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CARBON FOOTPRINTS OF LARGE COMPRESSION CHILLERS FOR DISTRICT COOLING – ACCOUNTING FOR TEMPORAL RESOLUTION OF THE ELECTRICITY SUPPLY

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Abstract. Compression chillers are a common technology used in district cooling networks, with fluctuating cooling loads and consuming different electricity mixes at different times. This work aims to study these effects on the CFs of operating three compression chillers in a district cooling plant in Austria, using LCA-based CF modelling. Electricity consumption dominates the chillers' CFs. While using the annual average electricity mix overestimated the CF for two warm-season and mixed-season chillers by 12% and 1%, respectively, it underestimated the CF for a mainly cold-season chiller by 6 %. Seasonal changes in electricity mixes and cooling loads were well suited to explain the calculated CF deviations and should be accounted for in carbon footprints dominated by renewables-rich electricity consumption.

Keywords: district cooling, compression chillers, carbon footprint, electricity mix, temporal resolution.

JEL Classification: Q42, Q51.

Introduction

District cooling networks are becoming increasingly popular as a means of meeting cooling needs in urban areas; consequently, their environmental impact is also coming into focus. Compression chillers are a common technology used in such networks, and their contribution to climate change can be quantified in terms of carbon footprint (CF).

Much of the CF of a compression chiller is due to the electricity required to operate it. For example, for compression heat pumps based on the same operating scheme, 75% to 90% of the total CF is due to electricity demand, depending on the mode of operation (Eicher et al., 2014; Li, 2015). However, the underlying footprint models are often based on an average annual electricity mix (Itten et al., 2012). On the other hand, if the electricity mix contains larger shares of renewables – as is the case in Austria – the effect of temporal CF variations can be masked by using annual averages, as load profiles also vary. For 2016, this causes the value for emissions caused by user-side electricity demand in Austria to fluctuate between 40 g CO_2eq/kWh in June and 363 g CO_2eq/kWh in December, whereas the annual average is 209 g CO_2eq/kWh (Lunzer et al., 2018). Thus, Khan et al. (2018) also argue that "quantification of the time variability of carbon intensity is necessary to understand the detailed patterns of carbon emissions in electricity systems, particularly as future systems are likely to increasingly rely on a mix of time-varying generation types such as wind, hydro and solar."

The aim of this work is to quantify the CFs of three compression chillers in a district cooling plant in Austria and to investigate the impact of an hourly resolution of electricity and load profiles compared to annual average mixes.

1. Materials and Methods

1.1. Chiller operation and load profiles

The three compression chillers are located at a larger (19.8 MW) district cooling centre, one of 21 plants that supply the district cooling network of the City of Vienna in Austria with a total cooling capacity of over 130 MW (Wimmer, 2018). The centre's cooling power is provided by a combination of compression and absorption chillers, as well as by free cooling during the cold winter months. The three chillers described here are rated at a total nominal capacity of 8.1 MW.

The study is based on data from the most recent pre-CoViD year, 2019, to exclude CoViD-related economic

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effects. Table 1 shows annual operational parameters both for each individual chiller and as a total. KKM 2 and KKM 3 have the same rated power, while KKM 1 has a lower rated power. Regarding the actual cooling output, KKM 2 has a higher output than KKM 1, approximately following their rated power, while KKM 3 provides only a small output as a backup. All three chillers have a comparable seasonal energy efficiency ratio (SEER) defined here as the ratio of cooling output over electricity demand.

Table 1. Annual cooling output and electricity demand of the three chilllers, individually and combined total. Pump electricity not included

Chiller	Nominal power, MW_{th}	Annual cooling output, MWh_{th}	Chiller operation, annual electricity demand, MWh_{el}	SEER, unitless
KKM 1	1.70	2.335	357	6.54
KKM 2	3.20	4.498	630	7.14
KKM 3	3.20	436	64	6.81
Total	8.10	7.269	1.051	6.92

Measured power consumption data with a temporal resolution were not available for the compression chillers, therefore the required values were calculated as follows. The cooling capacity of the produced cold water was calculated using utility data (G. Zisser, personal communication, 14.06.2022) for mass-flow and input- and output- water temperatures. While these values were available with a resolution of 15 minutes, they were aggregated to hourly values, since the electricity mix data was available only in hourly steps. To obtain the hourly electricity consumption of the compression chillers, the hourly coefficient of performance (COP_{real}) was calculated from the theoretical Carnot-based COP_{carnot}. The ratio between the two COP values was interpolated for each hour from seven COP_{real} values given in the chiller's data sheets for various operating points. The interpolation was based on a polynomial function of the 2nd degree.

