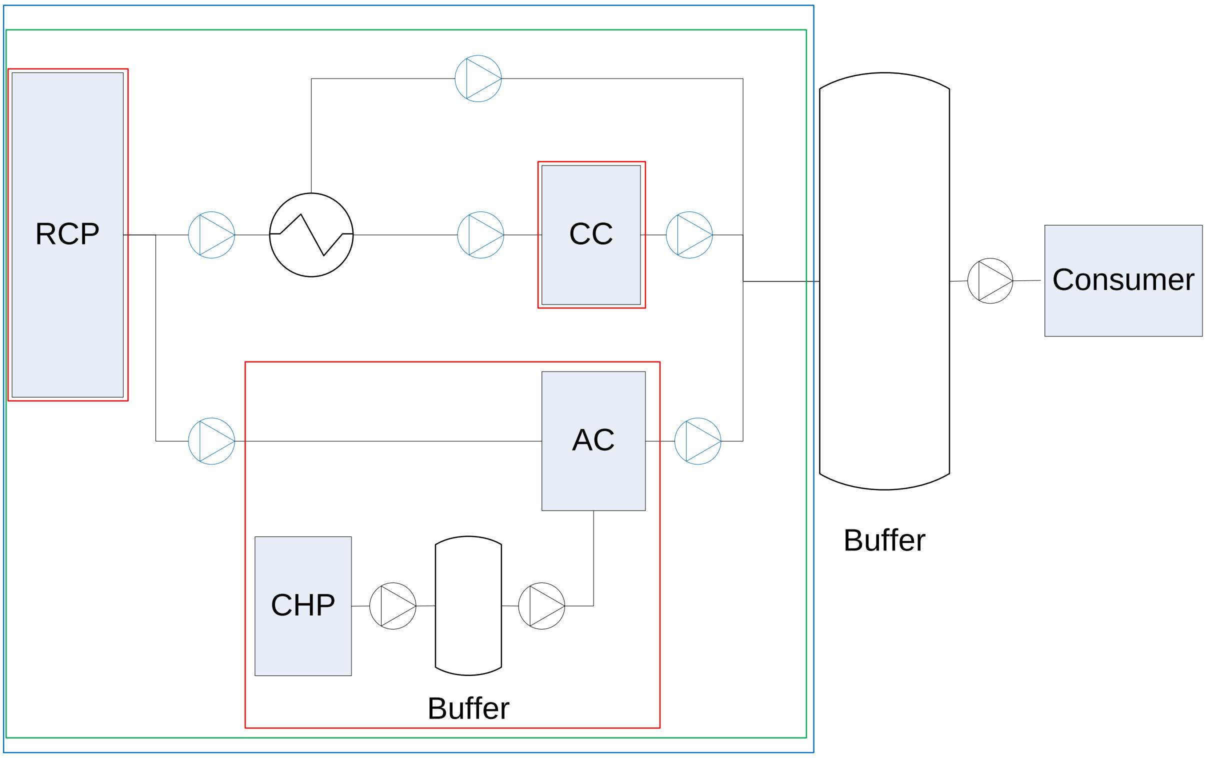

Figure 1: Low Temperature Cooling Energy System

For decoupling production time and usage as well as serving peak loads, the produced cooling energy is stored into a buffer storage. It has a capacity of 8000 litres. In total the buffer storage has a connected load of 720kW. The cooling cycle is planned to be operated at 9°C. Therefore it has a planned storage capacity of around 9kWh.

All pumps of the system in focus have a frequency converter either internally or externally. Therefore their operation can be flexible. However, not for all of them automatic control is implemented. The re-cooling and cooling water pump of the AC and the CRM as well as the pumps of the re-cooling plant connecting to DC and the CRM are controlled manually. Most of the time, they have a set-point of 100%.

3. Methodology

3.1. General Approach

This paper aims at optimising the primary low temperature energy supply. Therefore the primary energy factor (PEF) of one unit of low temperature cooling energy supply to the buffer storage is chosen to be the dependent variable to optimise.

All the components left of the low temperature storage buffer as depicted in Figure 1 are included into the calculation of the PEF of low temperature cooling energy. The PEFs will be classified in accordance with the load of the considered cooling machines. As a consequence operators will know at what demand what machine is the most efficient.

The PEF is calculated for different energy balance levels in order to show the impact of the different components of the system. The levels chosen are depicted in Figure 1: At first the red framed chillers themselves are looked at. Then the balance is extended to the heat sinks. This is the green framed area without the blue marked pumps. These are finally integrated into the calculations. During further analysis this last level will be referred to as the total PEF.

Single components have not been optimised so far. Based on the impact analysis it can be estimated where optimisation is most effective if any potential can be uncovered. The single component analysis and the analysis of their interaction will check for options of operating enhancement. Furthermore they will show at what operating parameters the results for the total PEF hold true.

3.2. Primary Energy Factors

In order to calculate the primary energy factor for each way of the cooling energy supply the factors for the single energy flows of each part of the system need to be determined. There are two forms of energy flows supplied to the chillers: Heat and electricity. Furthermore electricity is provided by the public grid and by cogeneration.

