The Seasonal Efficiency of Multi-Boiler and Multi-Chiller Installations

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Topic

The paper relates to two of the conference topics: HVAC and the Directive on Energy Performance in Buildings

Keywords

Seasonal efficiency, boilers, chillers, energy certification

Abstract

The Energy Performance Certification requirements of the Energy Performance of Buildings Directive highlight the need to have repeatable, robust but easy to use methods of assessing the annual efficiency of HVAC systems. This is also an important issue for energy-efficient system design in general. System efficiency depends on the efficiency of heat generators (usually boilers) and cold generators (often chillers) - as well as many other heat distribution and control factors. This paper focuses on the calculation of the annual heat (or cold) generator efficiency of multi-boiler (or multi-chiller) systems.

Standardised methods exist for estimating the annual efficiency of boilers (or chillers) in systems with only one heat (or cold) generator: The UK SEDBUK rating for boilers, and the American IPLV rating and the proposed European ESEER value for chillers are examples of such rating systems. These produce *product* ratings for operation under standardised conditions. However, many larger systems have multiple boilers or chillers, and these product ratings are of limited value in these circumstances. In addition, the standardised assumptions of sizing and climate may not apply in every situation.

Detailed energy simulations provide one means of estimating annual performance, but are too complex for many buildings, or for the early stages of design.

This paper describes a simpler procedure for calculating the seasonal performance of multi-boiler or multi-chiller heat or cold generation systems, taking account of the part-load characteristics of the individual heat or cold generators, their sizing, and the load distribution of the building. It inevitably requires some information about the part-load performance of the heat or cold generators, but is sufficiently flexible to accommodate different levels of data. For example, it can be used with the boiler part-load tests required for compliance with the European Boiler Efficiency Directive or the chiller part-load tests proposed by Eurovent for their certification system. The individual heat or cold generators do not need to be identical. Building load information can be specific to a particular design and climate, if this is available: alternatively standard distributions can be defined for regulatory purposes.

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Introduction

Estimates of HVAC system seasonal efficiency are required whenever annual energy consumption is calculated – notably within the requirements of the European EPBD . (1)

An important part of the calculation of seasonal *system* efficiency is the specific issue of the seasonal efficiency of heat generators (usually boilers) and cold generators (commonly chillers). This paper offers a framework for carrying out such calculations and discusses its practical application.

Much of the content has been developed within three activities:
- the development of draft European standards to support the EPBD (2)
- the development of application tools for UK implementation of Article 3 of the Directive (11)
- a multi-partner study of part-load issues relating to HVAC plant (3)

This paper first describes the theoretical background and then discusses different implementation options, depending on the extent of data availability. Finally a short worked example is presented.

For clarity the paper will focus on chillers, though the principles are equally applicable to boilers and to room air-conditioners. For boilers some of the issues that arise with chillers are absent. The general principles could also be applied to other situations where performance depends non-linearly on weather conditions – for example, to heat recovery systems.

1. Basic Principles

The ratio between the annual cooling load placed on a chiller and its corresponding energy consumption is its “seasonal efficiency” or, more accurately, “seasonal energy efficiency ratio” (SEER). However, this ratio is not constant for a given chiller, but depends on a number of other factors that vary with the application.

In particular, the efficiency of a chiller varies significantly with the load placed on it and with the temperature to which heat is rejected. For many chillers, the efficiency at part-load is less than at full load – though for others, the opposite is true. Generally, efficiency increases as heat rejection temperature falls. The two effects are usually of comparable size. For air-cooled equipment, the heat rejection temperature is closely linked to ambient air temperature but, for liquid-cooled equipment the temperature variations clearly depend on the source of the cooling fluid.

Seasonal performance indices for single chillers exist in the form of the American Integrated Part Load Value (IPLV) (4) and the proposed European Seasonal Energy Efficiency Ratio (ESEER) (5). Each of these is a weighted average of several part-load efficiencies measured under different part-load conditions and heat rejection temperatures – see Table 1. The primary purpose of these indices is for product labeling – to allow the easy identification of chillers of differing seasonal efficiency. For this reason, they need to be product- rather than application- specific and therefore to use a fixed set of weightings of the different part-load EERs. For building energy calculations this can be misleading when the load patterns or climate of the application are substantially different from those that underlie the standard weightings (6). For example, the implications of the application of the ESEER ratings in the UK were discussed at the previous IEECB conference (7).

