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Combined cooling, heat and power (Trigeneration) at Offenburg University of Applied Sciences

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ABSTRACT

The energy supply of Offenburg University of Applied Sciences (HS OG) was changed from separate generation to trigeneration in 2007/2008. Trigeneration was installed for supplying heat, cooling and electrical power at HS OG. In this paper, trigeneration process and its modes of operation along with the layout of the energy facility at HS OG were described. Special emphasis was given to the operation schemes and control strategies of the operation modes: winter mode, transition mode and summer mode. The components used in the energy facility were also outlined. Monitoring and data analysis of the energy system was carried out after the commissioning of trigeneration in the period from 2008 to 2011. Thus, valuable performance data was obtained.

ABBREVIATIONS

AbsChi	Absorption Chiller
BOI_1	Boiler 1
BOI_2	Boiler 2
CHP	Combined Heat and Power
CoHX_1	Condensing Heat Exchanger of Boiler 1
CoHX_2	Condensing Heat Exchanger of Boiler 2
CoHX_3	Condensing Heat Exchanger of Micro Gas Turbine
CoHX_4	Condensing Heat Exchanger of Internal Combustion Engine
COP	Coefficient of Performance
CoT	Cooling Tower
CWS	Cold Water Storage
EER	Energy Efficiency Ratio
EUF	Energy Utilization Factor
HS OG	Hochschule Offenburg
HVAC	Heating, Ventilation and Air-Conditioning
HWS	Hot Water Storage

ICE	Internal Combustion Engine
ICEHX	Exhaust Gas Heat Exchanger of Internal Combustion Engine
IEA	International Energy Agency
MGT	Micro Gas Turbine
MGTHX	Exhaust Gas Heat Exchanger of Micro Gas Turbine
PER	Primary Energy Ratio
PES	Primary Energy Saving
VDI	Verein Deutscher Ingenieure

G_i	Degree days for the year i	K·d
P_N	Nominal electrical capacity	kW
Q_N	Nominal thermal capacity	kW
Q	Thermal energy	kWh_{th}
T_{aN}	Utilization period at maximum capacity	h
V	Volume	m^3
W	Electrical energy	kWh_{el}

cw	Cooling water
i	Index of year
k	Index of month

INTRODUCTION

Trigeneration is an evolution of cogeneration (Chicco and Mancarella 2006). Universities, hospitals, airports, cold storage facilities, industrial plants especially food industry such as dairy, pasta industry, sugar factories, etc. require a supply of electricity, heat and cold (Chicco and Mancarella 2007; Compernolle et al. 2011). Therefore, in the recent years, systems for combined power, heat and cold production, so-called trigeneration systems, have been applied in increasing numbers. Trigeneration systems expand conventional Combined Heat and Power (CHP) systems (also called as cogeneration systems) with thermally activated chillers or air conditioning systems. In moderate climates, the typical load profile of the residential and non-residential sector comprises heat demand in winter and air-conditioning in summer. In hot climates, trigeneration system preferably provides cold water or air conditioning and possibly some hot water. Thus, in both cases by means of trigeneration, the utilization period at full load (full-load hours) as well as the mean utilization factor of the CHP prime mover increases.

As of 2007 statistics from International Energy Agency (IEA), CHP share of 9% was estimated in global power generation. The same source had estimated a significant contribution of combined heat and power generation to reduce CO_2 emissions. For the year 2015 it was given 4% ($170 Mt \cdot a^{-1}$), and for the year 2030 it was given 10% ($950 Mt \cdot a^{-1}$) (Kerr 2008). Usually, the following advantages were listed when discussing about trigeneration systems: higher efficiency, smaller transmission losses, and lesser environmental impacts (Zhou et al. 2012). Further, some authors had mentioned very globally about socio-economic and environmental benefits such as reduction in operation costs and reduced carbon emissions resulting in efficient use of energy resources (Carvalho et al. 2012).

There were many tests and experimental analysis conducted on trigeneration systems in the recent past. It can be distinguished between two main categories of trigeneration, each of them having many subcategories. Firstly, trigeneration systems which employ a mechanical compressor, and secondly, systems which employ thermally activated heat pumps. For instance, Easaw and Mulley (2010) had reported about the experimental analysis of trigeneration system in micro-scale. A LPG driven 4-stroke internal combustion engine was coupled to an electrical generator as well as to a compressor of an air-conditioning unit. The results showed that 60% of the fuel input was recovered as exhaust heat which was then used for heating water. More typical installations employ thermally activated heat pumps. For instance, an experimentally evaluated configuration in Angrisani et al. (2012) consists of a gas boiler, a 4-stroke internal combustion engine, and a thermal-chemical absorption system. It was reported that carbon emissions were reduced by about 26% with this configuration.

Many authors determined performance figures of trigeneration plant such as Energy Utilization Factor (EUF), Primary Energy Saving (PES), Primary Energy Ratio (PER), carbon emissions and fuel cost (Angrisani et al. 2012; Cervone et al. 2011; Kavvadias et al. 2010; Rocha et al. 2012). However, these investigations are often based on very global considerations. On the other hand, it is very important to understand performance and control strategies of trigeneration sub-systems to judge the potential of trigeneration systems. This paper describes a trigeneration system employing an absorption chiller. Further, it contains results on sub-system level for the period from 2008 to 2011.

