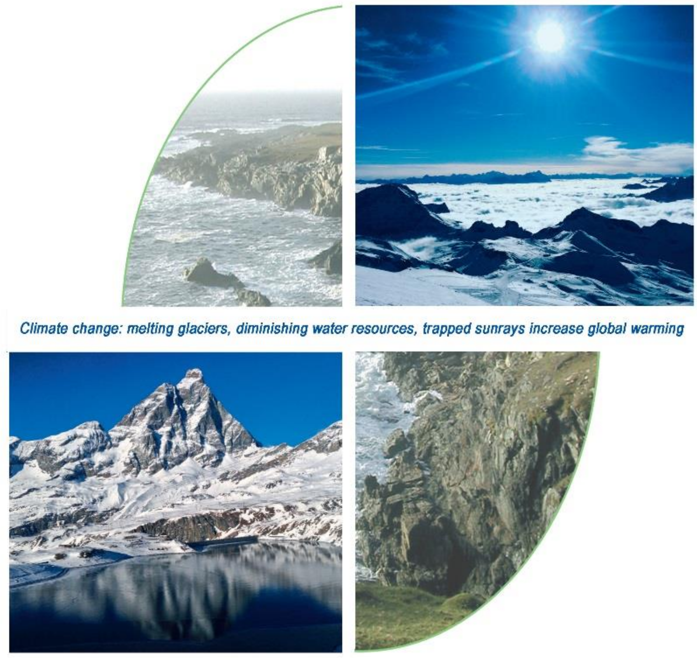

REDUCTION OF ENERGY CONSUMPTION BY APPLYING A NEW GENERATION OF CO_2 COMPRESSORS

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Abstract

The development of transcritical CO_2 systems in commercial refrigeration can be considered to be in a transition phase from cutting edge to state-of-the-art technology. However, the stress field of new developments is strong and characterized by challenging demands from the market: Further improvement of the annual energy efficiency, reduced system complexity and a decreased cost of ownership. One key to success in commercial refrigeration is the application of a new generation of energy efficient CO_2 compressors in a so-called baseline system. The features of this highly efficient compressor range, which is called ECOLINE+, is explained in this paper. The European standard EN13215 is considered as the standard method for the evaluation of the annual energy efficiencies. A more complex and time consuming method to calculate the annual energy efficiency is to consider the prevailing climate, more specific load profiles , the system configuration, operating times and resulting operating conditions of the compressors applied. This work provides an analytical study of different methods to calculate the annual energy efficiency for the new compressor generation compared to the standard compressor range and discusses the results of the comparison.

Keywords

A new generation of CO_2 compressors – Annual Energy Efficiency – EN 13215

1. Introduction

With the introduction of the “Klimaschutz 2020” program in December 2014, the German federal government defined ambitious targets for the reduction of greenhouse gases. Based on the level of 1990, the emissions must be reduced by at least 40 % until the year 2020 and even by 55 % one decade later. The savings consider all sectors, from energy related sectors to non-energy related, like agriculture and waste. One energy related sector is the refrigeration and air conditioning industry. The outstanding importance of energy efficiency is displayed in the fact, that the amount of indirect emissions equaled 46 Mt CO_2 eq. for the year 2015 in Germany (European Commission, 2016). Considering this, 4.9 % of the total GHG emission was produced due to the operation of systems in this branch of industry. With respect to the direct emissions, the balance showed as well that 3 Mt CO_2 eq. were emitted which represented 0.3 % of the total GHG emissions. Therefore, the German federal government introduced in December 2016 a new guideline for the refrigeration and air conditioning industry to support the achievement of the aforementioned objectives (Bundesanzeiger, 2016). As an integral cluster, the new guideline considers three measures: The increase the energy efficiency, the reduction of the demand for cooling in general and a further cutback of the application of HFC's as refrigerant. The guideline is linked to the F-Gas-Regulation 517/2014. It is estimated, that the measures additionally reduce the emission of F-Gases by 0.6 Mt CO_2 eq. by the year 2020. However, apart from regulations in Germany and other countries in the world, highest annual energy efficiencies are achieved in an ideal situation with a natural refrigerant in a simple and cost effective way. All these attributes are combined with the next generation of energy efficient products, that combines the natural refrigerant carbon dioxide with a GWP of 1 and highest efficiency for the lowest possible CO_2 footprint.