The primary energy factor of electricity from the public grid is chosen in accordance with the German standard on calculating the primary energy demand for buildings, the DIN EN 18599. At present it is 2.6 and represents the factor of the German annual average electricity mix of the public grid.

The combined heat and power plants are gas-fired. The primary energy factor for natural gas is 1.1. However, there are several methods for the allocation of a CHP’s fuel to its products and therefore for gaining the primary energy factor of heat and electricity of cogeneration. A detailed description of these methods can be found in Mauch et al (2010) and Verein Deutscher Ingenieure (2008).

Here the Electricity Credit Method is chosen for further analysis. This is as well in accordance with the DIN EN 18599. Therefore the PEF of heat is calculated as follows:

$$PEF_{Heat} = \frac{\dot{Q}_{Gas} \cdot PEF_{Gas} - \dot{Q}_{Elec} \cdot PEF_{Elec}}{\dot{Q}_{Heat}}$$

Here Q_{Gas} is the energy flow contained in the CHPs' gas input, Q_{Elec} and Q_{Heat} is the energy flow contained in the produced electricity and heat of the CHPs. The PEF_{elc} is the PEF of the electricity that is displaced through the CHPs' production. As there is no other internal electricity production this is the electricity of the public grid.

This method pays respect to the project's economical and technical circumstances as well as allows the evaluation of the technologies against the background of the ongoing energy economic development: Economic feasibility of the CHPs is only given if capacity utilisation is high. During summertime this was planned to be ensured by providing production lines in existing buildings on the campus but primarily the absorption chiller with heat. Therefore the absorption chiller justifies the installation of the CHPs - with heat as their main product and electricity as their by-product. However, the latter can be produced all day round. Therefore electricity is assumed to displace electricity of the base load mix. Base load, consisting mainly of nuclear power and coal has a primary energy factor of 2.9 according to Gemis 4.7 (Institute for Applied Ecology, 2011). As the public energy system changes and politics is increasingly heading towards a sustainable energy system with a large share of renewable energy and the dismantling of the load system, efficiency of the sole system gains importance. In order to estimate the validity of the results against this background the PEF is calculated with a PEF of one.

As cogeneration is only part of the building's energy system due to the AC the electricity used by the CRM and DC is evaluated by the primary energy factor of the public grid. The electricity caused by the AC is evaluated with the PEF of the assumed displacement electricity mix.

3.3. Integrating the Buffer Storage

There is one buffer storage in the system under consideration. It acts as a hydraulic separator evoking a time base shift: The heat the CHPs produce is not simultaneously used in the AC. Instead it is stored in the buffer storage. Consequently, the allocation of production and losses to one unit of cooling energy supply is not precise. The underlying problem is the determination of storage efficiency at a certain point in time.

Here storage efficiency is determined by the sum of energy leaving the buffer during ten load cycles and the sum of energy entering the buffer storage during this time. One load cycle is defined as the interval from starting to charge the buffer storage to the next time the buffer storage is about to be charged.

During one load cycle often more energy is discharged than charged. Therefore choosing one load cycle is not enough to map reality. Ten load cycles are chosen for approximation.

3.4. Data Selection and Preparation

The most recent data for one year is chosen. This is data from 1/8/2011 to 1/8/2012. In order to perform the analysis in a consistent and efficient way the incoming data is processed using the software DataStorage.

Calculations are based on meter data that comprise mistakes: Some values are not valid, as they do not fulfill the criterion of monotony. Therefore these values are masked out. Assuming that counters count correctly missing values are calculated by interpolation.