ENERGY FACILITY AT OFFENBURG UNIVERSITY

The trigeneration system at HS OG was built in the years 2006 and 2007, and the trigeneration process was set into operation from the year 2008. Figure 1 shows a scheme of the

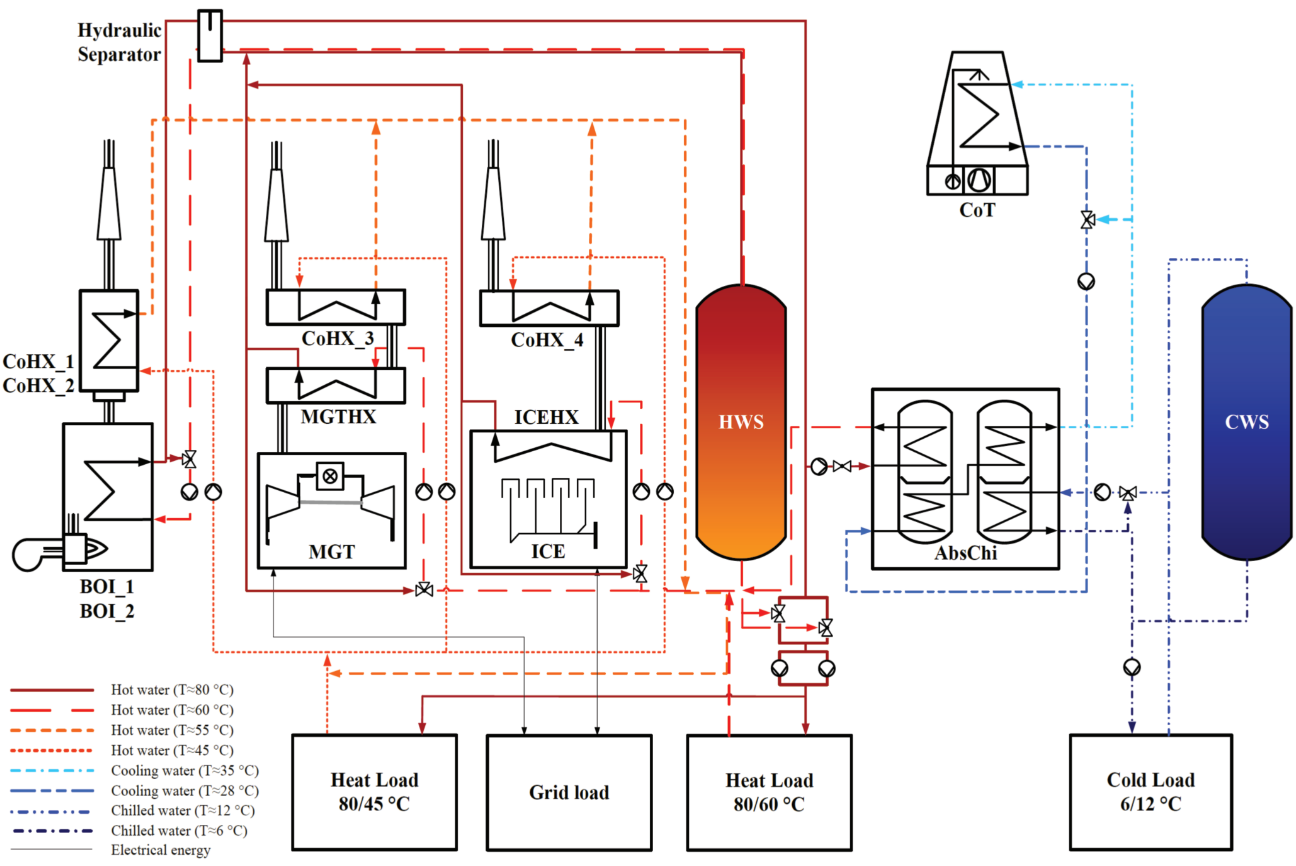

Figure 1. Simplified scheme of energy facility.

trigeneration system at HS OG. Several combinations of trigeneration systems exist and there is no standard architecture for the selection of sub-systems (Badea et al. 2010). In the case of HS OG, it consists of energy converters such as Boiler 1 (BOI_1), Boiler 2 (BOI_2), Micro Gas Turbine (MGT) and Internal Combustion Engine (ICE); unit operators such as Absorption Chiller (AbsChi), Cooling Tower (CoT), Condensing Heat Exchanger of Boiler 1 (CoHX_1), Condensing Heat Exchanger of Boiler 2 (CoHX_2), Condensing Heat Exchanger of Micro Gas Turbine (CoHX_3), Condensing Heat Exchanger of Internal Combustion Engine (CoHX_4), Exhaust Gas Heat Exchanger of Micro Gas Turbine (MGTHX) and Exhaust Gas Heat Exchanger of Internal Combustion Engine (ICEHX); and storages such as Hot Water Storage (HWS) and Cold Water Storage (CWS). Natural gas is used as a fuel to drive the energy converters. This energy facility is used to meet the thermal energy demands and a part of electrical energy demand at HS OG.

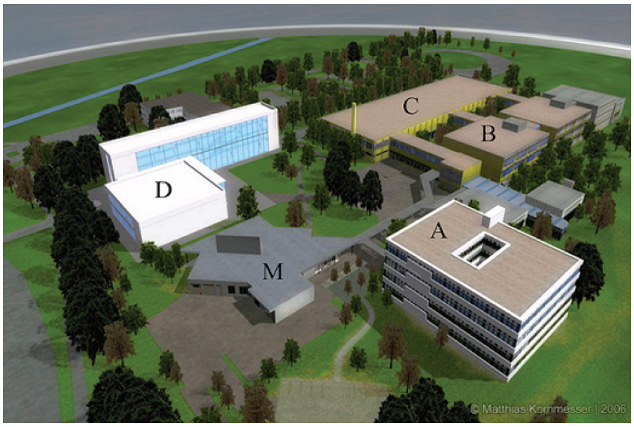

Figure 2. University building complexes (Gopisetty and Treffinger 2013).

HS OG consists of Building A, B, C, D and M as shown in Figure 2. Building A consists of administration and lecture halls. Building B has library, laboratories and also lecture halls. Building C is equipped with pilot plant stations, e.g. fluid machinery lab, machine tools lab, plastics processing lab, Heating, Ventilation and Air-Conditioning (HVAC) facilities, process engineering laboratories including the energy facility for supplying heat, cold and electricity. The chimney of the energy facility can be seen on the left side of Building C. Building D is also equipped with laboratories, offices and lecture halls of the faculty of media and information engineering. Building M is a cafeteria lounge. The total installed capacity of the energy facility is 3442.5kW thermal power for heat, 150kW cooling power and 115kW electrical power (Gopisetty and Treffinger 2013).

