Chiller systems' overall energy efficiency / A comparative study of Paris, Helsinki and Gothenburg

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Summary

The energy consumed by buildings increases to particularly high levels in urban environments and it becomes essential for the performance of the technical installations which provide cooling to be improved.

Different performance indicators are available. Manufacturers provide chiller performance coefficient: the Energy Efficiency Ratio (EER) estimates the consumption of the cooling facilities integrated into the site and the European Seasonal Energy Efficiency Ratio (ESEER) establishes a calculation that allows for changes in cooling loading rates during a year. However, designers or operators regard these approaches to assessing the performance of facilities in the field as representative of the real-life conditions. Based on this finding, a study has been set up, equipping different installations of varying design deployed in buildings set aside for a specific use, with instrumentation. This paper is mainly based on the measurements project executed in Paris that is added by the appropriate results from similar measurements done in Finland and for a system in Gothenburg. The aims of both measurement projects were to define the yearly performances of chiller systems.

The cooling power output of the installations measured varied between 100 and 1500 kW that is the most common size in the Paris urban area and Helsinki as well. Results collected from more than a year of measurements show that average EER values measured varied between 0.7 and 2.9 in Paris and Finland. The EER in Gothenburg was 2,8.

The main finding is that there is a wide gap between theoretical EER values and real-life performances of chiller systems. The results were nearly the same in all cities.

Overall performance deteriorates according to the installation running mode which consists in forecasting the site's refrigeration loading at the start of the warm weather period by distributing this loading between various chillers. Maintenance operations also significantly affect overall performance throughout the installation's service life.

Thus, it would seem that even if standards attempt to represent as best the diverse nature of the situation in the field, and if they are of use when designing installations, they do not take operating data into account. Only the deployment of a continuous data acquisition system allows us to assess actual consumption by cooling production equipment with the purpose of evaluating the installation's actual efficiency.

Introduction

The energy consumed by buildings is becoming particularly important in urban environments, on the one hand because urban population levels are continuing to rise (0) and on the other because the air temperature in dense urban areas is higher than in the surrounding areas, a phenomenon known as the «thermal island effect» (0).

This general increase in requirements, combined with the necessary reduction of greenhouse effect gases (according to the Kyoto Protocol and the 2007 European Summit) accentuates the need for efficient energy usage.

The deployment of a policy for improving energy and environmental performances constitutes an unavoidable step if we are to fulfil sustainable development commitments. In France, this deployment takes the form of the enactment of a new regulation (RT2005), designed to improve building energy efficiency and, in particular, the performance of refrigerating equipment solutions (0).

Accordingly, knowledge of refrigerating equipment energy efficiency constitutes essential information. For all that, approaches applied when assessing the performance of installations are rarely satisfactory and frequently create confusion among designers and operators.

Manufacturers issue a performance coefficient calculated on the basis of the chiller's rated capacity (100% of power output) under predetermined conditions (temperature conditions, duration of the measurement) and where the energy consumption taken into account is that for the compressor (plus that for fans in the case of air cooled condensers). This indicator can only be used to compare chillers with each other at their nominal duty point.

The Energy Efficiency Ratio (EER) is calculated for the chiller's rated capacity (100% of power output and for established temperature conditions (air temperature of 35°C at the condenser for water/water chillers). However, the energy consumed includes the electrical power consumed by the compressor and by accessories on the primary side (air condenser or air cooler fans, cold water pump, control units), i.e. all consumption excluding that required for distributing cooling throughout the buildings. This indicator can be used to assess the nominal performance of the cooling production system installed on the site.
However, over recent years, several studies have revealed that this criterion alone did not provide a picture of the true system performance because, in actual fact, they rarely run at full capacity (0, 0).