2. A New Generation of Energy Efficient CO2 Compressors

2.1 From the First Prototypes to ECOLINE+

BITZER started the development of CO_2 compressors already in the years 1995 to 1998, when the first prototype compressors for sub-critical CO_2 applications were designed and mainly supplied to research institutions like the DTI in Denmark. But also the first OEM customers focused on the application of CO_2 in the low temperature (LT) stage. Finally in the year 2000, the first commercial HFC/CO_2 cascade system was installed in Bettembourg in Luxembourg by the company Linde. It was the year 2002, when another highlight followed: The first HFC free McDonald's restaurant in Vejle, Denmark was opened. The system was designed and engineered by the DTI and features a propane/CO_2 cascade system with a propane chiller stage, thermosiphon circulation of CO_2 in the MT stage and dry expansion for the LT stage. A specially tailored CO_2-compressor was necessary, to fit the requirements for the small capacities.

Soon after this, BITZER started to develop compressors for transcritical applications in the year 2003. Then finally in the year 2004, Linde commissioned the first all CO_2 system for transcritical application in Wettingen, Switzerland. The system consists a so-called flash gas bypass (FGB) which helped the CO_2 technology, to commercialize step by step. Since then BITZER developed three different compressor ranges for all different types of CO_2 systems and has sold more than 75.000 CO_2 compressors by the end of the year 2016. The cornerstone of the ECOLINE+ range, was already founded in the year 2010 with the first field trials with line start permanent magnet (LSPM) motors. This motor technology is the key feature of the new generation of energy efficient compressors, which can be considered as the 4th generation of CO_2 compressors made by BITZER.

2.2 LSPM Motors

This motor technology is a hybrid solution and comprises an asynchronous stator and a squirrel-cage rotor with additional permanent magnets. The technology combines the robustness of an asynchronous motor (AS) and the higher efficiency of a permanent magnet motor. After starting the compressor, the rotor synchronizes with the operating frequency of the stator. Thus, it operates in synchronous speed and offers the advantages of zero rotor and magnetizing losses. This results in higher motor efficiencies. Figure 1 shows a comparison of motor efficiencies dependent on the relative power input of an LSPM motor and AS motor.

Furthermore, the applied motor technology is extremely flexible in its application and can be operated on mains and in connection with variable speed drive. However, the benefit in a semi-hermetic compressor is not only founded on a higher efficiency of the motor, but as well founded on higher mass flow rates. Due to the fact that the rotor of an LSPM motor runs synchronously, the drive gear of the compressor can compress a higher mass flow per time compared to an asynchronous motor, where the revolutions per minute are highly dependent on the torque requirement. Additionally, the mass flow rate is increased by a lower heat transfer of electrical losses into the suction gas, which results in a higher suction gas density of the refrigerant, before it is taken in into the suction chamber of the cylinder head.

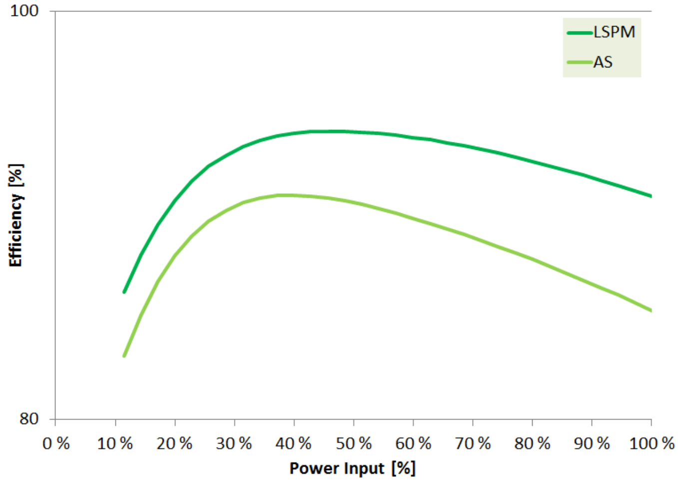

Figure 1: Comparison of motor efficiencies

Considering the aforementioned, a significant increase in COP can be taken into account. Certainly, the increase in COP is ultimately depended on the motor size and the torque requirement, which is displayed in figure 3 for various pressure ratios at constant suction conditions. The average upgrade in performance is in the range of 6 % (compressor connected directly to the power supply). This is stated in Figure 2, where the relative increase in COP is displayed for an equal compressor model, operating at constant suction conditions, but equipped with an LSPM or AS motor.

