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Assessment Methodology for Efficiency, CO_2-Emissions and Primary Energy Consumption for Refrigeration Technologies in the Industry

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Abstract. Process cooling and air conditioning are becoming increasingly important in the industry. Refrigeration is still mostly accomplished with compression chillers, although alternative technologies are available on the market that can be more efficient for specific applications. Within the scope of the project “EffiCool” a technology toolbox is currently being developed, which is intended to assist industrials users in selecting energy efficient and eco-friendly cooling solutions. In order to assess different refrigeration options a consistent methodology was developed. The refrigeration technologies are assessed regarding their efficiency, CO_2-emissions and primary energy consumption. For CCHP systems an exergetic allocation method was implemented. Two scenarios with A) a compression chiller and B) an absorption chiller coupled to a natural gas CHP system were calculated exemplarily, showing a greater overall efficiency for the CCHP system, although the individual COP of the chiller is considerably lower.

Introduction

The provision of process cooling and air conditioning for industrial needs is becoming increasingly important. Industrial sites feature a complex infrastructure such as R&D, administration, production and warehousing with a variety of different refrigeration tasks in various areas of the production plant. In practice conventional compression chillers are still used as standard solution for cooling in most cases, due to low investment costs and ease of implementation. However, these systems are not necessarily optimized in terms of energy efficiency, eco friendliness, and total lifetime costs.

Cooling has a high impact on the environment in terms of energy consumption and greenhouse gas emissions. The electric energy demand for refrigeration in Germany sums up 13.5 % of the total electrical consumption in Germany [1], resulting in carbon dioxide emissions of about 40 million tons per year. Additionally many of the fluorinated refrigerants used in compression chillers contribute to global warming and their utilization will be progressively restricted in the European Union [2]. However, there is a wide range of alternative refrigeration technologies already available today which can present a better, more efficient option for the given application than the standard solution.

The scope of the research project “EffiCool” within the framework of the Green Factory Bavaria joint research platform is to identify and assess efficient and environmentally friendly cooling solutions for industrial applications. A production site of a global market leading electronics company with its existing refrigeration supply system serves as prototype case, which can be found in a similar fashion at many industrial sites throughout Germany. One of the major goals of the project is to develop a technology toolbox, which is intended to assist industrials users in selecting energy efficient and eco-friendly cooling solutions. In this paper the assessment criteria applied for the technology toolbox are presented.

Technology Toolbox

The core of the currently developed technology toolbox is a database which merges information about different refrigeration technologies with a user-friendly interface, in order to be able to quickly present a pre-selection of suitable technologies for a given application and facilitate a first basic assessment. Key features are e.g. the achievable cooling temperatures, the efficiency expressed as coefficient of performance (COP), the capacity range available on the market, the specific investment costs etc. Depending on the user input (e.g. desired cooling temperature) the technology toolbox will present a selection of possible refrigeration technologies together with relevant information about the technology, including assessment of efficiency, carbon dioxide emissions and primary energy consumption.

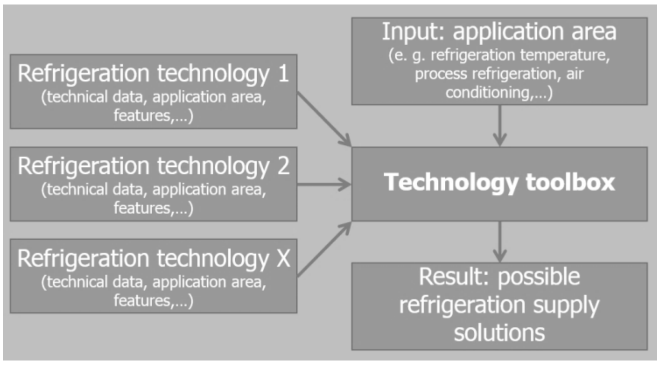

Figure 1. Schematic plan of the technology toolbox

Assessment Criteria for the Different Refrigeration Technologies

Coefficient of Performance. Energy efficiency is one of the main parameters for the assessment of refrigeration technologies for certain application cases. The energy efficiency of refrigeration technologies can be expressed as the relation of cooling capacity (output) to power consumption (input), which is generally denominated as coefficient of performance (COP)

$$COP = \frac{output}{input} = \frac{\dot{Q}_0}{P} \tag{1}$$

$\dot{Q}_0$: cooling capacity
P: power consumption
COP: Coefficient of performance

A key problem in evaluating the cooling efficiency is the fact, that the refrigeration technologies use different forms of input energy (electrical energy or thermal energy). This applies especially when different technologies with similar COP but different forms of energy input are to be compared, since the COP does not take into account the different exergetic qualities of the input energy.