It was in the USA that, for the first time, the following fact was taken into account: that chillers very rarely run under nominal conditions but mainly under partial loading, with stepped control of the refrigeration compressors. A performance indicator established by the American Refrigeration Institute (ARI) was subsequently adapted in Europe by Eurovent, the European Seasonal Energy Efficiency Ratio (ESEER) (Eurovent Standard 6-C003-2006) (0). Japan and Korea followed by China then took their inspiration from the American standards.
Faced with the diversity of quantification standards, a harmonization process is now in hand. Its purpose consists in allowing for the seasonal aspects associated with the system's power output fluctuations based on actual demand
Thus, the ESEER establishes the system's working conditions by assessing its efficiency according to its loading under specific water and external air temperature conditions. The amounts of energy produced for different loading conditions are estimated according to statistical analyses carried out for various buildings and operating conditions. Accordingly, the ESEER is the weighted sum of the EERs for four different loading conditions.
This indicator claims to be an assessment that is coming ever closer to actual operating conditions; a calculation that is as close as possible to actual conditions can be obtained, in a dynamic form, by considering the loading change curve according to external temperature fluctuations, the location and the number of reference hours.
However, an installation's energy efficiency is time-related and affected not only by the accessories and loading levels but also by this installation's longevity, its management mode and its maintenance. Although efforts will be made to ensure that future standards reflect the true situation in the field as closely as possible, establishing the true energy efficiency of a system integrated into its environment inevitably requires that the system's overall performance be measured over time, taking into account all the parameters that have an impact on this performance.

Within this context, we felt it advisable and appropriate to quantify and compare electrical consumption for various autonomous installations, in the long-term, in order to identify true annual average efficiency levels as well as the real impact made by accessories, control and maintenance.

1 Methodology

The Energy Efficiency Ratio of a cold production «system» is produced for the following sources of consumption: chillers, the primary pumping system, the cooling system used (air coolers or dry-coolers) and the power consumed by all accessories required for the installation's satisfactory operation (water treatment, maintaining pressure, automated control systems, ventilation and lighting). The power consumed by the pumps used to distribute cold energy throughout the building is not taken into account.

1.1 Instrumentation

Metering points have been established for the purpose of providing all information required for efficiency assessment.
The study was carried out on various sites using identical working methods and similar measurement instruments.
In Paris, the following parameters were measured on each of the installations:

- Temperature measurements (pt100 type sensors): evaporator inlet and outlet water and condenser inlet and outlet water or air,
- Flow rate measurements (electromagnetic flowmeters): water flow rate through the evaporator circuit and water/air flow rate through the condenser circuit
- Hygrometry and ambient air temperature
- Electrical power consumed by all equipment

Since January 2008, all installed measurement instrumentation has been connected to a data acquisition unit that logs figures at 10 minute intervals. Temperature measurements have been calibrated in situ using a master thermometer and an oven. The relative error on EER values has been estimated as +/- 4%. This figure applies to each of the installations studied.
In Helsinki, the measuring principle was the same but adjusted to local conditions.
In Gothenburg the measurement of electrical consumers was made in one point and included all main and auxiliary consumers.

1.2 Installation types

The installations selected concern various building types (Table 1) and this will have an impact on installation operating conditions. The choice was based on recent installations in good state of repair and that run throughout the year in order to limit the impact made by reduced efficiency when loading levels are very low. The power output range for the installations selected which varies from 100 to 1,500 kW cooling is the most representative for the dense Paris urban environment and in Helsinki and Gothenburg as well.
A 100 kW to 1.5 MW output power range has been established as part of this study.
Hospitals are required to be operational continuously 24/24 especially in the case of the surgical units and the computer rooms that require a constant power supply; commercial and office buildings usually operate at maximum load levels throughout the day from Monday to Friday.

Installation	Building type
A	Hospital including the surgical unit, waiting room and room
B	Hospital including surgical units and examination areas
C	Bank including computer rooms, an office UPS room, reception rooms, refectory.
D	Commercial buildings
E1	Pharmaceutical product stores and office
E2	Computer rooms
F	Hospital examination area

Table 1: Selected buildings in Paris

Installation	Building type
A	Commercial building (office)
B	Museum

C	Commercial building (Bank)
D	Civil service department

1.3 Installations in Paris

The installations have been in place for 19 years in the case of the oldest and one year in the case of the most recent (Table). The number of chillers and the compressor type will vary according to the rate power. Condensers are cooled by cooling towers on three of the sites, by a dry-cooler on one and by dry air coolers on three others.

Installation A cools a hospital and uses 6 screw compressors. Machines start-up is managed manually: 1 chiller from December to May, 2 chillers from May to June and from October to December, and 3 chillers from June to October. Power control is stepped for each unit.

Installation B cools a hospital and uses 6 screw compressors; their power output is controlled manually by switching off certain machines: 1 chiller from October to May, 2 chillers from May to October. Power control is stepped for each machine.

Installation C cools a bank and uses four piston compressors. two compressors are switched off and two compressors run in «local» mode through human action (computer room and UPS room have continuous air-conditioning).