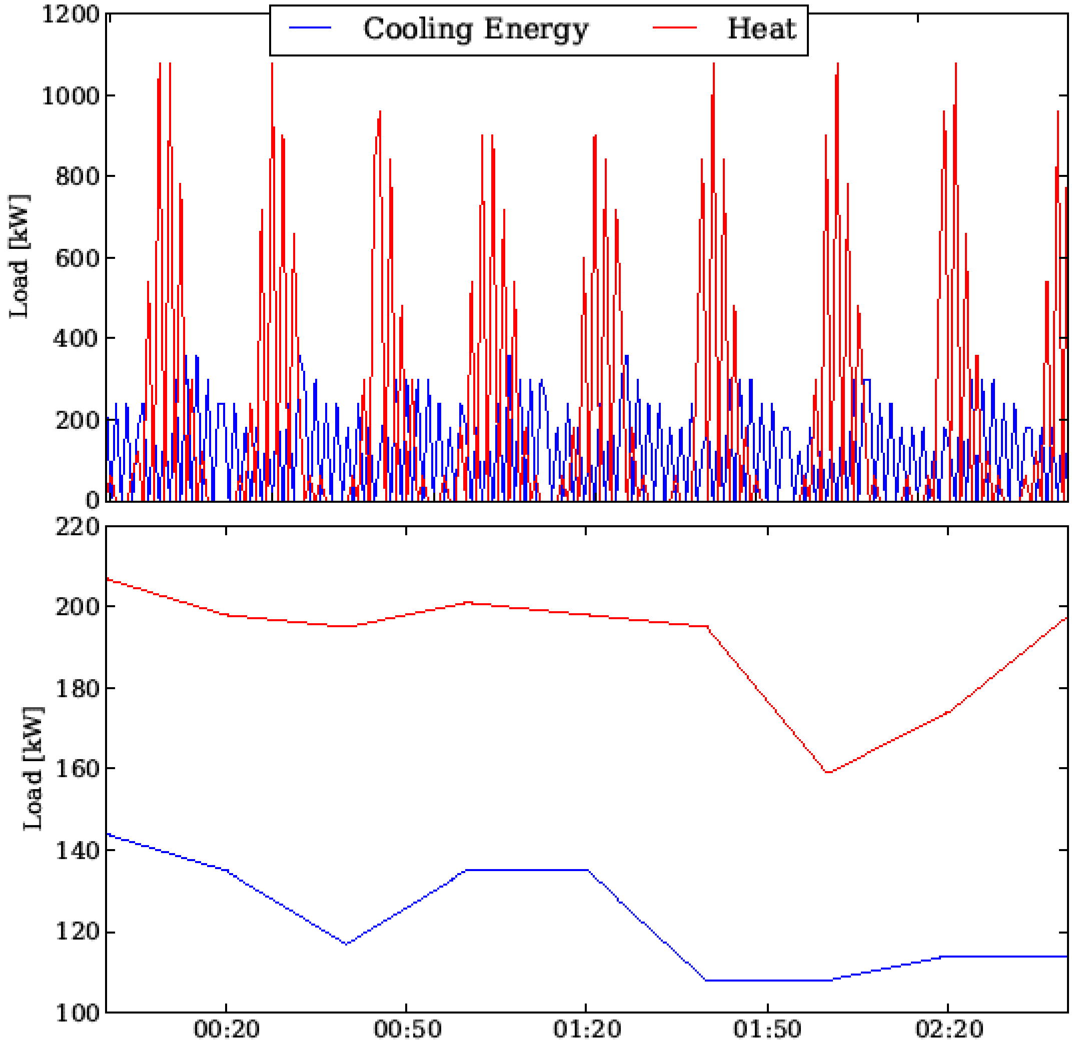

Figure 2: Choosing a Time Interval for the Analysis

Based on the result data calculation has been made. Figure 2 shows the obstacles to be tackled during this process:

- Data is collected every minute from the building control system. However, the buildings control systems receives data from the sensors at different and time-dependent intervals. Therefore data does not fit together at all times at this resolution. In Figure 2 this can be monitored in the upper graph. This is the derivation of the course of the counter values and every second value is zero. At the same time the machine is running. Therefore this shows that the data of this sensor has not been queried during the course of the minute. Comparing the course of data for heat and for cooling energy, these zero values can be observed at different points in time.

- Due to the systems inertia the output caused by a special input does not exit a component of the system at the same time as it enters the component. Furthermore a component sometimes operates at no quasi-static state. Figure 2 shows this for the AC. Although the machine is running for hours there are alternating peaks of heat and cooling energy. However, the production of the cooling energy is caused by the machine's heat input.

The analysis for optimising operation requires an analysis in accordance with the rules of a valid energy balance. Against the background of the above described obstacles, the underlying time interval of the analysis should be chosen that wide that this requirement is fulfilled. However, increasing width of the time intervals lead to a decreasing density of the results at high load levels and a high density of results is needed for all load levels of a component for optimising operation. Consequently, there is a conflict of sticking to the rules of making a correct energy balance and obtaining a significant result for the optimisation process. This is solved by choosing an interval of 20-minute average values. Single values still do not fulfill the requirements for the energy balance over one component and are taken out of the results.

3.5. Further assumptions

The energy consumption of pumps is so far not based on continuous measurements. However, temporary measurements have been undertaken for some of them at characteristic operating states. Here electricity consumption has been logged. For others the electricity consumption at the design point is assumed. Table 1 gives an overview of the assumed electricity consumption of the pumps.

Table 1: Assumptions for the Electricity Consumption of the Pumps

Pump	*Electricity [kW]*	*Quality of assumption*
Re-cooling water pump AC	*18.0*	*Measured*
Re-cooling water pump CRM/DC	*13.0*	*Design point*
Re-cooling water pump CRM	*3.1*	*Measured*
Cooling water pump AC	*2.2*	*Design point*
Cooling water pump CRM	*2.2*	*Design point*
Cooling water pump of DC	*1.6*	*Design point*

4. Results

4.1. Primary Energy Factor at the Status Quo

Figure 3 shows the results for the PEF of the different chillers for each of their load states and at the different energy balance levels as defined in Chapter 3.1. The results for the total PEF show, that DC has the lowest PEF at most times. If cooling demand cannot be provided by DC, operating the AC is the option to choose. In general the primary energy efficiency rises with increasing load level.

