Increased efficiency of combined heat and power plants by utilizing waste heat for resorption chillers and their combination with hydrocarbon chillers

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Abstract. The use of waste heat has long been a topic to increase the efficiency of large-scale industrial processes, but it is becoming as well important in the commercial sector and in small and medium-sized industrial plants. For a sustainable and decentralized energy supply it is necessary to utilize all exergy flows much more than before. Particularly in decentralized combined heat and power (CHP) plants, the annual coefficient of performance is low due to seasonal temperature fluctuations, as the generated heat cannot be used or can only be used partly during the summer and transitional months. Interface technologies such as sorption technology can be used to further increase the utilization rate of such CHP plants and provide cooling capacity at the same time. This concept allows the utilization of previously unused waste heat to generate cooling in the temperature range from -6°C to 15°C, without the necessity of significant amounts of electric energy for the operation of additional compression refrigeration systems. In a pilot project funded by the German Federal Ministry of Economic Affairs and Energy, a thermally driven refrigeration plant with a small cooling capacity of maximum 25 kW using the resorption principle was evolved under these aspects and installed in a supermarket. Special focus is given to the flexibility of the plant technology as well as to the potentials of combinations of thermally and electrically driven chillers with natural refrigerants such as hydrocarbons and ammonia and the integration of thermal storage for temporal decoupling or discontinuous availability of heat and cooling load.

1. Introduction
Nowadays research departments and industry put much effort in actions to increase the efficiency of machines and systems for energy saving in the range of a few percentage points. This is a time and money consuming procedure. A more effective way to deal with this subject is a more target-oriented overall view on interacting systems of energy producers and energy consumers. Supermarkets can provide a good example of such interaction since the end energy of various types and heat flows at various temperature levels are required: E.g. electric energy for lighting, heat for room heating or cold for the refrigeration of food. An interaction of all sources and consumers of energy is especially possible in the area of heat displacement in order to exploit the exergy of the energy sources used. Thanks to the financially promoted decentralization of electricity generation in many countries – particularly in the form of CHP plants (IEA, 2012) – the overall utilization of the exergy bound in the primary energy source natural gas or biogas is almost completely feasible. A supermarket is therefore a type of a reality laboratory for investigating the interaction of different systems. In the present case a CHP is operated for the generation of electrical and thermal energy with connected use of excess waste heat by a
resorption refrigeration system for the provision and storage of cooling capacity at a temperature range of -6 to 12°C.

2. Waste Heat Utilization with Sorption Refrigeration Systems

2.1. Combined Heat and Power Generation

The 2014 IPCC-Report of Working Group III (IPCC, 2014) says that “Combined heat and power (CHP) plants are capable of recovering a share of the waste heat that is otherwise released by power plants that generate only electricity. The global average efficiency of fossil-fuelled power plants is 37 %, whereas the global average efficiency of CHP-units is 58 % if both power and the recovered heat are taken into account. State of the art CHP plants are able to approach efficiencies over 85 %”. Therefore, it seems necessary to implement those systems in the future energy supply. On the other hand the International Energy Agency says in its World Energy Outlook 2012 (IEA, 2012) that “a key constraint on the deployment of CHP is the difficulty of distributing heat over long distances. Because of this, CHP-units must be located close to demand, potentially increasing costs.”

In the trade and commerce sector, especially the food retailing, it seems to be unfeasible to utilize the entire amount of heat while there is a demand on electric energy, which can only be provided in combination by the CHP plant. In summer or transitional months there is nearly no demand on heating but the need for air conditioning (A/C) is increasing while the demand for normal refrigeration is almost constant throughout the year. A possible solution to the waste heat problem could be the installation of a sorption refrigeration system to compensate the opposite demand for heating and cooling capacity.

2.2. Sorption Refrigeration Systems

Sorption refrigeration systems were developed in the middle of the 19th century with the necessity of industrial cooling. In a much quoted basic work (Altenkirch, 1954) on continuously operated sorption chillers, the so far very rarely used – and therefore almost unknown – configuration of the resorption chiller is presented. In p-T-diagrams, Altenkirch describes their essential components and working processes (cf. figure 1).

Both continuously operating systems are equally usable for the utilization of waste heat. The decisive factor for the selection is the focus on the respective task to be fulfilled, taking the quality and availability of the driving energy as well as other boundary conditions into account.