Installation D cools shops and uses eigth piston compressors. Four are switched off and four are brought into service according to client demand (one of the shops is always air-conditioned, even in winter). The compressors have stepped control.

Installation E1 cools building storage of pharmaceutical products, offices using two chillers with two screw compressors each. The E2 unit cools computer rooms using two chillers with three piston compressors each and one relief chiller more with two screw compressors.

Installation F cools a hospital's examination area and runs very occasionally, using three sealed scroll compressors. Control is stepped: 0% / 37% / 63% / 100%.

The efficiency coefficient for each of the chillers has been provided by the manufacturer for the specific reference temperatures quoted in table 1.
For each of the installations equipped with instrumentation, at least one technician is in attendance each day which means that the site is continuously monitored.

Building		starting	Chillers number	Compressors number	Refrigerant	Cooling system	Cooling power kW	Evaporator water temperature °C	
								Oulet	Inlet
A hospital		2000	3	6 screw	R134A	3 cooling towers	1260	5	30
B hospital		1996	2	6 screw	R22	2 cooling towers	940	6	30
C bank		1990	1	4 piston	R22	2 cooling towers	484	6	30
D stores		2008	4	8 piston	R407C	1 drycooler	776	7	25
E1 pharmaceutical storage		2006	2	4 screw	R134A	Aircooled	426	8	/
E2		1996	2	6 piston	R134A	Aircooled	661	7	/

computer room									
F hospital		2005	1	Sealed hermetique scroll	R407C	Aircooled	96	8	/

Table 3: Characteristics of sites equipped with instruments

1.4 Installations in Finland

All the installations in Finland were equipped with dry air coolers that are appropriate solution in Nordic climate. Installation in Finland are shown in Table 4.

Building	starting	Chillers number	Compressors number	COP (calculated, not measured)	Cooling power kW
A Office	N/A	2	6 pistons	3,1	600
B Museum	1998	2	4 pistons	3,6	760
C Bank	2001	4	2 screw	N/A	1030
D Civil service department	2001	2	4 pistons	2,7	572

Table 4: Installations in Finland

1.5 Installation in Gothenburg

The evaluated building in Gothenburg is an office building with two 500 kW electrical chillers cooled with air cooler.

1.6 Assessing the EERs

Measurements that have been logged are used to calculate the EER. This is the ratio of refrigerating power over electrical power consumed (by the primary pumps, the refrigeration units, the condenser pumps, the condenser cooling system and accessories such as chiller room ventilation, lighting etc.).

2 Results and discussion in Paris

The energy efficiency ratio was calculated using the measurements continuously logged for each of the installations over 24 months in the case of installations A and B and 12 months for C, D and F.
Data has only recently been logged on site E. Measurements had to be interrupted on site F; they could not be used because here, the installation only worked intermittently (running time was too short for the purpose of obtaining a reliable measurement).

The average EERs calculated using measurements carried out continuously over several months are relatively low.
Neither the designer not the manufacturer suggested calculating EER and ESEER during the design stage. The manufacturer COP is the only available parameter that the operator can use at present and that he regards as the installation's overall efficiency whereas measurements have demonstrated that these actual performance levels are 32 to 78% lower.

Installation	Measurement period	Average EER measured	Manufacturer's efficiency coefficient (chiller)	% EER / manufacturer COP
A	24 months	2 .02	4.26	53

B	24 months	2.87	4.78	40
C	12 months	2.14	3.15	32
D	12 months	0.84	3.87	78

Table 5: EER average measurements over the long term

As forecast by a number of parameters, energy consumption on the sites is a sensitive issue.
What is quite clear is that none of the installations was using chillers at maximum loading and this has an impact on efficiency.
Chillers are run at 35 % loading on site A (exceptionally at 45%), at 40 % on site B, at 25 % on site C and at 30% on site D.

Installation A and Installation B (hospitals)
We can report that the EER is lower in summer than in winter.
Only one chiller works continuously throughout the year. In order to anticipate and cope with high summer temperatures, the installation operating mode allows for increasing the number of compressors in service (**Erreur ! Source du renvoi introuvable.**) on a set date, regardless of true outside temperature levels. Although the installation's loading level increases, this loading is shared by the number of operational chillers in service and, therefore, running at part loading, thus increasing electricity consumption.
Furthermore, in the case of installation B, the increase in the site's refrigeration loading rate in January, March and then November is met by one single chiller and this results in an increased EER. Indeed, system management does not allow for the number of compressors in service to be doubled during these periods of the year.
Therefore, with regard to hospital installations, management promotes security during hot weather periods to the detriment of performance.

