Absorption chillers: their feasibility in district heating networks and comparison to alternative technologies

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Abstract

In recent years, a rising cold demand can be observed, which is e.g. due to increased requirements on climate control. The majority of this cold is currently provided by compression chillers. At the same time, district heating companies exhibit a lack of sales during summertime, which could e.g. be diminished by the operation of thermal driven cooling systems.

This work assesses absorption chiller technology in combination with boundary conditions implied by district heating systems. A theoretical comparison with compression chillers is provided and thereby interesting technology is identified. An analysis of the respective absorption chiller market in Germany is performed and a real case cold generation system is evaluated. Furthermore, the economic competitiveness to compression chillers is considered and environmental footprints are compared.

The LiBr-water single-effect absorption chiller is identified as the only reasonable machine, to be driven by district heat. Factors of highest influence are load factors, prices for heat, efficiency and size of the chillers. Possible application fields can be found e.g. in large office buildings, including server rooms. Absorption chillers are less appropriate for the use as stand alone systems and fluctuating load profiles, but conceivable as complementary to compression chillers, providing a constant base load. Buffer storages are essential for high load factors, continuous operating conditions and consequently efficiency. The calculated acceptable price for heat is significantly lower than typical market prices for district heat. Nevertheless, the provision of the product "cold" under agreed-upon conditions is conceivable as business model for district heating companies. **Keywords:** *absorption chiller, alternative technologies, district heat, real case example, market overview, economic analysis*

I. INTRODUCTION

Currently, the energy sector is undergoing a radical transition, affecting its general power generation and distribution structures. Due to climate change and finitness of conventional energy carriers, states all over the world define common climate goals like e.g. in the Kyoto Protocol [1]. They commit themselves to limit emissions and improve ressource-effectiveness. Furthermore the nuclear disaster in Fukushima in 2011, lead to a phase-out of nuclear energy in Germany, causing a dissappearence of large supply capacities. In the recent past, this gap was mainly closed by the addition of new renewable capacity. However renewables are dependent on external conditions and consequently fluctuating in time. In view of the above, conventional power plants like e.g. highly modern coal- and gas-fired power plants still play an important role in order to guarantee security of supply. These plants, producing currently more than 50% of the power required in Germany, are controllable but have the severe disadvantage of emitting greenhouse gases such as CO_2 while generating electricity. A smart way to reduce the ratio between emissions and provided energy is the upgrading of existing power plants to so-called Combined Heat and Power plants (CHP). Thereby the overall efficiency can be increased by enabling a simultaneous generation of usable heat and power. In the winter months, currently both heat and power can be provided economically through CHP generation. In several German cities, such as Stuttgart, even about 90% of district heat is provided by cogeneration. In summer however there is a discrepancy betweent the actual demand of heat and the heat that could be produced if the CHP plants would be operated in an optimal working point (cf. sales curve in figure 1). This lack of demand for heat in summer represents an ultimate obstacle for further extension of cogeneration respectively an even better utilization of existing units.

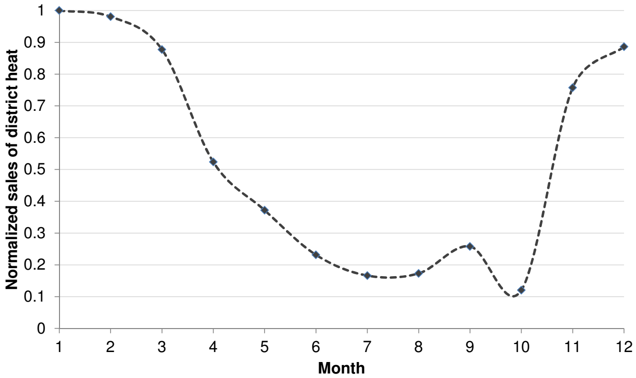

Figure 1. Qualitative sales curve of a district heating company

At the same time, a remarkable increase of cold demand can be observed in Germany and several other industrial countries, which can be traced back e.g. to higher demands on climate control in office buildings and increasing amount of data cen-

ters. Currently this demand is mainly satisfied by electrically driven compression chillers. However, thermal driven cooling systems such as absorption chillers, could possibly be another option. As absorption chillers require heat for its operation, the heat demands - especially in the summer months - could be increased. Vice versa, electricity used for climate control could be reduced.
In this work, the technological, economic and environmental maturity of thermal driven technologies, in particular of absorption chillers driven by district heat, is assessed as an competitive alternative to compression chillers.

II. COOLING TECHNOLOGIES

The considered cooling processes are performed in thermodynamic cycles. In such a cycle, a working fluid (refrigerant) passes several changes of state by the supply or removal of heat and/or work. At the end of this process chain, the fluid returns to its inital state.

A. *Compression chillers*

Figure 2 shows the basic working scheme of a compression chiller. Basically it consists of the four main components evaporator, compressor, condenser and expansion valve.