To select the appropriate system, temperature levels should be considered foremost. As shown in figure 1, three temperature levels are required to operate a sorption system – the heating temperature $T_D$, the recooling temperature $T_{CA}$ resp. $T_{RA}$ and the refrigeration temperature $T_0$. If cold temperature values over 4°C are targeted, Water-LiBr-Absorption and Water-Silicagel-Adsorption systems are available which can achieve higher coefficients of performance (COP) than ammonia-water systems. Therefore

![Figure 1. Comparison of an absorption refrigeration system with internal heat exchange, condensate precooling and without rectification (left) and a resorption refrigeration system with internal heat exchange (right) according to (Altenkirch, 1954)]
they are mainly used in the area of cold water generation in the process industry or for air conditioning, for example, in office buildings or server rooms (cf. table 1).

**Table 1. Typical generator, recooling and brine temperature ranges and reachable Coefficients of Performance (COP) of ad- and absorption processes of commonly used working pairs**

| Refrigerant | Sorbent | Process | Operation  | Generation Temp. $T_{G}$ (°C) | Recooling Temp. $T_{RC}$ (°C) | Brine Temp. $T_{Brine}$ (°C) | COP  |
|-------------|---------|---------|------------|-------------------------------|-----------------------------|-----------------------------|------|
| NH$_3$      | H$_2$O  | Absorption | continuous | 85 - 100                      | 20 - 35                     | -30 - 5                     | < 0.60 |
| H$_2$O      | LiBr    | Resorption | continuous | 70 - 120                      | 10 - 30                     | -10 - 12                    | < 0.55 |
| H$_2$O      | Silicagel | Absorption | continuous | 85 - 180                      | 20 - 40                     | 4 - 20                      | < 0.78 |

The use of water as the refrigerant is not suitable for providing cooling capacities below 0°C due to its triple point of $T_{TP} = 0.01$ °C, as it would freeze and block the evaporator and eventually also the expansion valve in conventional systems. For this case of application, other working fluid pairs are suitable. Usually ammonia-water absorption refrigeration systems (ARS) are used for this purpose, but due to their high technical and safety requirements they have been implemented almost exclusively for large-scale systems with cooling capacities of $Q_0 > 100$ kW.

With the so far almost forgotten technology of the resorption refrigeration system (RRS), which has been implemented in the current project, a system for the utilization of waste heat with a small cooling capacity ($Q_0 = 25$ kW) is available, which avoids these problems and can serve a wide range of different functions regarding partial load operation and temperature ranges. Due to the omission of the rectification and the dephlegmation of the ammonia vapor, as well as the reduction of the system pressure to $p_1 < 0.6$ MPa by the presence of the ammonia only in aqueous solution, the equipment requirements and thus the plant costs are significantly reduced. With regard to the thermal boundary conditions, the range of operation is considerably more flexible (cf. table 1), even though the temperature of decoupling of cooling capacity is limited to $T_0 \approx -10$ °C. Current operational experiences also demonstrate that in particular the operation under short- and varying boundary conditions with regard to the temperatures has just minimal effects on the plant performance, which can cause problems with conventional absorption systems.

2.3. **External Carnot Efficiency Ratio for Sorption Refrigeration Systems**

From a thermodynamic point of view, the evaluation of sorption chillers is more complex than for compression systems, since heat is used as driving energy instead of electricity. Thus only a specific part of the heat energy – the exergy – can be used. Therefore, it is useful to map the processes with regard to that temperature which determines the exergy. The basis for the calculation is the *External Carnot Heat Ratio* $\zeta_{Ce}$, which refers to the external fluid flows of a sorption chiller and is represented by equation 1 (Niebergall, 1959)

$$\zeta_{Ce} = \left(\frac{1}{T_{RC,1}} - \frac{1}{T_{G,m}}\right) / \left(\frac{1}{T_{Brine,\text{out}}} - \frac{1}{T_{RC,2}}\right)$$