Table 1 shows the demand structure for the building complexes at HS OG. The main energy demand is due to space heating and process heat. The cooling energy demand and electricity is primarily used for information and communication technology, lighting, and machines in laboratories, etc. It should be emphasized that the demand structure of the HS OG had been frequently changing. The main reasons are renovations of buildings and at least in the recent years a steady increase in the number of occupants. The heat demand and cooling demand are the maximum values which were estimated using the DIN standards (DIN 2003), VDI standards (VDIA 1996), building specifications (Ulrich Kuttruff; Martin Gass, personal communication, Offenburg University of Applied Sciences 2012) and manual measurements. Electrical demand off-peak and peak is the minimum and maximum value recorded between the period November 2011 and August 2012.

COMPONENTS

Table 2 lists the components of the energy facility and its corresponding capacities. In order to meet the peak demand for space heating at HS OG, there are two boilers having in sum a capacity of 3000kW. Absorption chiller has a capacity of 150kW. This lower capacity is indicated by the lower cooling demand compared to the heating demand. Similarly, MGT and ICE capacities are rather low as compared to the demand. Thus, only a part of the electrical load can be covered through the CHP units. The

Table 1. Demand structure of the building complexes at Offenburg University (Gopisetty and Treffinger 2013).

Building	A and M	B	C	D	Total
Heated surface area in m²	4763	9278	5879	4633	24553
Heat demand in kW	866	1381	788	259	3294
Cooling demand in kW	n.a.	93	168	144	405
Electrical demand in kW	70 (off-peak) - 530 (peak)				

n.a.=not applicable.

Table 2. Components of energy facility.

Component	Manufacturer, Type	Capacity
Boilers (BOI_1 & BOI_2)	Viessmann, Vitoplex 300 TX3 (Burner, Weishaupt)	Q_N=1500kW each
Micro Gas Turbine	Capstone, C65	P_N=65kW Q_N=120kW (winter) Q_N=127kW (summer)
Internal Combustion Engine	Buderus, BHKW Modul E 0834 DN-50	P_N=50kW Q_N=81kW
Condensing Heat Exchangers following BOI_1 and BOI_2	Viessmann Vitotrans 300	Q_N=105kW each
Condensing Heat Exchanger following MGT	Verdesis/Enalco, 390A-TE RVS	Q_N=16.8kW
Condensing Heat Exchanger following ICE	Verdesis/Enalco, 390A-TE RVS	Q_N=14.7kW
Absorption Chiller	Broad, BDH13IX71/86-32/27-9/15-20	Q_N=150kW
Cooling Tower	Gohl, VK 77/6	Q_N=350kW
Hot Water Storage	Delta Solar GmbH, PS 13000 Liter	V=13000L
Cold Water Storage	Delta Solar GmbH, PS 13000 Liter	V=13000L

condensing heat exchangers improve heat extraction from the exhaust gas and also increase the thermal efficiency of the plant. The cooling tower is required to reject heat at medium temperature from the absorption chiller to ambient air. Hot water storage and cold water storage have a capacity of 13000L each. They shall reduce the number of start-ups of CHP units.

The cooling demand mentioned in Table 1 is higher than the installed capacity of AbsChi shown in Table 2. The cooling load at HS OG is often very low compared to the cooling demand because of less occupants and occupancy in the months of July, August and September. Thus, electric air-conditioners are used in the event of additional cooling requirements.

Table 3. Comparison of utilization periods (T_{aN}·h^{-1}) (Gopisetty and Treffinger 2013).

Year		BOI_1 and BOI_2	MGT	ICE	AbsChi
2008	**Winter**	645	4939	2143	54
	Summer	14	1437	634	787
2009	**Winter**	723	4785	2816	114
	Summer	10	1242	905	812
2010	**Winter**	969	5100	3793	46
	Summer	27	1315	1238	693
2011	**Winter**	650	3910	3430	27
	Summer	0	774	673	374

DESIGN OF PLANT

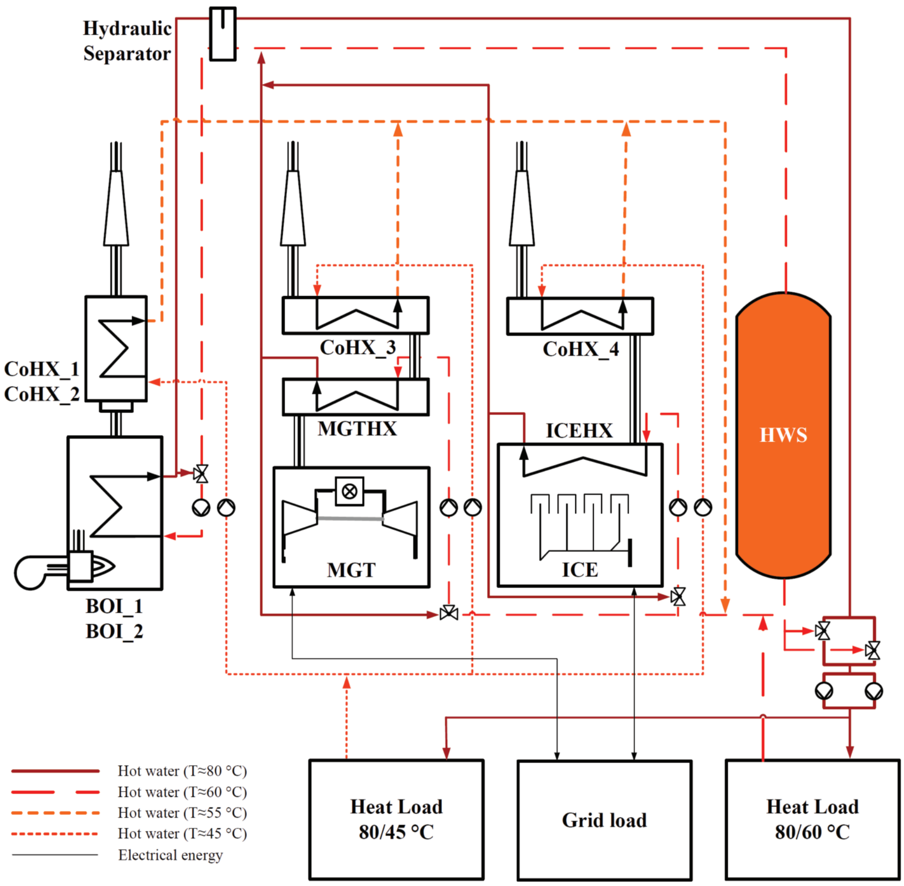

Figure 3. Winter mode - simplified scheme of energy facility.

