3. State of the art for energy use calculation methods for heat pump systems

3.1 Introduction (context of energy performance calculation methods and standards)

3.1.1 Context/Background

The need for energy performance calculation of heat pumps is a consequence of the evolution of legal requirements and available technologies concerning the energy performance of buildings. A similar trajectory can be observed in most advanced countries in the world.

Taking Europe as an example, before the first oil price shock in the years 1970s, there were no or little regulations about the energy performance of buildings. The first oil shock in 1973 triggered a wave of regulations that focused on heating and on limiting the installed heating capacity. The supporting standard was the heat load calculation, which is still used for basic sizing purpose (EN 12831 (CEN, 2017b)).

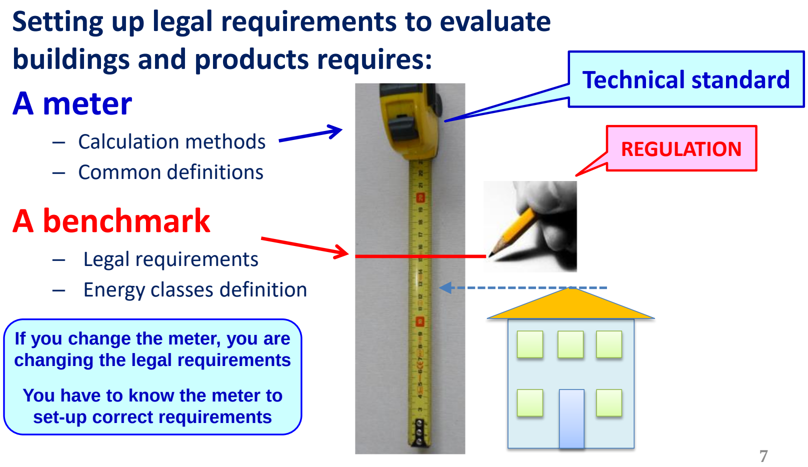
Besides the cost, the concern about resource depletion triggered attention on the energy performance. The next step around the years 1980s to 1990s were regulations limiting the energy need for heating, involving only the building envelope. The requirement applied to new buildings and the supporting standard was EN 832. The calculation of building envelope energy need for heating and cooling was soon standardised at the highest level (ISO) and EN 832 evolved as EN ISO 13790 and now EN ISO 52016-1:2017 (CEN, 2017a).

In the next decade (years 90s) technical systems were included in the energy performance calculation, starting with heating and domestic hot water systems. This was considered by local (national or regional) standards. Since technical systems may use several energy carriers, the concept of weighted energy was introduced. Initially, non-renewable primary energy was used as a reference, sometimes implicitly just to compare fossil fuels and electricity.

Then, the concern about energy performance was extended to include all comfort services (cooling, ventilation, dehumidification, lighting) and ultimately, following installations of PV panels, also exported energy had to be considered somehow. The extension to other services is justified because heating needs can be dramatically reduced by building envelope insulation whilst the other comfort services are little or not at all influenced by the building envelope properties (e.g. domestic hot water).

Now the new objective of decarbonisation implies that fossil fuel energy carriers be dismissed. Unless synthetic fuels are produced in significant amounts from non-fossil and carbon free sources, electricity will be the fundamental energy carrier to supply energy to buildings and the nearly obliged choice for space heating and cooling and domestic hot water preparation is heat pumping. Direct electric heating is inefficient compared to heat pumping and should be limited to small and localised loads.

Energy performance calculation methods are a fundamental supporting tool because any regulation that sets energy performance requirements needs a “meter”, so that buildings can be evaluated and compared to the requirements, whichever the purpose. As shown in Figure 3.1.1-1, the meter is the calculation method that provides the energy performance of the building to be compared with the regulated value.



Setting up legal requirements to evaluate buildings and products requires:

A meter

- Calculation methods
- Common definitions

A benchmark

- Legal requirements
- Energy classes definition

If you change the meter, you are changing the legal requirements

You have to know the meter to set-up correct requirements

Figure 3.1.1-1. The complementary role of regulations and calculation methods (technical standards)

The calculation method may also provide performance indicators for specific parts of the building (sometimes called “partial performance indicators”) to support the regulation of renovation work and/or to complement the overall energy performance requirement of the building to avoid efficiency trade-off between different parts. Examples of partial performance indicators are the energy need of the building envelope and the seasonal performance factor of a heat pump, which may be both regulated to avoid trade-off between envelope insulation and heating system efficiencies.

The calculation method can be detailed directly in the regulation, or the regulation may refer to technical standards, such as national or international standards (EN and ISO). The calculation method shall be stable because any change in the calculation method causes implicitly a change in the requirement, if requirements are not updated accordingly.

The calculation of the energy performance to demonstrate compliance and get a building permit is a common practice in most EU countries since years 1990s.

The first EPBD (energy performance of buildings) Directive 2002-91-CE established the obligation for all EU member states to:

- establish a calculation method of the energy performance of buildings;
- set minimum energy performance requirements for new buildings;
- require an energy performance certificate stating the amount of energy required to provide a standardised comfort level with standard climatic conditions and building use so that the building's energy performance becomes a factor in the real estate market when selling or renting.

The intent of the Energy Performance Certificate is to display the energy performance of the building when selling and renting so that it is part of the economic evaluation of the building. This mechanism makes the energy efficiency not only a regulatory requirement but also a market opportunity (higher value of the building).

The EPBD Directive left Member States with the freedom to choose their own calculation methods, provided they considered a list of influencing factors. This is because several EU countries already had their own methods in place for several years and the market of buildings is local. Unlike products, building do not travel across national boundaries and also building professionals usually operate on a local scale. So, there was not a strong feeling for a need of a unique European calculation and evaluation method. The argument of “national specific conditions” was always used to delay uniform EU calculation methods. It must be noted that energy performance calculation methods concerning the building envelope are almost uniform across Europe: EN 832 (and then EN ISO 13790 and now EN ISO 52016-1) (CEN, 2017a) are used everywhere. A variety of methods flourished especially for technical systems and for the final energy weighting, leading to quite different indicators (in terms of both quality and quantity) across EU countries. This variety of methods is even more evident for new technologies like heat pumps.

EPBD Directive evolved. The first recast (a new version is issued, the old is cancelled) of directive 2010/31/UE, introduced the concept of NZEB (nearly zero energy buildings) which was set as the target for new buildings.

In 2018, the EPBD was amended and the concern for the variety of calculation methodologies was first addressed. The EU Commission could not impose a common method, but each member state had to compare its calculation method with a set of so-called “overarching” EN standards.

A further recast of the EPBD directive has been approved in May 2024 and it will change the target to “zero emission buildings”, coherently with the general decarbonisation objective. The decarbonisation has huge impacts at a global scale but also on the individual building scale. The currently available energy carriers are listed in Table 3.1.1-1.

Table 3.1.1-1. Energy carriers and decarbonisation.

Energy carrier	Notes
Natural gas	To be dismissed
Oil	To be dismissed
LPG	To be dismissed
Electricity	No emission where used. Should be produced with renewable and carbon free sources. Available in every building
Biofuels	Available in a limited quantity. Biofuels require large plants for their production
Hydrogen and synthetic fuels	Should be produced with renewable and carbon free sources

The consequence of the decarbonisation is that the first three carriers must be dismissed. In several EU member states, natural gas and fossil fuels are already banned from new buildings and the EPBD recast is encouraging fossil fuels dismission in the whole EU. On the long run, this means that fossil fuel boilers will be phased out and cannot be used any more.

Biofuels can be available only in limited quantities. Hydrogen and synthetic fuels are still experimental. So, it is expected that in the short term, the heat pump will become the main heat generator for new buildings and, on medium term, it will be the main generator for existing buildings as well.

In several EU countries, there are already requirements that oblige to install heat pumps in new buildings with few exceptions (biofuel boilers, efficient district heating).

The urgent need for reliable heat pump energy performance calculation methods is therefore obvious.

3.1.2 Challenges

3.1.2.1 General challenges for energy performance calculation methods

To support regulations, the energy performance calculation methods should be:

- reasonably accurate;
- comprehensive, i.e. covering all relevant applicable technologies;
- applicable, that is based on available building and product data;
- understandable by practitioners;
- objective;
- software proof.

The overall accuracy is hard to evaluate because of the huge number of input data and of the uncertainty on each one of them. As an order of magnitude, an uncertainty up to 10% is expected or desired. The evaluation of accuracy is hard because in most cases there is no “real value” or “experimental value” to compare, due to the random influence of climate and use of the building. The evaluation is often done by comparing with other models that are assumed to be more accurate.

Comprehensiveness is required because since the calculation method is the tool to fulfil legal requirements (e.g. to get a building permit or a permit of use), failing to cover a technology means that this technology is de facto not allowed or its contribution will not be recognised for regulatory purpose. This is relevant, especially for technical systems, that may have several variants.

Applicability is an issue especially for technical systems, where the choice of the calculation model imposes the required input data. A coordination is needed between developers of building energy performance calculation methods and developers of product testing procedures. This is rarely the case with technical systems. Heat pumps are precisely an example of this issue.

Energy performance calculations are performed using software. Practitioners shall still be able to understand the methods so that they are aware of what is calculated by the software. They are held responsible for the result of the calculation that determines an authorisation from public authorities, so they must be in control of the calculation process. Calculation methods shall be objective, i.e. unbiased. If not, the comparison between alternative solutions would be incorrect and unfair.

Being software proof is an emerging requirement for calculation methods. Calculating the building energy performance implies several calculations, which are not feasible in the daily routine of professionals without the help of a computer. An Excel file can be enough only for very simple buildings and monthly methods, for research or software validation purpose. Complex buildings and hourly methods require the use of software. Developing the software based on standards requires that the method is fully unambiguous and that the chain of equations is complete.

All software models have inherent limitations. It is important that users understand the limitations of inputs and applications, so that they can ensure the answers are reasonable; unfortunately, it is too common that users simply trust complex simulation software to be “correct” and often make fundamental errors in the software’s use. Having full insight into the calculation method and being able to experiment would enable users to get a better feeling of capabilities, limitations, input requirements and sensitivity of the method. Additionally, tools should be developed to help validate both software processes and individual software results, providing cross-checks on basic parameters

All these requirements must be balanced when designing calculation methods.

To tackle some of these challenges, in the CEN environment, those responsible for drafting calculation methods are required to provide an Excel file for demonstration, verification, validation, quality assurance and education purposes.

3.1.2.2 Specific challenges on heat pumps energy performance calculation

The modelling of heat pumps, which are expected to become the main generation technology to provide space heating, raises several specific challenges.

- The performance of the heat pump is extremely sensitive to operating conditions and the efficiency spread is at least 1 to 3 in the expected operating range (whilst it is =+/- 10…15% for boilers).
- There are several types of heat pumps, depending on source and sink types (air, water, etc.), basic technology (vapor compression, absorption, etc.), which implies a variety of calculation options to achieve comprehensiveness.
- There are multiple internal control options (compressor speed, fan speed, etc.) and external control options (cut-off temperatures, priorities, etc.) that can significantly impact heat pump performance.
- The availability of standardized product data is limited and not finalized to energy performance calculation.
- Operating conditions are related to other parts of the calculation. The connection may imply iterations or approximations (e.g. exhaust air pump performance depends on temperature and flow rate of available exhaust stream.
- Products which are providing simultaneous heating and cooling are appearing on the market, which requires to integrate the calculation methods for the heating and cooling functions.

The increasing role of automation and controls, not to mention AI, is providing another layer of complexity. The compromise between simplicity versus accuracy is therefore hard to achieve for heat pumps.

3.1.2.3 Expected outcome of a "heat pump module"

The heat pump calculation is just a "module" within (a section of) the overall building energy performance calculation. Like any generation sub-system module, its objective is to answer the following three questions for each calculation interval (month, hour or bin):

- can the heat pump provide the heat supply (or heat extraction) required by the attached systems?
- what are the required inputs?
- are there secondary outputs (e.g. recoverable heat)?

In other words, given:

- the duration (hours) of the calculation interval;
- the required energy output (kWh) for each service (heating, cooling, domestic hot water);
- the required operating conditions for each service (e.g. leaving water temperature, room air temperature);
- the product data (hp properties and performance map);
- the system control options;

the heat pump module must calculate:

- the part of the required energy output that can be provided by the heat pump and/or the integrated back-up heater;
- the required driving energy;
- the required auxiliary energy;
- the recoverable heat, if any, is available and considered.

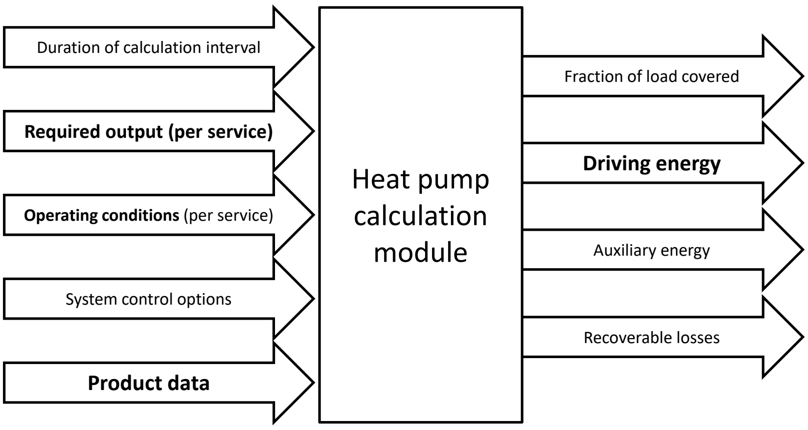


Figure 3.1.2-1. Inputs and outputs of a generic heat pump calculation module. The font size highlights the relative importance of input and output data

The duration of the calculation interval does not matter, unless the time interval is much shorter than 1 hour. One hour is already much longer than the expected transients of heat pump operation. Therefore, no dynamics is expected in a heat pump hourly calculation module. Figure 3.1.2-1 shows some inputs and outputs of a typical heat pump calculation module[4].

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[4] The most common calculation interval in the European countries is still monthly. There is a progressive shift to hourly calculation method (due to the necessity to handle increasing automation, intermittent operation, and interaction with the grid). The most likely next step might be a 15 minutes calculation interval, to align with the electric grid metering based on 15 minutes sampling. Even for this option, the internal dynamics to the heat pump is much faster and likely to be neglected.

3.2 Heat pump energy performance basics

3.2.1 Definition of energy performance indicators and common parameters

3.2.1.1 Energy performance indicators

The heat pump is a machine that forces the transfer of heat:

- from a cold medium (the “source”) at a lower temperature;
- to a hot medium (the sink) at a higher temperature.

The driving energy adds to the transferred heat on the sink side.

The efficiency of any machine is defined as the ration of a useful effect to the resource needed to get it.

For any heat pump in heating mode:

- the useful effect is the heat output to the sink;
- the resource used is the amount of driving and auxiliary energy that is needed to run the heat pump.

This ration is usually called COP (coefficient of performance). The energy captured from the external environment (from outdoor air, water, or ground) is not included, because it costs nothing.

For any heat pump in cooling mode:

- the useful effect is the heat extracted from the source;
- the resource used is the amount of driving and auxiliary energy that is needed to run the heat pump.

This ration is called EER (energy efficiency ratio).

NOTE 1 depending on the context, COP may be used for both heating and cooling, whilst EER is reserved for cooling.