Installation C (bank)**Erreur ! Source du renvoi introuvable.**:
The average EER measured for the period is equal to 2.12. It reaches the 2.7 level in October with a loading rate in excess of 25%.
The servers and the UPS room require a coolness supply that remains stable and constant throughout the year; however, the site's refrigeration loading level fluctuates according to office occupant demands.

Installation D (shops);
Until January 2009, the average EER for this installation was low (<1). Cooling energy consumption was low over this period, resulting in a low evaporator Δ T°.
The refrigeration loading level in winter is equal to approximately 10%.
The system was shut down from the 24th December 2008 to the 12th January 2009 due to a fault. This incident was of no consequence for this type of building (shops) during this period of the year which explains the lack of maintenance operation reactivity.
Other incidents were recorded from March onwards and they were linked to power failures.
This installation is monitored weekly and, therefore, consequences ensuing on technical problems can persist between two inspections.

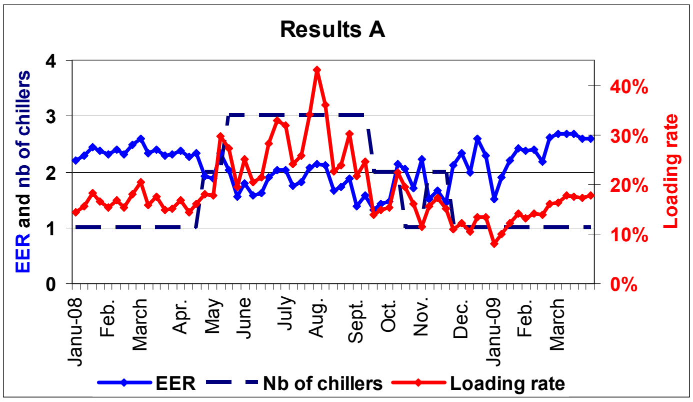
In general, for all the sites equipped with instrumentation, it is possible to immediately detect conditions that significantly affect the true EER. Some, covered by recommendations found in a number of publications, can, however, be detected during the site design phase or may be linked to the gradual drift that affects the installation through its service life.
In any event, lack of knowledge on consequences in terms of energy efficiency undoubtedly explains some investment choices.
Thus, for instance, evaporator and condenser pumps run for most of the time at a fixed output without any speed controller. This generates energy over consumption during the periods when the equipment is running under part loading.
Yet again, condenser cooling remains fixed throughout the year, regardless of weather conditions and of the chiller's loading level and this adversely affects the EER in winter. If cooling were governed by the real demand, this would reduce electricity consumption accordingly.

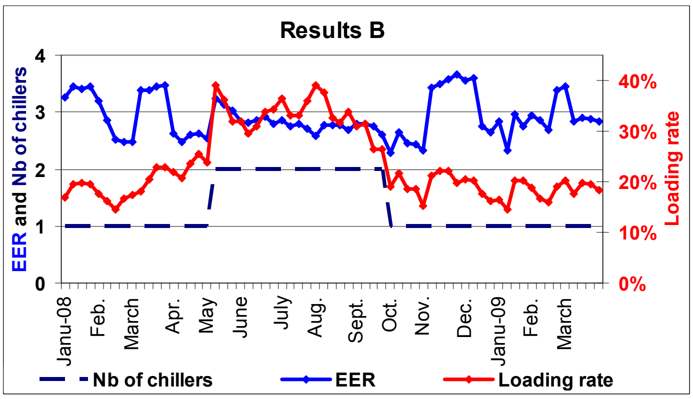
Similarly, measurements have demonstrated that temperature set points at the condenser inlet and at the evaporator outlet do not match nominal values. Therefore, it is obvious that the installation's true efficiency will be affected.

The true EER measured, in the same way as the EER and ESEER standard indices, depends on the condenser cooling technology used. Thus, a wet air-cooling tower will improve the installation's efficiency index. The cooling tower represents 5 to 24% of the installation's total electricity consumption; this figure is 28% for the dry cooler and 6% for the air condenser (data not shown).
On the other hand, only the true measurement of the EER can be used to accurately assess true chiller consumption which is directly affected by the way in which they are routinely managed.
Similarly, accessories often only require low power levels but they consume high amounts of energy over the year given the demand made on them, reflecting the behaviour of the individuals working on the site or the latter's configuration.