Primary Energy Consumption. The shortcomings of an assessment based purely on input energy can be overcome by considering the primary energy consumption. Primary energy can be defined as the direct available amount of energy in a source like coal, oil, wood or gas. The process to extract a secondary energy source (e.g. liquid fuel) out of a primary energy source is afflicted with several losses that depend on the kind of primary energy source used. Secondary energy represents the energy source available input energy to the consumer, e. g. for the operation of refrigeration technologies. In order to facilitate an ecological comparison between different technologies and forms of input energy, it is necessary to rate them based on total amount of primary energy consumed. This can be accomplished by introducing the primary energy factor (PEF). The PEF considers all conversion losses that accrue in the conversion process from a primary to a secondary energy source. Therefore the factors correctly depict the ecological valence of an energy source with its associated supply chain including exploitation and conversion losses. In our assessment the primary energy will be limited to the energy conversion, without considering, manufacturing, commissioning and decommissioning of refrigeration components. In order to establish a consistent methodology for the technology toolbox the data for the primary energy factors refers to the GEMIS-database, which is widely used for life-cycle and carbon footprint assessment, see Table 1.

Table 1. Primary energy factors *PEF* from GEMIS-database [3]

Supply chain (electric power)	PEF	Supply chain (heating power)	PEF
Power grid (local)	2.76 kWh_{pe}/kWh_{el}	**Waste heat**	0 kWh_{pe}/kWh_{th}
PV	1.17 kWh_{pe}/kWh_{el}	**Heating oil burner**	1.18 kWh_{pe}/kWh_{th}
Lignite power plant	2.40 kWh_{pe}/kWh_{el}	**Natural gas burner**	1.16 kWh_{pe}/kWh_{th}
Wind power onshore	1.03 kWh_{pe}/kWh_{el}	**LPG burner**	1.13 kWh_{pe}/kWh_{th}

Based on the data for primary energy factors and the coefficient of Performance (COP), the specific consumption of primary energy for cooling energy can be calculated as

$$PEF_{cooling} = \frac{PEF_{input}}{COP} \tag{2}$$

In the case of tri-generation a combined heat and power (CHP) system is used for the supply of thermal energy to a thermal heat pump, usually an absorption chiller, which provides cooling energy (CCHP, combined heating, cooling and power). CCHP systems provide power and heating or cooling energy at the same time from one common energy input source. Hence it is necessary to assign the primary energy consumption emissions to the respective energy flux by a suitable methodology, which considers the different valences of electrical and thermal energy. The primary energy factor of the input fuel (PEF_{input}) is then allocated to the CHP output products electricity and heat, which serve as input energy for the cooling process. Depending on the chosen allocation method and on which of the CHP products (electricity or thermal energy) is to be used, it is then possible to assign the primary energy factor ($PEF_{CHP,X}$) to the refrigeration process. The determination of the allocation factor α for electric and thermal energy will be described separately further down.

$$PEF_{CHP,el} = \alpha_{el} \cdot PEF_{input} \tag{3}$$

$$PEF_{CHP,th} = \alpha_{th} \cdot PEF_{input} \tag{4}$$

Carbon Dioxide Emissions. An additional ecological assessment criterion for the evaluation of refrigeration technologies are the emissions of carbon dioxide, caused by the operation of the refrigeration system. As for primary energy consumption the carbon-footprint analysis will be limited to the energy conversion steps with the respective supply chain for the energy input, but without considering manufacturing, commissioning and decommissioning of the refrigeration components.

The CO_2-emissions are calculated based on the specific CO_2 emission factors ε_{CO_2} for the respective form of secondary input energy divided by the COP of the refrigeration machine.

$$\varepsilon_{CO_2,cooling} = \frac{\varepsilon_{CO_2,input}}{COP} \tag{5}$$

In order to establish a consistent methodology with the primary energy demand, the data for the CO_2 emission factors again refers to the GEMIS-database. The CO_2-emission factors provided by GEMIS represent all greenhouse gas emissions caused by the provision of one unit of secondary energy, including the supply chain (exploitation, transport,…) and the emissions of other climate-relevant compounds such as methane and nitrous oxide. The latter are converted to CO_2-equivalent emissions, in order to reflect their different climate-warming potentials. It has to be noted that the CO_2-equivalent emissions factors do not include carbon dioxide emissions from renewable sources, since these are considered to be neutral with regard to global warming. Table 2 displays the CO_2 emission factors for different supply chains of electrical and thermal energy.