NOTE 2 In the US, which uses primarily IP units, COP and EER refer to a different convention of measurement units. COP is expressed as a ratio of like units (thus is the same as in SI units) whilst EER is expressed as Btu/(W·h) so it is on a different scale: EER in SI units = EER in IP units x 3,412.

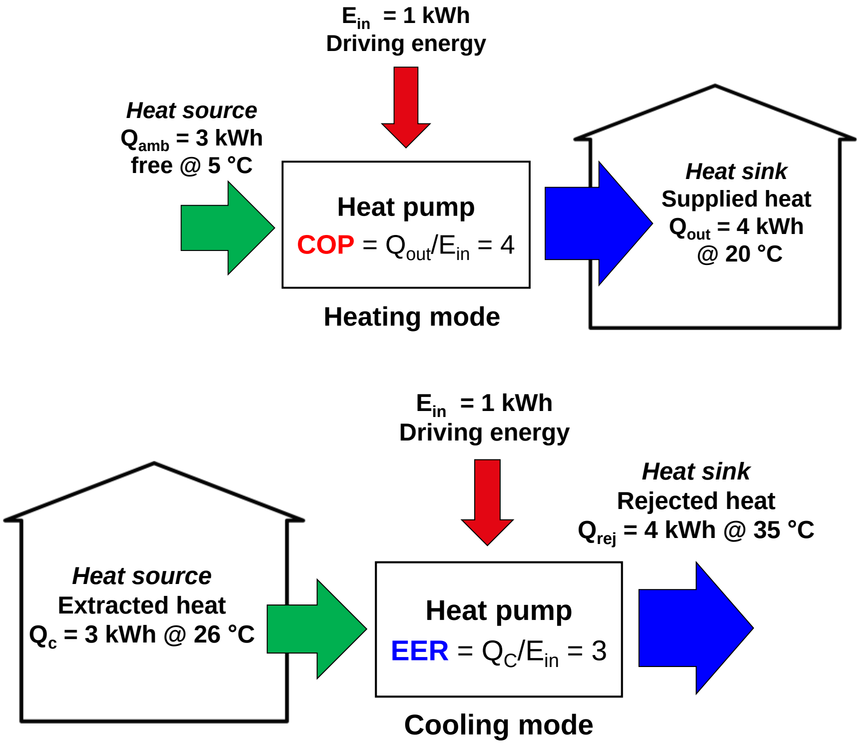

Figure 3.2.1-1. The basic definition of COP and EER

The basic definition of COP and EER is straightforward, but there are several possible variants depending on the considered time-span and scope of COP and/or EER evaluation (see Figure 3.2.1-1).
The instantaneous value of COP or EER is a ration of instantaneous power in a given operating condition whilst the average value of COP or EER in a time span (hour, month, bin, season, …) is a ration of cumulated energies over a defined calculation period.

$$\boldsymbol{instantaneous\ COP} = \frac{\boldsymbol{\Phi_{out}}}{\boldsymbol{\Phi_{in}}} \qquad \boldsymbol{instantaneous\ EER} = \frac{\boldsymbol{\Phi_{c}}}{\boldsymbol{\Phi_{in}}} \tag{3.2.1.1}$$

$$\boldsymbol{average\ or\ seasonal\ COP} = \frac{\sum_i \boldsymbol{Q_{out,i}}}{\sum_i \boldsymbol{Q_{in,i}}} \qquad \boldsymbol{average\ or\ seasonal\ EER} = \frac{\sum_i \boldsymbol{Q_{c,i}}}{\sum_i \boldsymbol{Q_{in,i}}} \tag{3.2.1.2}$$

COP and EER can be based on either calculated or measured data.
Concerning the scope, in principle it can be the entire “heat pump” device, but it can be restricted to the compressor or enlarged to include auxiliary devices such as the integrated back-up heater, the heat source or heat rejection auxiliaries.
Concerning the services provided, the scope can be heating, domestic hot water, cooling, or a combination thereof.
Figure 3.2.1-2 provides an example of different possible scopes according to the part of the installation which is being evaluated:

- HP is the heat pump scope that considers only the driving energy W_{hp} (electricity to the compressor) and internal auxiliaries $W_{aux,int}$ (e.g. evaporator and condenser fans of an air to air heat pump);
- whilst GEN is the “generation scope” that includes external auxiliaries $W_{aux,ext}$ (e.g. circulation pumps) and back-up heater input W_{bu}.

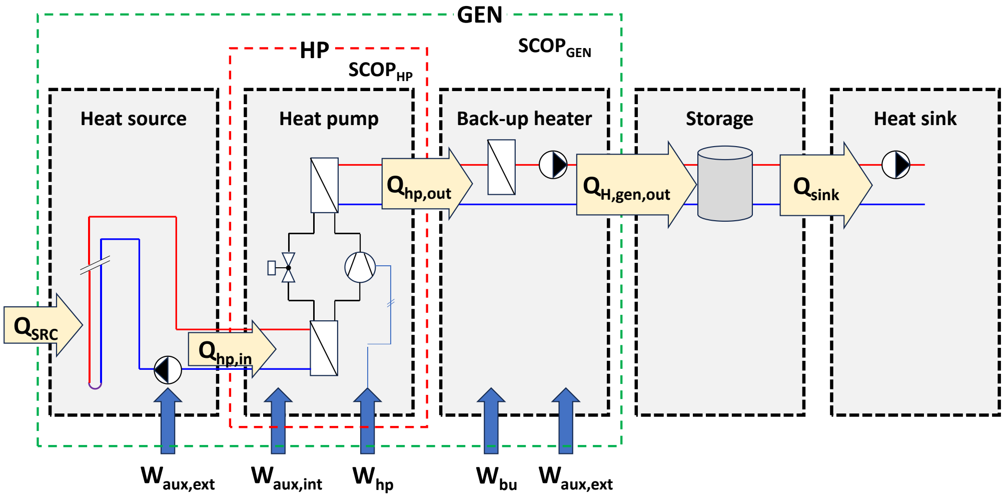

Figure 3.2.1-2. Example of possible scopes of COP and EER

When reporting a COP or EER value, all the boundary conditions must be clearly stated.

- A mere statement such as “*the COP of the hp is 3,0…*” means nothing.
- A complete statement should be (for example) “*the calculated seasonal COP of the heat pump for the heating service, including all auxiliaries, is X …*”. For a seasonal COP, the climate assumptions must also be clearly specified.
- When reporting instantaneous COPs and EERs, a code can be added to indicate the type and temperature of source and sink, like A7W35. Unfortunately, this coding does not indicate the applicable part load, which is also significantly influencing the instantaneous efficiency of a heat pump.

In general, the quality of the reference to boundary conditions in the technical documentation of products is poor, e.g. relying on notes specifying the applicable operating temperatures and load for the specified efficiencies.

Building energy performance calculation methods shall provide seasonal values of the COP and EER according to the GEN boundary of Figure 3.2.1-2, based on product data which are instantaneous data related to HP boundary.

3.2.1.2 Common parameters (product data)

The properties of the heat pump are defined by a series of parameters, such as:

- maximum capacity and part load range;
- temperature limitations for both source and sink (operating range);
- declared efficiencies in a set of operating conditions, which are often stated as declared capacities and input power across those conditions.

The maximum capacity of the heat pump is relevant for sizing and to assess if it can provide the required services in the calculation interval. The maximum capacity may depend on:

- evaporation temperature;
- maximum driving power (control limitation for inverter type heat pumps);
- condensation temperature.

The maximum capacity is not well defined in the EN standards. EN 14511 (BSI, 2018) only defines a “nominal capacity” which is stated by the manufacturer. Even though this is mostly interpreted as nominal capacity = maximum capacity, this is not always the case.

The part load range (or the minimum output power with continuous operation) is seldom declared by the manufacturer. This information is important because:

- on off cycling has detrimental effects on both efficiency and life span of heat pumps;
- turndown ratio is limited (1:2 to 1:3) compared to other generators, like e.g. boilers that easily reach 1:5;

- oversizing and the increase of maximum power at the extreme outdoor temperature for AA and AW heat pumps brings to frequent on-off cycling.

The operating range of the heat pump applies to assess if it can provide the required services. Example of such limitations are:

- minimum source temperature may be critical in cold climates (no heating available in the coldest days);
- maximum sink temperature may be critical based on the design of the indoor distribution system, or to provide domestic hot water service. Thermal cycles for legionella prevention may require a back-up heater;
- maximum source temperature may be critical (depending e.g. on refrigerant used) for domestic hot water service in temperate and warm climates (e.g. no domestic hot water is available if outdoor temperature exceeds the maximum operating temperature of the condenser).

Efficiency (COP) depends strongly on influence factors (see next clause). Any declared efficiency value shall be accompanied by operating conditions information such as source temperature, sink temperature and load factor.

Conventionally efficiencies are reported with tags like “A7W35” that specify the type and temperature of source and sink. However, this convention lacks an indication about the load factor at which the COP was measured. A tagging like A7W35P100 could incorporate the information that the declared COP is for full load (provided there is a clear definition on “full load”- see next clauses).

3.2.2 Influence factors

3.2.2.1 Introduction

Calculating the energy performance of a heat pump means considering the effect of significant influence factors, like:

- source and sink temperatures;
- part load operation;
- system control options;
- auxiliary energy use;
- defrosting.

3.2.2.2 Source and sink temperatures

The sensitivity to source and sink temperature is in the range of 2 to 3% per °C temperature change.

The source from which to extract heat for heating or to which to reject heat for cooling may be:

- external air;
- exhaust air;
- internal air;
- ground;
- ground water;
- surface water;
- special devices like solar collectors.

Source and sink temperature is a data input coming from:

- climatic and environmental data, for outdoor air, groundwater, surface water, that cannot be controlled;
- results of other parts of the calculation for ground coupled heat exchangers, exhaust air, indoor air, that can be controlled only to some extents by system sizing and operation mode;
- results of other parts of the calculation for required leaving water temperature that can be controlled by system sizing and operation mode.

3.2.2.3 Part load

Since part load is defined as the ratio of actual load to full load, before defining part load, full load must be defined. For heat pumps, full load capacity is a moving target (because it depends on evaporation temperature and maximum driving power) and a clear definition of full load is not yet available in the EN and ISO standards. It is sometimes assumed that “nominal load” is “full load” but for several products, there are different values for “maximum load” and “full load” at different operating conditions.

“Full load” should be the maximum heat power output under given operating conditions (source and sink temperature). The first issue is that full load capacity depends mainly on the evaporation temperature (hence on the cold source temperature) and somehow also on the condensation temperature (sink temperature). A possible definition of part load is the ratio of actual required capacity (actual load) to the maximum capacity at the same operating conditions (CR, capacity ratio).

Instead of using a moving target, EN 14825 (BSI, 2022) defines part load as the ratio of actual load to a fixed power P_{des} (“design power”) which is just a reference power to set test conditions, adding to the uncertainty.

The second issue is that the full load capacity may be limited by internal controls of the heat pump to avoid compressor and power supply overload or to improve efficiency. In this case, it is important to understand that limiting the maximum capacity by controls has implications on the turndown ratio.

Additionally, part load operation can be:

- either continuous operation at reduced power (e.g. reduced compressor drive frequency);
- or intermittent operation (on-off cycling) at a given minimum power.

These two modes require different calculation procedures.

The impact of part load operation on efficiency is because of several causes:

- compressor performance decay at lower loads;
- energy lost for each start-up of the compressor during cycling;
- change in temperature drop across evaporator and condenser heat exchangers, as detailed in the next clause.

When modulating (inverter technology), the change in temperature drop across heat exchangers may have a positive effect (may, because this effect depends on the control strategy of the fan, see next clause), so that part load operation may be initially beneficial until compressor efficiency decays and intermittency losses prevail and COP eventually drops at low loads. Given that most of the time heat pumps work at part load, this is challenging to consider correctly.

Intermittent operation is characterised by at least two parameters:

- duty cycle, that is the fraction of time with compressor ON. The output power is mostly determined by this parameter;
- cycling frequency, that is how often the compressor starts and stops. The decay in COP looks mostly related to this parameter.

Figure 3.2.2-1 illustrates these concepts.

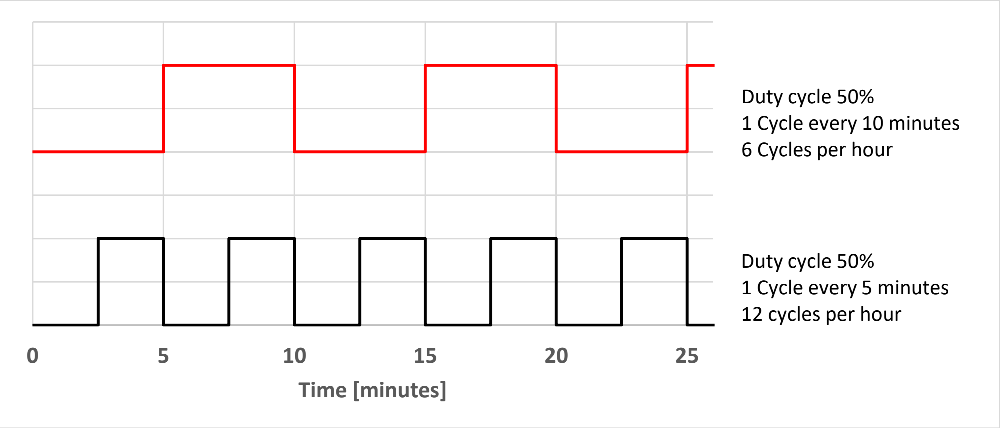

Figure 3.2.2-1. Example of different cycling frequency with the same duty cycle

Both operating modes shown are characterised by a 50% duty cycle, meaning that the average power is approximately 50 % of the power when ON in both cases. However, the operating condition with a higher

frequency of start stops (i.e. a shorter cycle time) is less efficient (because each start stop causes e.g. depressurisation of circuits) and causes compressor wear (poor lubrication during compressor start).
The cycling frequency is determined by several factors such as:

- available volume of water for the heat pump and flow rate in hydronics systems;
- volume and geometry of the conditioned room for air-based system;
- control settings of both heat pump and installation.

which make the evaluation difficult since they depend highly on building and systems design choices.

3.2.2.4 Temperature difference of external fluids across evaporator and condenser

An additional hidden challenge is the fact that, for practical purpose, operating conditions are defined according to the available and accessible source and sink temperatures, like:

- external air (or ground loop) temperature as source temperature for heating mode and sink temperature for cooling mode;
- room air or leaving water temperature as sink temperature for heating mode and source temperature for cooling mode.

However, the relevant temperatures that define the operating conditions of the thermodynamic compression cycle are the evaporation (source side) and condensation (sink side) temperatures.
This is shown in Figure 3.2.2-2.

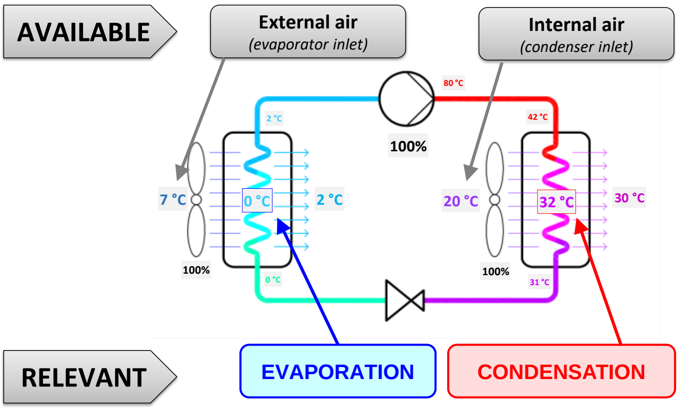

Figure 3.2.2-2. Example of the relationship between available temperatures and relevant temperatures for an air to air heat pump in heating mode

There are two main possible contributions to the difference between available and relevant temperatures.