The parameters necessary for calculating equation 1 are the arithmetic mean temperature of the heat supply $T_{G,m}$, the outlet temperature of the brine at the evaporator/degasser $T_{\text{Brine, out}}$, the recooling temperature of the cooling water at the outlet of the absorber/adsorber $T_{RC,1}$ and the recooling temperature of the condenser/resorber $T_{RC,2}$. Different External Carnot Heat Ratios $\zeta_{Ce}$ result for different application cases, which are exemplarily shown in table 2. For this investigation equal outlet temperatures of the cooling water were assumed ($T_{RC,1} = T_{RC,2} = T_{RC}$).
Table 2. External Carnot Heat Ratios $\zeta_{Ce}$ for brine Temperatures below (left) and above (right) 0°C

| Application case            | $T_{G,m}$ (°C) | $T_{RC}$ (°C) | $T_{Brine}$ (°C) | $\zeta_{Ce}$ |
|-----------------------------|----------------|--------------|------------------|--------------|
| Deep-Freezing               | 80             | 15           | -30              | 0.99         |
|                             | 80             | 22           | -30              | 0.77         |
|                             | 80             | 30           | -30              | 0.57         |
|                             | 120            | 15           | -30              | 1.44         |
|                             | 120            | 22           | -30              | 1.17         |
|                             | 120            | 30           | -30              | 0.93         |
| Normal Cooling (Supermarket)| 80             | 15           | -6               | 2.34         |
|                             | 80             | 22           | -6               | 1.57         |
|                             | 80             | 30           | -6               | 1.05         |
|                             | 120            | 15           | -6               | 3.40         |
|                             | 120            | 22           | -6               | 2.38         |
|                             | 120            | 30           | -6               | 1.70         |
| Air Conditioning            | 80             | 20           | 8                | 3.98         |
|                             | 80             | 27           | 8                | 2.22         |
|                             | 80             | 35           | 8                | 1.33         |
|                             | 120            | 20           | 8                | 5.96         |
|                             | 120            | 27           | 8                | 3.50         |
|                             | 120            | 35           | 8                | 2.25         |
| Cold Water Production       | 80             | 20           | 16               | 12.28        |
|                             | 80             | 27           | 16               | 3.95         |
|                             | 80             | 35           | 16               | 1.94         |
|                             | 120            | 20           | 16               | 18.39        |
|                             | 120            | 27           | 16               | 6.22         |
|                             | 120            | 35           | 16               | 3.29         |

Figure 2. External Carnot Heat Ratio $\zeta_{Ce}$ for brine Temperatures below 0 °C

Figure 3. External Carnot Heat Ratio $\zeta_{Ce}$ for brine Temperatures above 0 °C

The values of table 2 are illustrated in figure 2 and figure 3. It can be seen that the decisive influencing value for the given application cases is the spread between the cold decoupling and recooling temperature levels. Especially for applications in air conditioning (A/C) or cold water production, the External Carnot Heat Ratios are significantly higher than for deep-freezing (DF) or normal cooling (NC).
For the development of a realistic efficiency ratio it is also necessary to consider the system itself, which can be described by the actually achievable Heat Ratios (COP). Assuming that the COPs, approximately given according to table 1, are achieved for the most favourable conditions in the case of normal cooling and air conditioning, the Heat Ratio \( \zeta \)

\[
\zeta = \frac{\dot{Q}_0}{\dot{Q}_H}
\]  

(2)

can be used to determine the External Carnot Efficiency Ratio \( \eta_{Ce} \)

\[
\eta_{Ce} = \frac{\zeta}{\zeta_{Ce}}
\]  

(3)

The results are summarised in table 3.

**Table 3.** External Carnot Efficiency Ratios \( \eta_{Ce} \) regarding the Heat Ratio \( \zeta \) (COP) of different sorption systems for Normal Cooling (NC) and Air Conditioning (A/C)

| Application case                     | Sorption System | Refrig. Sorbent | System | \( T_{G,m} \) (°C) | \( T_{RC} \) (°C) | \( T_{Brine} \) (°C) | \( \zeta_{Ce} \) | \( \zeta \) | \( \eta_{Ce} \) |
|--------------------------------------|-----------------|-----------------|--------|---------------------|------------------|----------------------|----------------|----------------|----------------|
| Normal Cooling (Supermarket)         | NH\textsubscript{3} | H\textsubscript{2}O | Absorption | 80 | 15 | -6 | 2.34 | 0.50 | 0.21 |
|                                      | NH\textsubscript{3} | H\textsubscript{2}O | Resorption | 80 | 15 | -6 | 2.34 | 0.45 | 0.19 |
|                                      | NH\textsubscript{3} | H\textsubscript{2}O | Absorption | 120 | 15 | -6 | 3.40 | 0.60 | 0.18 |
|                                      | NH\textsubscript{3} | H\textsubscript{2}O | Resorption | 120 | 15 | -6 | 3.40 | 0.55 | 0.16 |
| Air Conditioning                      | NH\textsubscript{3} | H\textsubscript{2}O | Resorption | 80 | 20 | 8 | 3.98 | 0.55 | 0.14 |
|                                      | H\textsubscript{2}O | LiBr            | Absorption | 80 | 20 | 8 | 3.98 | 0.65 | 0.16 |
|                                      | NH\textsubscript{3} | H\textsubscript{2}O | Resorption | 120 | 20 | 8 | 5.96 | 0.60 | 0.10 |
|                                      | H\textsubscript{2}O | LiBr            | Absorption | 120 | 20 | 8 | 5.96 | 0.78 | 0.13 |