Table 1

Comparison of IPLV and proposed ESEER for air-cooled chillers				
	ESEER		IPLV	
% part load	**Temperature C**	**Weighting**	**Temperature C**	**Weighting**
100	35	0.03	35	0.01
75	30	0.33	26.7	0.42
50	25	0.41	18.3	0.45
25	19	0.23	12.8	0.12

IPLV and ESEER implicitly assume the use a of a single chiller, carefully sized to match the peak cooling load of a building. In practice, larger systems will commonly contain more than one chiller (or boiler) and the total installed capacity is rarely an exact match to the building load.

The section below describes the basic theory that underlies these indices and shows how the same principles can be extended to energy calculations that reflect building characteristics and use, climate, and the number and sizing of chillers installed.

2. Theory

2.1. The Objective

To calculate the energy consumption of a chiller or a set of chillers in an air-conditioning system, given knowledge of:

- the cooling demands placed on it (or them)
- the energy efficiency under a number of part-load conditions.

The same processes can also be applied to complete cooling systems and to heating systems. [1]

2.2. Combination of Load Frequencies and Part-load Performance Measurements

Over some period of time the cooling demand on a chiller is L (kWh). During this period, energy C (kWh) is used to meet this demand.

Efficiency is defined as L/C. The inverse, Energy Input Ratio EIR is often more convenient to use.

Then C = EIR.L

Clearly, over some longer period of time the total consumption is simply the sum of the consumption during different time periods. [2]

$\sum C = \sum (EIR.L)$

and we can define an overall EIR as $\sum C / \sum L = \sum (EIR.L) / \sum L$

Note that, if we express the equation in terms of efficiency instead of EIR, the overall efficiency is the harmonic mean of the individual efficiencies. (That is the reciprocal of the sum of the reciprocals)

[1] For many boilers, efficiency at 30% and 100% of rated output is known in order to comply with the Boiler Efficiency Directive. Ambient temperature is not an issue.
[2] For simplicity subscripts denoting the range over which summations are made are not shown

More generally, when L is zero, there may still be an energy consumption. In this case EIR is infinite and efficiency zero (irrespective of the size of the no-load consumption). Denote such zero-load consumption as C_o .

$\sum C = \sum (EIR.L) + \sum C_o$

and overall EIR is $((\sum EIR.L) + \sum (C_o)) / \sum L$

EIR is a function of L and of heat rejection temperature: for air-cooled chillers outdoor temperature.

This calculation can, in principle, be carried out for each individual time step (say each hour) within the calculation period of interest. It can be simplified by determining the frequency of occurrence of each level of demand (and temperature) during the period of concern. This is the basis of "bin analysis". For example a "bin" might be defined as containing the number of hourly occurrences of a cooling load between 35% and 40% of the design cooling load of the building that are coincident with ambient air temperature between 24 C and 26 C.

Denote the frequency with which each condition occurs as F, and associate a value of EIR with each bin. Then (noting that the summation is now over frequency classes rather than hours)

$\sum C = \sum (F.EIR.L) + F_o.C_o$

The frequencies and the demands may be further combined to generate *demand weightings*, W = F.L

$\sum C = \sum (W.EIR) + \tilde{F_o}.C_o$

2.3 Seasonal performance indices

Seasonal performance indices can be calculated in the form of an ***overall EIR***, for the period, that is:

$(\sum (F.EIR.L) + \tilde{F_o}.C_o) / \sum L$

or

$(\sum W.EIR) + \tilde{F_0}.C_o) / \sum L$

The overall seasonal EER is the reciprocal of this overall EIR

A "mean partial-load factor" can be defined as

PLV_{av} = SEER/EER

This approach, combined with standardized part-load EIRs for different types of chiller, and for single-chiller systems where the chiller is carefully matched to the peak load, is used in reference (10)

2.4 Calculation of Representative EIRs

Each bin has to have an associated EIR value. However, each bin has a finite size (for example, from 45% load to 55% load) within which there may be significant variations of EIR – especially if the bin size is large.

Strictly speaking, the EIR for each bin should be calculated from the distribution of loads within the bin in the same way as the seasonal figure is calculated from the bin data. Pragmatically, it is rarely possible to do this, and it is necessary to estimate EIR by, for example, taking a value that represents the mid-point of the bin range, or the average of the values at the two bounding conditions for the bin.