- The temperature difference between inlet and outlet of the external fluid across the evaporator and the condenser.
  Figure 3.2.2-2 shows that external air is entering the evaporator at 7 °C (the available information) but it leaves the evaporator at 2°C. To allow capture of heat with a reasonable flow rate, a temperature difference of 5°C is required.
  Similarly, indoor air is entering the condenser at 20 °C (the available information) but it leaves the condenser at 30°C. To allow release of heat with a reasonable flow rate, a temperature difference of 10°C is required on this side (typically higher than on the external side for comfort reasons).
- Any heat exchanger has an approach, that is a residual temperature difference between the fluids that are exchanging heat. In Figure 3.2.2-2, the evaporation temperature shall be 2°C below evaporator

outlet temperature to capture heat from external air and condensation temperature shall be 2 °C higher than condenser outlet to allow heating indoor air to 30 °C[5].

This is a huge impact, especially for air-to-air heat pumps. Taking as an example the operating conditions shown in Figure 3.2.2-2:

- The maximum theoretical COPin transferring heat from an environment at θ_C=7°C (source) to another at θ_H=20 °C (sink temperature) COP_{Carnot,src_snk} is 22,5, as shown in equation (3.2.2.1).

$$COP_{Carnot,src\_snk} = \frac{\theta_H + 273,15}{\theta_H - \theta_C} = \frac{20 + 273,15}{20 - 7} = 22,5 \tag{3.2.2.1}$$

- The practical maximum theoretical COP ($COP_{Carnot,max}$) due to the temperature differences on the heat exchangers is only 9,5 because the compressor must transfer heat from the evaporation temperature θ_{evap} = 0°C to the condensation temperature θ_{cond} = 32 °C, as shown in equation (3.2.2.2).

$$COP_{Carnot,max} = \frac{\theta_{cond} + 273,15}{\theta_{cond} - \theta_{evap}} = \frac{32 + 273,15}{32 - 0} = 9,5 \tag{3.2.2.2}$$

- Since the current technology achieves approximately 45 % of the Carnot COP (this is the “exergetic efficiency” η_{exe}, that is the ratio of the actual COP to the corresponding theoretical Carnot COP), the expected COP according to evaporation and condensation temperatures is 4,3 and not 10,1 as expected according to source and sink temperature. This is shown in equations (3.2.2.3) and (3.2.2.4).
  - Expected COP according to source and sink temperature $COP_{exp;src\_snk}$:

$$COP_{exp,src\_snk} = COP_{Carnot,src\_snk} \cdot \eta_{exe} = 22,5 \; x \; 0,45 = 10,1 \tag{3.2.2.3}$$

  - Expected COP according to evaporation and condensation temperature COP_{exp}:

$$COP_{exp} = COP_{Carnot,max} \cdot \eta_{exe} = 9,5 \; x \; 0,45 = 4,3 \tag{3.2.3.4}$$

The impact of the temperature difference across evaporator and condenser for this sample operating conditions is a 57% reduction of the COP, which is not negligible at all.

The magnitude and impact of the temperature differences across source and sink heat exchangers depends on:

- source and sink heat exchangers sizing;
- type of source and sink (for water sinks, the available temperature is already the outlet);
- required load;
- control strategy of the external fluid flow rate (e.g. evaporator and/or condenser fan speed control).

Considering the available temperatures instead of the relevant temperatures for the calculation therefore introduces a distortion which depends on the heat pump type. If this approximation is not acceptable, the calculation method may include algorithms to estimate evaporation and condensation temperatures, but this requires additional assumptions and data.

3.2.2.5 Control options

Despite its apparent simplicity, there are several control options of the heat pump system that significantly affect its performance.

Control options can be classified in several ways. One possible classification is according to the responsible for the set-up:

- user adjustable parameters that can be set by the end user;

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[5] The “external fluids” are those fluids from which heat is captured or to which heat is rejected by the refrigerant. The refrigerant (where evaporation and condensation occur) is separated from the external fluids (where available temperatures are measured) by heat exchangers that introduce temperature differences.

In total, for the given operating conditions, the temperature difference between sink and source:

- appears to be 13 °C (20 – 7) if calculated according to available temperatures;
- but is actually 32 °C (32 – 0) if calculated according to relevant temperature.

- control options and parameters that can be specified and set by the professionals involved in the heat pump installation, commissioning, maintenance, and operation (designer, operation and maintenance (O&M) staff);
- control options that are embedded into the heat pump firmware and that are only accessible by the manufacturer.

Examples of user adjustable parameters are:

- the temperature set-point of a heat pump domestic hot water heater;
- the operation time schedule.

User adjustable parameters are linked to the level of service (comfort level). The calculation method may handle them for energy auditing purpose. For regulatory purpose a standardised level of service is assumed for a fair comparison.

Examples of control options that are set according to the specific design are:

- the outdoor temperature reset of leaving water temperature;
- the bivalent temperature, that is the temperature at which a back-up generator is started;
- the hysteresis of on-off controls;
- building automation functions.

These control options should be specified in the design and/or during commissioning and considered in the calculation.

Examples of embedded control options are:

- the modulation range of the inverter heat pump;
- the fan speed control of source and/or sink when air is the external fluid;
- the defrosting logics.

Most energy performance calculation methods of heat pumps make a considerable number of assumptions and several control options are not explicitly considered. It is therefore important that products are tested with representative settings of controls.

3.2.2.6 Auxiliaries

The driving energy is feeding the heat pumping process. For vapor compression heat pumps, the driving energy is usually the electricity to the electric motor of the compressor. The declared COP or EER of a heat pump always includes the driving energy.

Auxiliary energy, as opposed to the driving energy, is used for tasks that help the operation of the heat pump. The main purposes of auxiliary energy are:

- circulating the external fluids across the evaporator and condenser;
- powering controls;
- heating the crankcase to avoid liquid refrigerant in the compressor.

For the purpose of the connection of product data with the calculation methods, auxiliaries are classified in two categories:

- ”internal auxiliaries”, which are already included in the declared COP or EER and shall not be calculated again;
- “external auxiliaries”, which are not included in the declare DOP and EER and therefore must be accounted for separately and added to get the COP within the “GEN” scope of Figure 3.2.2-2.

Example of internal auxiliaries are:

- the evaporator and/or condenser fan of an air coupled heat pump;
- control circuits.

Examples of external auxiliaries are:

- the lifting pump of a ground-water heat pump;
- the cooling tower of a water cooled chiller;
- the back-up heater energy.

A practical rule to identify internal and external auxiliaries is:

- Internal auxiliaries are under direct control of the manufacturer and are independent of the case specific installation. An example is the evaporator and/or condenser fan of an air coupled heat pump: it is part of the supplied machine and controlled by the manufacturer’s firmware. The manufacturer is totally responsible for the sizing of these auxiliaries.
- External auxiliaries are not under control of the manufacturer, and they depend on installation specific conditions. An example is the lifting pump of a groundwater coupled heat pump. The manufacturer does not know where the heat pump will be installed and which is the required lifting height.

There are also cases where the auxiliary energy of a component is considered partly internal and partly external. A frequent example is the circulating pump incorporated into a heat pump. The pump is controlled by the heat pump automation, but in the product testing, only the energy allocated to the pressure loss within the condenser is counted into the testing. This makes sense because the attached hydraulic circuit is not under the control of the manufacturer that tests the product.

Auxiliary energy use may be quite relevant for ground coupled systems, systems using groundwater and for heat rejection of air-cooled chillers.

There are no standardised ways to define the power of external auxiliaries and to account for their varying power according to load.

3.2.3 Connection with the overall building energy performance calculation

Due to the high sensitivity of the heat pump efficiency on the operating temperatures, it is important that the other parts of the calculation provide an accurate estimation of the source and sink temperature. Sink temperature (required leaving water temperature from the heat pump) calculation for hydronic systems depends on:

- heating terminals properties and sizing compared to the required heat output;
- heating circuits control options
- distribution temperature control options
- allowed operation time
- ratio of flow rate in the distribution and generation circuits.

If this is not calculated accurately, the calculated COP of the heat pump will be affected.

3.3 Current methods

3.3.1 EN standards

3.3.1.1 EN standards

In Europe, in the context of CEN, a set of standards has been developed to cover the calculation of the energy performance of a whole building. These standards were drafted following two mandates (financing) provided by the EU commission to support the EPBD directive implementation. The first set of EN standards for energy performance of buildings was published in 2007 and it has been revised in 2017. This set of standards is known as “EN-EPB standards” and Figure 3.3.1-1 shows its overall organisation in modules.

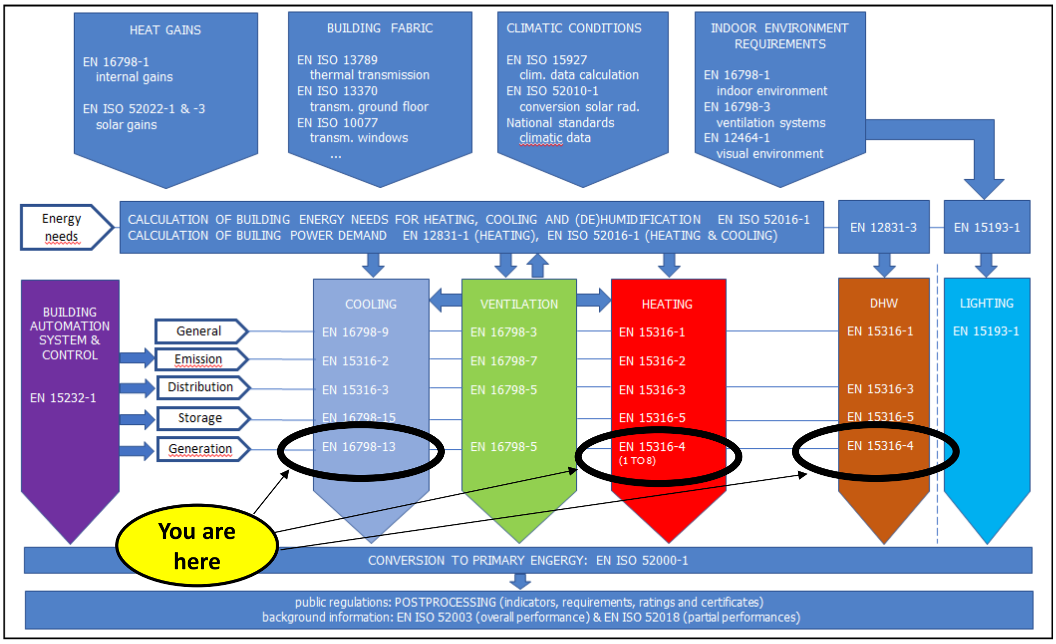

Figure 3.3.1-1. The structure of the set of EN–EPB. “You are here” balloon indicates the modules covering heat pumps for heating, cooling and domestic hot water)

Individual EN-EPB standards are developed to be a piece of the overall calculation. Therefore, their structure and formatting must comply with common technical and editorial rules given in the CEN Technical specification CEN-TS 16679:2014 (CEN, 2014) to ensure compatibility of modules and suitability for implementation by software developer (“software-proofness”). This includes common rules for:

- symbols, subscripts, and definitions;
- organisation of the text, with predefined clauses for output data and input data which must be listed and defined, including the source of input data and the intended destination of output data;
- explicating any option or choice by using “identifiers” to label them and avoid any ambiguity;
- supporting national customisation by providing a template for the required input data in normative annex A, whilst a default input data set is given in informative annex B to allow immediate use of the standard (but the default input data-set can be superseded by national application documents, since it is informative). In the ISO environment, this includes possible reference to supporting national standards;
- providing an XLS file, with a predefined structure (three sheets dedicated to input data, step-by-step calculation procedure, and output data respectively) to demonstrate and test the proposed calculation procedure;
- providing an accompanying technical report with all supporting information (informative contents).

EN 15316-4-2:2017 (CEN, 2017c) is the current module dedicated to heat pumps.
The whole package is not used “as is” in its entirety in any EU country, which is still free to have their own building energy performance calculation procedures for regulatory purpose.
Several EN-EPB standards, especially those concerning the building envelope like EN ISO 52016-1 (CEN, 2017a) (and related supporting standards) are in use in most EU countries. Some, like EN 15316-4-2 (CEN, 2017c) are not used as is but national experts participating in the EN committees introduce elements from the EN standards into their national calculation schemes.
A convergence process of EN and ISO standards in the field of energy performance of buildings is in progress since EN-EPB standards are being converted into EN ISO standards. Several EN-EPB standards, especially for the building envelope part and for heating and domestic hot water systems, are already EN ISO standards since they have been developed jointly under CEN lead. ISO already reserved a block of numbers (ISO 52000 series) to allow a complete coverage of the energy performance of buildings.

3.3.1.2 EN 15316-4-2: heating mode

3.3.1.2.1 Status

EN 15316-4-2 (CEN, 2017c) is the EN EPB module for the calculation of the efficiency of heat pumps in heating. The first release of EN 15316-4-2 was issued in 2007 and the current version was published in 2017.

A draft for a major revision was prepared and submitted to CEN public enquiry at the end of 2021. Because of the scope extension to cooling mode, the draft is currently being reworked again by an active task group in CEN-TC 228 WG4 (CEN, 2017d). The release for the second public enquiry is expected within the end of 2024.

The description in the following relates to the current draft of the revision.

3.3.1.2.2 Context

This standard was originally developed in 2007 when:

- heating systems in Europe were mostly water based;
- there was no other standardised information than rated COP and capacity at full load for the operating conditions defined in EN 14511 (BSI, 2018).

The later development of EN 14825 (BSI, 2022) for product rating purpose, required some static tests at part load conditions.

Given these two different sources of product data (EN 14511 (BSI, 2018) and EN 14825 (BSI, 2022)), two calculation methods have been developed within EN 15316-4-2 (CEN, 2017c):

- the so called “path A” is based on full load performance data according to EN 14511 (BSI, 2018);
- the so called “path B” is based on part-load data according to EN 14825 (BSI, 2022).

3.3.1.2.3 Output data

For each calculation interval, EN 15316-4-2 (CEN, 2017c) provides the following output data:

- the part of the required output that can be supplied by the heat pump (the remaining load has to be provided by another generator, if available);
- the required driving energy;
- the required auxiliary energy;
- the amount of heat captured from the environment (this is required in the EU context because legally it is accounted for as use of renewable energy);
- the recoverable heat released to the conditioned space.

These results are provided separately per each service provided by the heat pump.

3.3.1.2.4 Structure and rationale

The current draft EN 15316-4-2 (CEN, 2017c) applies the following procedure for each calculation interval.