Control strategy

The control strategy for the operation of energy facility is based on the thermal energy demand in the building complexes. Subsequently, the electricity generated by the CHP units is mainly used for self-supply. Due to relatively low electrical power of CHP units, electricity is fed only in rare situations in the grid. CHP units form the base load of the energy facility. Boilers are used during the peak load period in winters. In summer, the AbsChi is put into operation to supply the cooling energy demand. In all the modes, storages are used for peak shaving.

Modes of operation

Winter mode

The operating modes of the energy facility are typically classified as follows: winter mode, transition mode, and summer mode. The control strategy for winter mode is applied when the outside air temperature is less than 15°C for about 10h to 12h on a daily average of 3 consecutive days (Abuiyada 2009; König 2006). Then, the systems such as MGT, ICE, BOI_1 and BOI_2 are set in operation as shown in Figure 3. They are continuously operated during the winter mode. The return temperatures from the heat load to the energy facility are 60°C and 45°C, respectively. Correspondingly, the supply temperature to the building is 80°C. In this mode, MGT and ICE run throughout the winter season and the peak demand is met by BOI_1 and BOI_2. During the winter mode, the room temperature is conditioned to be set at a constant value of 22°C. In this mode, AbsChi along with CoT is shut down and CWS is not in operation (König 2006).

Transition mode

The switchover to transition mode occurs when the outside air temperature is in between 15°C and 18°C for about 10h to 12h on a daily average of 3 consecutive days (König 2006). In general there are two transition zone periods in a year, the winter transition mode and the

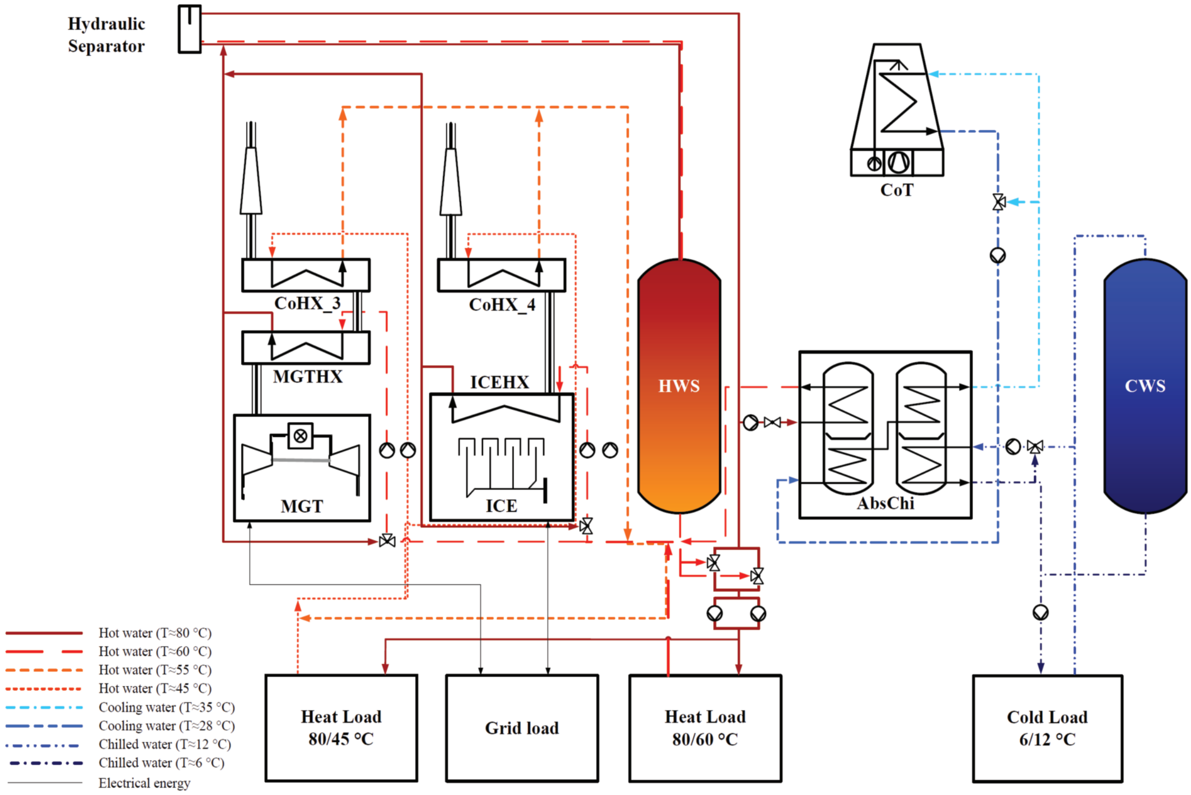

Figure 4. Transition mode - simplified scheme of energy facility.

summer transition mode. The winter transition mode occurs mostly during the months of April and May whereas the summer transition mode occurs during the months of September and October. The boilers are shut down and only the CHP units operate throughout this period. The peak shaving during this period is done by means of HWS and CWS. A simplified scheme of the transition mode operation is illustrated in Figure 4. During the transition mode, the room temperature is also designed to be 22°C (König 2006).

Summer mode

The control strategy for summer mode is applied when the outside air temperature is more than 18°C for about 10h to 12h on a daily average of 3 consecutive days. The summer mode's cooling demand is met with the help of AbsChi. The AbsChi is driven by thermal energy generated at about 80°C by the CHP units, i.e., MGT and ICE. Additionally, some portion of thermal energy is used for supplying hot water demand to the buildings in parallel to the AbsChi operation. During the off-peak load period or in the case of demand fluctuations, the excess thermal energy produced from CHP units and AbsChi is stored in the HWS and the CWS. The summer operation mode is shown in Figure 5. In this mode, only AbsChi and CHP units along with the HWS, CWS, CoT are in operation. During the summer mode, the room temperature is designed to be considerably lower than the outside air temperature. For example, when the outside air temperature is 32°C then the room temperature would be 28°C (König 2006).