2.5 Multiple Chillers

For systems with multiple chillers, a combined EIR value must be calculated for each bin, representing a combined EIR of all the operating chillers (and the load conditions on each – for example, one chiller at full output and a second one at 50% of full output). Note that this is *not* obtained by averaging EERs (unless the harmonic average is used) but by adding consumptions and determining the combined total consumption. The later worked example illustrates this.

2.6 Calculations for systems

The same theory may be applied to complete systems. In this case, it is convenient to subdivide the energy into two classes: auxiliary energy A (kWh) that is used principally for energy transfer (fans and pumps) and for controls; and direct consumption, C (kWh) (used for the generation of heating or cooling by chillers, boilers and their ancillary equipment). For system calculations, direct consumption depends not only on the on the efficiency of conversion of fuel or electricity to heat (or cold) but also on the efficiency of distribution of heat (or cold).

System EIR may be defined as the ratio between the total cooling (or heating) demands in the spaces being conditioned and the energy consumed by chillers or boilers. Auxiliary energy will be calculated separately (for example as a multiple of installed fan power and operating hours). [3]

Some distribution systems alter the frequency distribution of loads placed on chillers – for example by switching to full fresh air and no chiller operation when outdoor air temperatures are sufficiently low.

3. Practical Application

3.1 Background

Ideally the theory would be applied to data that are specific to the building and system under consideration, to the actual or expected pattern of use, and to the local climate. This requires detailed information on chiller performance [4] over a wide range of conditions, and detailed estimates of building cooling demand – from detailed simulation, for example. Such detailed information is rarely available, and simplifications have to be made. This section describes how this may be done in ways that are consistent with various levels of available data.

Simplifications fall into two related areas: chiller information and bin definitions.

Simplifications inevitably reduce the resolution of the calculation. However, the basic data will always be uncertain to some degree, and high theoretical resolution does not necessarily mean more precise or reliable results. For many applications, consistency of approach will be more important than fine degrees of apparent accuracy. For energy performance certification purposes, standardized assumptions will be necessary.

Figure 1 summarises the suggested hierarchy of decisions and simplifications.

3.2 Simplification of Load Frequency Data

Draft CEN standards (2) distinguish between dynamic building energy calculations, typically at hourly intervals, and simplified methods than generally work with monthly time intervals.

When building cooling demands are calculated on an hourly basis, the production of hourly bins (of joint demand and ambient temperature) is straightforward. Alternatively the calculated hourly loads

[3] Alternatively, EIR could be defined to include both direct and auxiliary energy consumption.
[4] Either from manufacturers' data or by detailed modelling. The characteristic time constants of chillers and packaged air-conditioners are usually such that it is difficult to define efficiency meaningfully for periods much less than, say ten minutes, while for some equipment, the variations of performance with load can be difficult to represent over periods much in excess of an hour.

can be used directly with chiller performance data if this is available. For standardised energy calculations, standardised weather data are obviously required.

When cooling demands are calculated monthly or annually a standardised set of load frequencies (or demand weightings) can be used. These could be generated in several ways, of which computer simulations of characteristic buildings under standardised weather conditions are perhaps the most satisfactory. Clearly, these standardised demand frequencies will best match those of the building under consideration if the simulations are for a similar building with a similar air-conditioning system, similar pattern of use and located in a similar climate.