However, although wet method cooling produces a favourable EER, regulations in some European countries and especially in France, require the deployment of means designed to manage the risk of legionnaire's disease associated with these installations. Therefore, these means generate additional consumption (injection pumps for chemical treatments, the regular water circulation system for the condenser circuit etc.) that can be directly attributed to maintenance and overhaul actions, but that reduce the installation's true efficiency even further.

However, beyond this extremely specific aspect governed by regulations in some countries only, maintenance operations are necessary in order to maintain performance levels throughout the installation's service life.
In some extremely dense and high activity urban areas, very frequent air condenser or air cooled condenser cleaning will prove necessary because of, among other causes, bird feathers, high dust levels and a high insulation capacity film of greasy contamination that is invisible to the naked eye and that significantly affects machine efficiency.





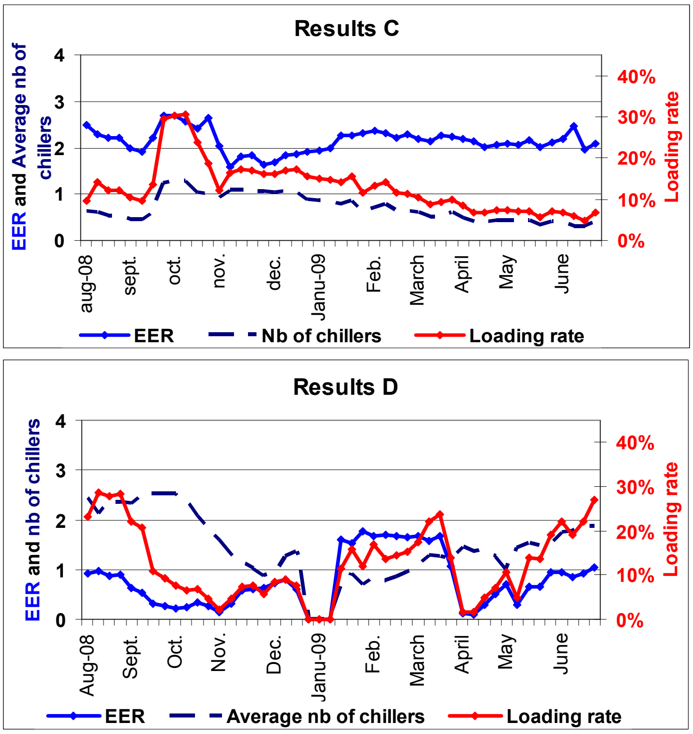


Figure 1: EER and site loading rate measurements

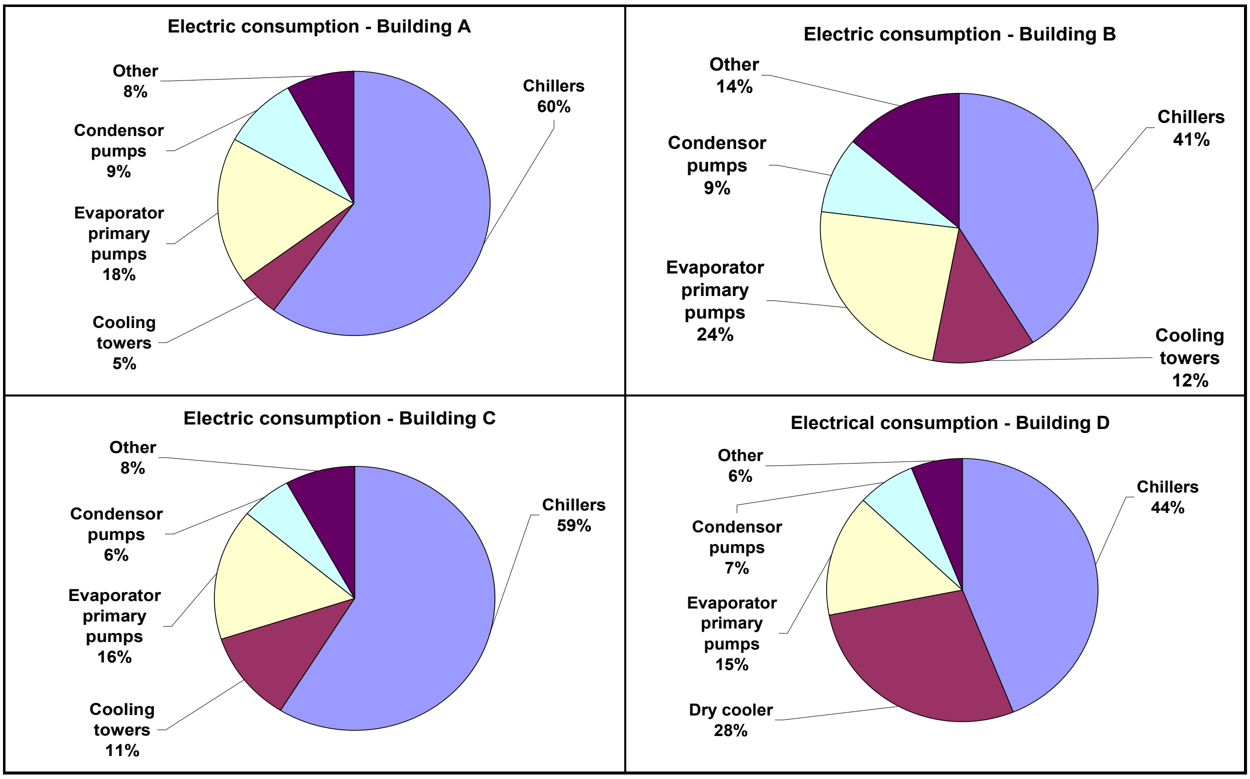


Figure 2: Electricity consumption distribution for each site

	Chilled water temperature °C		Condenser temperature °C		ΔT°	
	Return	Out	inlet	outlet	evaporator	Condenser
A	12	7	30	35	5	5
B	11	6	30	35	5	5
C	11	6	30	35	5	5
D	12	7	25	30	5	5

Table 6: Installation nominal operating conditions

	Chilled water temperature °C		Condenser temperature °C		ΔT°	
	Return	Out	inlet	outlet	evaporator	Condenser
A	7.45	6.11	25.30	27.32	1.34	2.02
B	8.21	6.64	25.39	26.07	1.58	1.31
C	12.45	10.43	29.80	32.45	2.01	2.63
D	10.40	10.01	27.34	28.51	0.39	1.17

Table 7: Installation true operating conditions

3 Results in Finland

The measurement period in Finland varied between 12 and 24 months. The results were nearly the same as they were in Paris despite of different type of climate.
The EER of the water chillers varied between 2.1-5.6 and the entire system EER with all the auxiliary devices varied between 0.7-2.4. The auxiliary devices represented approximately 50 % of overall electricity consumption. Another half is consumed by the chillers itself. The key average measured values are gathered to table 6.