The values from table 3 are shown graphically in figure 4. Despite the higher COP of the H\textsubscript{2}O-LiBr or NH\textsubscript{3}-H\textsubscript{2}O absorption systems compared to the resorption system, the decisive factor is rather the temperature of the heat source (resp. the decoupling of cold) than the actual COP. Hence, it can be derived that the quality of a sorption refrigeration plant does not only depend on the Heat Ratio, but also on the utilization of small temperature differences between heating and recooling level, while achieving large temperature differences between decoupling of cold and recooling level at the same time.
Comparing the efficiency of a resorption system relative to conventional absorption systems, the results shown in table 4 are obtained. It becomes clear that the resorption system falls behind especially in the area of air conditioning with the H₂O-LiBr system although the absolute values are not significant higher. Besides the presented thermodynamic factors, the choice of the most suitable sorption refrigeration system depends also on the necessary flexibility of the system as well as the installation, operation and maintenance costs.

Table 4. Comparison of Resorption Systems (RRS) with Absorption Systems (ARS) regarding the External Carnot Efficiency Ratios for normal cooling and air conditioning.

| Application case          | \( T_{\text{G,in}} \) (°C) | \( T_{\text{RC}} \) (°C) | \( T_{\text{Brine}} \) (°C) | \( \eta_{\text{Ce,ARS}} \) (Absorption System) | \( \eta_{\text{Ce,RRS}} \) (Resorption System) | \( \frac{\eta_{\text{Ce,RRS}}}{\eta_{\text{Ce,ARS}}} \) |
|---------------------------|-----------------------------|---------------------------|-----------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Normal Cooling (Supermarket) | 80                          | 15                        | -6                          | 0.214                                         | 0.192                                         | 90 %                                          |
| Air Conditioning          | 80                          | 20                        | 8                           | 0.163                                         | 0.138                                         | 85 %                                          |
|                           | 120                         | 15                        | -6                          | 0.177                                         | 0.162                                         | 92 %                                          |

3. Integration of a CHP-unit and a Resorption Refrigeration System in a Supermarket

3.1. CHP in the Heating and Cooling Supply of a Supermarket

Without the operation of a sorption refrigeration system, 69% of the electricity consumed by the examined supermarket is needed for the cold supply, what can be seen in figure 5 and is based on the measuring over one week. Regarding this fact a glance on the consumers of cooling and heating capacity is necessary since both have to be taken into account if the installation of a CHP plant including an additional sorption refrigeration system is planned. Figure 5 shows that the spectrum in terms of heating and cooling capacity is very diverse and several temperature levels can be identified.

**Figure 5.** Utilization of electrical energy in the examined supermarket near Stuttgart (Germany) with a total area of 1300 m²