Calculated hourly electricity consumption resulted in highly variable load profiles over the study year 2019 (Figure 1).

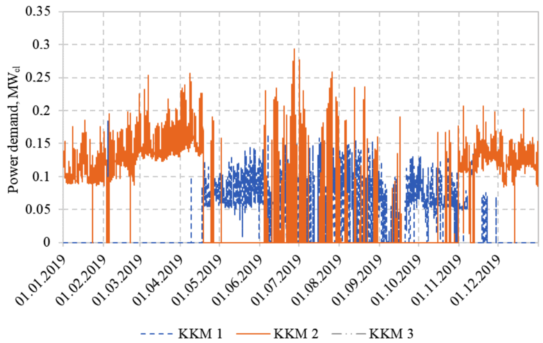

Figure 1. Load profile of the three chillers during the year 2019

Apart from short phases, KKM 1 was mainly used during the warmer season. It was not in operation until mid-April. From November, the operation of KKM 1 decreased significantly again. On the other hand, almost all of the cold during the cooler season was provided by KKM 2, with an interruption from mid-April until early June. Over the summer, KKM 2 was back in partial operation until there was another lull between mid-September and early November. From November, KKM 2 provided the main cooling power.

For the water pumps that supply the chillers, the hourly electricity consumption was assumed to be proportional to the chillers' hourly electricity demand. The proportion was derived from the nominal electricity consumption of pump and chiller, respectively.

1.2. Hourly weighted Austrian electricity consumption mix

For modelling the electricity mix, nationwide data for Austria from 2019 were obtained from electricityMap (electricityMap, 2022). ElectricityMap data cover hourly data on electricity consumption, production, imports and exports for the entire year 2019. Nationwide Austrian data were used, as there is no isolated grid for Vienna. In addition, hourly data on the production mix from Germany and the Czech Republic were also obtained. For modelling the chillers' CF, their individual load profiles as described in the preceding chapter were used as hourly weights to develop a chiller-specific, weighted, hourly electricity consumption mix. This weighted consumption mix was derived in three steps:

First, weighting factors f_i of hour i were calculated for each hour I from the individual load profile of each chiller. The factors are the ratio of the hourly electricity consumed by the chiller to the annual electricity consumed.

Second, the technology-specific shares of electricity production in Austria were weighted with the corresponding hourly weighting factor f_i and added up over the year. This resulted in the share of an energy source from Austrian production in Austria's electricity consumption mix weighted with the load profile. To illustrate (calculation according to the electricityMap database; electricityMap, 2022), on July 15th, 2019 at 11 a.m., the chiller KKM 1 consumed 0,091 MWh_{el}. If this is compared to the total annual energy requirement of KKM1 of 357 MWh, a weighting factor f_i of 2.5·10E-04 results for this hour. Subsequently, the share of hydropower in Austria's electricity production mix in that hour (38.05%) is multiplied with the weighting factor f_i, resulting in a 0.01% weighted share of hydropower in the hour under consideration. These hourly weighted shares were then added over the whole year to obtain the load-weighted share of hydroelectricity in Austria's electricity production. This was carried out for each electricity-generating technology, yielding an

Austrian electricity production mix weighted with a KKM's individual load profile, i.e., the hourly-weighted production mix.

In a third step, this same procedure was repeated for the German and Czech production mixes, so that load-weighted production mixes could be used to represent imports into Austria. Imports from other neighbouring countries (CH, HU, SLO, northern IT) were less than 2% of the total weighted electricity consumption, so they were modelled with their average production mixes from the ecoinvent database. Note that electricity exports from Austria to neighbouring countries were ignored, as they are conceptualized to consist of the same mix as the national consumption mix.

1.3. Life-cycle assessment model

The CFs include not only the provision of electricity for the chillers, but also the production of the chillers including the refrigerant and estimated emissions from annual refrigerant losses. R134a is the refrigerant used in all three chillers. Annual refrigerant losses during the operation of the chillers were given by the utility at 2% of the filling quantity as given in the chillers' data sheets. For the production of the chillers, the ecoinvent process "heat pump production, brine-water, 10kW | heat pump, brine-water, 10kW | Cutoff, U – RER" was adapted. For this purpose, the mass of the individual materials in this ecoinvent process was scaled up to obtain the total mass of the respective KKM.