RESULTS AND DISCUSSION

Table 3 shows the utilization periods of BOI_1, BOI_2, MGT, ICE and AbsChi. In this case, winter was considered from January until April and from October until December and summer from May until September. Equation 1 defines definition of the utilization period at nominal capacity. In a similar way, Equation 1 was formulated for BOI_2, MGT and ICE. According to VDI 4608 Part 1 (VDI 2005) the utilization period at nominal capacity is defined as the ratio of the quantity of energy output over a period of time to the nominal capacity of the installation. From the Table 3 it can be interpreted that CHP units, namely, MGT and ICE had operated for longer hours. Detailed information on the operation of the components on a monthly basis is shown in Figure 6, 7, 8, and 9 for the years 2008 to 2011. The operation pattern during these four years had similarities. The CHP units were almost

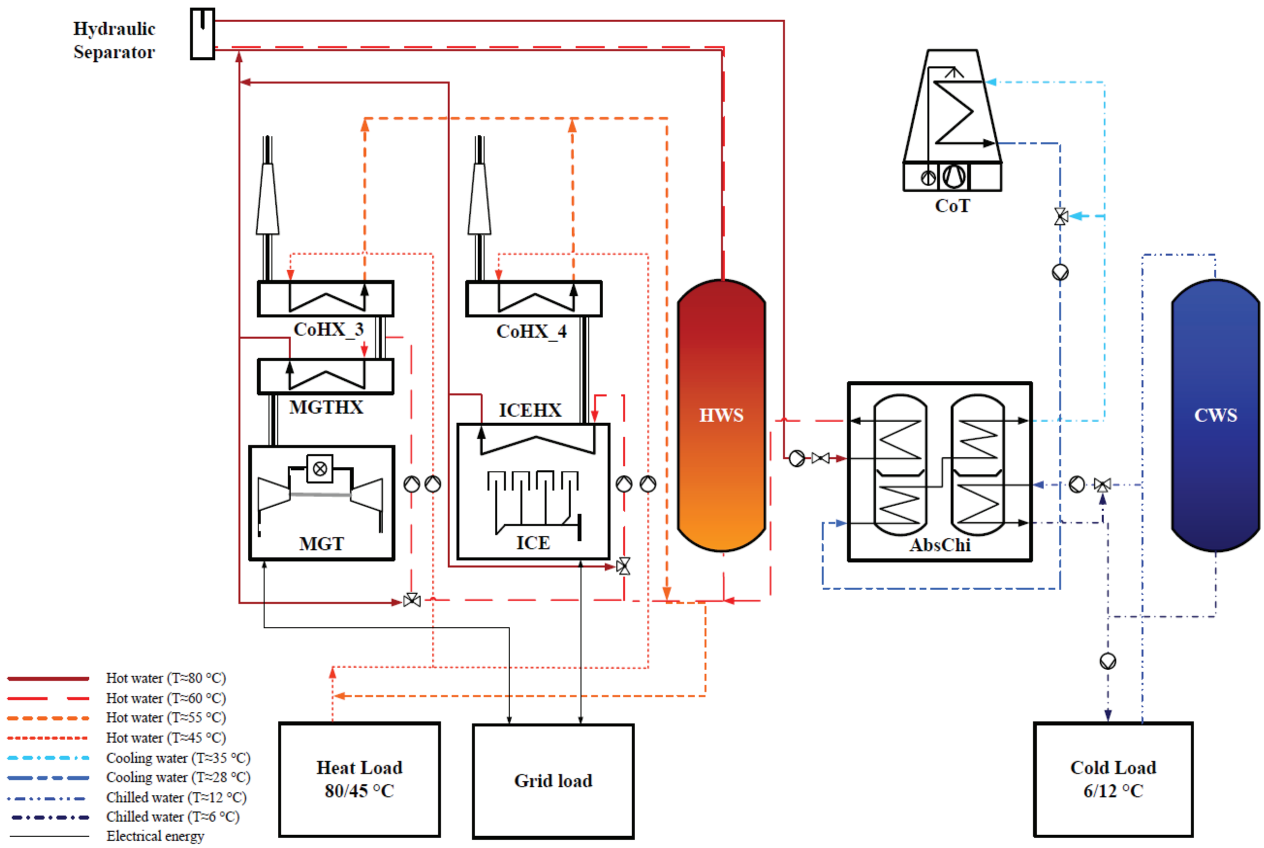

Figure 5. Summer mode - simplified scheme of energy facility.

operated with higher thermal energy output in winter and with lower thermal output in summer and transition periods (see upper left diagrams in Figure 6, 7, 8, and 9), and accordingly, the generation of electricity varies (compare upper right diagrams in Figure 6, 7, 8, and 9).

$$T_{aN} = \frac{\sum_{k=1}^{12} Q_{BOI\_1,i,k}}{Q_{N,BOI\_1}} \tag{1}$$

The thermal output of the boilers is shown in the lower left diagrams of Figure 6, 7, 8, and 9. The operation of boilers was high during peak winters and peak heat demand in buildings. The year 2010 had a very high peak (thermal energy output) for BOI_1 and BOI_2, it was about 400MWh$_{th}$ for month of December. It can be attributed to very high heating degree days (G2010) of 3431 K·d and the start of complete operation of building D in 2010. BOI_1 and BOI_2 operate mostly on part load with 50% to 60% of gas input. The gas input, i.e., the amount of natural gas supply is one of the control variables for boiler load at HS OG. However, the utilization periods for BOI_1 and BOI_2 were very low as compared to the CHP units as the boilers were used only during the middle and peak load conditions (see Table 3).