Table 2. CO_2-equivalents from GEMIS-database [3]

Supply chain (electric power)	CO_2-equivalent	Supply chain (heating power)	CO_2-equivalent
Power grid (local)	605 g/kWh_{el}	**Waste heat**	0 g/kWh_{th}
PV	49 g/kWh_{el}	**Heating oil burner**	319.43 g/kWh_{th}
Lignite power plant	1008 g/kWh_{el}	**Natural gas burner**	249.98 g/kWh_{th}
Wind power onshore	9 g/kWh_{el}	**LPG burner**	276.73 g/kWh_{th}

In the case of tri-generation (CCHP) it is again necessary to allocate CO_2-emissions to the output products heat and power. This can be accomplished following the same methodology as presented for the primary energy demand.

$$\varepsilon_{CO_2,CHP,el} = \alpha_{el} \cdot \varepsilon_{CO_2,input} \tag{6}$$

$$\varepsilon_{CO_2,CHP,th} = \alpha_{th} \cdot \varepsilon_{CO_2,input} \tag{7}$$

Allocation Factor. If using CHP for the supply of energy to a cooling system, the CO_2 emissions and the primary energy consumption have to be adequately allocated to the output products heat and power. Several allocation methods have been developed in the past, which either assign primary energy and CO_2 based on the share of the provided amount of energy or by considering a separate production of electricity and heat in a defined reference process [4] [5] [6] [7]. It has to be noted that the coupled production of both, electricity and heat, causes the problem that an allocation based purely on energy (electricity/thermal energy) does not reflect their different exergetic values. Therefore we chose an allocation method, which rates the CHP output products according to their exergy. Electricity is rated with an exergetic factor on one in this context, while the exergy of the heat output is rated according to its working capacity in an ideal Carnot cycle. Therefore additional information about the CHP process is required, such as the supply flow and return flow temperatures (T_{sf}, T_{rf}) to calculate the upper temperature of the Carnot cycle (T_{hc}) and the ambient temperature (T_{amb}) for the lower temperature of the cycle. The physical correctness of this access approach makes the exergetic allocation method a suitable tool for the ecological evaluation provided with the toolbox.

For the correct calculation, some assumptions concerning the CHP process are necessary which have to be provided by the user:

- Supply flow heat circle (T_{sf})
- Return flow heat circle (T_{rf})
- Ambient temperature (T_{amb})
- Electrical output (P_{el})
- Thermal output (P_{th})
- Fuel input (P_{fuel})

Based on the input made by the user and the data of the CHP process it is now possible to apply the following scheme for the calculation of the fuel shares for the CHP products heat and electricity:

$$T_{hc} = \frac{(T_{sf}+T_{rf})}{2} \tag{8}$$

$$\eta_c = 1 - \frac{T_{amb}}{T_{hc}} \tag{9}$$

$$\eta_{el} = \frac{P_{el}}{P_{fuel}} \tag{10}$$

$$\eta_{th} = \frac{P_{th}}{P_{fuel}} \tag{11}$$

$$\alpha_{el} = \frac{\eta_{el}}{\eta_{el}+\eta_c \cdot \eta_{th}} \tag{12}$$

$$\alpha_{th} = \frac{\eta_c \cdot \eta_{th}}{\eta_{el}+\eta_c \cdot \eta_{th}} \tag{13}$$

The allocation factor α can then be applied for further calculation of primary energy consumption and CO_2 emissions as describe above.

Application of the Technology Toolbox

In order to exemplify the methodology two different refrigeration scenarios delivering the same amount of electric and cooling energy are calculated. In scenario A, the power supply is from the public grid and a compression chiller is used for refrigeration. The compression refrigerating machine has an assumed capacity of 405 kW and a COP of 3.0. In scenario B, the electricity is generated by a natural gas CHP system and the waste heat of the CHP is used in an absorption chiller. The CHP system is assumed to be state of the art with an electrical output of 550 kW and a thermal output of 578 kW. The absorption chiller has a COP of 0.7 and a cooling capacity of 405 kW. The annual utilization is 6,000 hours.