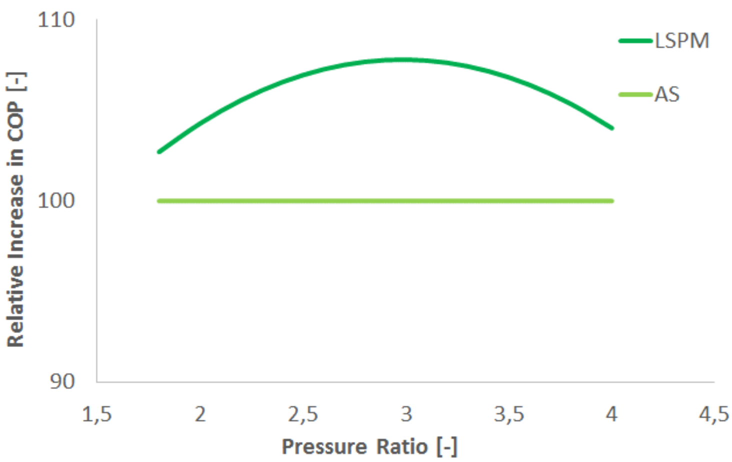

Figure 2: Relative increase in COP depended on the pressure ratio

2.3 Additional Features

The additional features of the ECOLINE+ compressor range are not subject of this prevailing work but are worth mentioning. The compressor range offers as an option a mechanical capacity regulation. The so-called CRII system it is specifically designed for a high switching frequency. This results in a quasi-stepless capacity adaptation to the system cooling demand and rapid reactions to system changes. Such a capacity regulation shows an alternative to the application of frequency inverters, offers a good control quality combined with easy use and flexible application. This world novelty for compressors for transcritical CO_2 applications is operated by the IQ-module CM-RC-01. The module can operate also other integrated functions of the compressor, like the oil return management, switching of the crankcase heater or monitoring of the operating conditions and application envelop.

3. Evaluation of Energy Efficiency

Due to the rising importance of the efficiency in the refrigeration and air conditioning industry, the evaluation of the energy efficiency has gained momentum. A proper study of the energy balance based on continuous and adequate accurate measurements under real operating conditions is the ultimate method. But in preparation of an installation it becomes state-of-the-art to estimate the energy consumption or compare the energy efficiency of different solutions. The common evaluation of the energy efficiency is the ratio between the cooling capacity and power input. Mostly this is displayed in the coefficient of performance (COP) or energy efficiency ratio (EER). Taking into consideration that the cooling demand in most of the applications is not constant due to the variation between day and night time operation, the ratio between absorbed energy and used energy on an annual or seasonal basis is more a significant and powerful statement. In the following, the energy efficiency is evaluated on basis of the seasonal energy efficiency ratio (SEPR) according to the EN13215 and the subsequent defined annual energy efficiency.

3.1 Seasonal Calculation in Refrigeration According to the EN13215

With the EN13215:2016, which came into force in 2016, a seasonal calculation method for refrigeration units which takes part load efficiency and ambient temperature into account has been standardized for the first time. The former European standard 13215:2000 described how to publish performance data of condensing units for refrigeration in full load. The latest revision describes how to publish performance data in part load and how to calculate an seasonal efficiency performance ratio (SEPR). The publication of part load data and SEPR is required by the Commission Regulation (EU) No 2015/1095 (Ecodesign).