The lower right diagrams of Figure 6, 7, 8, and 9 show the chilled water capacity provided by the AbsChi and also its Energy Efficiency Ratio (EER). The EER was estimated using the Equation 2. The EER of absorption chiller is the ratio of usable cooling energy to the driving thermal energy (Herold et al. 1996). It is also called as Coefficient of Performance (COP).

$$COP_{i,k} = \frac{Q_{cw,i,k}}{Q_{AbsChi,i,k}} \tag{2}$$

The utilization period of AbsChi was highly dependent on the operation of building B and C until 2009, and from 2010 onwards it was also dependent on operation of building D. The AbsChi was employed only during summer and transition mode driven by thermal energy (operated with less capacity) from MGT and ICE. The EER of AbsChi during the 4 year period had ranged between 0.10 and 0.84. The peak EER for this

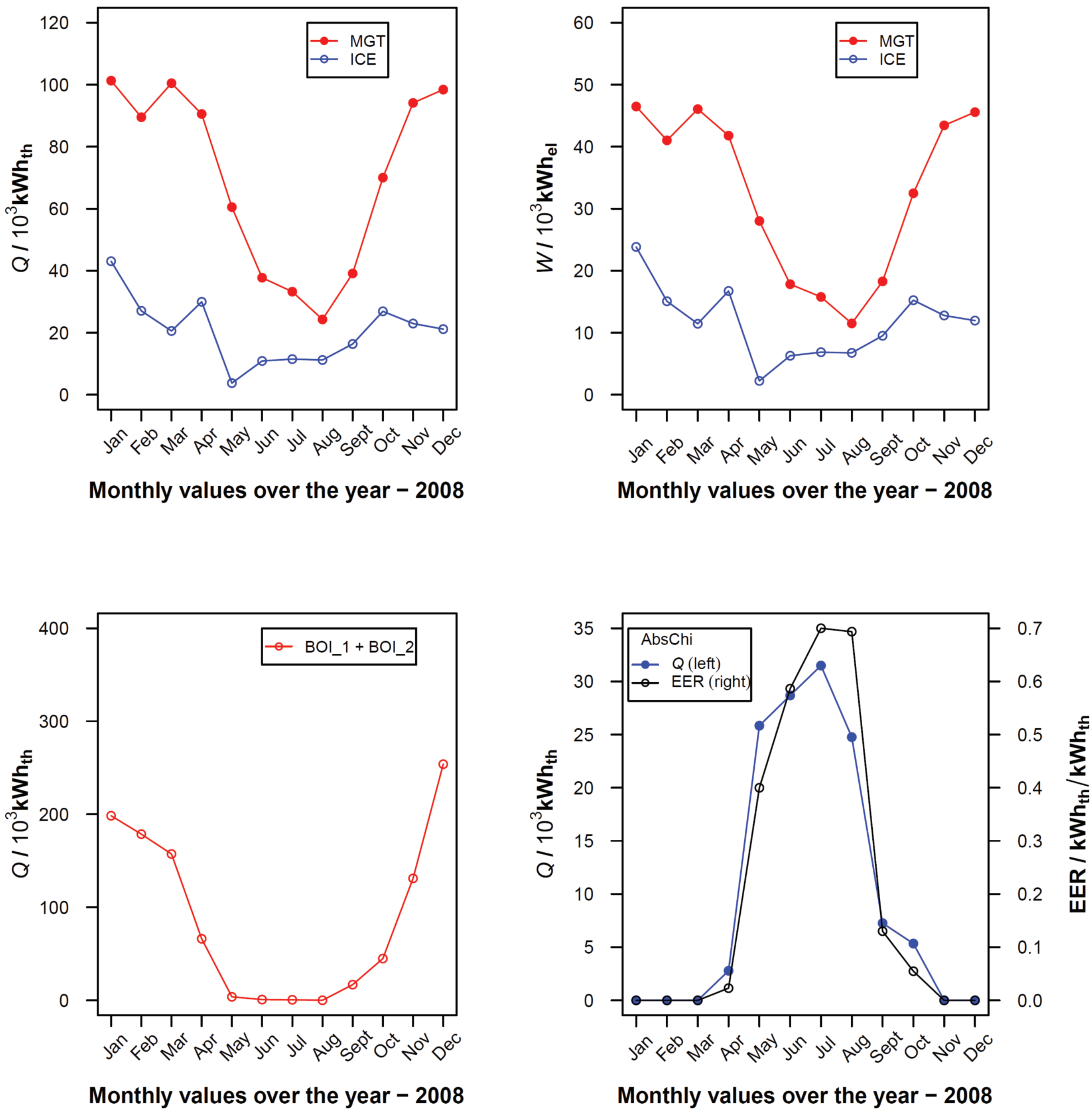

Figure 6. Analysis of energy facility - 2008.