**Figure 6.** Temperature levels, cooling and heating capacities in the examined supermarket

Subscripts:
CHP… hot water outlet at CHP-unit; DHW…Domestic Hot Water; H,stat…static heating; H,con…convective heating; RC…recooling; amb…ambient; A/C…air conditioning; NC…normal cooling; DF…deep-freezing
As usual today, the provision of deep-freezing \((T_{DF} \approx -25 ^\circ C)\) is implemented in a lower cascade stage (in this specific case \(CO_2\) direct evaporation system) at which the condensation temperature corresponds to the normal cooling level \((T_{NC} \approx -4 ^\circ C)\) of the supermarket. Thus, the \(CO_2\) deep-freezing system can be operated efficiently in the subcritical area. Due to the low temperature of the critical point, \(CO_2\) systems, for instance for the provision of normal cooling, cannot be operated in subcritical mode during months with high ambient temperatures. The transcritical operation leads to lower \(COP\) values compared to other cycles and refrigerants dealing with the same external boundary conditions. Due to the restrictions of the EU-F-Gas-Regulation, the focus is nowadays on flammable refrigerants, such as \(hydrocarbons\) (e.g. propane (R290)). But for their use the demands on safety have to be taken into account. This is why \(cold\ brine\ systems\) are increasingly becoming the standard, allowing the use of flammable or toxic refrigerants in refrigeration systems, located in areas of less safety requirements, for instance outside of the building. However, the advantage of such a cold brine system also arises from the fact that several cold generators can supply this system, which enables also the use of thermally driven sorption refrigeration systems.

In order to operate sorption systems, a waste heat potential is necessary. As already mentioned, CHP-units as a potential heat generator are particularly attractive for the use in the retail sector, which is why supermarket chains are increasingly considering investments in this area. So far, the obstacles for their implementation have been the impossibility of the utilization of excess waste heat in summer and transitional months as well as the temperatures of the heat extraction \((T_{CHP} \approx 90 ^\circ C)\), which are significantly higher than the requirements (e.g. the provision of heating energy for domestic hot water (DHW) generation \(T_{DHW} \approx 70 ^\circ C\), static heating \(T_{H,stat} \approx 60 ^\circ C\) and ventilation devices \(T_{H,conv} \approx 45 ^\circ C\)).

The leading variable for the design of a CHP-unit usually is the base load of the consumed electrical energy. Corresponding national laws regulate the possibilities of feed-in remuneration of surplus electrical energy. In general, the amount of electrical energy fed into the grid must not exceed a certain percentage of the annual energy output, which in turn defines the nominal output of the CHP-unit. This also determines the nominal heating capacity depending on the type of CHP-unit (with or without exhaust gas heat exchanger). For CHCP (combined heating, cooling and power) applications, it is useful to decouple the highest possible amount of heating capacity, which has also been done in the examined market by using a CHP-unit with an exhaust gas heat exchanger.

3.2. Combined External Container Solution

In the course of a project funded by the German Federal Ministry of Economics and Energy, a supermarket was restructured.

![Diagram of heating and cooling network](image-url)

**Figure 7.** Installed Heating and Cooling Network of the examined supermarket after restructuring.
This includes the installation of a CHP-unit (nominal electrical power of $P_{\text{CHP}} = 48$ kW$_{\text{el}}$ and a heating capacity of $Q_{\text{CHP}} = 80$ kW$_{\text{th}}$), a brine circuit with connected deep-freezing chillers, propane chillers (3 times $Q_{0,\text{PC}} = 25$ kW$_{\text{th}}$) and a resorption refrigeration system ($Q_{\text{RRS, max}} = 25$ kW$_{\text{th}}$) using waste heat to provide A/C and normal cooling. The network of heating, cooling and electrical energy generators resulting from the retrofitting is illustrated in Figure 7.

A special requirement was to assemble the system as a compact unit in the external area of the supermarket. Therefore the implementation of the CHP and the resorption system was realized as a container-solution. In addition, the A/C and NC propane chillers were installed in another container located close by, and the resorption plant was coupled into the piping network of these chillers. It can also be seen that a boiler is installed in addition to the CHP-unit. This existing unit has been preserved and now serves as failure redundancy for the CHP-unit for heating supply of the supermarket. A special aspect and sub-task of the project was the installation of a latent energy storage (ice storage) and the investigation of their influence on the flexibilization of cooling load and generation. Furthermore, various sensitive storage tanks (hot water, A/C and NC) can be seen, which are necessary for the operation of the resorption plant, but also for the temporal decoupling of load and generation. The realized container with the relevant components is illustrated in Figure 8.

![Figure 8](image_url)

Figure 8. Installed combined external Container solution including CHP-unit, RRS, heating heat exchanger and sensitive storages

4. Operating Characteristics

As already mentioned, it is necessary to consider not only the design point of a sorption system, but also the load profiles. This shows how varying boundary conditions affect the system and what kind of Key Performance Indicator (e.g. COP, $\eta_{Ce}$) can validly evaluate a sorption system. A further look at the monthly load profiles of the entire system reveals the complexity of the system.