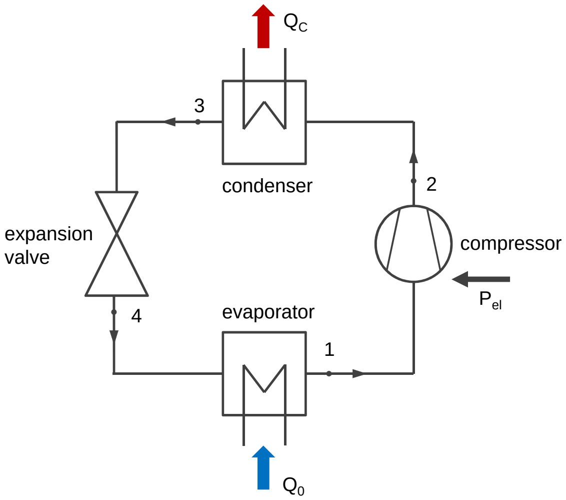

Figure 2. Basic working scheme of a compression chiller (according to [2])

The actual cooling effect is achieved in the evaporator. Heat is deprived from the system to be climatized and used to evaporate the refrigerant. Following, the vapor is compressed, thereby heatened up and consequently condensed to dispose of the previously absorbed heat. Through expansion, the refrigerant returns to its initial state. The compressor requires electric power in order to work. The efficiency of compression chillers, called Coefficient of Performance (COP), is determined as ratio between provided cooling performance (Q_0) and required electrical power (P_el) to run the process:

$$COP = Q_0/P_{el} \tag{1}$$

The use of cooling agents has changed drastically over the years, which is mainly due to the consciousness of global warming and ozone depletion potential of former refrigerants. Still several different cooling agents exist, being chosen dependent on compressor type (e.g. reprocating piston, rotary piston, scroll, screw or turbo compressors [3]) and boundary conditions of the specific application.

B. *Absorption chillers*

The basic working scheme of absorption chillers is similar to that of compression chillers (cf. figure 3).

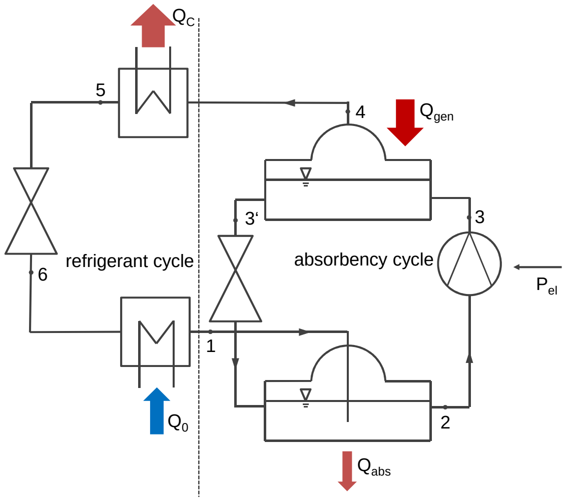

Figure 3. Basic working scheme of an absorption chiller (according to [2]

However the electrically driven compressor is substituted by a thermal driven secondary cycle (absorbency cycle), in which an absorbency circulates. In the absorber, cold refrigerant vapor meets the refrigerant-weak solution at low temperature. Thereby the solution absorbs the vapor and its absorbency mass fraction (x) decreases by

$$\Delta x = x_{rich} - x_{poor} \tag{2}$$

A solution pump then lifts the refrigerant-rich solution to the higher condenser pressure. However the required power that is needed to run the solution pump is significantly lower than the power, that is needed to compress pure refrigerant vapor, like in compression chillers. In the generator, heat is supplied (Q_{gen}) and the refrigerant desorbed from the absorbency. Thereby the refrigerant is vaporized again while the absorbency remains in liquid state. The cooling agent then passes the regular "refrigerant cycle", whilst the refrigerant poor solution leaves the desorber. It expands and enters the absorber again to absorb refrigerant vapor. [4] The efficiency of absorption machines is generally given by the heat ratio between cold performance (Q_0) and supplied heat in the generator (Q_{gen}). In general it is also called Coefficient of Performance (COP).

$$COP = \frac{Q_0}{Q_{gen}} \tag{3}$$

In this consideration, the minor required amount of electricity, which is basically needed to run the solution pump, is neglected.

In practice, so far two different working fluid pairs for absorption machines have established. The refrigerant-absorbency combination, used for low temperature applications is water-ammonia, whilst LiBr-water is the suitable working pair, when cold water temperatures higher than about 5-6°C are required. For the use of district heat solely single-stage LiBr-water absorption machines seem to be appropriate. Due to hot water temperatures that are typically about 80°C in summer, solely these machines can guarantee meaningful $COPs$. Typical rated $COPs$ of such LiBr-water machines are in a range between 0.6 to 0.8.