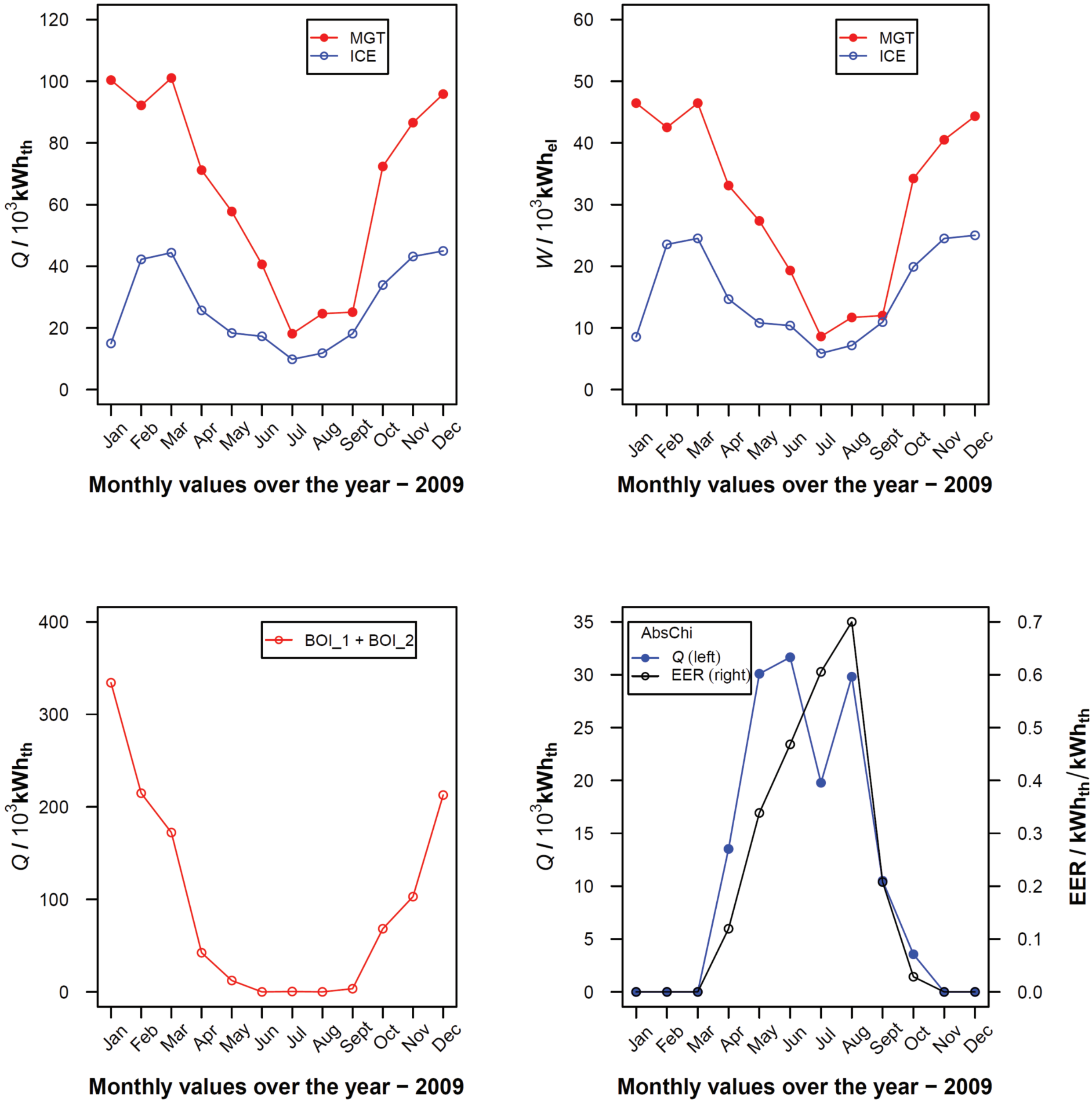

Figure 7. Analysis of energy facility - 2009.

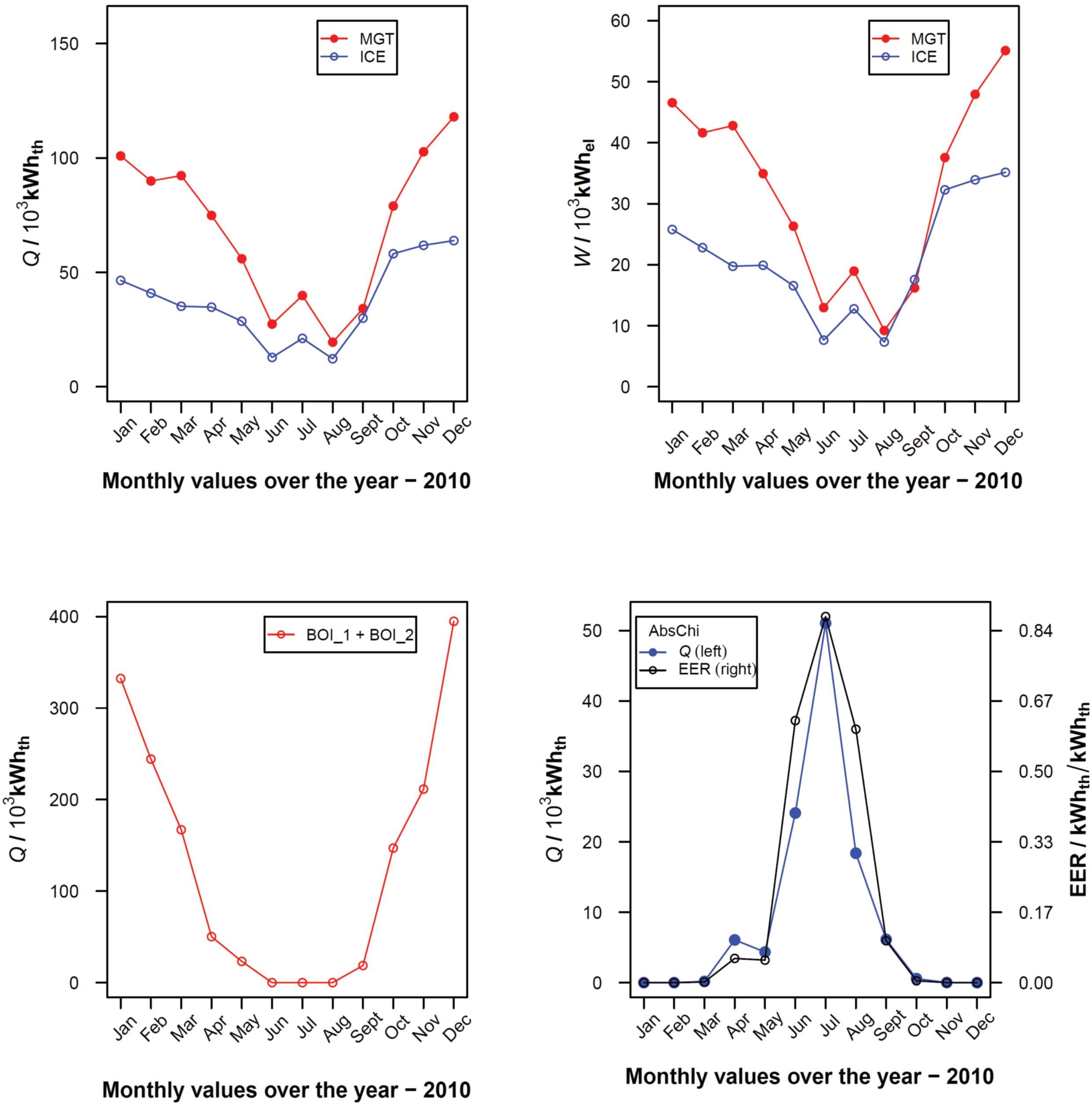

Figure 8. Analysis of energy facility – 2010.