- The required energy output per each service and the duration of the calculation interval are input data coming from EN 15316-1, the general part for heating and domestic hot water systems. This makes the module usable for monthly, bin and hourly calculation intervals. Some dynamic features, like allowing to provide in the next hour the missing heat for space heating because of a simultaneous domestic hot water requirement, are available only for the hourly calculation interval.
- The source temperature is determined according to the heat pump type, and it is assumed to be an input value, either climatic data for air source heat pumps or the result of a dedicated module for other sources like e.g. ground coupled heat pump. Simple models are proposed as default options.
- The sink temperature (e.g. required leaving water temperature for water heat pumps) is calculated for each calculation interval in the general part of heating and domestic hot water systems EN 15316-1.
- For direct expansion and condensation heat pumps, the room temperature and humidity also impacts the performance. In the EN environment, these data are available for an hourly calculation interval in EN ISO 52016-1.

- The EN environment can provide a reasonably accurate calculation of the required operating conditions for each calculation interval.
- Operational and control options (e.g. temperature limits of source and sink, service scheduling, control commands) are checked to decide if the required services can be provided in the calculation interval.
- Priorities are assigned if several services are required in the calculation interval. The most common by far is domestic hot water preparation, first at full load then space heating.
- Given the operating conditions, the maximum available output is calculated for each service. This calculation depends on the selected calculation path.
  - for path A, it is based on the interpolation of a performance grid (maximum power as a function of the combination of a given number of source and sink temperatures);
  - for path B, the maximum available power is assumed to be that at the declared bivalent point (a constant value, independent from source and sink temperature).
- Given the required output per service, the available maximum power, the total calculation interval duration and the priority rules, the operation time and the part load are determined for each service.
- The driving energy input is calculated for each priority. This calculation is performed according to a selected “path” (i.e. calculation method).
  The same procedure is repeated independently for each different operating condition required in the same calculation interval (e.g. space heating, domestic hot water preparation).
  - **Path A** is based on a performance grid of COP at full load at a given number of source and sink temperatures according to EN 14511 (BSI, 2018) (an example is shown in Figure 3.3.1-2).
    Firstly, the COP at full load $COP_{100\%,ci}$ (Equation 3.3.1.1) for the specific source and sink temperature in the calculation interval ci, is determined by interpolation of the full load performance grid.

$$\boldsymbol{COP_{100\%,ci} = f(\theta_{source,ci};\theta_{sink,ci})} \qquad (4.3.1.1)$$

    Then the $COP_{100\%,ci}$ at full load is corrected to consider the effect of part load operation and modulation type. There are currently several options to perform this correction, as described in the following clauses. The COP at the actual part load COP_{ci} in the calculation interval ci can be obtained by applying a multiplication factor or by adding a correction term, depending on the calculation options.

$$\boldsymbol{COP_{ci} = COP_{100\%,ci} \cdot f_{corr;COP}(LR) \quad or \quad COP_{100\%,ci} = COP_{100\%,ci} + \Delta_{COP}(LR)} \qquad (3.3.1.2)$$

    where LR in Equation (3.3.1.2) is the ratio of the required capacity to the maximum capacity in the same operating conditions.
    Finally, the required heat output for heating $Q_{H;hp;out,ci}$ is divided by the corrected COP_{ci} to obtain the required driving energy $E_{H;hp;out,ci}$:

$$\boldsymbol{E_{H;hp;in,ci} = \frac{Q_{H;hp;out,ci}}{COP_{ci}}} \qquad (3.3.1.3)$$

  - **Path B** is based on measurements of part load COP according to EN 14825 (BSI, 2022). Six testing points are defined, labelled A to G (see Table 3.3.1-1 for their definition), but only four with different source temperature, sink temperature and required power output $\Phi_{hp;out,X}$ are always available because of possible (and frequent) duplicates, such as bivalence point set as -7 °C so that A=F.
    For the available testing points X (A to G), the evaporation and condensation temperatures are estimated to get the exergetic efficiency $\eta_{exe,X}$ of the compressor.

$$\boldsymbol{\eta_{exe,X} = \frac{COP_X}{\eta_{Carnot}(\theta_{evap,X};\theta_{cond,X})} = \frac{COP_X}{\frac{\theta_{cond,X} + 273,15}{\theta_{cond,X} - \theta_{evap,X}}}} \qquad (3.3.1.4)$$

The exergetic efficiency η_{exe} of the compressor is the ratio of the actual COP to the ideal Carnot COP for the same evaporation and condensation temperatures.
It is assumed that the temperature differences between

- source temperature and evaporation temperature
- sink temperature and condensation temperature

are proportional to the require power output.
The effect of intermittent operation is included in the exergetic efficiency of testing points with a lower capacity than minimum continuous operation. It is then assumed that the exergetic efficiency of the compressor to be a function of the required power output only.

$$\eta_{exe} = f(\Phi_{hp;out}) \tag{3.3.1.5}$$

For any power between the two test points, the exergetic efficiency is found by linear interpolation.
Given these assumptions:

- the exergetic efficiency is found for the required power output
- and the COP is calculated according to evaporation and condensation temperature in the actual operating conditions in the given calculation interval.

Finally, the required output is divided by the COP to obtain the required driving energy.

- If the heat pump output does not fully cover the required heat for any service, the possible contribution of an integrated back-up heater is calculated.
- Required auxiliary energy for external devices, such as heat capture or rejection systems, is calculated. The required input data is the auxiliary power at zero, minimum and maximum load.
- Losses to the surrounding environment are calculated.
- Results are collected to provide the required calculation results per service.

3.3.1.2.5 Required input data

The basic input data for Path A is a couple of performance grids for capacity and COP at maximum load.
Source temperatures defined in EN 14511 (BIS, 2018) are -7, 2, 7 and 12 °C for air source heat pumps.
Additional external temperatures may be considered for cold climates and summer operation (e.g. for domestic hot water preparation).
Typical sink temperatures are 20 °C for air heat pumps and 35, 45 and 55 °C for water heat pumps.
Other source and sink temperatures are defined depending on the source and sink type.

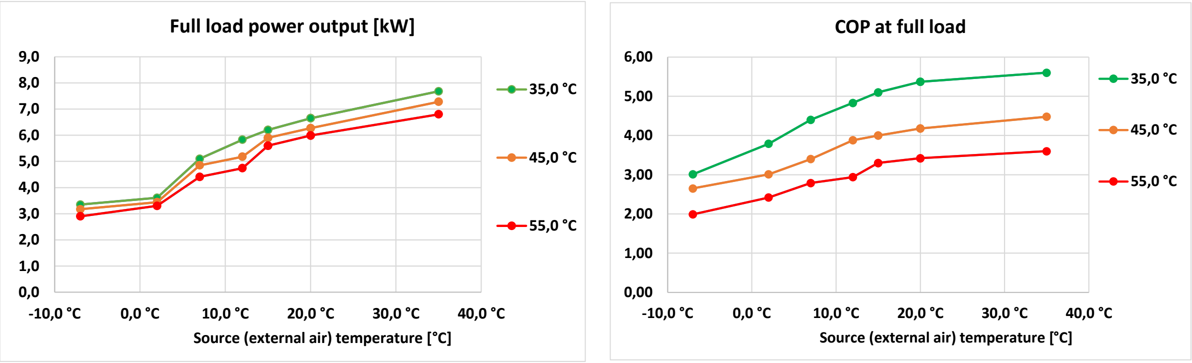

Figure 3.3.1-2. Sample full load performance grids according to EN 14511 for input to path A calculation of an air to water (AW) heat pump. Each curve is the maximum capacity or the COP of the heat pump as a function of the source temperature for a given flow temperature (LWT leaving water temperature).

3.3.1.2.6 Required input data for path B

The basic inputs for Path B are the measured COP and output power in 6 testing points according to EN 14825, some of which may be coincident. Table 3.3.1-1 shows the testing conditions (source and sink temperature) and a sample set of declared values (testing power and COP) for air to water heat pumps, modulating power, average climate, and low leaving water temperature (35 °C nominal). In the shown data-set, the manufacturer assumed a bivalence temperature (point F, BIV) of -7°C. Design external temperature (point E, DES) for the average climate is -10 °C.

Table 3.3.1-1. Test data according to EN 14825 for input to path B calculation. AW heat pump.

Point		**A**	**B**	**C**	**D**	**E** **DES**	**F** **BIV**
Source temperature	°C	-7	2	7	12	-10	-7
Sink temperature	°C	34	30	27	24	35	34
Testing power (Pd)	kW	4,6	2,9	1,9	1,9	4,2	4,6
COP (COPd)	-	3,21	4,66	6,56	8,49	2,25	3,21

Only this data set (average climate and low temperature) is used because it is mandatory for the purpose of product labelling. EN 14825 defines additional sets for different reference climates (warm climate and cold climate) and operating temperatures (medium and high) but they are optionally declared and therefore not used in the calculation. The method needs some small adaptations for the different heat pump types (AA versus AW, WW and WA).

3.3.1.2.7 Common input data to all calculation paths

Additional data required for all calculation paths are:

- descriptive data of the heat pump (e.g. type of source, main technology), to establish the calculation procedure options (namely the calculation path depending on national options);
- stand-by and crankcase heater auxiliary power in W;
- data on external auxiliaries (not included in the heat pump), usually in the shape of auxiliary power at stand-by and maximum capacity;
- maximum power of the back-up heater;
- energy carrier type for the heat pump and for the back-up heater;
- operation limits (minimum and maximum source and sink temperatures)
- control options (priority between services).

3.3.1.2.8 Correction for part load in path A

The draft EN 15316-4-2 (CEN, 2017c) contains several methods to correct the COP according to part load because there is still ongoing discussion about the most suitable method depending on the heat pump type. They are briefly discussed in the following.

The part load factor LR (load ratio) in path A is defined as the ratio of the actual required power output in the calculation interval to the maximum power output in the given operating conditions (source and sink temperature).

- Default multiplication factor of full load COP $f_{corr;COP}$(LR)

  This method assumes that the full load COP shall be multiplied by the correction factor $f_{COP;LR}$, which is a function of the part load ratio LR. The correction factor is assumed to be independent of any other operating conditions, that is $f_{COP;LR}$= f(LR).

  Default functions $f_{COP;LR}$= f(LR) are given for absorption heat pumps (single stage and modulating) and for combustion engine driven heat pumps.

The function may be presented as a table of values, then linear interpolation is used for intermediate values of LR.

A further possibility is to calculate the correction factor with equations 28 (air source heat pumps) and 29 (water source heat pumps) of EN 14825 (BSI, 2022), which use the Cd factor to adapt the shape of the curve.

Typical values for the default correction factor are given in Figure 3.3.1-3.

This method is deemed to be most suitable for heat pumps whose COP is not severely affected by part load, such as air to water and water to water heat pumps.

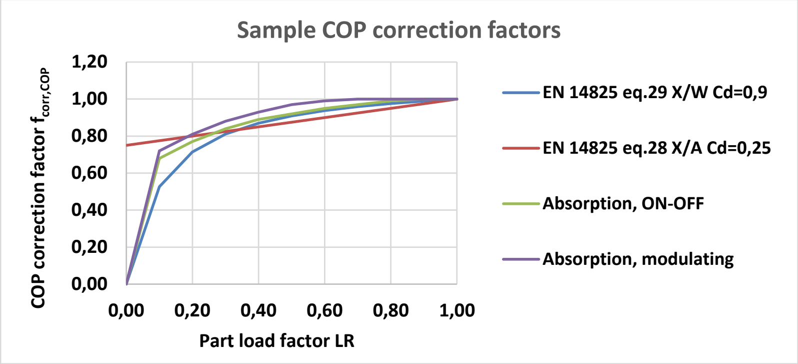

Figure 3.3.1-3. Sample COP correction factors $f_{corr;COP}$(LR)

This method does not require product data, since it is based on default functions. The parameter Cd can be optionally determined by the manufacturer according to EN 14825 (BIS, 2022).

- Default additive term Δ_{COP}(LR) (Figure 3.3.1-4)

  This method is taken from DIN V 18599-5 (DIN, 2016a) and it assumes a default additive term to COP for:

  - optimal load factor, assumed to be 60% of maximum load (LR = 0,60);
  - minimum continuous operation load factor (LR = 0,3…0,5).

  Default values of the additive term are in the following range:

  - for optimal load factor: +0,2…+0,4
  - for minimum continuous load: previous optimal correction term - 0,4…0,6

  At zero load (LR=0,0), the COP is assumed to be 0.

  For intermediate values of the load factor LR, the COP is interpolated linearly.

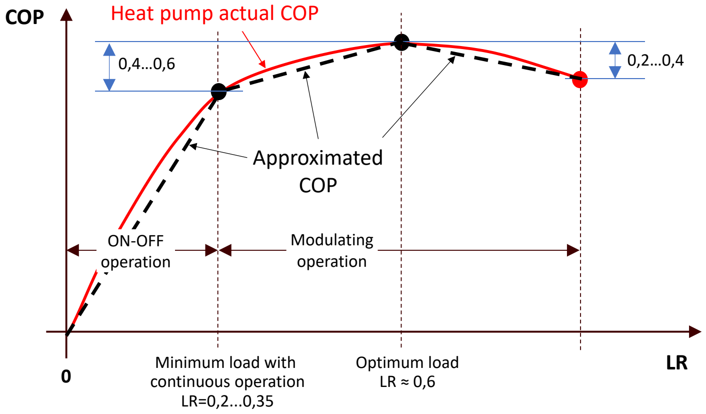

Figure 3.3.1-4. Δ_{COP}(LR) additive term according to DIN V 18599-5 (DIN, 2016a)

  This method is intended for air to water heat pumps.

- Constant internal auxiliaries and COP increase at minimum load

  This is the method that was included in the original EN 15316-4-2 in 2017 (CEN, 2017c). This method was taken from the French regulation RT 2012.

- First, the auxiliary energy included in the declared COP is separated from the driving energy. If not measured, this internal auxiliary energy is assumed to be 2% of the driving energy.
- The compressor COP is calculated, considering only the net driving energy. This results in a slightly higher compressor COP than the heat pump COP.
- It is assumed that the compressor COP will have a higher value at minimum modulation than at full load. There is a default correlation and several other proposals on how to estimate this increase, still under discussion. The result is in the range +10%…+30% for air to water heat pumps.
- When the load is in the range between minimum continuous operation and full load, the compressor COP is considered being linear with LR and the auxiliary power constant. Net driving energy and internal auxiliary energy are summed again to determine the heat pump COP at any part load.
- When the load is below the minimum for continuous operation,
  - either equation 29 of EN 14825 (BSI, 2022) is used to correct the COP at a minimum continuous load;
  - or the impact of intermittency is estimated according to a correlation that considers the transient during each compressor start and the type of heating terminals

  The resulting behaviour is illustrated in Figure 3.3.1-5.