Nevertheless, both for absorption machines as well as for compression machines, several different design possibilites exist. These different interconnections are however not adressed in this extended abstract, but in the corresponding dissertation.

C. Comparison and additional components

The different energy input of the technologies has high influence on the heat rejection capacity that is required in order to maintain stationary conditions. The energy, that is supplied fist in the evaporator (Q_0) and secondly in the compressor/generator (P_{el}/Q_{gen}) needs to be released to the environment again. This is typically done by heat sink systems, working either by convection (dry cooler), humidification (evaporative coolers) or a combination between both (hybrid dry coolers). Compression systems receive pure exergy as energy input, in form of electricity. In contrast heat flows, that drive absorption systems, obtain additionally a large amount of anergy (cf. figure 4). This anergy needs to be released to the environment as well and consequently absorption chillers require larger heat rejection capacities, increasing investment-, demand-related costs as well as space requirements.

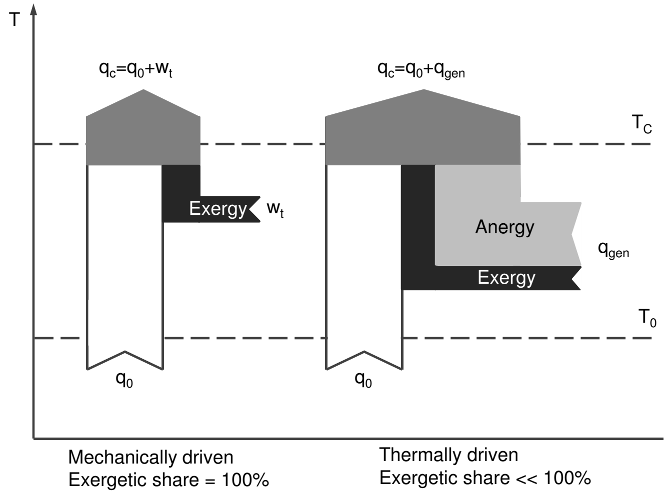

Figure 4. Energy flows in cooling machines (illustration according to [5], [4])

A further important component for cooling systems in general are buffer storages, that are usually integrated like hydraulic seperators. These storage capacities are required to balance short term fluctuations and are especially important for absorption chillers. This is due to a worse dynamic behaviour in comparison to compression chillers. By an appropriate dimensioning of buffer storages, load factors can be increased and changes in load are diminished. This optimizes the thermodynamic, as well as the economic efficiency of absorption chillers (cf. section VI).

Table I summarizes the main key informations and differences of the two technologies and rates them in terms of different categories as advantageous or disadvantageous over the respective other technology.

Table I. COMPARISON: COMPRESSION VS. ABSORTION CHILLERS (DATA PARTIALLY FROM [4])

	Compr. chiller	**Abs. chiller**
Driving energy	electricity	heat
Efficiency	$COP = Q_0/P_{el}$	$COP = Q_0/Q_{gen}$
Typical efficiencies	3-6	0,6 - 0,8
Advantageous (+) / Disadvantageous (-)		
Compactness	+	-
Investment costs	+	-
El. consumption	-	+
Heat rejection	+	-
Maintenance	-	+
Dry recooling	+	-
Dynamic behaviour	+	-
Reliability	-	+
Partial load	-	+
Environmental compability of working fluids	-	+

III. FIELDS OF APPLICATION

Absorption chillers can only compete with compression chillers when used in the right application, underlying a reasonable load profile and supporting the benefits of the system. In particular, the load profile should ensure:

- a preferably constant base load in the respective cooling interval without extreme and sudden load changes and consequently enabling high load factors
- preferably high required cold water temperatures T_0

The cold water temperature can even be considered as a hard factor, leading to an exclusion of fields in which temperatures, lower than the limit of the chosen technology ($\leq$ 5°C for LiBr-water single-stage chillers), are required. Within the observed sectors - the industrial sector and the sector air-conditioning in buildings - this leads to an omission of cold intensive industries such as food production industy, chemical industry, construction-and building-materials industry and electrical industry. Still fields within the industrial sectors remain, such as automotive, mechanical engineering, process cooling, paper and cellulose industry, pharmaceutical industry and plastic and rubber processing, that often require cold of about 6°C. [6]

Within the sector air-conditioning in buildings, the usually required temperatures, fit into the working range of LiBr-water absorption machines. The sector can be divided into the groups residential buildings and commercial-, office-, industrial buildings, as well as datacenters.

Residential buildings represent the most inconstant and unpredictable group, additionally displaying typically rather small cold demands, for which the higher investment costs of absorption machines preponderate. Consequently residential houses currently do not represent a promising target group for the equipping with absorption machines.