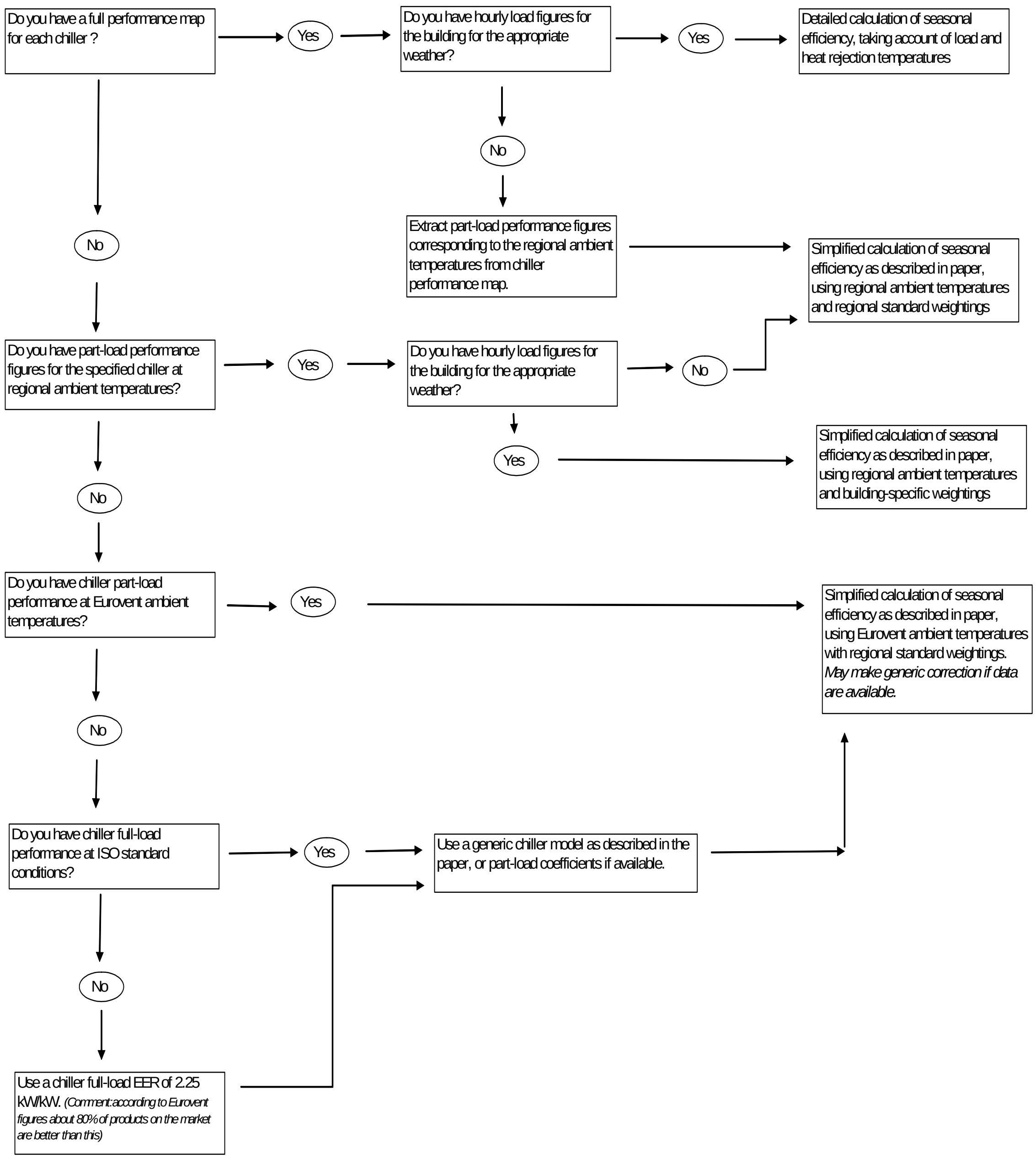

Figure 1. Hierarchy of simplification decisions

Since the efficiency of air-cooled chillers depends on ambient air temperature, the demand frequencies should ideally be accompanied by associated ambient air temperatures. Failing this, it may be possible to estimate ambient temperatures from the demand figures – the two variables are usually correlated, though imperfectly. The implications of inappropriate temperatures are discussed in the section dealing with chiller performance simplifications.

The EECCAC project (6) derived load frequency distributions from building energy simulations for a wide range of system types at three sites: London, Milan and Seville. As (7) points out, the loads placed on the chiller system can vary with the type of cooling system installed, as well as with weather and building design and use. Similar building energy simulations (using a different simulation tool) have been carried out for a wider range of building designs (though all offices) and locations, but for fewer systems, in the UK (3).

Figure 2 shows a sample distribution for an office in London, with a 4-pipe fan-coil cooling system.