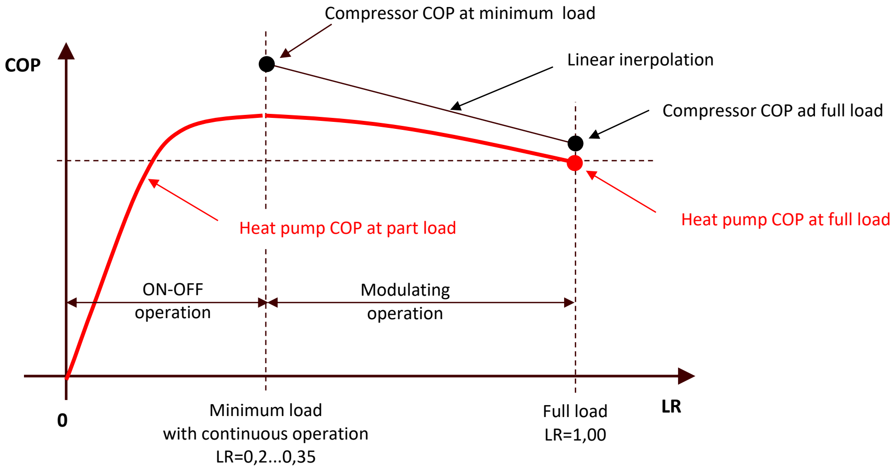

Figure 3.3.1-5 – Heat pump COP at part load for AW heat pumps with the constant internal auxiliary method of EN 15316-4-2:2017 (CEN, 2017c).

3.3.1.2.9 Sample calculation

The reaction of a calculation method to changing operating conditions can be shown by repeating the calculation for several intervals and changing one operating condition at a time. Figure 3.3.1-6 shows the calculated COP (red line, scale on the right) of an air to water heat pump with varying load (blue line, scale on the left), from 0 to 6,4 kW, for two leaving water temperature levels (30 °C and 40°C) and for three different external air temperatures (-8, 0 and +10 °C).

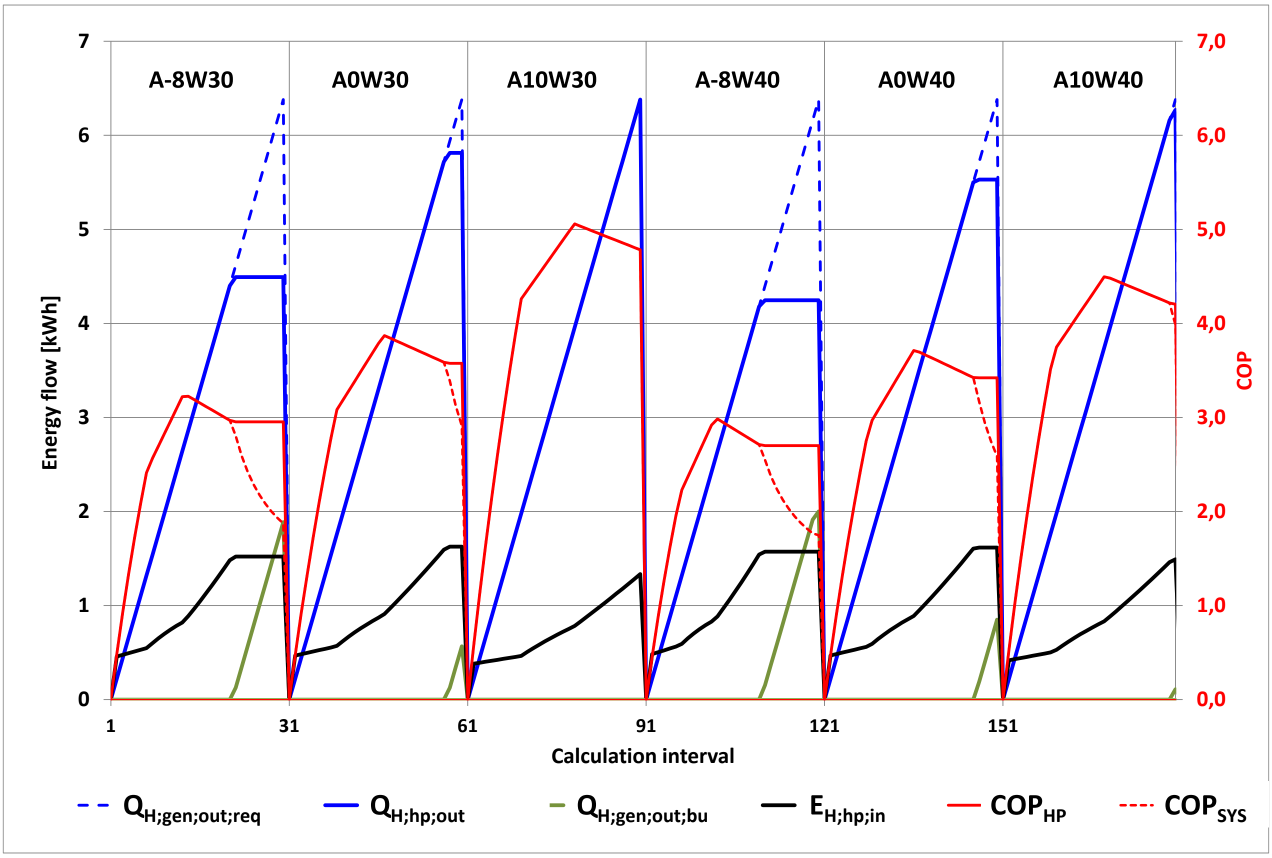

Figure 3.3.1-6. Sample calculation results

Each operating condition is identified by the code (e.g. A-8W30) on the top of the graph.
The calculation is repeated 30 times for each operating condition, linearly increasing the required heat output $Q_{H;gen;out;req}$, shown by the dashed blue line.
Depending on the air and water temperature, the actual heat pump output $Q_{H;hp;out}$, shown by the solid blue line, will be equal to the required amount and will cover it. When the maximum capacity of the heat pump is reached for the given operating conditions, the dashed blue line (required output) appears because it cannot be fulfilled by the heat pump. The graphs show clearly the high sensitivity of the maximum capacity to external temperature (A-8W30 versus A0W30 versus A10W30, maximum capacity is 4,5 kW, 5,8 kW and 6,6 kW respectively) and the smaller effect of leaving water temperature (e.g. A-8W30 versus A-8W40).
When the heat pump cannot provide the required output, the back-up contribution $Q_{H;gen;out;bu}$ appears, shown by the green line. Here, an electric heater is assumed, and the electricity input can be considered equal to the heat output.
The COP of the heat pump COP_{HP} is shown by the solid red line. Again, the strong influence of both operating temperatures and part-load operation is clearly visible.
When the heat pump cannot provide the required output, the generation system efficiency COP_{SYS} appears (dashed red line), Until there is no back-up required, COP_{HP} and COP_{SYS} are equal, and the solid red line (COP_{HP}) covers the dashed red line (COP_{SYS}). When the back-up contribution increases, the system COP drops quickly.
This kind of presentation is used to test and compare energy performance calculation methods.

3.3.1.2.10 Known issues

The main issue is the coordination between the tested product data and calculation methods. Product data should be defined according to the needs of the users of the data, i.e. in coordination with the calculation methods using those data. This happened for product testing and labelling (EN 14825) but did not happen for energy performance calculation, which has a different purpose and different data needs. Therefore, the energy performance calculation methods were developed with two alternatives to best fit the available data:

- Path A assumes that the effect of part load is independent of the source and sink temperature. There are uncertainties about how to evaluate the effect of part load and several methods are still under consideration for this feature. Path A looks suitable for AW and WW heat pumps where the sensitivity of COP to part load during continuous operation (not intermittent) is limited. Path A looks less suitable for air-to-air heat pumps where the effect of part load operation on COP can be much greater.
- Path B uses the data declared for product labelling according to EN 14825. There are only 6 data points, some of which may be duplicate, and at each point all operating conditions are changing. Additionally, they cover a marginal part of the operating range of the heat pump. Extrapolation to distant operating points has risks. Some manufacturers are willing to stick only to these points because they are already tested and declared for product classification purpose, but “safety” from official declaration does not compensate for inadequate data.

  Path B requires a specific procedure for each variant of heat pump configuration (e.g. air to air, air to water inverter type, air to water on-off type).

Other issues include:

- the effect of intermittent operation (start-stop duty cycle and frequency, see item 3.2.2.3), which is currently introduced via default correlations;
- the definition of auxiliary energy needs and its connection with part load operation;
- the variety of heat pumping technologies, sources and sinks makes it difficult to design a unique and comprehensive calculation method; extensions are required to cover additional types of heat pumps, not yet explicitly covered, like heat pumps with solar assisted evaporator;
- missing connection with heat pump water heaters test data;
- additional calculation procedures are needed for special sources like the ground coupled heat exchanger. These calculation procedures are not yet fully available in the CEN environment;

3.3.1.2.11 Foreseen developments

According to the comments received during public enquiry, this standard should be extended to cover cooling (chillers), either as an alternative or simultaneous service. This means that EN 16798-13 (CEN, 2017e) (see the following) should be incorporated into or referenced by the future EN 15316-4-2 (CEN, 2017c).
A CEN working group is actively working (2024) on the revision of the standard.

3.3.1.3 EN 16798-13 (cooling mode)

3.3.1.3.1 Status

EN 16798-13 (CEN, 2017e) is the EN-EPB module covering the heat pumps in cooling mode. The first version of this standard was published in 2017 by CEN TC 156.
Following a change in the respective scopes of CEN TC 156 and CEN TC 228 (CEN, 2017d), the contents of EN 16798-13 (CEN, 2017e) should be transferred and incorporated (with possible amendments) into the new revision of the EN 15316-4-2 (CEN, 2017c), which will cover the energy performance calculation of heat pumps in both heating and cooling mode.

3.3.1.3.2 Context and background information

As for heating mode, also for cooling mode there were and there are still two possible sources of product data in the EN environment:

- EN 14511 (BSI, 2018), providing performance data at “nominal” load;
- EN 14825 (BSI, 2022), providing performance data for a selected number of part load operating conditions.

The original intent was to develop a method based on the available data for product testing according to EN 14825 (BSI, 2022). Research was performed in 2009 by Swiss experts seeking a calculation method for chillers and the outcome (Zweifel, 2009) was that the four test points of EN 14825 (BSI, 2022) could not

provide enough information to build a comprehensive performance map. The conclusion was that at least one additional point was required to complete the calibration of the performance map.
The results of this research were considered and therefore EN 16798-13 (CEN, 2017e) included:

- a method based on EN 14825 data (BSI, 2022), but requiring information in an optional additional 5th point;
- methods based on EN 14511 data (BSI, 2018);

thus, replicating the situation of EN 15316-4-2 (CEN, 2017c) for the heating mode, with path A linked to EN 14511 (BSI, 2018) and path B linked to EN 14825 (BSI, 2022).

3.3.1.3.3 Output data

For each calculation interval, EN 16798-13 (CEN, 2017e) provides the following output data:

- the required driving energy;
- the required auxiliary energy;
- the part of the required cooling output that can be supplied by the chiller (the remaining load can be provided by another generator, if available);
- the amount of heat rejected to the environment;
- the recoverable heat for heating purpose and its maximum supply temperature;
- the recoverable heat released to the conditioned space.

3.3.1.3.4 Available methods

Similarly to EN 15316-4-2 (CEN, 2017c), EN 16798-13 (CEN, 2017e) includes several calculation options to make the best possible use of available data.

- Method 1 allows the use of product data according to either EN 14511 (BSI, 2018) or EN 14825 (BSI, 2022) and is intended for the calculation in hourly intervals or temperature bins and for all possible types of cooling generators.
- Method 2 allows the use of data from EN 14511 (BSI, 2018) only and is intended for monthly or hourly calculation intervals for chillers, split and VRV/VRF systems.

3.3.1.3.5 Method 1

3.3.1.3.5.1 Method 1 rationale

If available, the method starts with the evaluation of the contribution of free cooling operation, that is providing cooling directly with the heat rejection equipment and by-passing the compressor.
The fundamental equation to calculate the driving energy input $E_{C;ge;el;in}$ for the remaining load is simply:

$$E_{C;gen;el;in} = \sum_{j=1}^{n} \frac{Q_{C;gen;in,j}}{EER_j} \tag{3.3.1.6}$$

There is a sum in Equation (3.3.6) because this standard also handles the option of having several chillers (or compressors) operating in parallel, each providing the amount of cooling $Q_{C;gen;in,j}$. The index j is omitted in the following for simplicity. There are several options to calculate EER_j.[6]

3.3.1.3.5.2 Method 1 using EN 14825 data

The basic assumption is that the exergetic efficiency η_{exe} of the compressor is a 3rd order polynomial function of the part load factor $f_{C;PL}$.

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[6] NOTE This standard follows the physical flow of heat in the selection of subscripts. The “chiller output” is called $Q_{C;gen;in}$ because the cooling effect (the useful output of the chiller) is an incoming heat extracted from the distribution or from the installation room.

$$\eta_{exe}(f_{C;PL}) = C_1 \cdot (f_{C;PL})^3 + C_2 \cdot (f_{C;PL})^2 + C_3 \cdot (f_{C;PL}) + C_4 \qquad (3.3.1.7)$$

The constants C_1 to C_4 and the parameter $\Delta\theta_{corr}$, which is used in the following, are determined by solving a system of five linear equations whose coefficients are determined according to the test results. This requires five independent data to solve the system. Since the four test points of EN 14825 (BSI, 2022) are somehow “aligned” in the space of the operating conditions, for a good identification of the performance map of the chiller, the fifth testing point should be away from them (Zweifel, 2009 for more details). If no data is available form a suitable 5th point, EN 16798-13 (CEN, 2017e) provides the option to replace them with calculated data based on the previous 4 points.

The part load factor $f_{C;PL}$ is defined as the ratio of the required capacity to the actual maximum capacity of the chiller, depending on operating conditions.

$$f_{C;PL} = \frac{Q_{C;gen;in}}{Q_{C;gen;in;max}} = \frac{Q_{C;gen;in}}{\Phi_{C;gen;in;n} \cdot f(\theta_{rej}; \theta_{C;gen:in}) \cdot t_{ci}} \qquad (3.3.1.8)$$

The function $f(\theta_{rej}; \theta_{C;evap;out})$ describes the change in capacity depending on source (evaporation) and sink (condensation, rejection) temperature. For vapor compression chillers, the change in maximum capacity is estimated according to this default equation:

$$f(\theta_{rej}; \theta_{C;gen:in}) = f(\theta_{rej}; \theta_{C;evap;out}) = \frac{\dfrac{273,15 + \theta_{C;evap;out}}{\theta_{rej} - \theta_{C;evap;out} + \Delta\theta_{corr}}}{\dfrac{273,15 + \theta_{C;evap;out;n}}{\theta_{cond;in;n} - \theta_{C;evap;out;n} + \Delta\theta_{corr}}} \qquad (3.3.1.9)$$

where:

- $\theta_{c;evap;out}$ is the required leaving temperature from the evaporator;
- $\theta_{C;evap;out,n}$ is the leaving temperature from the evaporator in nominal conditions;
- θ_{rej} is the relevant rejection temperature, which is:
  - the external air temperature, for air cooled chillers;
  - the wet bulb external air temperature, for wet operation of water-cooled chillers;
- $\theta_{cond;in,n}$ is the inlet temperature to the condenser in nominal conditions;
- $\Delta\theta_{corr}$ is the additional temperature difference between evaporation and condensation due to heat transfer across the evaporator and condenser, which is calculated according to product data.

Assuming:

- $\theta_{C;evap;out,n} = 7$ °C
- $\theta_{cond;in,n} = 35$ °C
- $\Delta\theta_{corr} = 12$ °C

the resulting values of $f(\theta_{rej}; \theta_{C;evap;out})$ are shown in Table 3.3.1-2.

Table 3.3.1-2. Example of values provided by Equation 3.3.1.9.