In contrast to residential buildings, the other mentioned groups imply an improved predictability of the cold demand. Furthermore, the size of the buildings is often big enough to provide a sufficiently large cooling demand, thus creating the basis of a cost-efficient operation of absorption machines. The different groups of cold consumers usually cannot be strictly separated but occur in combination. For example big office buildings often have server rooms in addition to the actual office space. The cold demand of pure office space and commercial buildings generally can be characterized by a strong dependence on the outside temperature and thus imply a high cold demand in summer and a rather low/non-existent demand in winter. Data centers and server rooms usually exhibit a more constant and permanent cold demand over the course of the entire year, being less dependent on ambient conditions.

To support these assumptions, figure 5 shows four normalized annual load duration curves of two customers of EnBW and FUG Ulm[1]. The two corresponding buildings are big office buildings, include additional server rooms and in case of the red line (Medical Health) some production facilities. It can be seen that both buildings display a certain cooling demand over the course of the complete year. This basic demand is most likely due to the mentioned server performance and/or due to production heat that needs to be purged. Rated refrigeration capacity is requested solely for a very distinct proportion of the year.

IV. MANUFACTURER REVIEW

Table II provides an overview over the German LiBr-water absorption chiller market. Given are manufacturers, retailers in Germany (in case of foreign manufacturers), as well as the performance range of the offered machines.

In its basic working scheme, the machines are similar to each other and indications published by the manufacturers are solely appropriate to get an overview over the respective offers but barely enables a meaningful comparison. The given specifications do not necessarily underly uniform assumptions. However boundary conditions such as considered temperatures for hot water, recooling water and cold water are decisive parameters for such machines. In view of the above, the listed manufacturers, respectively their German sales partners were contacted and asked to adapt offers and specifications for boundary conditions, that are appropriate for the use of district heat. Table III summarizes the assumptions, that are underlying these requested cases.

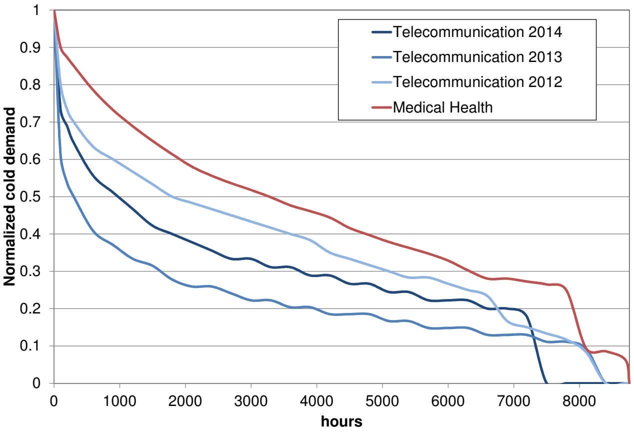

Figure 5. Normalized annual load curves of chosen office buildings (Customers of FUG Ulm and EnBW)

Table II. OVERVIEW: MANUFACTURERS OF LIBR-WATER ABSORPTION CHILLERS (WITHOUT CLAIMING COMPLETENESS) [7] [8] [9] [10] [11] [12] [13] [14]

Manufacturer	**Performance range**	**Retailer in Germany**
Yazaki	17.5 - 75 kW	Gasklima, Johnson-Controls
World Energy	105 - 4571 kW	Gasklima
York	280 - 3150 kW	Johnson-Controls
EAW	15 - 200 kW	-
Shuangliang	350 - 4650 kW	Ruetgers
Carrier	264 - 1846 kW	-
Zephyrus (Shinsung Engineering)	53 - 3511 kW	Benndorf-Hildebrand
Thermax	60 - 3943 kW	Trane

Table III. REQUESTED BOUNDARY CONDITIONS

	Appl.1: Ind. cooling	**Appl.2: Air-cond.**
Performance	100kW/500kW/1000kW	100kW/500kW/1000kW
Hot water	80°C/65°C	80°C/65°C
Cooling water	25°C/32°C	25°C/32°C
Chilled water	12°C/18°C	6°C/12°C

Feedback was received by four of the manufacturers. In the following, names of the companies are not explicitly given, but named Manufacturer 1-4 (also called Man1-4). Since an allocation of the data to a specific company would not bring an additional value, confidentialy is kept. Figure 6 shows the specific investment costs, given for application 2 (air-conditioning). The investment costs of the different machines vary remarkably, especially for the small cold performance (100kW). For the two bigger performances, the costs are in a similar range. A cost function, given in literature [15], is in line with the high prices of Man4 for small cold performances and proceeds in similar ranges to the

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[1] Local district heating company of Ulm

other manufacturers for increasing cold performances.
The intented hot water outlet temperature is not always met and e.g. Man1 exceeds this value (here values in between of 68°C and 72°C). Recommendations for buffer storage capacities vary remarkably. Man4 recommends to dimension the storage in order to be able to bridge cold demand for rated performance for a minimum time of 15 to 20 minutes. Man3 recommends a minimum buffer capacity of 3.25 l/kW for air-conditioning and 7.5 l/kW for process cooling applications. Man3 generally recommends a storage capacity of 6-8 l/kW. The indications of Man1 and Man3 lead thereby to significantly smaller buffer storages compared to Man4 and if laid-out at minimum values, the respective storages would rather act as hydraulic compensator than as real buffer storage.