4.1. Typically Daily Load Profiles

In the following figures daily load profiles of the resorption refrigeration system (RRS) are shown. The depicted values are the average cooling capacity $Q_{0,\text{RRS}}$ per hour, the average consumed heating capacity $Q_{\text{RRS}}$, the ambient temperature $T_{\text{amb}}$, which is the leading variable for the temperature of the cooling water $T_{\text{RC, in}}$, which than again has a significant effect on the performance of the system, which means the $\text{COP}$ as well as the External Carnot Efficiency Ratio $\eta_{Ce}$.
Figure 9 demonstrates a load profile of a Sunday (store is closed to the public) with ambient temperatures below 10 °C for almost 24 hours. Due to this low ambient temperature $T_{\text{amb}}$, there is nearly no effect on the cooling water temperature $T_{\text{RC,in}}$ can be observed. In normal cooling mode, the cooling water temperature is kept at a value between 12 °C and 13 °C to ensure a pressure difference between the resorber and degasser which is necessary for stable operation. Despite the low ambient temperatures, no significant amount of heat is demanded for heating the supermarket. This is due to the fact that the supermarket is closed on Sundays and the room temperature is kept at the level of the night-time reduction. This results in an almost constant cooling capacity of 17-19 kW throughout the day.

In conjunction with the heating capacity of 45-49 kW shown in Figure 10, a constant COP of approx. 0.39 and an External Carnot Efficiency Ratio $\eta_{\text{Ce}}$ of approx. 0.19 is obtained at a cold decoupling temperature of continuously -5 °C.

The load profile from Figures 9 and 10 can now be used for the design and operating condition of a continuous sorption plant, but it does not do justice to the dynamics in the environment of a supermarket. This can be seen, for example, in Figure 11. In this case, the average daily outdoor temperature is also not higher than 10°C, but there is a significant decrease in cooling capacity and COP in the time period from 6 to 8 a.m. and from 10 a.m. to 1 p.m. This can be attributed to an equally significant increase in the cooling water temperature. Reason for this is that the supermarket has to be reheated after the weekend. Accordingly, the CHP plant does not have a sufficient heating capacity to heat the market and
operate the RRS. This is detected by the control system in form of a decrease in the hot water temperature supplied to the RRS.

![Figure 11. Daily load profile – Date: 25th March 2019 (Monday) – of the examined Supermarket near Stuttgart (Germany)](image)

The reason for the increase in the cooling water temperature in these periods is a deliberate bypass operation in the recooling system. In the installed resorption system it is not possible to switch over to partial load operation by reducing the pump frequency and thus the solution circulation. This is due to the fact that unregulated volume flow limiters are used, the pumps ensure only the solution circulation in both partial cycles and the pressure levels are thus only determined by the temperatures of the external flows. By manipulating the leading variable $T_{RC}$, the Carnot Heat Ratio becomes significantly less optimal for the operation of a sorption plant, which leads to a deterioration of the plant performance (COP).

$$\zeta_{Ce} = \left( \frac{1}{T_{RC,1}} - \frac{1}{T_{G,m}} \right) / \left( \frac{1}{T_{Brine, out}} - \frac{1}{T_{RC,2}} \right) = \left( \frac{1}{300 K} - \frac{1}{355 K} \right) / \left( \frac{1}{268 K} - \frac{1}{300 K} \right) = 1,3$$ (4)

Due to the deteriorated absorption process but with constant temperature levels in the desorbers, the solution now has a lower concentration at the outlet of absorber and resorber. This leads to a reduced desorption of ammonia in the desorber and degasser and thus to a reduced consumption of heating capacity by the RRS. This ensures a sufficient heating capacity for the heating of the supermarket.

![Figure 12. Daily load profile – Date: 10th May 2019 (Friday) – of the examined Supermarket near Stuttgart (Germany)](image)
Figures 12 and 13 show the influence of the cooling water temperature as a result of the increase in the ambient temperature. While the outside temperature on the 10th of May (c.f. figure 12) is in the range of 10-17°C and its influence on the cooling capacity and the COP is rather insignificant, the profile on the 14th of August (c.f. figure 13) is rather unsteady.