			θ_{rej} °C				
			25	30	**35**	40	45
$\theta_{C;evap;out}$	°C	**7**	1,33	1,14	**1,00**	0,89	0,80
		12	1,36	1,16	1,02	0,90	0,81
		17	1,38	1,18	1,04	0,92	0,83

A correlation based on empirical coefficients is provided for absorption chillers.

If the part load factor $f_{C;PL}$ is lower than the minimum for part load operation $f_{C;PL;min}$, then this minimum value is used. This means that there is no correction for intermittent operation.

It is assumed that the additional temperature differences across evaporator and condenser is proportional to the load and the value in nominal conditions is $\Delta\theta_{corr}$.

The resulting equation of the EER of a vapor compression chiller is:

$$\boldsymbol{EER} = \frac{\boldsymbol{273,15} + \boldsymbol{\theta_{C;evap;out}}}{\boldsymbol{\theta_{cond;in}} - \boldsymbol{\theta_{C;evap;out}} + \boldsymbol{f_{C;PL}} \cdot \boldsymbol{\Delta\theta_{corr}}} \cdot \boldsymbol{\eta_{exe}}\left(\boldsymbol{f_{C;PL}}\right) \tag{3.3.1.10}$$

Again, an empirical equation with default coefficients is provided for absorption chillers.

Method 1 using EN 14825 data for cooling mode is based on a similar assumption, like path B of EN 15316-4-2 (CEN, 2017c) for heating mode: the compressor exergetic efficiency is assumed to be a function of the actual load.

3.3.1.3.5.3 Method 1 using EN 14511 data

Method 1 can also be used with product data, according to EN 14511 (BSI, 2018).

The evaluation of the maximum capacity is the same.

The EER is calculated assuming constant exergetic efficiency:

$$\boldsymbol{EER} = \boldsymbol{EER_n} \cdot \frac{\dfrac{\boldsymbol{273,15} + \boldsymbol{\theta_{C;evap;out}}}{\boldsymbol{\theta_{cond;in}} - \boldsymbol{\theta_{C;evap;out}}}}{\dfrac{\boldsymbol{273,15} + \boldsymbol{\theta_{C;evap;out;n}}}{\boldsymbol{\theta_{cond;in;n}} - \boldsymbol{\theta_{C;evap;out;n}}}} \tag{3.3.1.11}$$

where the subscript “n” identifies data at nominal (rated) conditions and the other terms have the same meaning as in the previous equations.

With this option, the EER is corrected according to operating temperatures only, and there is no influence of part load.

3.3.1.3.5.4 Auxiliary energy

External auxiliaries, such as heat rejection loop pumps and fans, may be quite relevant.

Reference is made to EN 15316-3 (CEN, 2017c) for the calculation of the auxiliary energy of any circulating pump for primary loop and/or heat rejection loop.

For other heat rejection equipment (e.g. cooling tower fans), EN 16798-13 (CEN, 2017e) assumes that the auxiliary energy use be proportional to the rejected heat power. The ratio is evaluated according to rated nominal values.

3.3.1.3.6 Method 2

3.3.1.3.6.1 Auxiliary energy

Method 2 is based on the correction of the rated EER according to several factors that are assumed to be independent of each other. The fundamental equation is

$$\boldsymbol{E_{C;gen;el;in}} = \frac{\boldsymbol{Q_{C;gen;in}}}{\boldsymbol{PLV} \cdot \boldsymbol{EER_n} \cdot \boldsymbol{f_{EER;corr}}} \tag{3.3.1.12}$$

where

- PLV, the “part load value”, incorporates the effect of part load operation of the compressor, rejection systems, free-cooling and cascade connection of multiple units;
- $f_{EER;corr}$ is a correction factor that takes into account the change in source and sink temperature. For vapor compression chillers the assumption is constant exergetic efficiency.

3.3.1.3.6.2 Required input data

The required input data is the rated efficiency EER_n according to EN 14511 (BSI, 2018) and a few operating parameters (e.g. source and sink temperature, auxiliary power, thermal power of the rejection system), all under nominal conditions.
Configuration and control options are also required as an input, like e.g. control mode of multiple generators, control mode of the heat rejection system.

3.3.1.3.6.3 PLV part load value

The part load value PLV is given by the equation:

$$\boldsymbol{PLV = f_{C;PL,k} \cdot f_{hr;PL} \cdot f_{hr;fc} \cdot f_{C;mult}} \tag{3.3.1.13}$$

The term $f_{C;PL,k}$ accounts for the effect of part load operation of the compressor.
The relative load $f_{C;PL}$ is given by:

$$\boldsymbol{f_{C;PL} = \frac{Q_{C;gen;in}}{Q_{C;gen;in;max}} = \frac{Q_{C;gen;in}}{\Phi_{C;gen;in;n} \cdot t_{op}}} \tag{3.3.1.14}$$

The relative load $f_{C;PL}$ is evaluated against the nominal capacity (instead of against the maximum capacity depending on operating temperatures, as in Method 1).
The values of $f_{C;PL,k}$ are given as a function of $f_{C;P}$ in default tables, depending on the type of chiller and on modulation options. As an example, the values of $f_{C;PL,k}$ for air cooled air conditioners are given in Table 3.3.1-3:

Table 3.3.1-3. Sample default part load factors.

Relative load $f_{C;PL}$	**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
Type of system	Part load factor $f_{C;PL,k}$									
On-off split system	1,34	1,34	1,34	1,34	1,27	1,23	1,16	1,09	1,02	0,95
On-off multi split system	0,68	0,73	0,77	0,8	0,86	0,93	0,95	0,97	0,94	0,9
Inverter split system	1,52	1,54	1,57	1,69	1,45	1,31	1,21	1,09	1,03	0,95
Inverter multi split system	0,77	1,18	1,42	1,55	1,54	1,46	1,35	1,19	1,06	0,92

It has to be noted that due to the position of the “part load factor” $f_{C;PL,k}$ in Equations (3.3.1.13) and (3.3.1.14):

- values less than 1 mean an increase in efficiency
- values higher than 1 mean a decrease in efficiency

The term $f_{hr,PL}$ accounts for the effect of part load operation of the heat rejection system. It is given by:

$$f_{hr;PL} = a_2 \cdot \theta^2 + a_1 \cdot \theta + a_0 \qquad (3.3.1.15)$$

where

- θ is a reference temperature that depends on the heat rejection type and location;
- default values of the coefficients a_2, a_1 and a_0 are given in the informative annex B of EN 16798-13 (CEN, 2017e).

The calculation of the reference temperature depends on the heat rejection system.

The term $f_{hr,fc}$ accounts for the effect of an optional free cooling system. If there is no free-cooling, then $f_{hr,fc}$=1 (neutral value). Otherwise default values are given in annex B of EN 16798-13 (CEN, 2017e).

The term $f_{C,mult}$ accounts for the effect of the presence of multiple compressors. If there is only one compressor, then $f_{hr,mult}$=1 (neutral value). Otherwise default values are given in annex B of EN 16798-13 (CEN, 2017e).

3.3.1.3.6.4 Auxiliary energy

Depending on the chiller type, external auxiliary energy (i.e. not included in the declared COP or EER), when relevant, is considered proportional to the rejected heat and is corrected according to part load factor and to free cooling operation. Default correction factors are provided in the informative annex.

3.3.1.3.7 Known issues

The connection with product data was a main concern. Despite the effort, most features of the calculation methods, such as the correction for part load and/or operating temperatures, are controlled by default equations and default coefficients depending on the heat pump type and control options. This cancels the comparison between products and hides their specific properties, good or bad.

The method was developed and checked on big water-based chillers. It looks less suitable for small air-to-air heat pumps.

3.3.1.3.8 Foreseen developments

EN 16798-13 will be incorporated into EN 15316-4-2 (CEN, 2017c), especially to handle simultaneous heating and cooling.

For methods relying on EN 14825 (BSI, 2022), the procedure with the 5th point is being replaced by the interpolation of exergetic efficiency of the test points with the same method as for heating.

3.3.2 EnergyPlus

3.3.2.1 Status

EnergyPlus (US DOE, 2024) has its roots in both BLAST and DOE-2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. BLAST was developed by the Construction Engineering Research Laboratory (CERL) and the University of Illinois while DOE-2 was developed by Berkeley Lab and many others. In the late 1990s, concerns about the limitations of BLAST and, both the metric and inch-pound versions, of DOE-2, along with the challenges of maintaining their outdated codebases, led to the decision to combine development efforts into a new program called EnergyPlus. The first release of EnergyPlus was in April 2001 (version 1.0) and has been under revision since then. The U.S. Department of Energy released the latest version (23.2.0) in September 2023.

EnergyPlus calculates the heating and cooling loads, indoor environment conditions, and equipment operations throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. It is the simulation engine around which a third-party interface can be wrapped. When using EnergyPlus for demonstrating compliance with ASHRAE Standard 90.1 (ASHRAE, 2022), an appropriate interface is usually used in order to choose models in EnergyPlus and parameters for the models, which are required to do the simulation according to ASHRAE Standard 90.1 (ASHRAE, 2022).

3.3.2.2 Context and background information

EnergyPlus is an open-source building energy simulation program based on BLAST and DOE-2 (US DOE, 2024). It works as a modular system integrated with a heat balance-based zone simulation with time steps of less than an hour. IEA BESTest building load and HVAC tested EnergyPlus based on the directives of ASHRAE 140 (Method of Test for Evaluating Building Performance Simulation Software) (ASHRAE, 2023). So far, the ASHRAE 140's tests show that EnergyPlus provides reliable results with a good fit compared with actual building envelope performance parameters.

3.3.2.3 Output data

EnergyPlus has several different types of outputs, but initially, the most important ones to understand are the tabular output reports that summarise the simulation results. These reports contain monthly and annual energy consumptions of a building's main systems and equipment (lighting, air conditioning, etc.), life cycle analysis parameters, and economics.

3.3.2.4 General structure

EnergyPlus models and allows the analysis of buildings' energy consumption and environmental impacts. Its structure and rationale provide detailed insights into building performance, aiding architects, engineers, and policymakers in making informed energy efficiency and sustainability decisions.

The following items briefly explain the EnergyPlus structure.

- Input Processing:
  EnergyPlus begins with the input processing stage, where users define the building geometry, materials, occupancy schedules, HVAC systems, and other relevant parameters using text-based input files. This step ensures the software accurately captures the building design's intricacies and operational characteristics.
- Simulation Engine:
  EnergyPlus simulation engine employs various algorithms and computational models to simulate the dynamic interactions between the building envelope, internal systems, and external environmental conditions. It calculates energy consumption, thermal comfort, indoor air quality, and other performance metrics over time.

- Output Generation:
  Upon completing the simulation, EnergyPlus generates comprehensive output reports, including graphical visualisations, tables, and text files, to present the results in a user-friendly format. These outputs allow stakeholders to analyse the performance of different building components and systems under diverse operating conditions.
- Post-Processing and Analysis:
  Users can further analyse the simulation results using post-processing tools or third-party software to extract insights, identify optimisation opportunities, and compare alternative design strategies. This iterative process facilitates the refinement of building designs to achieve higher energy efficiency and occupant comfort levels.

EnergyPlus rationale is listed below:

- Accuracy and Detail:
  EnergyPlus prioritises accuracy and detail in its simulation capabilities to provide reliable building performance predictions. Accounting for factors such as thermal mass, solar radiation, airflow, and occupant behaviour offers a realistic representation of how buildings behave under varying conditions.
- Flexibility and Customisation:
  The software's modular structure allows users to customise simulations to specific project requirements and research objectives. Whether modelling residential homes, commercial offices, or specialised facilities, EnergyPlus offers the flexibility to incorporate diverse building typologies and system configurations.
- Support for Decision-Making:
  EnergyPlus empowers users to make data-driven decisions regarding building design, retrofits, and operational strategies. By simulating the energy and environmental performance of different scenarios, stakeholders can evaluate the cost-effectiveness of various interventions and prioritize measures that yield the most significant energy savings and environmental benefits.

3.3.2.5 HVAC and heat pump energy calculation

In general, EnergyPlus represents HVAC equipment at various levels of detail and users can choose a particular model considering the complexity and available data for their simulation use case. The part-load performance of mechanical equipment, which is one of the requirements from ASHRAE Standard 90.1 (ASHRAE, 2022), is taken into consideration in EnergyPlus as shown in the following example for electric chillers. An example of energy calculation models for heat generator: Electric Chiller Model Based on Condenser Entering Temperature (object name Chiller:Electric:EIR) is presented in the EnergyPlus Documentation (US DOE, 2024)

This model simulates the performance and the power consumption of electric liquid chillers, such as reciprocating liquid chillers, centrifugal liquid chillers and screw liquid chillers. It also models the power consumption of condenser fans if modelling an air-cooler or evaporatively cooled condenser. This model does not simulate the thermal performance or the power consumption of associated pumps or cooling towers.

It is said that these model and associated performance curves are developed using performance information for a specific chiller and that they should normally be used together for an EnergyPlus simulation. It is also said that changing the model’s input values or swapping performance curves between chillers should be done with caution.

Power consumption ($P_{chiller}$) of an electric liquid chiller is calculated by the following equation:

$$P_{chiller}(W) = \frac{\dot{Q}_{ref}}{COP_{ref}} \times CFT \times EIRFT \times EIRPLR \times CCR \qquad (3.3.2.1)$$

where $\dot{Q}_{ref}$ is the chiller capacity at reference conditions for temperature and flow rates, COP_{ref} is the reference coefficient of performance, CFT is the cooling capacity factor as a function of temperature curve,

$EIRFT$ is the energy input to cooling output factor as a function of temperature curve, $EIRPLR$ is the energy input to cooling output as a function of part-load ratio (PLR), and CCR is the chiller cycling ratio, which is the coefficient to determine the power consumption below the minimum part load ratio.

$$CFT = a_1 + a_2(T_{cw,ls}) + a_3(T_{cw,ls})^2 + a_4(T_{cond,e}) + a_5(T_{cond,e})^2 + a_6(T_{cw,ls})(T_{cond,e}) \qquad (3.3.2.2)$$

$$EIRFT = b_1 + b_2(T_{cw,ls}) + b_3(T_{cw,ls})^2 + b_4(T_{cond,e}) + b_5(T_{cond,e})^2 + b_6(T_{cw,ls})(T_{cond,e}) \qquad (3.3.2.3)$$

$$EIRPLR = c_1 + c_2(PLR) + c_3(PLR)^2 \qquad (3.3.2.4)$$

$$CCR = \min\left(\frac{PLR}{PLR_{min}}, 1.0\right) \qquad (3.3.2.5)$$

where $T_{cw,ls}$ is the leaving chilled water setpoint temperature (°C), $T_{cond,e}$ is the entering condenser fluid temperature (°C), PLR is the part-load ratio = (cooling load) / (chiller's available cooling capacity), and PLR_{min} is the minimum part load ratio, below which the chiller cycles on and off to meet very small loads and the power consumption during the on cycle is the same as when the chiller is operating at the minimum part load ratio.