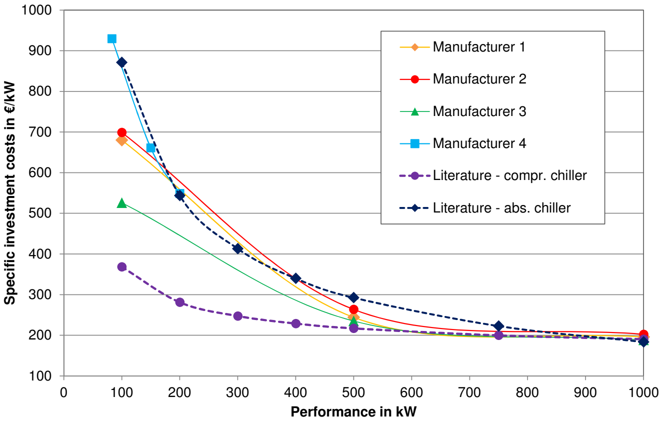

Figure 6. Specific investment costs of absorption chillers, (Application 2)

Summarizing, several players are active in the German absorption chiller market. When used for air-conditioning applications and driven by district heat, specific investment costs exceed the respective values of compression chillers. These differences are particulary pronounced for small performance classes. Consequently in small applications, these costs can hardly be compensated by potentially lower ongoing and operational costs (cf. section VI). This leads to a strong limitation of possible application fields of absorbers, making only large scale systems economically feasible. In order to open the market also for smaller machines, research is currently focusing on such systems. [16]

V. PRACTICAL EXAMPLE

A real operating example of an office building, that includes server rooms, was evaluated in order to validate indications in literature and given by manufacturers in practice. Analyzed is a project of the municipal utility Stadtwerke Karlsruhe, that provided the operation data for this contemplation. After the complete refurbishment of an office building of a big insurance company in 2010/2011, Stadtwerke Karlsuhe got the mandate to renew an existing cold supply system, that so far consisted of two reprocating piston compression chillers (construction year 2004, refrigerant R 407c), each having a cold capacity of about 280kW. These machines were taken over as peak load machines and supplemented by an up to date Carrier absorption chiller, having a rated cooling capacity of 335kW. A buffer storage with a volume of 8m^3 is included. This storage would have been chosen even bigger, if the spatial conditions would not have limited the dimensioning. Free cooling is enabled through installation of a plate heat exchanger and a respective connection with the recooling system. Thereby a hybrid dry cooler is used.
The building displays a cold demand of at least 20-40kW over the course of the entire year, which is required for the server rooms, and the increased cold requirements in the warmer months. Figure 7 shows the produced cold, listed in the different technologies, from the start of operation in June 2012 to October 2014 as well as the COP of the absorption chiller.

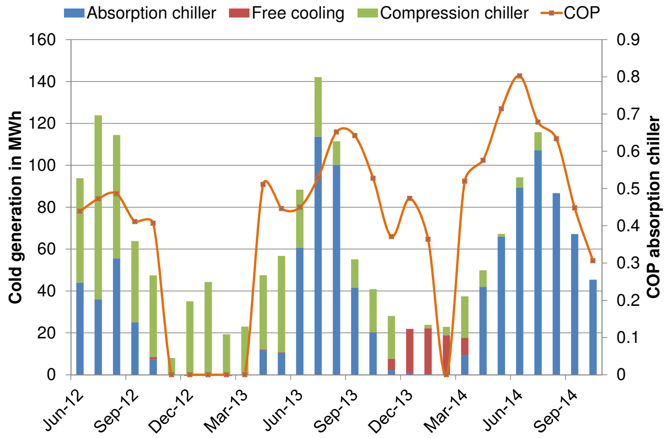

Figure 7. Way of cold provision and monthly average COP of the absorption chiller in the given project

It can be seen, that both the share of the cold, provided by absorption chillers, as well as the COP of the machine could be increased in the second year of operation. From October 2012 to October 2013, the average effective COP of the absorption chiller was about 0.56. In the consequent year, the value could be increased to about 0.62. The COP reaches its highest values during the summer months and respective low values, in winter months. The increase of the COP and the loadfactor of the absoption machine can be traced back to slight adjustments regarding the control of the system, which have been made on the basis of operational experience of the system. A further increase of the utilization of the absorption chiller - and probably also the COP - would be possible, if a bigger buffer storage could be integrated.
Summarizing, the most important results of the analysis are:

- The adjustment of the control of a cold generation system incl. absorption chiller and the identification of optimal operation conditions takes time
- The COP of about 0.62, reached in the second year of operation, shows good agreement with indications given by manufacturers and could probably even be increased in consequent years

- The size of the buffer storage takes over a crucial role with regard to load factors and COPs of absorption chillers
- Spatial conditions can be a limiting factor for the successful implementation of absorption chillers
- Absorption chillers can take over a high share of the overall cold production in office buildings

VI. ECONOMIC EVALUATION

The economic evaluation is based on the guideline 2067 of the Association of German Engineers [17], that deals with the economic efficiency of buidling installations in general. Calculations have been made according to the annuity method, a dynamic investment appraisal. Thereby both on-off investments and ongoing payments during a chosen period of observation are converted into a constant periodical payment - an annual installment.