The calculation method for seasonal performance described in EN13215 is based on a calculation method, which was developed for the EN14825 in 2011. For this kind of calculations a temperature -, a load - or refrigeration demand profile is required as well as a calculation rule. In EN13215:2016 the temperature profile of Strasbourg 2009 based on ASHRAE Weather Data has been chosen. Strasbourg has been chosen as it is supposed to represent the average European climate. The temperature profile consists of 1 degree centigrade bins, ranging from -19°C to +38°C. A certain number of occurrence hours per year is assigned to each bin. The numbers of hours in total are 8760 which is exactly one year. Load profiles have been defined for medium temperature and low temperature applications. Full load operation or 100% load is assigned to the 32°C ambient temperature bin. 80% load for low temperature and 60% load for medium temperature is assigned to the 5°C ambient bin. Between these bins the load is linearly interpolated. The load profile is simplified and is supposed to take the behaviour of an average refrigeration system into account not a specific application. The calculation method is based on 4 operating points, which are shown in Table 1.

	Load [%]	Ambient temp. [°C]	Evaporating temp. [°C]
A	100	32	-10
B	90	25	-10
C	75	15	-10
D	60	5	-10

Table 1: SEPR calculation - operating points

For the bins or ambient temperatures not described in Table 2, efficiency and power consumption is interpolated between the described bins. Temperatures above 32°C or below 5°C ambient are treated like 32°C or respectively 5°C. If a condensing unit is not able to achieve the required part load percentage, a degradation factor of 0,25 is used to reduce the COP and increase the power consumption in the calculation. If a unit cannot achieve the required part load capacity it is assumed that the unit goes into on/off mode and thus uses more energy to consistently rebuild system pressure. The degradation factor is calculated in according to Equation 1.

$$COP_{degraded} = COP * (1 - 0{,}25 * \left(1 - \frac{Q_{0_{required}}}{Q_{0_{actual}}}\right))$$

Equation 1: Degradation factor

To calculate the SEPR, the cumulated cooling capacity for all bins is divided through the cumulated power consumption. Although this method does not take specific applications into account, it offers a reasonable way to compare refrigeration systems, refrigerants or different kind of capacity regulators.

3.2 Annual Energy Efficiency

The approach of an analytically determined annual energy efficiency is derived from the determination of the seasonal energy efficiency ratio according to the SEER according to the EN14825 and was applied for previous publications (Javerschek and Reichle, 2013 and 2016). Based on temperature bins in steps of 2.5 K, the ratio between absorbed energy and used energy is calculated on an annual basis. As well as in the standardized calculation, this approach applies a factor for degradation in case that the required cooling demand cannot be matched with the capacity regulation. The factor is calculated according to equation 1. Temperature profiles were generated by applying the Weather Data Viewer 4.0

by ASHRAE, Inc. (2009). However, the considered climate profiles consider the duration of each temperature bin dependent on the daytime. Additionally, the applied method considers profile, which distinguishes between the cooling demand when the “shop is open or closed”. It is considered that the shops are open from 8.00 in the morning to 20.00 h in the evening. The applied profile is based on average data in commercial refrigeration and is not universally valid. As highlighted in Table 2, it defines the required evaporator capacity as a function of the ambient temperature.

t ambient [°C]	< 0	0	5	10	15	20	25	30	>30
MT load “shop open [%]	65	65	65	65	72	83	93	100	100
MT load “shop closed [%]	30	30	30	30	32	43	53	60	60

Table 2: Applied load profile for the calculation in chapter 4.3 and 4.4

4. Calculation of the Seasonal Energy Performance Ratio and Annual Energy Efficiency

4.1 Introduction

This chapter discusses the potential for an increased energy efficiency by applying the ECOLINE+ compressor range compared to the standard compressor range. Two different methods are applied to determine the enhancements, the SEPR calculation according to the EN13215 as well as the in chapter 3.2 mentioned method.

All calculations in the following are based on a simplified model for the determination of the temperature difference between the heat sink and gas cooler outlet and condensing temperature, respectively. From the maximum ambient temperature down to 30 °C, a temperature difference of 2 K is considered. A proportional increasing difference is applied between <30 °C and 20 °C. The temperature difference equals 8 K for heat sink temperature of 20 °C and is kept constant again down to 0 °C. With an ambient temperature of 0 °C it is considered that the applied compressors operate with the minimum discharge pressure based on -10 °C evaporating temperature. Finally, the algorithm of Dr. Vollmer (1996) was applied to calculate the optimum discharge pressure levels for the conditions of supercritical gas cooling.