The performance curves for more than 160 chillers, including the default curves for reciprocating and centrifugal chillers are provided in the EnergyPlus Reference Datasets (Chillers.idf), which can be obtained when users download EnergyPlus. The performance curves were developed from information collected over a 10-year period from 1991 to 2001 based on procedures described on ARI Standard 551/591. According to the descriptions of the model (US DOE, 2024), EER (COP) values defined in AHRI 551/591 (ANSI/AHRI, 2023) are calculated at the various load capacity points (100%, 75%, 50% and 25% part-load ratios) by using the Equations (3.3.2.5.1) to (3.3.2.5.5). This relationship seems to mean indirectly that the performance curves (3.3.2.2) to (3.3.2.5.3) equivalently represent energy efficiency under various conditions of chillers as the test method prescribed in AHRI 551/591 represents. However, AHRI 551/591 (ANSI/AHRI, 2023) does not provide a method for the curve fitting of the performance data provided using its procedures. Therefore, the EnergyPlus should use a suitable method for the curve fitting in order to provide the coefficients of Equations 3.3.2.1 to 3.3.2.5.

When using EnergyPlus to verify building compliance with ASHRAE Standard 90.1 (ASHRAE, 2022) and US building energy codes, specific rules apply. According to Appendix G of ASHRAE Standard 90.1 (ASHRAE, 2022), which outlines the performance rating method using simulation programs, these programs must meet certain requirements, such as the capability to model part-load performance curves for mechanical equipment.

3.3.2.6 Required input data

EnergyPlus uses text-based files to provide inputs and outputs. The input files provide information regarding the envelope, occupation profiles, and the main parameters of lightning and air conditioning systems. The calculation requires rated values and the coefficients of the correlation curves (two correlation curves for full load performance and one for part load effect).

3.3.2.7 Known issues

While EnergyPlus is a highly regarded simulation software in building energy analysis, it is not immune to certain limitations and known issues. These issues can impact the accuracy of simulations and may require workarounds or additional scrutiny by users. Here are some of the known issues associated with EnergyPlus.

- Complexity and Learning Curve:
  EnergyPlus has a steep learning curve, especially for users unfamiliar with the underlying principles of building energy simulation or the software's input syntax. The software's complexity can be daunting for beginners and may require significant time and effort to master.
- Limited Graphical Interface:

EnergyPlus lacks a fully integrated graphical interface for model creation and result visualisation. While third-party interfaces like OpenStudio and DesignBuilder offer graphical front ends, they may only cover some aspects of EnergyPlus's capabilities, leading to potential workflow inefficiencies.

- Validation and Calibration:
  Despite the development team rigorously validating and testing EnergyPlus, discrepancies between simulated and measured building performance have been reported. Calibration of simulation models to match real-world data is essential but can be challenging because of uncertainties in input parameters, model assumptions, and measurement errors.
- Simulation Speed and Resource Requirements:
  EnergyPlus simulations can be computationally intensive, especially for large and complex building models or simulations with high temporal resolution. Running simulations with detailed HVAC systems or incorporating advanced features like Computational Fluid Dynamics can require significant computational resources and time.
- Modelling Assumptions and Simplifications:
  EnergyPlus relies on various assumptions and simplifications to model complex physical processes within buildings. While these simplifications are necessary for computational efficiency, they can introduce uncertainties and inaccuracies, particularly in scenarios where the assumptions could be better suited.
  Modelling of equipment performance is often a basic polynomial curve fitting. Manufacturers usually provide tables and curves.
- Limited Weather Data Coverage:
  EnergyPlus relies on weather data to simulate outdoor environmental conditions. While it provides access to a wide range of weather files from different sources, gaps in coverage for specific locations or periods may impact the accuracy of simulations conducted in those regions.

3.3.2.8 Foreseen developments

The potential areas of development for EnergyPlus are:

- Improved User Interface:
  Enhancing the EnergyPlus user interface could improve accessibility and ease of use. This could involve developing more intuitive graphical tools for model creation, result visualisation, and scenario analysis, reducing the reliance on text-based input files and third-party interfaces.
- Integration with Building Information Modelling (BIM):
  Integrating EnergyPlus with Building Information Modelling (BIM) software is a promising development that can streamline the building design and simulation workflow.
- Expanded Library of Components and Systems:
  Future developments in EnergyPlus may include an expanded library of building components, HVAC systems, and renewable energy technologies to support more comprehensive energy simulations.
- Enhanced Performance and Scalability:
  Future versions of EnergyPlus may focus on enhancing simulation performance and scalability.
- Integration with Machine Learning and Data Analytics:
  EnergyPlus could integrate data-driven algorithms and offer personalised recommendations for energy-efficient building design and operation based on historical performance data and real-time sensor inputs.
- Open Data and Collaboration Initiatives:
  Future developments in EnergyPlus may include initiatives to promote open data sharing, model interoperability, and collaborative research efforts. This could involve the establishment of standardised formats for sharing simulation models and results and the development of online platforms for community engagement and knowledge exchange.

3.3.3 National energy code of Canada for buildings

3.3.3.1 Foreseen developments

The NECB is a model code in the sense that it helps promote consistency among provincial and territorial energy codes for buildings. Persons involved in the design or construction of a building should consult the provincial or territorial jurisdiction concerned to determine which energy code applies.

The NECB (NCEB, 2020) succeeds in the 2017 edition (First edition was issued in 1997). The development of the NECB 2020 has been supported by the National Research Council of Canada (NRC), Natural Resources Canada, and other stakeholders. The NECB 2020 will help to improve the energy efficiency of new buildings and reduce greenhouse gas emissions, contributing to long-term benefits for both Canada's economy and the environment.

3.3.3.2 Context and background information

The NECB comprises three divisions: Division A for compliance, objectives and functional statements, Division B for acceptable solutions, and Division C for administrative provisions.

The objectives of the NECB are achieved by measures, such as those described in the acceptable solutions in Division B, that are intended to allow the building or its elements to perform the eleven functions, among which limitation of unnecessary energy consumption for heating and cooling (F95), for service water heating (F96), etc.

Buildings shall comply with

a. the prescriptive or trade-off requirements stated for each portion of buildings (envelope, lighting, HVAC, etc.),
b. the performance requirements stated in Part 8 of Division B, or
c. the tiered performance requirements stated in Part 10 of Division B (for buildings whose occupancy is unknown).

According to the performance requirements (b) stated in Part 8, the annual energy consumption of the proposed buildings (to be checked for their compliance with the code) shall not exceed the building energy target (annual energy consumption) of the reference building. Calculation methods for the annual energy consumption of the proposed and reference buildings need to satisfy specifications described in Section 8.4.2.2 of Part 8.

3.3.3.3 Output data

The result is the annual energy consumption of the proposed building and the building energy target (annual energy consumption) of the reference building.

3.3.3.4 Method (structure and rationale)

In the annual energy consumption calculation for HVAC systems in the proposed building, part-load performance curves of heat sources shall be consistent with the equipment detailed in the building specifications. However, where part-load performance curves for the proposed building's system are not available, the performance curves provided in the NECB for the calculation for the building energy target of the reference building shall be used.

In Section 8.4.5 Part-Load Performance Characteristics, the performance curves for boiler, furnace, direct-expansion cooling equipment, electric chiller, cooling tower, electric air-source heat pump, absorption chiller and fuel-fired service water heater are provided.

An example of the performance curve for electric air-source heat pump (Section 8.4.5.7) is overviewed in the following:

$$P_{operating} = P_{rated} \times EIR\_FPLR \times EIR\_FT \times CAP\_FT_{EAS} \qquad (3.3.3.1)$$

where:

$P_{operating}$: electric input in kW of the reference heat pump
P_{rated}: rated electric input in kW at AHRI test conditions
EIR_FPLR: electric input ratio adjustment to rated efficiency due to changes in heat pump load, which is determined by Equation (3.3.3.2)
EIR_FT: electric input ratio adjustment to rated efficiency due to environmental variables, which is determined by Equation (3.3.3.3)
CAP_FT_{EAS}: heating capacity adjustment, which is determined by Equation (3.3.3.4)

The performance curves for parameters in Equation (3.3.3.1) are provided with coefficient values as follows:

$$EIR\_FPLR = a + (b \times PLR) + (c \times PLR^2) + (d \times PLR^3) \tag{3.3.3.2}$$

Where:
PLR : part-load ratio based on available capacity (not rated capacity)
$a = 0.0856522,$
$b = 0.9388137,$
$c = -0.1834361, and$
$d = 0.1589702.$

$$EIR\_FT = a + (b \times t_{odb}) + (c \times {t_{odb}}^2) + (d \times {t_{odb}}^3) \tag{3.3.3.3}$$

Where:
t_{odb} : outdoor-air dry-bulb temperature in °F,
$a = 2.4600298,$
$b = -0.0622539,$
$c = 0.0008800, and$
$d = -0.0000046.$

$$CAP\_FT_{EAS} = a + (b \times t_{odb}) + (c \times {t_{odb}}^2) + (d \times {t_{odb}}^3) \tag{3.3.3.4}$$

Where:
t_{odb} : outdoor-air dry-bulb temperature in °F,
$a = 0.2536714,$
$b = 0.0104351,$
$c = 0.0001861, and$
$d = -0.0000015.$

3.3.3.5 Required input data

As already mentioned, in the annual energy consumption calculation for HVAC systems in the proposed building, part-load performance curves of heat sources shall be consistent with the equipment detailed in the building specifications. Depending on the performance curves and models, input data varies. If any consistent performance curves are not available, the performance curves for the reference building are used. In that case, for electric air-source heat pumps, as shown in the above-mentioned equations, 1) rated electric input in kW at AHRI test conditions, 2) rated capacity at AHRI test conditions, 3) present load (heat need) on heat pump, and 4) outdoor dry-bulb temperature are needed as input data.

3.3.4 Japanese standard, BECS

3.3.4.1 Status

In Japan, implementing the method of primary energy calculation for residential and non-residential buildings for compliance checking under the Building Energy Conservation Standard (hereafter abbreviated as 'BECS') as a national law was initiated in April 2013.

Compliance with the BECS shall be mandatory for all kinds of new buildings after April 2025. It means no new construction of any buildings shall be permitted without compliance with the BECS.

National calculation programs, which are called 'Web-Program' are available online (ECSC, 2024a, b), and is maintained by the Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) and organisations including two national research institutes, National Institute for Land and Infrastructure Management and Building Research Institute.

3.3.4.2 Context and background information

The energy calculation programs can calculate energy uses for space heating, space cooling, ventilation, domestic hot water, lighting and elevators. They are being updated twice a year, but the calculation methods for heat pump systems for space heating and cooling and domestic hot water have not yet been changed since 2013. In this review, energy calculation methods for 1) room air conditioners (hereafter abbreviated as 'RAC' or 'RACs') (3.3.4.3), 2) heat pump systems for HVAC of non-residential buildings (3.3.4.4) and 3) heat pump water heaters called 'EcoCute' (3.3.4.5) shall be overviewed.

3.3.4.3 The energy calculation method for RACs for BECS

Room air conditioners (RACs) have become the most popular equipment for space heating, especially in mild climate regions (major climatic condition) in Japan. It is partly because they fit the Japanese lifestyle to air condition houses partially and intermittently. Therefore, reliable energy calculation methods, which can compare energy efficiencies of different equipment, including floor heating systems with boilers, have been crucial for the BECS.

3.3.4.3.1 Input and output data

The input data representing RACs' characteristics are the rated COPs for heating and for cooling based on the test standard, JIS C 9612 (JIS, 2013a). The input data representing thermal characteristics of the building envelope are overall heat loss coefficient and overall solar heat gain coefficient, which are calculated from input data for dimensions and thermal characteristics of portions of the building envelope.

The energy calculation method for RACs was developed by referring to the results of field monitoring projects (BRI, 2013).

3.3.4.3.2 Method (structure and rationale)

Figure 3.3.4-1 and Figure 3.3.4-2 are the results for a room air conditioner, which were obtained by experiments in a laboratory without fixing the compressor speed or airflow rate. A series of experiments was carried out for temperature conditions in Table 3.3.4-1 and for air conditioners of various rated capacities and manufactures.

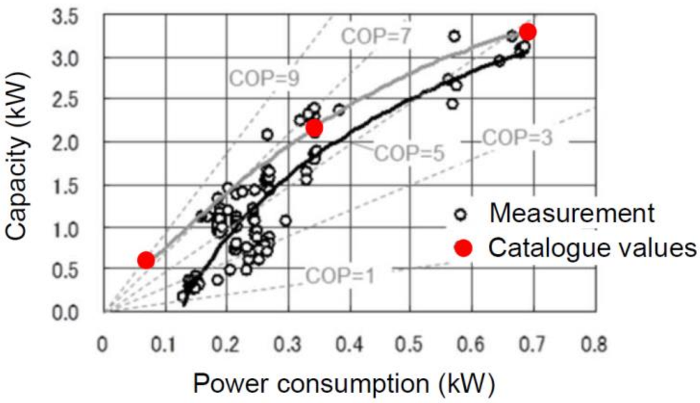


Figure 3.3.4-1. Capacity and power consumption (cooling) for a room air conditioner with the rated capacity 2.2 kW

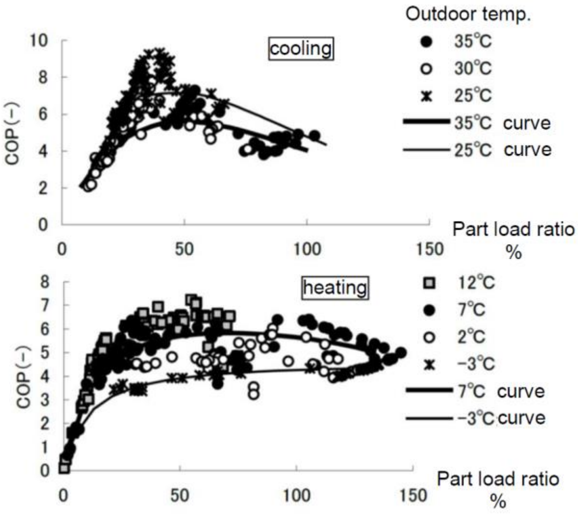
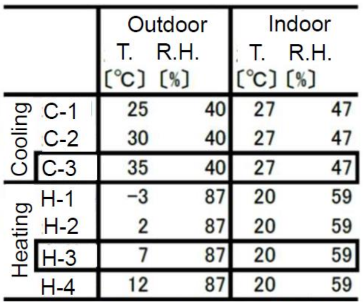


Figure 3.3.4-2. Part load ratio and COP (EER) for a room air conditioner with the rated capacity 2.2 kW

Table 3.3.4-1. Experimental conditions (temperature and humidity)



		Outdoor		Indoor	
		T. [℃]	R.H. [%]	T. [℃]	R.H. [%]
Cooling	C-1	25	40	27	47
	C-2	30	40	27	47
	C-3	35	40	27	47
Heating	H-1	−3	87	20	59
	H-2	2	87	20	59
	H-3	7	87	20	59
	H-4	12	87	20	59

Note C-3 and H-3 are the rated conditions in JIS B 8615-1 (JIS, 2013b)

The following characteristics can be found for the room air conditioners:

- The maximum COP (EER) appears at approximately 50%-part-load-ratio to the maximum capacity,
- Below 50%-part-load-ratio, COP (EER) decreases rapidly due to increased ratio of fan power and decreased energy efficiency of compressors,
- Relative changes of COP (EER) under different outdoor temperature conditions vary according to capacities.

- The results of COP (EER) measured in the experiments are lower than values in the catalogue, which are measured according to JIS standard (JIS C 9612:2013 (JIS, 2013a)). It is partly due to lower airflow rates in the experiments. On average, the measured COP (EER) was lower than the published values by approximately 15%.