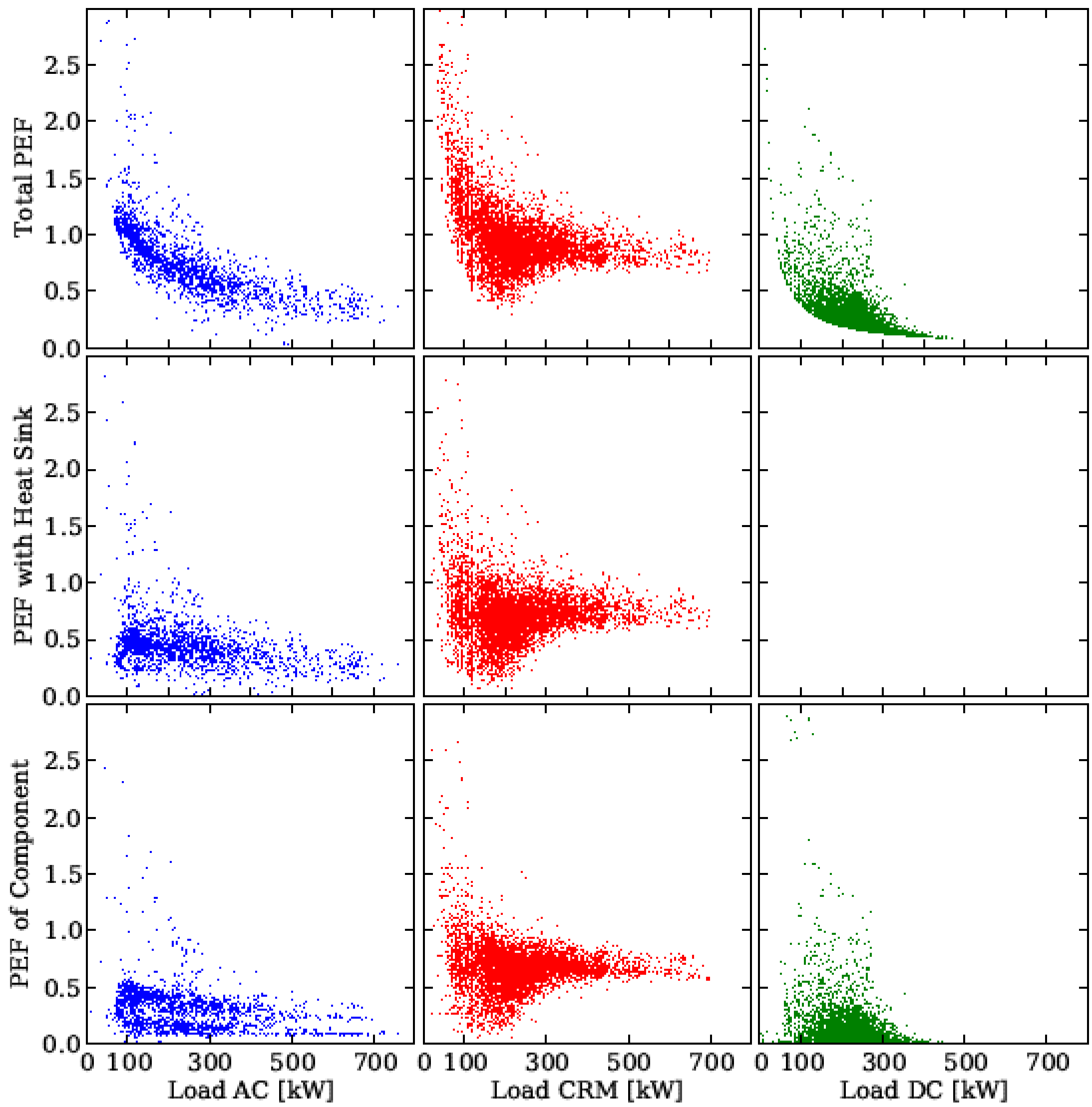

Figure 3: Calculated Present Primary Energy Factors of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) at Different Load Levels based on Measured Data

The results of the sole component of the AC are for high load levels lower than for the CRM. In the load range from 100 to 200kW they are partly level-off. The energy efficiency of the AC is only 0.7 compared to the one of the CRM with 4. However, the heat of the CHPs has only an average PEF of 0.17, whereas the PEF of the electricity of the public grid for the CRM is 2.6.

The integration of the heat sink - the re-cooling plant - into the considerations increases the PEF only slightly, as the average efficiency of the re-cooling plant is 18. The re-cooling plant impacts the results for the AC more than those for the CRM. This is due to the fact that the re-cooling plant has with 20 during the operating time of the AC a lower average energy efficiency than during the operating time of the CRM with an average efficiency of 26. Furthermore the electricity consumption caused by the AC is evaluated with a PEF of 2.9, whereas the electricity consumption caused by the CRM is evaluated with a PEF of 2.6 (cp. Chapter 3.2).