4.2 SEPR According to EN13215

The calculations were carried out for a unit with a single capacity controlled compressor with a nominal capacity of 55 kW based on an evaporating temperature of -10 °C and an ambient temperature of 32 °C. Furthermore the unit was considered to consist a capacity control by variable speed drive (VSD). For the proper determination of the SEPR according to the standard, defined suction gas conditions of 10 K superheat were considered. The annual energy consumption was determined as well as the SEPR value for three different climates. The compressor types considered for these calculations were 4DTC-25K with an asynchronous motor and 4DTC-25LK with a line start permanent magnet motor. It is highlighted in Figure 3 that calculations were carried out for three different climates. The diagram indicates the absolute energy consumptions of the compressors on the primary y-axis. It is an obvious result of the calculations, which a considerable amount of energy used, can be saved on an annual basis by applying a compressor with an advanced motor technology. From left to right: For a moderate, cold and hot climate, the annual savings amount to 8976, 8084 and 11615 kWh/a, respectively. Furthermore, the secondary ordinate shows the resulting SEPR. The improvements equal in average 13 % (Variable speed drive – VSD).

4.3 Detailed Calculation of the Annual Energy Efficiency

In a next step, the calculations were performed according to the method described in chapter 3.2. The major difference was that the load profile does distinguish between the situation "shop is open or shop is closed" as shown in Figure 3. Apart from this, the boundary conditions like described in chapter 4.2 were kept equal. The results show a correlating trend of the relative improvements of the values investigated. However, the deviations of the absolute values are significant. A cross-comparison between both methods indicates that the different load profile has a substantial influence on the results of annual energy efficiency and energy consumption. Based on the differentiated load profile and the accumulated operated time while the shop is closed, the annual energy consumption is reduced by 5298 kWh/a in Strasbourg, 3942 kWh/a in a cold climate like Helsinki and even 17444 kWh/a in Athens. This indicates, that a differentiated load profile offers advantages for the calculation of the annual energy consumption.

However, the results shown in Figure 4 draw attention to the fact that the application of an average load profile for significant different climate zones leads to deviations in a cross-comparison with the method according to EN13215.

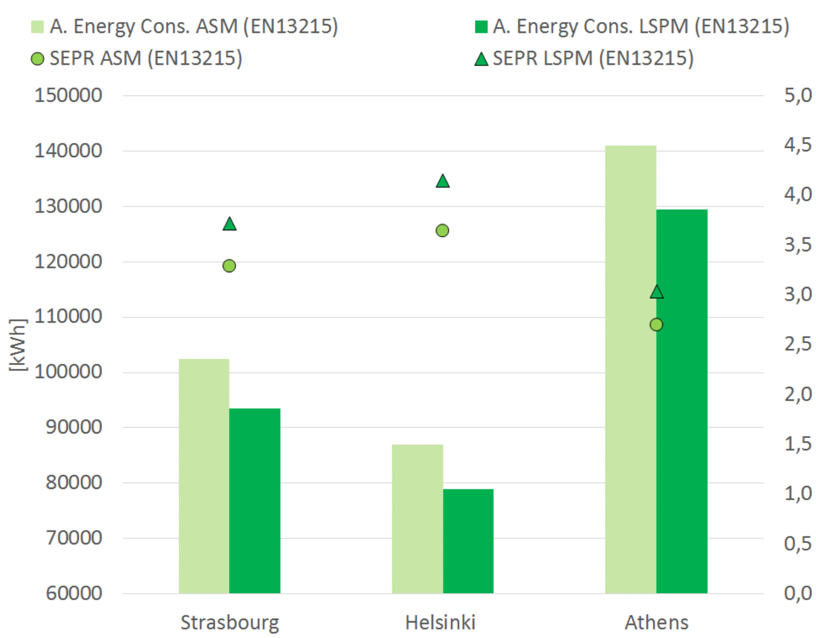

Figure 3: Results of the calculations according to the EN13215 for three different climate zones

The deviations between the SEPR and the values for the annual energy efficiency equal 3,7 % in Strasbourg, even 9,2 % in Helsinki and -2,7 % in a hot climate like Athens. In order to evaluate the influence of a realistic system configuration, the calculations were performed as well for a unit, that applied a flash gas bypass, including a medium pressure vessel and an internal heat exchanger (IHX) between gas cooler outlet and the flash gas. The results show, that the deviations compared to the simplified system with defined and constant suction gas superheat can be neglected.