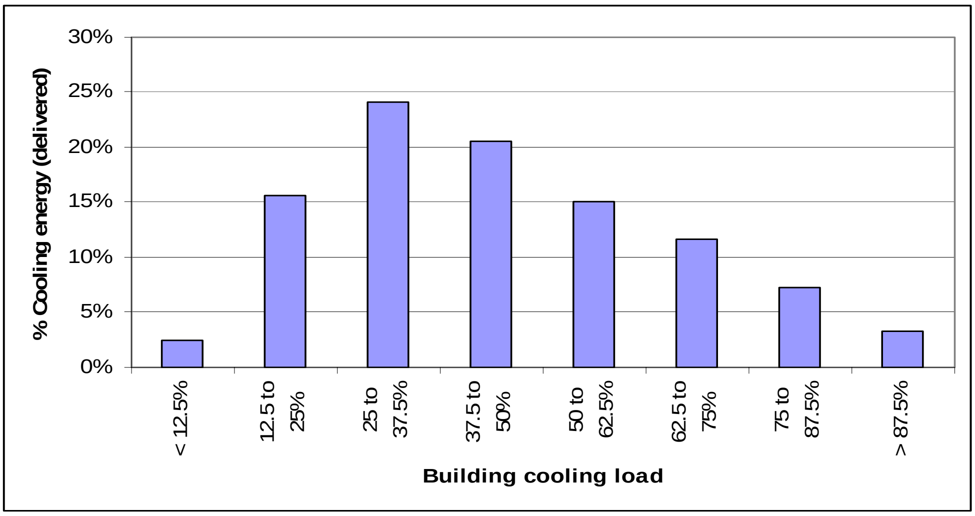

Figure 2. Example building load distribution.

3.3 Approximation of Chiller Performance Data

Ideally the chiller performance should be evaluated at each time step of the cooling demand calculation. This requires a full (and reliable) performance map for the chiller(s) that are installed or proposed. Some manufacturers are able to provide this information, but it is not always publicly available nor independently verified.

If a full chiller performance map does not exist, measurements under standard “full-load” conditions and some part-load conditions may be available.

The EECCAC project concluded that a minimum of four demand weightings (each associated with an ambient temperature representing the mean value associated with these load conditions) was necessary to distinguish between chillers of differing performance. The US IPLV rating (4) also uses four part-load conditions. Values were determined by the EECAC project for a range of climates and systems. For a fan-coil system located in London, they were:

Table 2 Example Demand Ratings

Relative frequency of occurrence (% of operating hours)	Cooling demand as percentage of design load	Relative demand weighting (frequency of occurrence x proportional demand)	Mean ambient temperature associated with demand
60.8%	25%	42.3 %	16.1
34.9%	50%	48.5 %	20.1
4.2%	75%	8.7 %	24.6
0.2%	100%	0.5 %	27.6

There are several existing and proposed sources of chiller performance information under conditions other than full load standard test conditions. For example Eurovent is proposing to include part-load tests into its certification programme (5). Draft CEN standard prCEN/TS 14825 describes part-load tests, as does Italian standard UNI 10963. ARI standard 550.590 defines four part-load tests required for the ARI IPLV rating; and the EECCAC project proposes European tests equivalent to the ARI tests.

The particular temperature conditions prescribed for the part-load tests will not be appropriate for all climates (7) and cannot apply to each individual chiller in a multi-chiller installation with the chillers operating in sequence. Manufacturers may be able to provide sufficient information to interpolate to appropriate national or regional temperatures, where these are known. If this is not possible, data relating to the “wrong” temperatures has to be accepted. A limited number of calculations on the impact of using ESEER temperatures – which reflect Southern European conditions – in the UK suggests that the error will be of the order of 5% to 10%. As it will always be in the same direction (better efficiencies, reflecting the lower summer temperatures in the UK), the impact on equipment selection choices is probably not great. (With the caveat that chillers with free-cooling capability might be under-valued).

Sometimes only full-load performance under standard test conditions is known. For many chillers this information is available from Eurovent Certification, most readily accessed via www.ukepic.com. Under these conditions, part-load performance values have to be estimated using generic models. For example using the procedure previously used in ARI standards (8) (current ARI standards require part-load testing), or that proposed by Bettani et al (9). Reference (10) contains standardized part load performance factors for several types of chiller and room conditioner.

When no information is known about the chiller (for example in existing systems or in the initial stages of design), it will be necessary to use a default value for full-load performance, and apply the generic part-load estimates mentioned above. From Eurovent certification data the EER of the average European air-cooled air-conditioning chiller is about 2.5. Approximately 80% of chillers have values above 2.25, so this could be a suitable default assumption

3.4 Suggested Data Sources

This section summarises key points from figure 1 and from the preceding discussion.

EER values: in order of preference:

1. Part (and full-) load EERs measured under climatic conditions appropriate to the application. For example, suitable ambient temperatures have been defined for London, Seville and Milan by the SAVE project EECCAC. Some manufacturers have full performance maps of equipment that includes this level of detail, but this information is not always publicly available or independently verified.