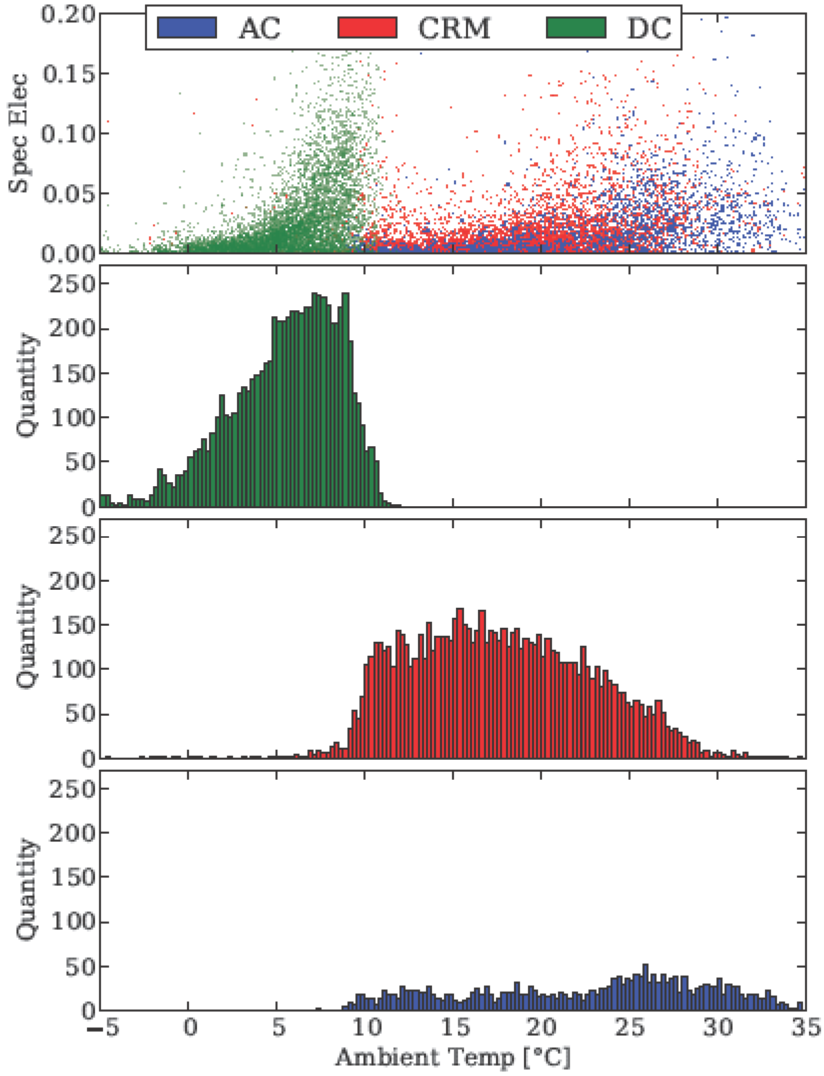

Figure 4: Specific Electricity Consumption (Spec Elec) of the Re-cooling Plant during its Operation caused by the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) and its Absolute Frequency

DC, the AC and the CRM are planned to be operated at different ambient temperature levels and the re-cooling plant is a three staged machine. If ambient temperature rises, first ventilation and later wet cooling is turned on. Therefore it is expected that the specific electricity consumption per unit of cooling energy grows when temperature rises. If this holds true the results of the PEF are not comparable and need to be considered against the background of the ambient temperature.

However, the data of Figure 4 show that this assumption is only valid to a certain extend. Here the electricity consumption of the re-cooling plant is allocated to the operation of the different chillers. The electricity consumption caused by DC is often higher than the consumption caused by the AC and the CRM, although the AC and DC are operated at higher temperature levels. Furthermore the AC is also operated at lower temperatures than planned. Therefore the comparison of the results is possible.

The primary energy consumption of the pumps impacts the results for the PEF mainly at lower output levels. This is shown by the difference of the first and the second row of the graphs of Figure 3. It is due to the fact, that most of the pumps are not automatically controlled, but set to a fixed flow rate (cp. Chapter 4.2) and their high electricity consumption at this point: The pumps of the AC have a total power of 20.2kW, those of the CRM have a total power of 18.8kW and those of the DC have a total power of 14.6kW (cp. Chapter 3.5). Therefore the impact on the result of the AC is again higher than that on the results of the CRM, as the power of the AC's pumps is 2kW higher than that of the CRM. The impact on DC is the smallest one.

Overall pumps have the highest impact on the results of the PEF, though at low levels. As operating times are mainly at these load levels, further verification of the optimisation potential seems to be worthwhile. The process in the components of the chillers themselves has the second biggest and the re-cooling plant the lowest impact on the PEF.

4.2. System analysis

Table 2 gives an overview of the average efficiency of the system components of the regarded period. These are the results of the machines operating states. Therefore stand-by losses are not considered.

Table 2: Efficiency of the Components

Component	*Efficiency*
Absorption Chiller	*69%*
Compression Refrigeration Machine	*4*
Direct Cooling	*10*
Re-cooling Plant	*18 (AC: 20, CRM 26)*
Combined Heat & Power Plants	*85%*
High Temperature Buffer Storage	*96%*