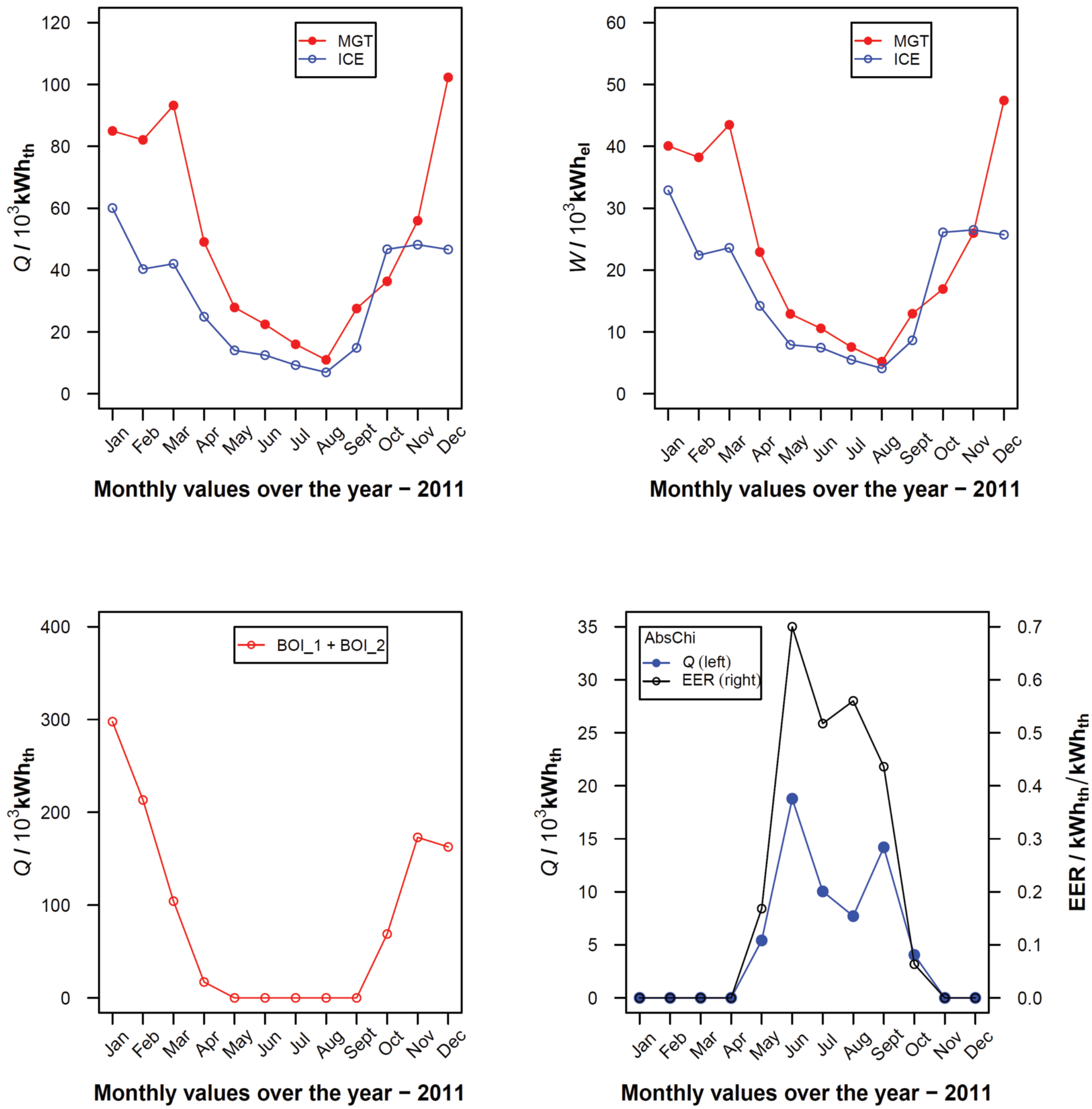

Figure 9. Analysis of energy facility – 2011.

period was obtained during the months of July and August which happens to be the hottest period of summer in Germany. During the 4 year analysis period, the EER trend was relatively different in the year 2010 which can be seen in the lower right diagram of Figure 8. Typically, the cooling started from the months of March/April and ended by September/October. In the year 2010, it was quite different as there was a steep increasing slope from May which had reached maximum in July followed by an immediate decreasing slope. This effect could possibly be the influence of the cooling control strategies of the new building D which has to be studied and analyzed more in detail corresponding to external and internal parameters. However, the utilization period for the year 2010 was 693h which is quite high.

SUMMARY AND CONCLUSIONS

Monitoring and data analysis for the trigeneration system was carried out for a 4 year period to gain understanding regarding the behavior and performance of the energy facility under dynamic conditions such as increasing number of students, dynamic climate and continuous retrofitting of buildings. The plant was working properly during this period, that is, the energy facility was able to provide necessary thermal energy and a part of electrical energy for the building complexes at HS OG with high utilization periods. Also, the reliability of the plant had been quite satisfying so far. Employing trigeneration process helps in promoting the concept of decentralized energy system and also renewable energy production near the demand site. HS OG had implemented the trigeneration system at its university campus to promote the concept of decentralized energy system.

The next step is to extend the monitoring and data analysis to develop a method for energy analysis based on scarce data as the data available to conduct detailed analysis is limited in the case of HS OG (Gopisetty and Treffinger 2013). It is also intended to carry out an energy and economic analysis for the trigeneration system to understand energy and economic savings in detail.

ACKNOWLEDGEMENTS

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