As individual boundary conditions of each single project can be of critical importance for the profitability of absorption systems, universally valid statements can not easily be made. Consequently, the presented results solely represent a certain selection but through a sensitivity study tendencies and dependencies on certain parameters are detected. An analysis tool was developed to be able to perform fast estimations of the profitability of a certain project in the future and to calculate cold production costs for various different cold supplying systems and load profiles.

In the following first the considered cold concepts and the assumptions, taken in a base scenario, are presented. Following, the critical prices for heat, the composition of cold generation costs and the sensitivities of the single technologies are presented.

A. Considered cold concepts

Table IV shows cold concepts for which the economic efficiency is assessed and compared in this work. The different cold concepts consist of compression and/or absorption chillers and additional buffer storage capacity as well as evaporative recoolers, both being adapted to the respective sizes of the machines.

Table IV. CONSIDERED COLD GENERATION CONCEPTS

	Absorption chiller			**Compression chiller**		
	YES/NO	$Q_{0,AC}$ / $Q_{0,System}$	Share of annual cold provision	YES/NO	$Q_{0,CC}$ / $Q_{0,System}$	Share of annual cold provision
1	NO	0	0%	YES	1	100%
2	YES	1	100%	NO	0	0%
3a	YES	0.4	76%	YES	0.6	24%
3b	YES	0.4	53%	YES	0.6	47%
4a	YES	0.4	76%	YES	1	24%
4b	YES	0.4	53%	YES	1	47%

Table V. ASSUMPTIONS TAKEN IN THE BASE SCENARIO

Consumer's price index	1,625 %
Period under observation (T)	15 a
Effective COP compression chiller Effective COP absorption chiller	4 Adapted[2] - underlying rated value: 0.75
Number of full-load hours	3000

B. Base scenario

Table V and VI shows the most important assumptions and settings that are taken for the economic analysis of the presented cases.

Table VI. UNDERLYING PRICES FOR ENERGY CARRIERS

	Price	**Price index**
electricity	17 ct/kWh	3%
water	2 €/m^3	1.625%
heat	15 €/MWh	3%

C. Critical price for heat

Figure 8 shows the production costs of cold that are calculated for the six different cold provision concepts in dependency for the price for heat, for an underlying maximum cold performance of 1000kW. An important value is thereby the critical price for heat. This value describes the price for which the cold generation costs of the respective concept matches the costs of a production by pure compression chillers. It increases with higher cold performance and furthermore the higher the load factor of absorption chillers is. Graphically a decrease of cold performance shifts the lines in the diagram in upward direction, whilst an increase leads to a shift in downward direction. Obviously, the higher the share of cold provision by absorption chillers, the higher is the dependency on the price for heat. Table VII shows the critical costs for heat for different rated performances.

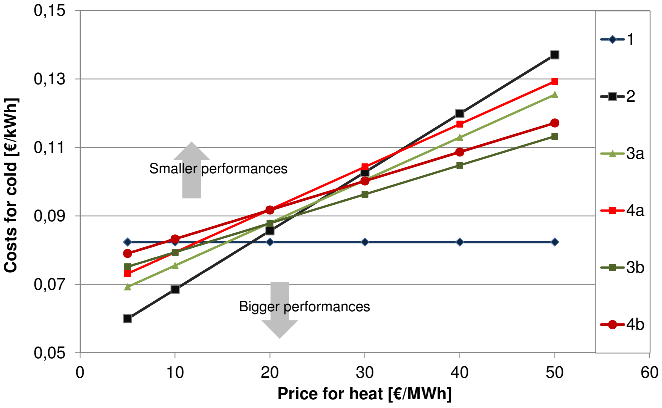

Figure 8. Costs for cold in dependency of the price for heat (cold concepts of table IV)

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[2] The calculation is done by super-imposition of a selected partial load curve and the annual load duration curve of the cooling demand

Table VII. CRITICAL PRICES FOR HEAT (VALUES IN €/MWH)

Max. performance	**Concept**				
	2	**3a**	**4a**	**3b**	**4b**
500 kW	15.3	11.8	8.2	7.5	2.6
1000 kW	18.1	16.5	12.8	13.5	9.0
2000 kW	20.1	18.5	15.6	16.8	13.0

D. Composition of cold production costs

Figure 9 shows the composition of the costs for cold generation for both, absorption and compression chillers and two different performance sizes.