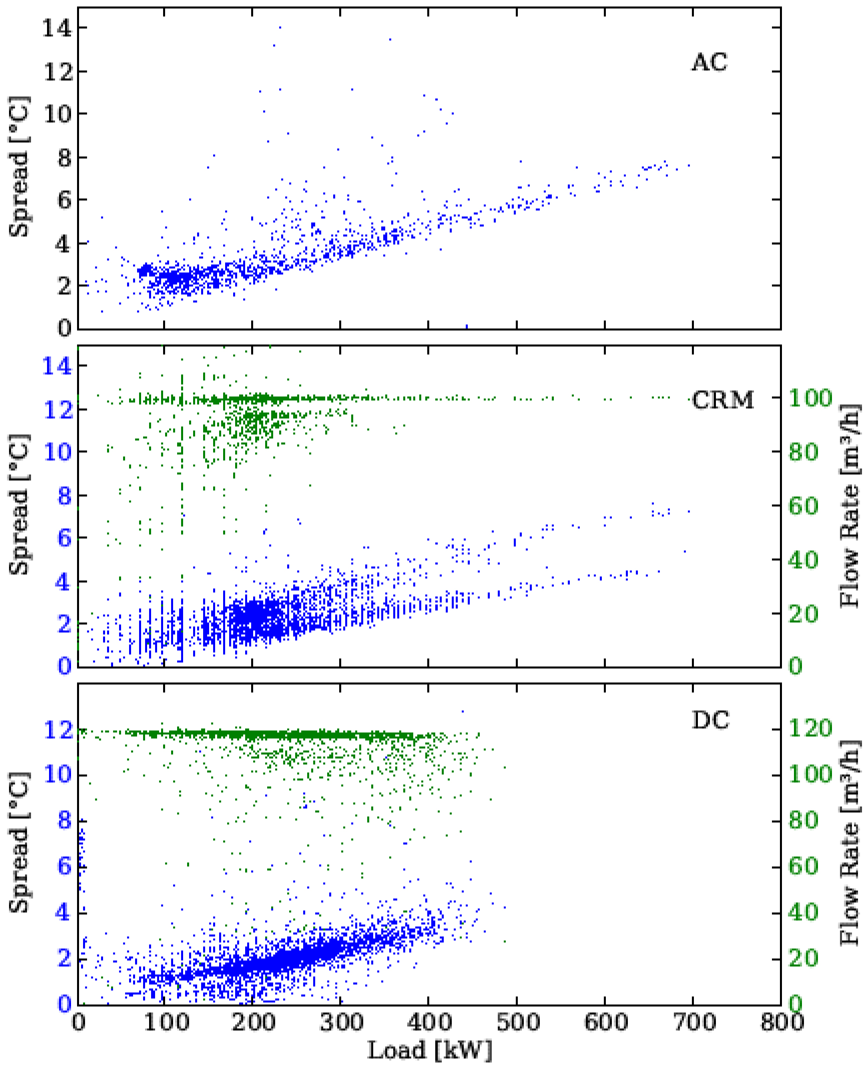

Figure 5: Spread and Flow Rate of the Re-cooling Water of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC)

The analysis of the system parameters - inlet and outlet temperatures, spreads and flow rates - shows that efficiency can be increased by flow rate control. For instance, Figure 5 shows the spread and flow rate of the re-cooling temperature for the different cooling options. For most of the time the flow rate of the CRM and DC is at a constant level of $100m^3/h$ or rather $120m^3/h$. All spreads and - what is not shown - all outlet temperatures of the machines are increasing with increasing load level. Only inlet temperatures stay constant. The spread of the planned 6°C is hardly ever reached. If flow rates were controlled electricity consumption of the pumps could be reduced. This is just one example. Planned spreads of the cooling water of the CRM and the AC are not reached due to the same reason. The outlet temperatures at the cooling water side of the AC, the CRM as well as the DC are with more than 10°C more than 2°C above the planned 8°C.

The spread of the inlet and outlet temperature at the heat side of the AC with more than 30°C is double the planned value of 15°C. Figure 6 shows its source, the parameters of the CHPs. Their temperatures are spread widely. The outlet temperature of the high temperature heat of 95°C is not always reached. However, the measured spread is more than the planned 15°C.

The outlet temperature of the low temperature heat of 50°C is most of the times not reached. In the load interval from 250 to 650kW, its measured outlet temperature is between 30 and 50°C. However, the spread is often above the planned 6°C. Two levels of flow rates can be identified. The flow rate leaps to the second level when the second CHP is turned on.