Figure 13. Daily load profile – Date: 14th August 2018 (Tuesday) – of the examined Supermarket near Stuttgart (Germany) according to (Ziegler, 2018)

In particular, an increase in COP and cooling capacity between 8:30 and 9:30 a.m. can be observed despite the increase in the ambient temperature. This does not seem to be thermodynamically explainable initially, but can be understood using Figure 14. The increase in both values can be related to a variation in the temperature of the cold decoupling. As a result of the high ambient temperatures, in addition to normal cooling, also air-conditioning is required in the supermarket. A consumption of cooling capacity by the air conditioning ventilation unit is detected by an increase in the temperature level in the sensitive A/C storage tank. The implemented control system of the resorption system reacts by switching a three-way valve to provide A/C (+4°C) instead of normal cooling (-4°C), which also improves the External Carnot Heat Ratio.

$$\zeta_{Ce} = \left(\frac{1}{T_{RC1}} - \frac{1}{T_{G,m}}\right) / \left(\frac{1}{T_{Brine, out}} - \frac{1}{T_{RC2}}\right) = \left(\frac{1}{302 \, K} - \frac{1}{355 \, K}\right) / \left(\frac{1}{277 \, K} - \frac{1}{301 \, K}\right) = 1.7$$ (5)

This in turn has an influence on the External Carnot Efficiency Ratio, which is constantly above 0.2 on a daily average despite a relatively low COP, and which appears to be quite competitive compared to other sorption systems.

Figure 14. Daily load profile (Heating and Cooling capacity) – Date: 14th August 2018 – of the examined Supermarket near Stuttgart (Germany)
4.2. Monthly Load Profiles
As a result of the downtimes of the CHP, only a few continuous monitoring results are available over a period of one month. Therefore, the period from 17th January to 16th February 2019 is only an example for illustration purposes.

Figure 15. Monthly electrical energy consumption and load profile – Date: 17th Jan. – 16th Feb. 2019 – of the examined Supermarket near Stuttgart (Germany)

Figure 15 shows the load profile of the electricity demand of the supermarket (secondary axis), as well as the daily amount of electrical energy generated by the CHP, including the grid feed-in and the purchase. The Sundays stand out clearly. On these days, when the supermarket is closed, the base load is low, which leads to an overproduction of electrical energy and thus to significant amounts of energy fed into the grid (250-350 kWh$_{el}$). The maximum achievable electrical power output (48 kW$_{el}$) of the CHP is slightly exceeded at daily peak load times, although the amount of generated and consumed energy on a monthly average is almost equal.

Figure 16. Monthly heat consumption profile – Date: 17th Jan. – 16th Feb. 2019 – of the examined Supermarket near Stuttgart (Germany)
Looking at the heat decoupled from the CHP unit and used in the various consumers in Figure 16, it is clear that the CHP unit is heat-led and not electricity-led. This is necessary for the operation of a resorption system, since due to its thermal inertia it cannot be started up and shut down as often and quickly as a compression chiller. If the CHP fails or is maintained (6th - 7th Feb.), on the one hand the driving energy waste heat for the resorption plant is missing and on the other hand more electrical energy has to be purchased from the grid.

5. Conclusions
Combined heat and power plants are a necessity in terms of the European Union's objectives for increasing the efficiency of energy generation plants. However, in order to be able to operate these CHP plants more efficiently than conventional large-scale power plants, it is necessary to use excess waste heat, which is generated as a secondary product during the generation of electrical energy using CHP. Sorption refrigeration systems can represent an interface technology here. One of the most important aspects is the case of application and which sorption plant appears to be best suited for the application. It was explained in detail that not only the COP but more the External Carnot Efficiency Ratio should be used for the selection of the appropriate plant, as this also takes the boundary conditions of the system environment (temperature levels of heating, cooling and recooling) into account. Particularly in the area of low cooling capacities ($Q_0 > 100$ kW), high demands are placed on flexibility and low investment costs, but even more attention is paid to low operating costs, as the purchase of the systems is mostly subsidized by the government. In the current project, it could be shown that the technology of the resorption system combines these advantages for a supermarket application and can therefore be used as an alternative to conventional sorption refrigeration systems. For this purpose, among other things, the daily load profiles were evaluated in order to show the changing boundary conditions and to demonstrate the flexibility of the resorption system technology.

In future publications further analyses concerning the monthly and annual data evaluation will be presented. These allow a derivation of the annual operating costs and thus a calculation of amortization periods, which form the basis for the economic efficiency calculation when purchasing a thermally driven refrigeration system.

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