The functional unit for the CF calculation results was set to 1 MWh_{th} of cooling, as delivered to the district cooling network by the evaporator of the chiller. LCA modelling was conducted with the openLCA software version 1.10.3 (GreenDelta GmbH, Berlin, Deutschland) using adapted processes from the ecoinvent database version 3.8 (cut-off; Wernet et al., 2016). The carbon footprint was characterized using the climate change impact category in the impact assessment method ReCiPe 2016 Midpoint (H).

2. Results and discussion

2.1. Weighted electricity mix

Load-weighted electricity mixes vary between the individual chillers, depending on the electricity source (Figure 2).

For wind power, the difference of its share in the consumption mix is rather small when the load-weighted mixes of KKM 1 and KKM 2 are compared with the annual average mix. However, in the weighted KKM 3 mix, the wind-power share is only about half as large as in the annual average mix, namely 5% vs. 10% (100% = total consumption of the chiller). The largest deviations between various chillers (hourly-weighted mix) and the Austrian annual average mix occur with hydropower. Here, the largest deviation from the annual average occurs at KKM 1 with slightly more than 5%, followed by KKM 2 and KKM 3. There is a decrease in electricity from natural gas at KKM 1 and KKM 3, whereas the same share is slightly higher with KKM 2 than with the annual average. In the case of imports from Germany, there is also a decrease of about the same size at KKM 1 and KKM 3, while the value increases at KKM 2. Overall, shares of fossil generation and fossil-richer imports from DE and CZ are higher than the annual average for KKM 2, but lower for KKM 1 and 3.

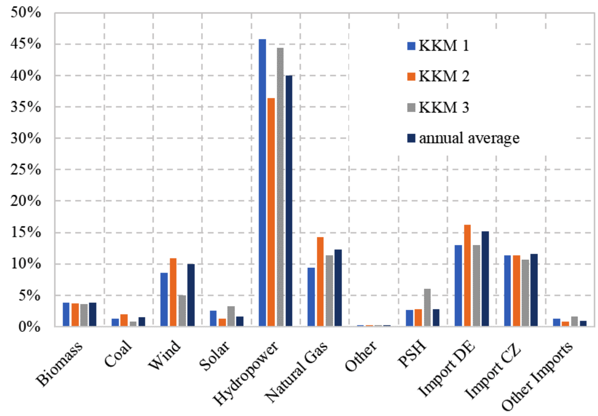

Figure 2. Electricity consumption mixes for the chiller units KKM 1 to KKM 3, weighted according to the load profiles of the individual chillers, compared to an (unweighted) annual average electricity mix. 100% = total annual consumption for a chiller or for Austria as a whole.
Based on 2019 data (electricityMap, 2022). PSH = pumped storage hydro power; other = power production unknown; other Imports = Imports from Switzerland, Slovenia, Hungary, Northern Italy

2.2. Environmental impact of cooling by chillers, individually and combined

Differences in the underlying electricity mixes translate into differences between the CFs of the studied chillers (Table 2. Specific carbon footprints (CF) for each individual chiller and the combined cooling output in kg CO2eq./MWhth of cooling output, based on three different electricity mixes. Percentages: Hourly-weighted CFs = 100%). While the hourly-weighted mix results in a lower CF for KKM 1 and KKM 3, it gives a higher CF for the KKM 2. For comparison, specific CFs were also calculated based on the annual average Austrian mix in the ecoinvent database. Those CFs are comparable to those based on the annual average electricityMap data, but higher by approximately 7 $CO_{2eq.}/MWh_{th}$ for each unit and the combined cooling output as well. Interestingly, for the combined cooling output, there is little difference between the hourly weighted and the annual average (electricityMap) CFs (less than 0.1%).