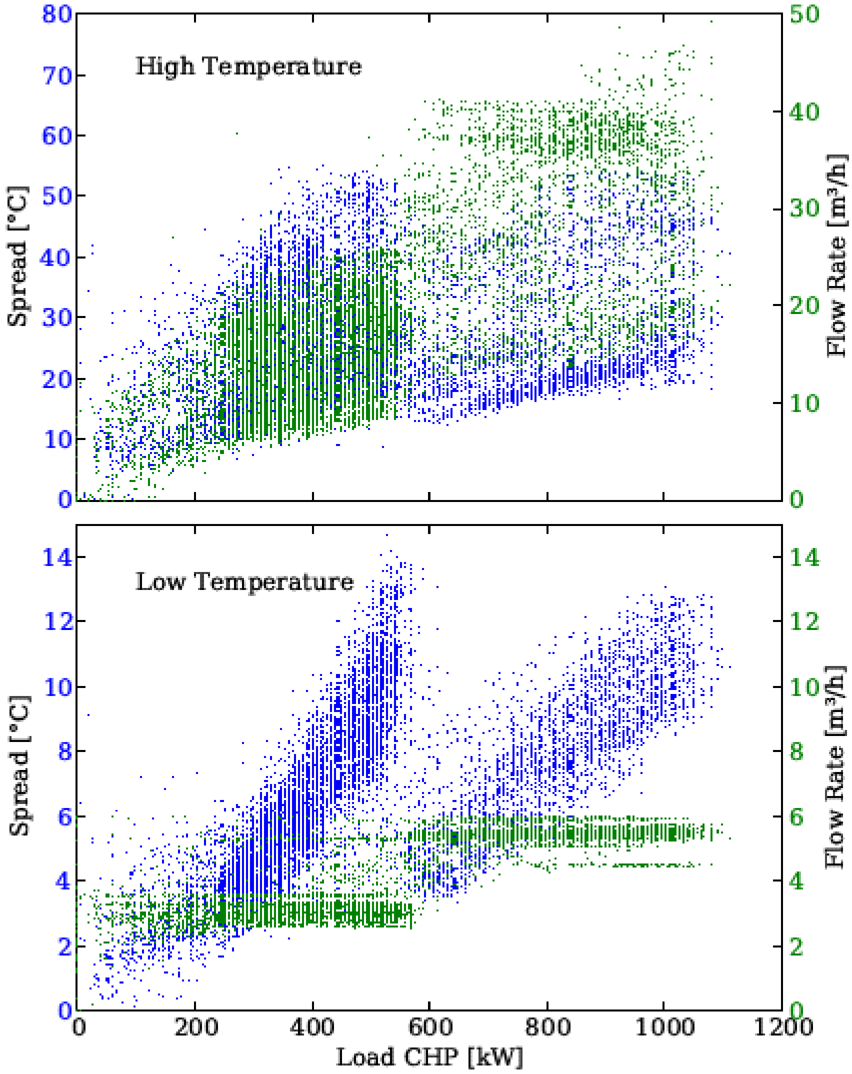

Figure 6: Spread and Flow Rate of the Combined Heat and Power Plants' High Temperature Heat

Another option for increasing the system efficiency is to lower the re-cooling temperature of the CRM and the AC. As an example Figure 7 shows that most of the time the re-cooling temperature of the CRM is above the ambient temperature. As the efficiency of the re-cooling plant is higher than that of the CRM, its capacity should be used as far as possible.

Figure 3 shows, that efficiency rises with increasing load level. Against this background and the fact that low temperature cooling energy is first stored in a buffer storage before it is consumed, intermittent operation might be an option to consider. Measured outlet temperatures of the cooling water of the chillers and the control parameters of the building's automation system show that the actual storage capacity is higher than the planned 9kWh. For the operation of DC it is 42kWh and for the operation of the CRM it is 28kWh. As Figure 3 shows, chillers are operated most of the time below the load level of 300kW. Therefore increasing load level would result in operating the chillers above 300kW. However, even if a capacity of 42kWh is assumed, loading time would be about eight minutes at this level and only three and a half at the load level of 700kW. Therefore this is no option at the present operating parameters. However, these depend also on the requirements of the consumers. Consequently, an analysis of the demand side might change the outcome.

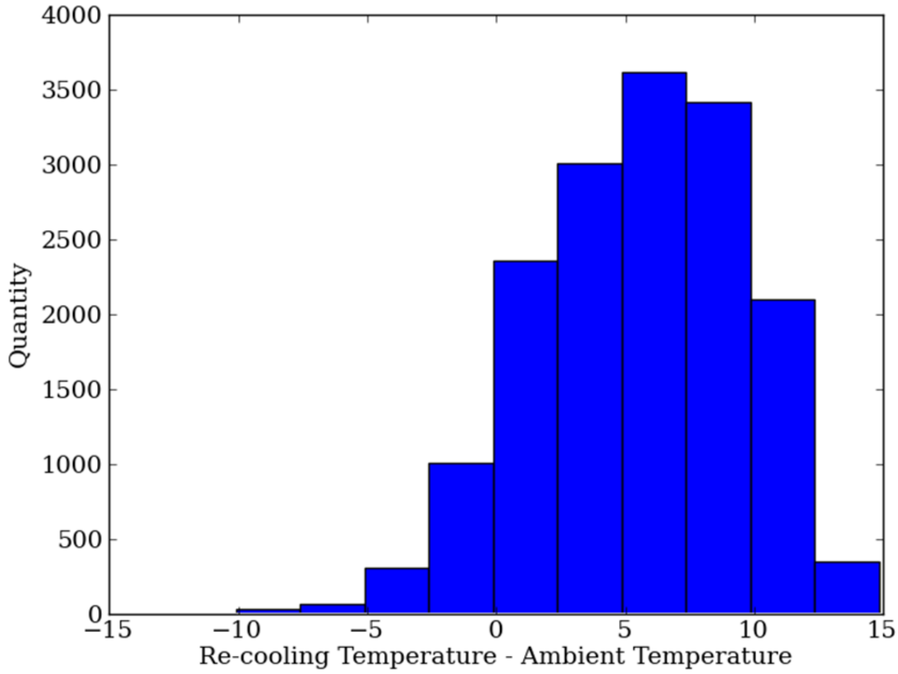

Figure 7: Difference between the Re-cooling Temperature of the CRM and the Ambient Temperature and their Absolute Frequencies

5. Conclusion and Outlook

In terms of primary energy consumption and with the underlying operating parameters first DC and if demand exceeds the capacity of DC the AC should be operated at present. As the pumps have the biggest impact on the results of the PEF and the system analysis has shown that this is due to constant flow rates, it is recommended to control all pumps automatically. As the necessary hardware is already installed, only the suitable strategy has to be implemented in the building automation control system.