2. Part (and full-) load EERs measured under standardised conditions, even though these are not an ideal match for the local climate. Eurovent intends to require such measurements at 25%, 50%, 75% 100% rated output for standardised European conditions for its certification scheme. (ref)

3. Measured full load EER in accordance with CEN (and ISO) standards, with default assumptions for part-load performance.

Load frequency distributions: in order of preference

1. Building and system-specific distributions calculated typically from hourly values.

2. Standard national or regional values. For example, the weightings derived for London, Seville and Milan by the SAVE project EECCAC.

4. Illustrative Example of Estimation of Seasonal EER

This example illustrates the processes of:
- determining load frequency distributions
- determining multi-chiller EER from data for single chillers
- mapping the chiller rating data onto the load frequency distribution
- estimating seasonal EER

The general principles illustrated here are applicable to any set of chiller or boiler part-load conditions and sizing. In practice it may be convenient to build the process into software such as a spreadsheet. Suggestions for data sources are made at the end of this section.

4.1 Load frequency distributions

Either from load calculations for a specific building, or a standard national or regional assumption, we have a *frequency* distribution of different fractional cooling loads (where 1 = the peak load). For energy calculations, we need to convert this into an energy demand distribution, by multiplying the frequency by the part-load fraction. This generates a *load-weighted* distribution. In the chart below, the frequency distribution for an office in the UK is shown as a broken line, and the load-weighted distribution as a solid line.

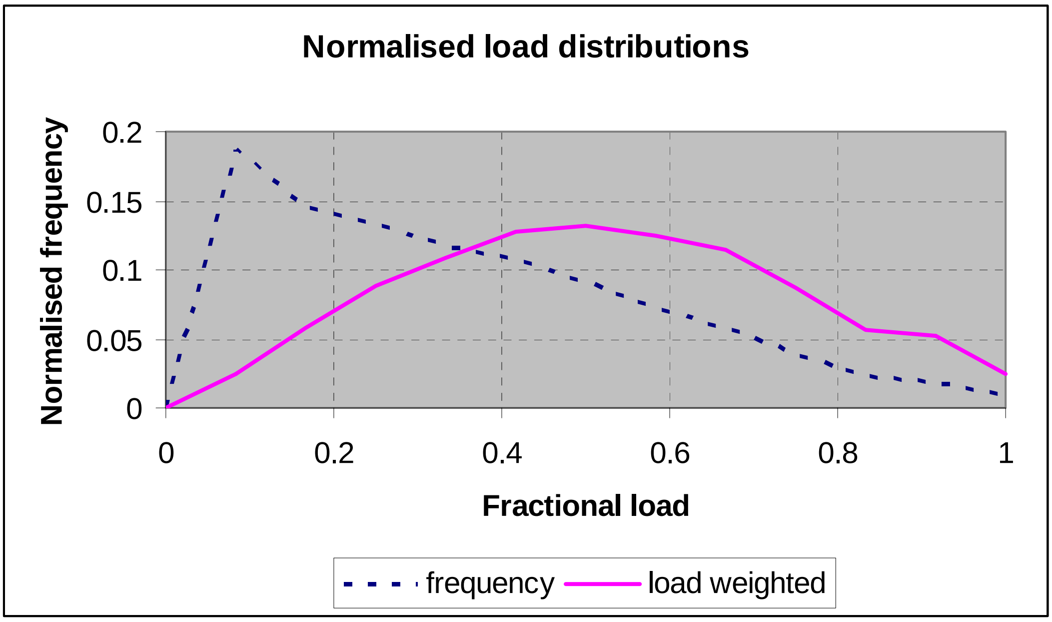

Figure 3: Normalised Load Distribution

For later stages in the calculation, it is convenient to convert the load-weighted distribution into a cumulative distribution as shown below.