Absorption chillers exhibit significantly higher investment costs than compression chillers, however this effect vanishes for higher cold performances. Consequently the specific fixed cost share is dependent on the size of the chiller as well as it is the case for operation related and other costs. In contrast, the demand related costs of both technologies are not dependent on the size but solely dependent on the operating parameters (efficiency of chillers and other components such as pumps and recooling systems) as well as the expenditures for energy carriers and consumables. For the given assumptions, the demand related costs of absorption systems are lower than those of compression systems. For the higher cooling capacity (1000kW) even the higher investment costs can be compensated and the overall costs for cold generation are lower.

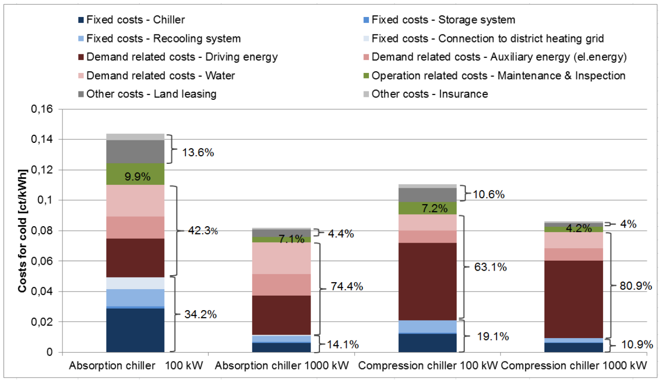

Figure 9. Composition of the costs for cold production

E. Sensitivities

For the calculations presented above, the assumptions of the base scenario were taken. For the reason that these taken assumptions are not necessarily universally valid, sensitivities of the costs for cold generation are assessed by variation of different influencing factors. The investigation is thereby conducted for each technology individually as this is considered to be the best possibility to deduce trends. In figure 10 and 11 the results of this contemplation are shown. Starting from the base scenario, that matches the constraints of the preceding considerations and a rated capacity of 500kW, single parameters are varied in two directions - meaning the single values are decreased up to 100% in case of negative values and respectively increased for positive values.

1) Absorption system: The biggest influence on the costs of cold generation has the COP and the number of full-load hours of the chiller, where a negative exponential behavior can be observed. Furthermore the size of the chillers plays an important role, as already stated before. Asorption chillers have a strong, linear dependency on the price for heat, and a minor strong linear dependency on the price for electricity. The respective price indices have a less severe influence on the costs of cold production as well as the weighted average costs of capital (WACC).

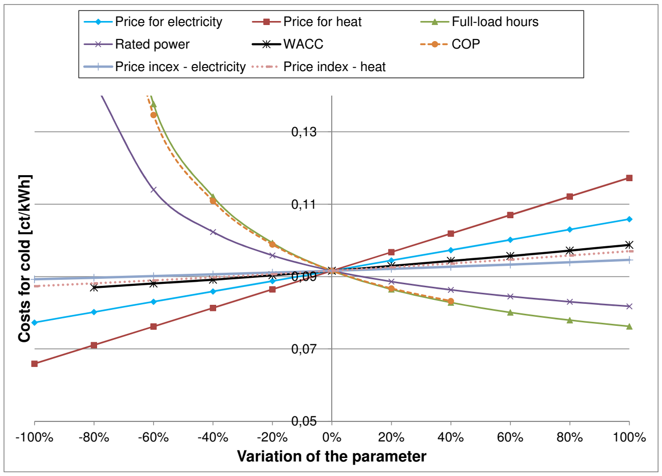

Figure 10. Influence of certain parameters on the costs for cold prodcution by absorption chillers

2) Compression system: Similar to the absorption chiller, the compression chiller shows a strong, negative exponential dependency on the number of full-load hours and in particular on the COP of the system. The compression chiller reacts significantly less sensitive on the variation of the rated power. Only for bigger deviations in negative direction - meaning a strong reduction of rated power - a higher increase in costs can be observed. Particularly pronounced is the linear dependency on the price for electricity. This behavior can be explained by the high share of the demand-related costs for electricity on the overall costs for cold production. The variation of the electricity price index does not lead to such disctinctive deviations of the costs for cold, nevertheless it shows a higher dependency compared to the absorption chiller, which is due to the higher electrictiy requirements of the machine. With regard to the WACC, variations are less pronounced compared to the absorption chiller and are generally small.