Furthermore energy efficiency can be increased by decreasing the inlet temperature at the re-cooling side of the AC and the CRM.

Intermittent operation is no alternative to chose. However, further integration of the demand side into a further analysis might change this.

Against the background of a changing energy system leading towards an energy supply with an increasing share of renewable energies, the importance of energy efficiency of the regarded system itself will increase. Therefore Figure 8 shows the results of the PEF of the systems with an underlying PEF of one. This assumes that all input comes from renewable resources.

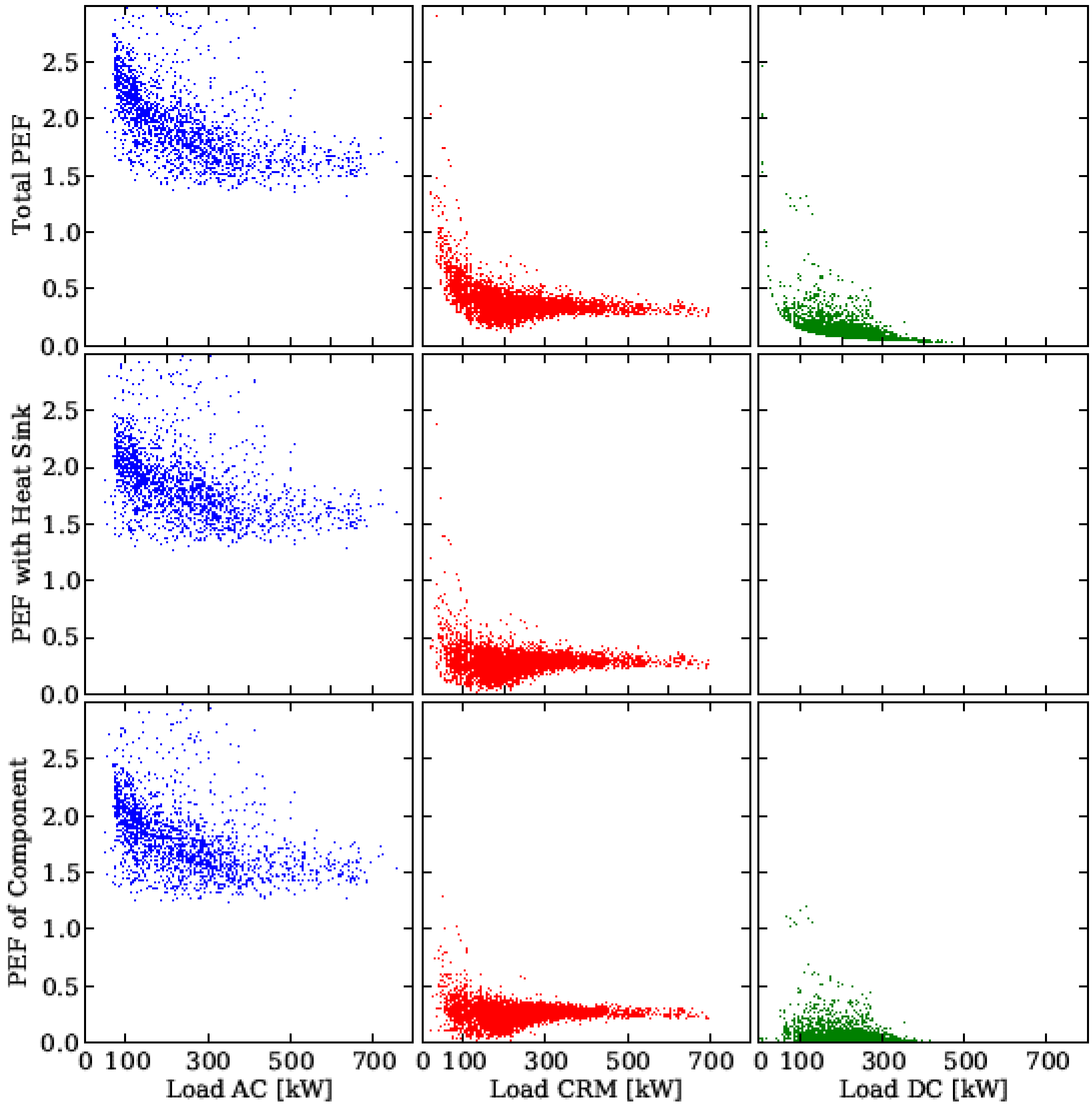

Figure 8: Calculated Future Primary Energy Factors of the Absorption Chiller (AC), the Compression Refrigeration Machine (CRM) and Direct Cooling (DC) at Different Load Levels based on Measured Data

DC still is the source with the lowest primary energy consumption. However, the AC will not be efficient in future unless the operating parameters will change. Its PEF is for all load levels above the maximum PEF of the CRM. Therefore using an AC like this seems to be only a temporary option.

6. Acknowledgements

The work presented in this paper has been largely developed in the project "Campus Energy 21". This is conducted in cooperation with the Dürr AG and founded by the German Federal Ministry of Economics and Technology.

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