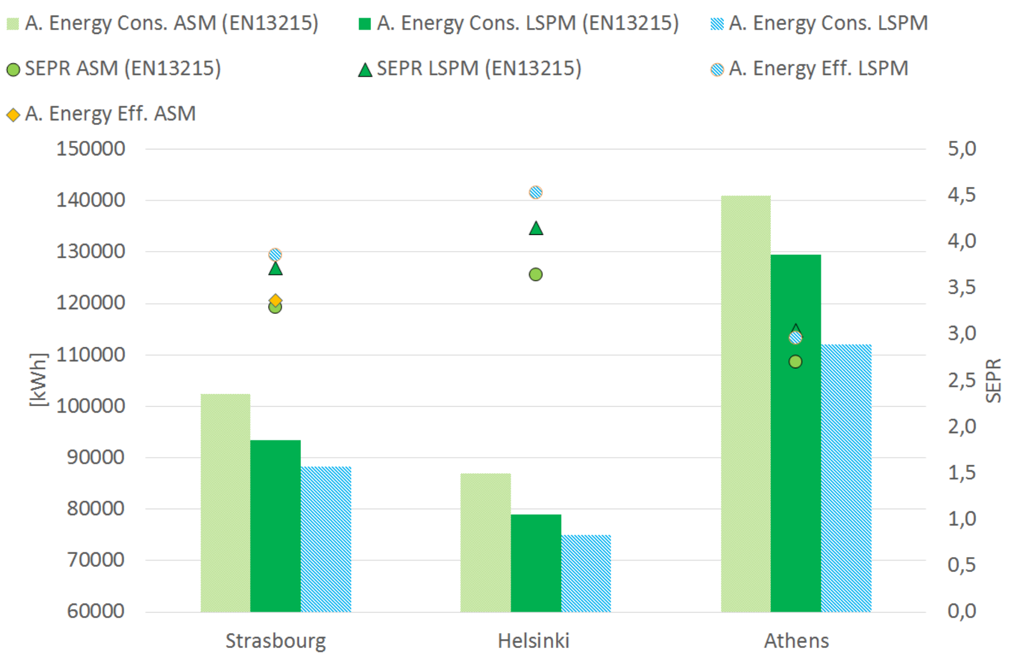

Figure 4: Results of the cross-comparison between the two different calculation methods discussed

4.4 Detailed Calculation for a Parallel Compounded System

In order to evaluate the potential in energy savings in a parallel-compounded system, detailed calculations of the annual energy consumption and annual energy efficiency were carried out. For this prevailing work, the worst case for the ratio between the effort to be made and the benefits gained was evaluated: A parallel compounded system with only two compressors, where it is obvious, that operating time of the second compressor is relatively little compared to the lead compressor with VSD. The boundary conditions were: an unit with two compressors, lead compressor with VSD, nominal capacity based on an evaporating temperature of -10 °C and an ambient temperature of 32 °C, system with FGB and IHX, suction conditions variable and dependent on the load and ambient conditions.

As already mentioned in chapter 2.2, the application of a LSPM provides also an advantage in terms of a higher mass flow rate and due to this a higher cooling capacity. Under nominal conditions, the unit has a rated capacity of 198 kW for the case that both compressors are applied with a standard motor. The capacity is increased to 212 kW, when both compressors are equipped with a LSPM motor. Therefore, the annual energy consumptions stated in Figure 5 are standardized. The calculations were only carried out for Strasbourg by applying the introduced calculation scheme in chapter 3.2.

Three options are considered: Lead compressor with VSD and fixed speed compressor with AS motors, lead compressor with VSD and fixed speed compressor with LSPM motors and finally lead compressor with VSD equipped with LSPM motor and the fixed speed compressor with AS motor. The results show, that the annual energy consumption of such a unit is significantly reduced from 218823 kWh/a down to 207549 kWh/a by applying two LSPM motors instead of standard motors. By comparing the second and the third option, the results show as well, that the configuration with two LSPM motors offers an additional reduction of just 1463 kWh/a compared to the third option. This is not very much but must be interpreted in the context of the operating hours.