VII. ENVIRONMENTAL INDICATORS

For the given assumptions of the base scenario and considering $COPs$ of absorption/compression machines of 0.75 respectively 4, the absorption chiller exhibits with about 0.86 $\mathrm{kWh}_{prim}/\mathrm{kWh}_{cold}$ significantly higher primary

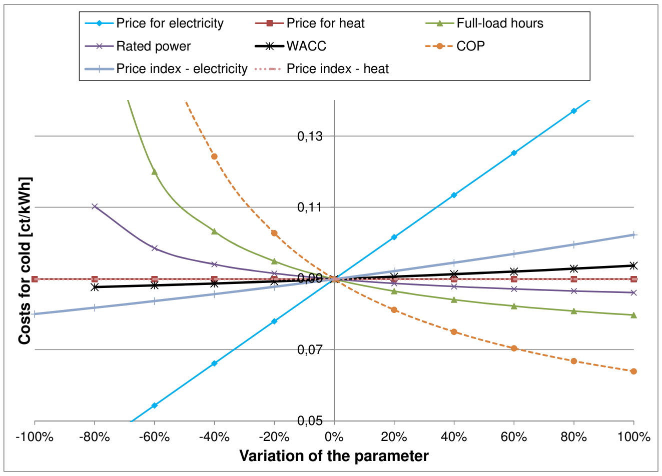

Figure 11. Influence of certain parameters on the costs for cold production by compression chillers

energy demands than compression systems, with roughly 0.52 kWh$_{prim}$/kWh$_{cold}$. Similar, absorption systems imply higher specific CO_2 emissions with about 243.2 g$_{CO_2}$/kWh$_{cold}$ compared to the compression chiller system with roughly 173.9 g$_{CO_2}$/kWh$_{cold}$, for the given assumptions. Table VIII shows the underlying primary energy factors (f_p) and CO_2 equivalency factors (β).

Table VIII. PRIMARY ENERGY AND CO_2 EQUIVALENCY FACTORS [18] [19] [20]

District heat	German electricity mix
f_p = 0.5484 kWh$_{prim}$/kWh$_{end}$	f_p =1.8 kWh$_{prim}$/kWh$_{end}$
β = 150 g$_{CO_2}$/kWh$_{end}$	β = 617 g$_{CO_2}$/kWh$_{end}$

Table IX. PRIMARY ENERGY DEMAND AND SPECIFIC CO_2 EMISSIONS

	Compression chiller	Absorption chiller
Primary energy demand	0.52 kWh$_{prim}$/kWh$_{cold}$	0.86 kWh$_{prim}$/kWh$_{cold}$
Specific CO_2 emissions	173.9 g$_{CO_2}$/kWh$_{cold}$	243.2 g$_{CO_2}$/kWh$_{cold}$

VIII. CONCLUSION

By the theoretical analysis of the different technologies, LiBr-water absorption chillers could be identified as the only appropriate thermal driven technology. As a consequence, lucrative application fields are limited to areas in which cold temperatures $\geq 6°$C are required. Examples are e.g. big office buildings, that include server rooms or production facilities and consequently imply rather constant cold demands.

The evaluation of a real cold supplying system of a municipal utility showed high agreement between theoretical specifications and real operating characteristics. The influence of buffer storages on the operational performance, load factors and in consequence on the economic efficiency of absorption machines could be detected. It could be approved, that high amounts of cold can be provided by absorption system in such office buildings.

The economic analysis of the different technologies highlights the influence of the performance on the costs for cold generation. When used for air-conditioning applications with rather small cooling performances, compression chillers seem significantly superior and an application of absorption chillers can hardly be recommended. With increasing performance class, this difference vanishes and absorption chillers could even be the cheaper solution. The critcal prices for heat, for which absorption chillers become competitive, are significantly lower than the price that is typically paid for district heat. In this respect, the operation of absorption chillers is solely representable, if the consumer does not pay for the product "heat" in order to operate own absorption systems, but for the product "cold". This can be offered in form of a contracting model, meaning that the costumer agrees on a contractually defined price per purchased amount of cold. Thereby the high investment costs are omitted for the consumer.

In general, it is not suggestive to compare the different technologies separately, due to the operational characteristics of absorption chillers. Absorption chillers should be used as base load machine and complemented by compression chillers, taking over the peak loads. Furthermore, a purely economical evaluation of the cold supplying systems is not advisable, because of different qualities that are implied by such systems. If a redundancy is required, absorption chillers represent a meaningful supplementation to compression chillers. Malfunctions of one system can be bridged by the respective other system, as well as supply gaps of one of the driving energy sources, due to the different driving energy input. For example emergency power supplies can be dimensioned significantly smaller, due to the distinctly lower electricity requirements of absorption systems.

Analyzing environmental indicators, it can be stated, that the cold produced by absorption chillers causes more emissions than compression chillers. This is a result of the increased share of renewable energies in the electricity mix, leading to lower CO_2 equivalency factors (β) and primary energy demands (f$_p$). Though, in combination with a supply of heat by district heating grids, the overall ecological footprint might be advantageous, due to the fact, that the primary energy demand as well as the specific CO_2 emissions of district heat is superior to those of decentral oil- or gas-fired heating systems.

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