Installation	Average measured EER	Calculated performance based on manufacturers COP	calculated / measured values
A	1.9	3.1	61 %
B	1.1	3.6	31 %
C	2.1	4.9 (chillers only)	43 %
D	2.2	2.7	81 %

Table 8: Measured average EER values in Finland

4 Results in Gothenburg

Measuring data from the production plant in Gothenburg was collected during 2006 and 2008. Measurements of the system were completed with simulation of individual electrical consumers.

The global system including auxiliaries (air cooling, pumps etc.) showed an ESEER of 2,8.

5 Conclusions

The loading curve and operating conditions show that refrigeration equipment, often over-designed on the grounds of security, cannot run under optimum conditions throughout the entire year.
Continuous performance measurements are used to accurately typify an installation's overall operation.
In addition to performance assessment, measurements can also be used to identify the real power-hungry sources such as accessories that cannot be ignored and form part of the general energy consumption picture.
Installation operation and maintenance are governed by the use made of the building. However, they very significantly affect the installation's real-life efficiency.
Even if standards provide the best representation of the diverse reality found in the field (EER and ESEER), they do not take these operating data into account. There is a huge difference between theoretical EER values and real-life performance of chiller system.
Consequently, the installation of a data acquisition system constitutes a *sine qua non* condition used to assess true consumption by refrigeration equipment if the installation's real efficiency is to be assessed.

Standard EER and ESEER are used to produce assessment based on the building type, the location of the installation, the heat loading type and the installation's requirements. Additionally, the EER and ESEER have the advantage of making energy comparisons possible between similar or equivalent systems, using the same reference unit.

However, the absence of measurement instrumentation (electricity meters and thermal energy meters) on most installations excludes any possibility of efficiently monitoring energy performance levels over time.

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