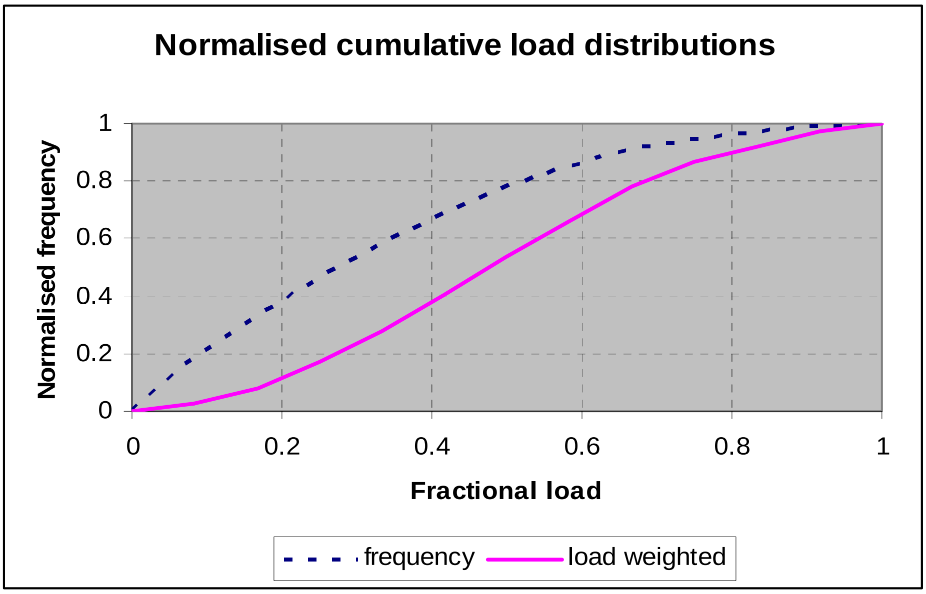

Figure 4: Normalised Cumulative Load Distributions

4.2 Combined chiller performance

In the example, we assume two identical chillers, each capable of providing 75% of the peak load, operating in sequence, each with part-load performance values of

Table 3:

% part-load	EER
100	2.8
75	2.7
50	2.5
25	2.0

With two chillers we therefore have eight combinations for which we can calculate an EER. [5] These are shown in the table below . Because the example system is oversized, three of the conditions are for loads in excess of the peak load.

When both chillers are operating, the combined EER is determined by dividing the relative demand on each chiller by the appropriate EER, summing the total consumption and dividing the result by the total demand.
Thus with 1 chiller operating at 100% output and the other at 25%, we have
Chiller 1 consumption = 1/2.8 = 0.357
Chiller 2 consumption = 0.25/2 = 0.125
Total consumption = 0.482   Combined EER = 1.25/0.482 = 2.59

[5] If the chillers do not operate in sequence, the procedure has to be modified accordingly.

Table 4:

Chiller 1 fractional load	**Chiller 2 fractional load**	**Chiller 1 EER**	**Chiller 2 EER**	**Combined EER**
0	0	N/A	N/A	N/A
0.25	0	2.0	N/A	2.00
0.5	0	2.5	N/A	2.50
0.75	0	2.7	N/A	2.70
1	0	2.8	N/A	2.80
1	0.25	2.8	2.0	2.59
1	0.5	2.8	2.5	2.69
1	0.75	2.8	2.7	2.76
1	1	2.8	2.8	2.80

4.3 Mapping the chiller ratings on to the load frequency

Each of these chiller rating points maps onto the building's load frequency distribution, as shown in Figure 5 as solid vertical lines:

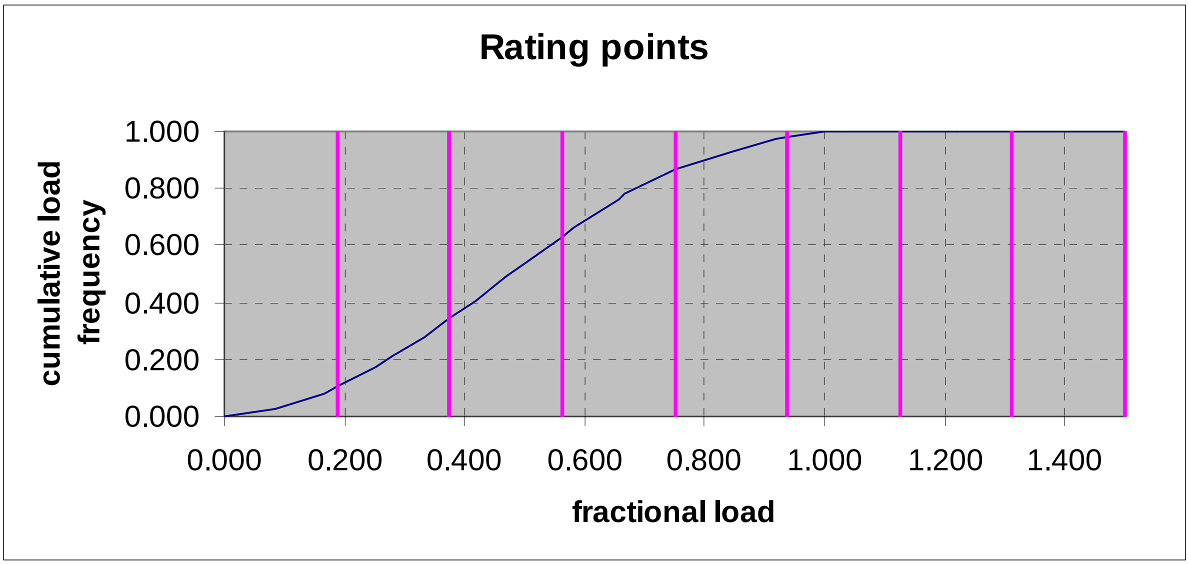

Figure 5:

We need to associate each rating point with some proportion of the cooling energy demand. We do this by first finding the *building* fractional load that is midway between each chiller rating point. This divides the frequency distribution into a number of bands, each of which contains one chiller rating point. (The lowest band has a lower limit of zero building load). This is illustrated in Figure 6, where the band boundaries are shown as broken vertical lines.

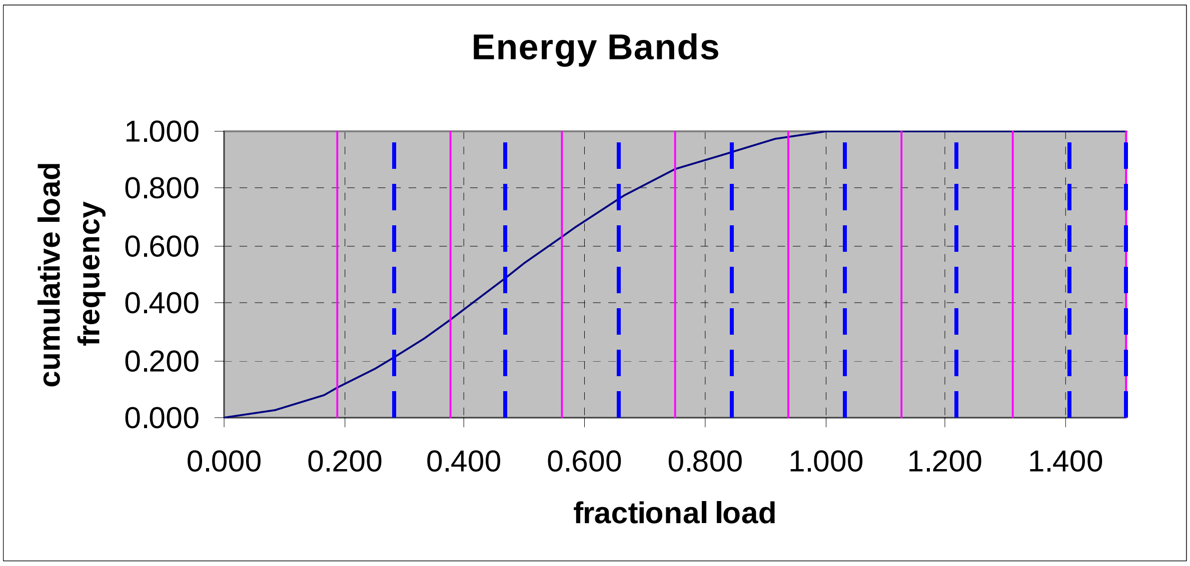

Figure 6

The weighting for each rating point is the difference of the cumulative loads at each of the two boundary conditions. (It may be necessary to interpolate between known values of the load frequency distribution to determine these values).

We then have to divide each demand weighting by the appropriate EER to calculate the total consumption and can then derive the seasonal EER.

The process is illustrated in the table below.

Table 5:

Chiller 1 fractional load	**Chiller 2 fractional load**	**Building fractional demand**	**Demand weighting for the demand level**	**Combined EER**	**Energy consumption**
0	0	0	0	N/A	0
0.25	0	0.188	0.104	2.00	0.0520
0.5	0	0.375	0.238	2.50	0.0952
0.75	0	0.563	0.290	2.70	0.1074
1	0	0.750	0.234	2.80	0.0836
1	0.25	0.938	0.115	2.59	0.0444
1	0.5	1.125	0.019	2.69	0.0071
1	0.75	1.313	N/A	2.76	N/A
1	1	1.500	N/A	2.80	N/A

Total (normalised) energy consumption = 0.3897
Combined seasonal EER = 1/0.3897 = 2.57

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