If the contributions of the individual chillers to the combined cooling output (Table 3) are considered the following stands out: Although for the combined cooling

Table 2. Specific carbon footprints (CF) for each individual chiller and the combined cooling output in kg CO_2eq./MWh_{th} of cooling output, based on three different electricity mixes. Percentages: Hourly-weighted CFs = 100%

Chiller Unit	Hourly weighted Mix (electricityMap)	Annual average Mix (electricityMap)	Annual average Mix (Ecoinvent)*
KKM 1	46.79	52.26 (+11.70%)	59.06 (+26.23%)
KKM 2	50.70	47.82 (–5.68%)	54.04 (+6.59%)
KKM 3	75.37	76.43 (+1.40%)	82.95 (+10.06%)
Combined Cooling	50.92	50.96 (+0.08%)	57.39 (+12.70%)

* ecoinvent process "market for electricity, low voltage | electricity, low voltage | Cutoff, U – AT" corresponds to the Austrian consumption mix

output, the difference between the CFs based on the annual mix and the hourly weighted mix is very small (Table 2; <0.1%), differences in the contributions of the individual chillers to these two footprints can be seen. Thus, using the hourly weighted mix, the share of KKM 2 is higher (+3.55%), whereas the share of KKM 1 and KKM 3 is lower (–3.43% and –0.12%, respectively).

Table 3. Contribution of the various chillers to the overall result for the CF and percentage deviation relative to the annual average mix depending on the electricity mix used

Chiller Unit	Hourly weighted Mix	Annual average Mix	Difference to hourly (Hourly = 100%)
KKM 1	29.51%	32.94%	–3.43%
KKM 2	61.61%	58.06%	+3.55%
KKM 3	8.88%	9.00%	–0.12%

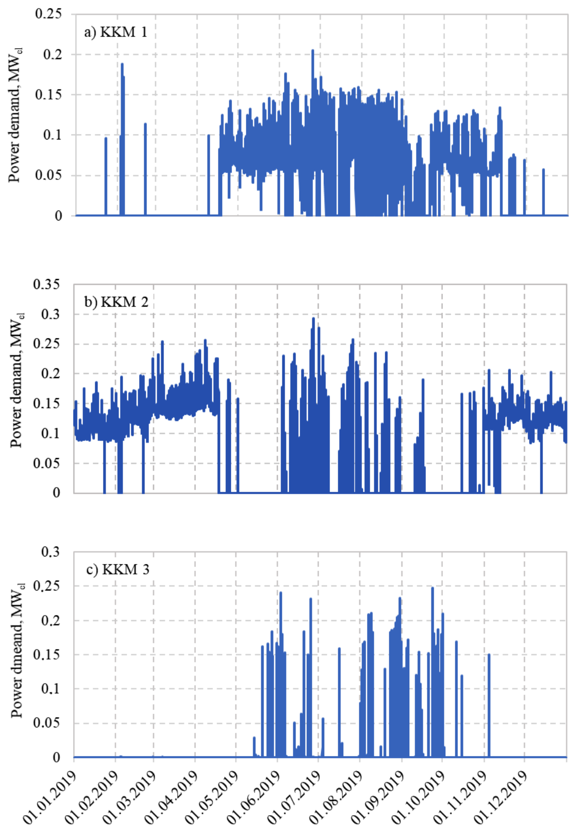

Figure 3. Load profile of the three chillers (a-c; KKM 1 through KKM 3) during the year 2019

Results in Tables 2 and 3 can be explained by the fluctuating composition of the hourly weighted electricity mix over the year in combination with the different periods during which the chillers were in operation (Figure 3).

The main operations period of KKM 1 were the summer months (Figure 3a), when there is typically a higher share of hydropower and other renewables in the Austrian electricity mix, whereas the share of electricity from gas in Austria and the imports from Germany tend to be lower than the annual average, thus lowering the overall CF for KKM 1 relative to an annual average.

In contrast, KKM 2 was mainly operated during the winter months (Figure 3b), when hydropower and solar generation contribute relatively little and larger shares of high-CF natural gas and imports from DE and CZ become more prominent in the electricity mix. Therefore, the use of the hourly-weighted electricity mix results in a low share of electricity from hydropower from Austria compared to the annual average, with a higher portion of electricity from gas and imports from Germany. This translates into a higher overall CF when the hourly weighted mix is considered, with a dampening of the effect by increased wind power contributions during the colder seasons.

KKM 3 only covered peak loads that occur especially in summer and fall (Figure 3c). This results in a decrease of electricity from wind, natural gas and imports from Germany in the hourly weighted mix compared to the annual average mix. However, on an hourly basis, the share of electricity from hydropower, solar and pumped storage power plants also increases. In total, the shares of low-carbon and high-carbon electricity generation balance each other out and there is only a minor impact due to a time-based hourly resolution.