The energy supply is supposed to be from the German grid in scenario A, accordingly the factors for the electricity mix in Germany are used for the assessment of the CO_2 emissions and the calculation of the primary energy consumption. For the CHP plant in scenario B an allocation following the methodology presented above must be performed. The following tables show the parameters for the allocation and the calculated allocation factors. The input fuel of the CHP system is assumed to be natural gas.

Table 3. Input parameters for the exergetic allocation

parameter	
electrical output CHP	550 kW
thermal output CHP	578 kW
Fuel input CHP	1,291 kW
Supply flow temperature	90 °C
Return flow temperature	70 °C
Ambient temperature	20 °C

Table 4. Calculated allocations factors

allocation factors	
α_{el}	0.85
α_{th}	0.15

The calculated allocation factors for electrical and thermal energy are used to calculate the CO_2 emissions and the primary energy consumption for the CCHP system in scenario B. Compared to scenario A the cooling system in scenario B saves about 200 tons CO_2 per year, which corresponds to reduction by 40 %. The primary energy consumption is reduced by approx. 2,400 MWh/a.

For better comparison the results from both refrigeration scenarios are used to calculate the specific CO_2 emissions and the specific primary energy factor for the electrical and cooling energy. Scenario B with a CHP system and an absorption chiller achieves savings compared to scenario A concerning the emissions as well as the primary energy consumption and can thus be considered to be more energy efficient on an overall scale, although the COP of the refrigeration system itself is lower (COP of absorption chiller 0.7 vs. COP compression chiller 3.0).

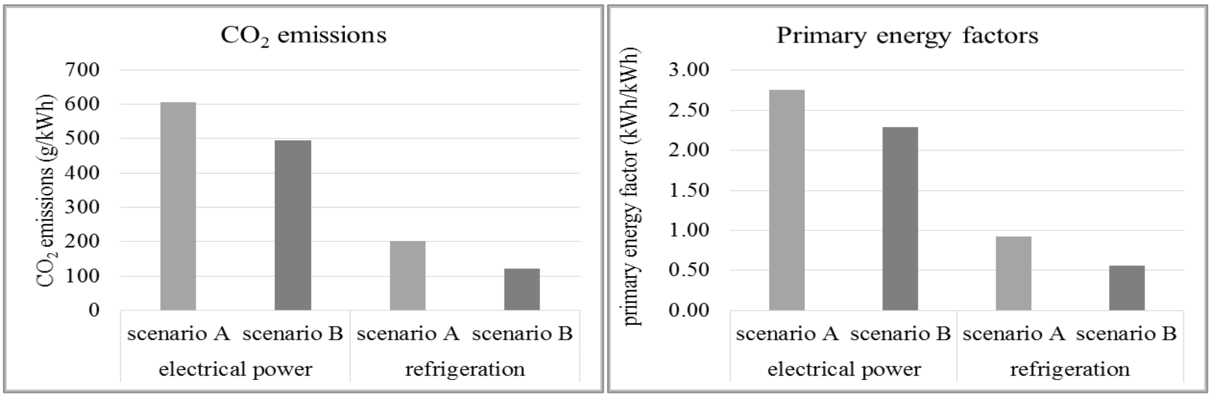

Figure 2. Specific CO_2-emissions and primary energy factors for scenario A and B

Summary

Process cooling and air conditioning are becoming increasingly important in the industry. In most cases, refrigeration is accomplished with a compression refrigerating machine. However, alternative refrigeration technologies are available on the market that might prove to be more efficient for specific applications on an overall scale. Currently a technology toolbox aimed at supporting industrial user in selecting appropriate cooling technologies is being developed within the project “EffiCool”.

Due to the different forms of input energy (electrical power or thermal energy), the different refrigeration technologies must be assessment with standardized criteria. Thus a methodology comprising the COP, the CO_2 emissions and the primary energy consumption was developed. In the case of CCHP systems with coupled generation of electrical and thermal energy, an allocation must be performed for correct assessment of the electrical and thermal energy output. In order to assess the different values of electric and thermal power, an exergetic method was chosen.

In the application example, two scenarios are considered with a compression chiller and an absorption chiller. The heat source for the absorption refrigerating machine is a natural gas CHP system. The results show that with the CCHP system the emissions as well as the primary energy consumption for provision of electric and cooling power can be reduced, although the COP of the chiller itself is by far lower.

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