The second compressor of such a 212 kW unit accumulates in this calculation only 1600 operating hours. The evaluation of the operating hours for different system configurations is subject for further work. As criteria to evaluate the ratio between cost and benefit for a parallel-compounded system, the focus should be on the compressors in operation at the rating points C and D as shown in Table 2. Compressors that are in operation under these conditions, should be equipped in any case with a LSPM motor.

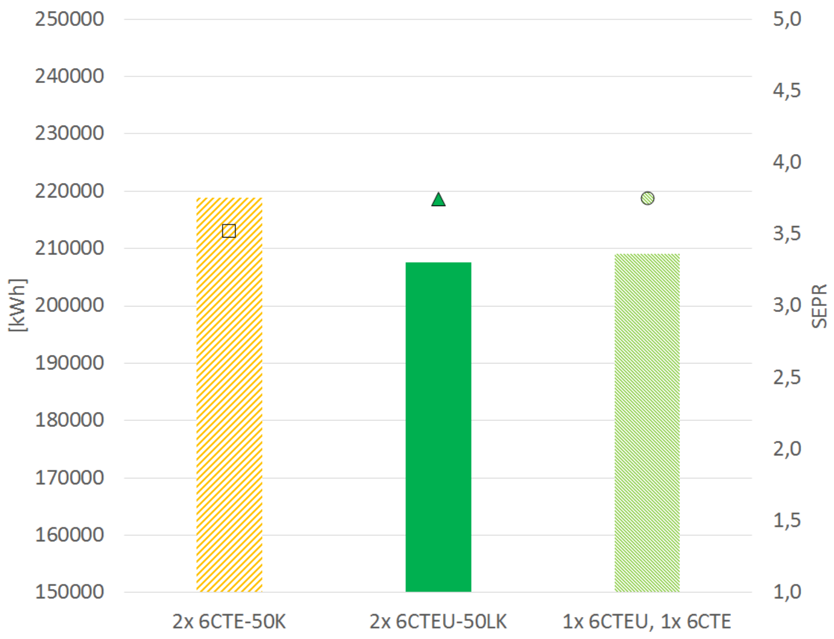

Figure 5: Results of the comparison between different system configurations for a moderate climate

5. Conclusions

The advanced technology with LSPM motors shows a significant contribution to reduce the annual energy consumption in commercial refrigeration systems. Regardless of the calculation method applied, the relative reduction of the annual energy consumption is significant and in average in the range of 13 % (Variable Speed Drive – VSD) in a moderate, cold and hot climate. In combination with the natural refrigerant CO_2, the new compressor range shows the perfect match for the reduction of the indirect and direct greenhouse gas emissions and can therefore help the industry to reduce the carbon footprint. The question, how to evaluate the energy efficiency was discussed intensively. The results of the calculations show, that the calculating method according to the EN13215 is a good method to calculate the seasonal energy performance ratio. Initially developed for single staged condensing units, the method can also be used for more complex systems with flash gas bypass and internal heat exchangers. Even though the consigned load profile of the EN13215 does not distinguish between “shop open or closed”, the method shows a good approximation to evaluate the relative potential for energy savings. However, for the evaluation of the absolute savings in annual energy, the detailed calculation scheme presented and applied in this work is the preferred method of choice. Nevertheless, for significant different climate zones the application of a general load profile is only a compromise. By calculating the annual energy efficiency for a simple parallel-compounded system, this work shows as well that the annual operating time of a high efficient compressor has a significant and strong influence on the potential for energy savings. Finally, this work introduced a good approximation for the ratio between the effort to be made and the benefits gained, by considering the annual operating hours for the two coldest rating points according to the EN13215.

6. Nomenclature

AS	Asynchronous Motor
COP	Coefficient of Performance [-]
EER	Energy Efficiency Ratio [-]
FGB	Flash Gas Bypass
HFC	Hydro-Fluorocarbons
HP	High pressure
FGB	Flashgas-Bypass
IHX	Internal Heat Exchanger
LT	Low temperature
LP	Low pressure
LSPM	Line Start Permanent Magnet
MT	Medium temperature
Mt CO2 eq	Million tonnes CO_2 equivalent
SEER	Seasonal Energy Efficiency Ratio [-]
SEPR	Seasonal Energy Performance Ratio [-]

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