Over the year, these three profiles also largely cancel each other out. Therefore, the combined cooling output of all three chillers, the CF was found to be very similar between the hourly weighted electricity mix and the

Table 4. Contribution of the life-cycle subprocesses to the chillers' overall CF

	KKM 1			KKM 2			KKM 3		
	Hourly Mix	Annual average Mix	Ecoinvent Mix	Hourly Mix	Annual average Mix	Ecoinvent Mix	Hourly Mix	Annual average Mix	Ecoinvent Mix
Electricity consumption	82.31%	84.16%	85.98%	85.16%	84.27%	86.08%	54.63%	55.25%	58.77%
Chiller production	6.45%	5.77%	5.11%	5.55%	5.88%	5.20%	38.49%	37.95%	34.97%
refrigerant losses	11.12%	9.97%	8.82%	9.19%	9.74%	8.62%	6.18%	6.11%	5.62%

annual average mix (Table 3, bottom row). In particular, the hourly weighted mixes of KKM 1 and KKM 2 approximately cancelled each other out because their combined operations were distributed over most of the studied year 2019.

The contribution analysis (Table 4. Contribution of the life-cycle subprocesses to the chillers' overall CF) shows the dominant contribution of the electricity consumption to the chillers' total CF: For KKM 1 and KKM 2 the share of electricity consumption in the total CF is around 82% to 85%, the share of the production of the chillers is around 6% and that of the CF caused by refrigerant losses during operation is between 8% and 11%. For KKM 3, the contribution of electricity consumption is less dominant; it ranges from about 54% to 58%, while that of production increases from 35% to 38% and that of refrigerant losses from 5% to 6%. This is due to the fact that KKM 3 serves to cover peak loads and therefore supplies less cooling output over the lifetime (Table 1). This has the effect that the emissions caused during production are distributed over fewer MWh of refrigeration output, increasing not only their share of total CF as shown in Table 4, but also increasing the absolute value of the specific CF (Table 2).

Conclusions

Electricity mixes vary between the individual chillers; the difference between load-weighted mixes of individual chillers and an annual average mix is highest in the case of hydropower, with the share in the weighted KKM 1 mix slightly more than 5 percentage points higher than that in the annual average mix. Such differences in the underlying electricity mixes translate into differences between the specific CFs of the studied chillers: Electricity consumption dominates the chillers' total CF (82%, 85%, and 55%, respectively, for KKM 1-3), followed by the contributions of chiller manufacturing and refrigerant leaks. Differences for individual chillers between load-weighted and annual average specific CFs were in favour of the hourly weighted mixes in the case of KKM 1 and KKM 3, but the load-weighted CF was higher than the average-based CF for KKM 2. The annual average CFs based on electricityMap data were lower by approximately 7 $CO_{2eq.}/MWh_{th}$ than annual average CFs based on the Austrian ecoinvent electricity mix.

Differences in electricity mixes and CFs between the chillers can be explained by the different periods during which the chillers were in operation: The KKM 1 chiller was mainly operated during the summer months when production from hydropower and other renewables in Austria is higher. This contrasts with KKM 2, which was mainly operated during the winter months, when Austrian renewables production is lower. The KKM 3 chiller operated in summer and fall, and the different generation characteristics of these two seasons cancelled each other largely, leading to relatively small differences with the annual average results. This also applied to the combined cooling output of all three chillers together.

Overall, the study demonstrates that using an annual average electricity mix rather than a time-resolved mix can over- or underestimate the carbon footprints of compression chillers, in the case presented here in a range of – 5.68 % to + 11.70%. Such deviations may be well explained by a closer examination of seasonal fluctuations in (renewables-rich) electricity mixes, and by comparing these with the chillers' load profiles. To the author's knowledge, this is the first examination of the effect of seasonally variable electricity mixes on seasonally variable loads on the carbon footprint of large industrial chillers. In the specific case studied here, opposing results for individual chiller units largely cancelled each other. However, this can be assumed to be the exception rather than the rule. Wherever variable electricity mixes supply variable load profiles, a time-resolved calculation of carbon footprints may substantially improve the environmental impact assessment of such energy systems.

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