The following equations are applied in the calculation of COP at various conditions for part load ratio and outdoor temperature. The function, $f_\theta(L)$ is determined by the test results for a representative room air conditioner.

$$\boldsymbol{COP_i = \frac{COP_d \cdot L_r \cdot f_\theta(r_\varphi)}{f_\theta(r_\varphi \cdot L_r) \cdot r_\gamma}} \tag{3.3.4.1}$$

Where
- COP_i : COP (EER) at any part load ratio, L_r at outdoor temperature, θ
- COP_d : COP (or EER) at the rated capacity multiplied by correction factor, 0.85
- L_r : part load ratio, ratio of the capacity at the time to the rated capacity of the air conditioner
- $f_\theta(L)$: ratio of the power consumption (W) for part load ratio, L at the time to the rated power consumption (W) of the air conditioner
- r_φ : ratio of the maximum capacity (L_{Smax}) to the rated capacity (L_{Sd}) of the standard room air conditioner, divided by the ratio of the maximum capacity (L_{max}) to the rated capacity (L_d) of the room air conditioner, of which energy use is being calculated as shown by the following equation.

$$\boldsymbol{r_\varphi = \frac{L_{Smax}}{L_{Sd}} \div \frac{L_{max}}{L_d}} \tag{3.3.4.2}$$

- r_γ : ratio of the power consumption at the rated capacity at outdoor temperature, θ to the power consumption at the rated capacity at the standard outdoor temperature (cooling: 35°C, heating: 7 °C).

3.3.4.3.3 Example calculations input and results

Figure 3.3.4-3 shows an example of average heating and cooling COP throughout seasons, based on the heating and cooling energy calculation (Sawachi et al., 2010). In the calculation, a wooden detached house of about 120 m^2 floor area with three different levels of envelope performance (insulation and solar shading) is assumed. The results shown in the figure are for the air conditioner in the living and dining room, of which the floor area is about 30 m^2 including the kitchen. The rated values of the air conditioner are shown in Table 3.3.4-2.

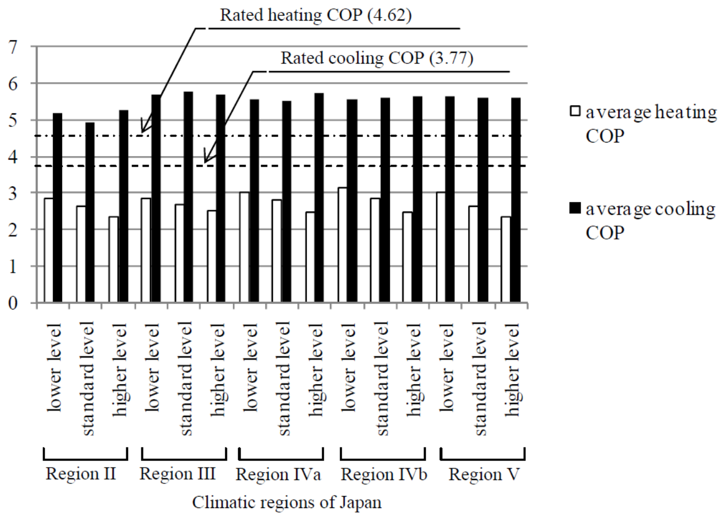


Figure 3.3.4-3. Examples of seasonal average COPs for heating and cooling for different climatic and building envelope performance ('lower', 'standard' and 'higher')

Table 3.3.4-2. Specification of the room air conditioner, of which seasonal average COPs are calculated

Rated heating COP	Rated heating capacity	Maximum heating capacity	Rated cooling COP	Rated cooling capacity	Maximum cooling capacity
4.62	6.90 kW	9.33 kW	3.77	5.60 kW	5.82 kW

3.3.4.3.4 Known issues

As mentioned above, the function, $f_\theta(L)$ is determined by using test results for a representative room air conditioner, but there may be room air conditioners with better energy efficiency at low part load ratio. One important issue is how the better characteristics at low partial load ratio should be certified. Before room air conditioners, for variable refrigerant flow (VRF) systems, a test protocol to certify other characteristic functions is under development as introduced in Section 1.3.4 'Load-based test to obtain the relationship between partial load ratio and energy efficiency of VRF systems by Better Living' in this report.

3.3.4.3.5 Foreseen developments

On the side of improvement of energy efficiency of room air conditioners under low part load condition, there are already some products, of which compressors have special mechanisms. There seems to be a barrier for those products to be introduced more broadly into the market, because there is a lack of a standard, which can evaluate their superiority.

3.3.4.4 The energy calculation method for residential heat pump water heaters (EcoCute) for BECS

Residential heat pump water heaters have been produced since 2001 in the Japanese market, and their accumulative number of sold units is 9.39 million units at the end of Fiscal Year 2023, according to the statistics by JRAIA (JRAIA, 2024).

3.3.4.4.1 Input and output data

JIS C 9220, ‘Residential heat pump water heaters’ (JIS, 2018) is the product, testing and rating standard, where annual energy efficiency e_{rtd} is defined. In the energy calculation method for BECS, as the firstly developed method, annual energy use is calculated by using a linear regression equation between e_{rtd} and the annual energy use for a four-member family. In the last stage of the calculation, the annual energy use for DHW shall be adjusted taking the total floor area of the house and expected number of family member into consideration.

3.3.4.4.2 Method (structure and rationale)

When the regression equation was made, the 30-consecutive-day hot water usage pattern, which comprises the mixture of 6 daily patterns (three patterns for ‘weekday’/’holiday-to-stay’/’holiday-to-go-out’ for each of two hot water daily usage volume ‘large’/’small’) was applied to test the amount of supplied hot water and the power consumption for summer, medium season and winter.

The test with 30-consecutive-day hot water usage patter for three seasonal outdoor temperature conditions is a very heavy task and has been performed only when the energy calculation method should be revised. More importantly, the test shall be conducted not only for the control setting at the time of factory shipment but also the second control setting, which heats hot water in the tank up to the second lowest temperature, are used as the settings of the units to be tested.

The algorithm of the energy calculation is fully described in the published specification of the program (BRI&NILIM, 2016a).

3.3.4.4.3 Example calculations input and results

An example of energy calculation by using the Web-Program for residential buildings is shown in Figure 3.3.4-4. In this example, it is shown that the annual energy use by EcoCute with annual energy efficiency e_{rtd} of 3.5, according to JIS C 9220 (JIS, 2018) is 14,417 MJ/year, while standard energy use for this house is 25,091 MJ/year.

Step 1: ‘JIS Efficiency’ for the EcoCute product can be identified easily in its catalogue. The JIS Efficiency is defined together with its test method in JIS C 9220: 2018 as an input data for the building energy calculation program.

Step 2: Input the JIS Efficiency (3.5 in this example) in the screen of the building energy calculation program (below).

Catalogue value, JIS Efficiency e_{rtd} is being input.

エネルギー消費性能計算プログラム 住宅版 詳細入力画面 Ver.3.6.0 (2024.04)

3 〈2〉で「給湯専用型:電気ヒートポンプ給湯機（CO2冷媒またはR32冷媒）（太陽熱利用設備を使用しないもの）」を選択した場合、熱源機の評価方法を入力して下さい。

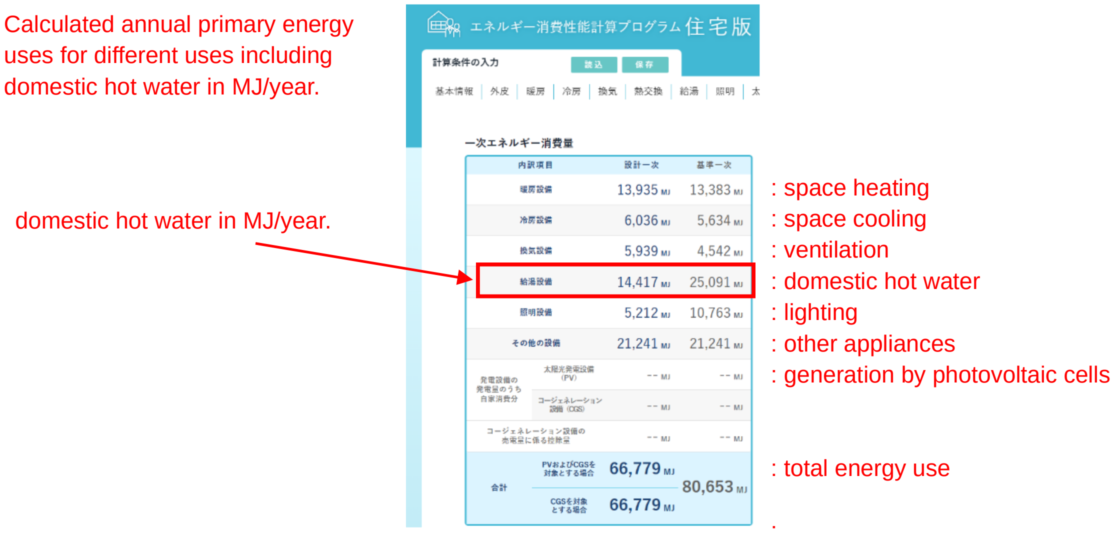
電気ヒートポンプ給湯機の指定 ?
○ 品番を指定しない（規定値を用いる）
● 品番を指定しない（JIS効率を入力する）
○ 品番を指定しない（パラメータを入力する）
○ 品番を指定する

品番を指定しない場合
品番を指定せずに計算した結果を公的な届出や補助金の申請に利用する場合は、「品番を指定しない（規定値を用いる）」または「品番を指定しない（JIS効率を入力する）」を選択します。

JIS効率 ? 3.5 -（小数点以下1桁）

昼間沸上げ ?
● 評価しない、または昼間沸上げ形ではない
○ 評価する

Step 3: After starting the calculation, energy use for domestic hot water (14,417 MJ/year in primary energy basis in this example) can be obtained with energy uses for other purposes (below).



Calculated annual primary energy uses for different uses including domestic hot water in MJ/year.

domestic hot water in MJ/year.

エネルギー消費性能計算プログラム 住宅版

一次エネルギー消費量

内訳項目		設計一次	基準一次
暖房設備		13,935 MJ	13,383 MJ
冷房設備		6,036 MJ	5,634 MJ
換気設備		5,939 MJ	4,542 MJ
給湯設備		14,417 MJ	25,091 MJ
照明設備		5,212 MJ	10,763 MJ
その他の設備		21,241 MJ	21,241 MJ
発電設備の発電量のうち自家消費分	太陽光発電設備（PV）	-- MJ	-- MJ
	コージェネレーション設備（CGS）	-- MJ	-- MJ
コージェネレーション設備の売電量に係る控除量		-- MJ	-- MJ
合計	PVおよびCGSを対象とする場合	66,779 MJ	80,653 MJ
	CGSを対象とする場合	66,779 MJ	

: space heating
: space cooling
: ventilation
: domestic hot water
: lighting
: other appliances
: generation by photovoltaic cells
: total energy use

Figure 3.3.4-4. An example of energy calculation for an EcoCute (Step 1 to Step 3)

3.3.4.4.4 Known issues

The method introduced above is the initial method for energy calculation for EcoCutes and tends to make a safe side estimation of energy use. A more detailed method has been developed and is already available within the same Web-Program (BRI&NILIM, 2016a).

3.3.4.4.5 Foreseen developments

It is strongly recommended to develop testing standard(s) to certificate other characteristic curves for energy-efficient heat pump systems and other heat sources.

3.3.4.5 The energy calculation method for heat pump systems for HVAC in non-residential buildings for BECS

3.3.4.5.1 Input and output data

Heat pump systems for HVAC systems in non-residential buildings are grouped into categories, such as air-source heat pumps, absorption chillers, variable refrigerant flow systems. The input data to represent the energy performance of each heat pump system is the rated capacity, and the rated energy use for space heating and cooling according to specified testing standards.

3.3.4.5.2 Method (structure and rationale)

The heating and cooling needs calculation is done by a quasi-hourly calculation for each of the conditioned rooms in non-residential buildings. The conditions of room usage (e.g., internal heat gain, outdoor air intake, occupancy density, etc.) are defined for 201 room categories according to ISO 18523-1 (ISO, 2016). The energy use by heat and cold generators including heat pump systems is calculated by using the calculated heating and cooling needs, outdoor dry-bulb/wet-bulb temperature, part load ratio, supplied water temperature, and characteristic curves for each type of heat and cold generator (Fujii et al., 2009; BRI&NILIM, 2016b). Operating hours of heat pumps are allocated to six ranges of outdoor temperature and eleven ranges of part load ratio.

The characteristic curves for heat pump systems for cooling are exemplified in Figure 3.3.4-5.

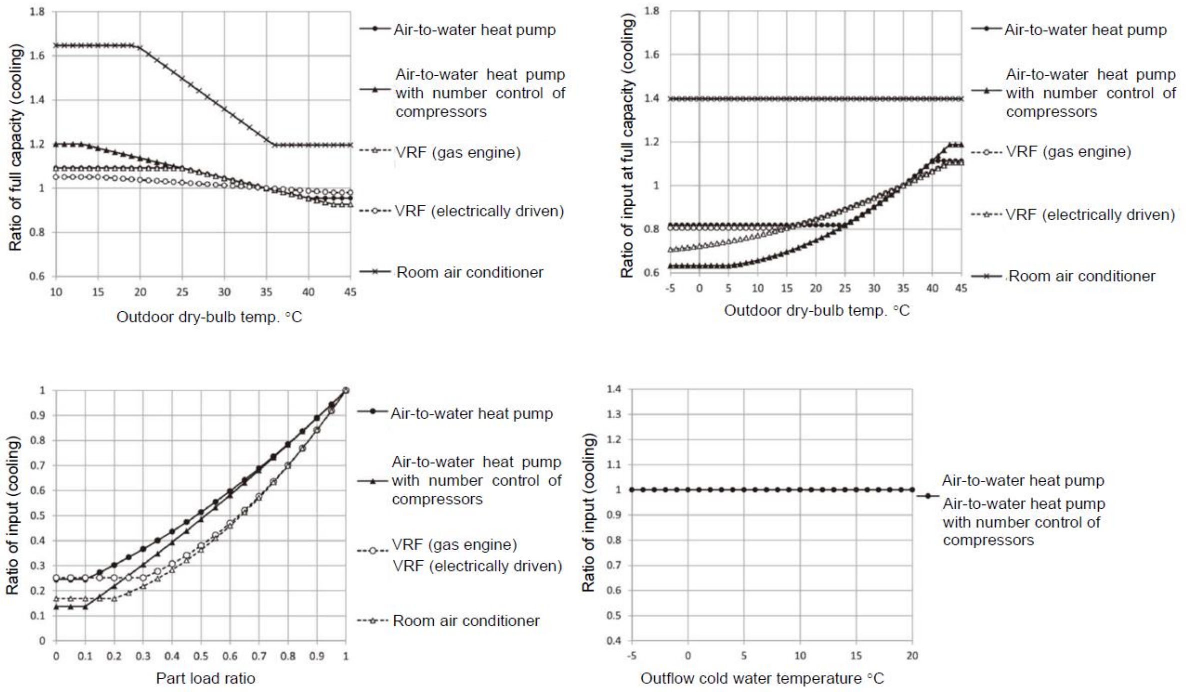
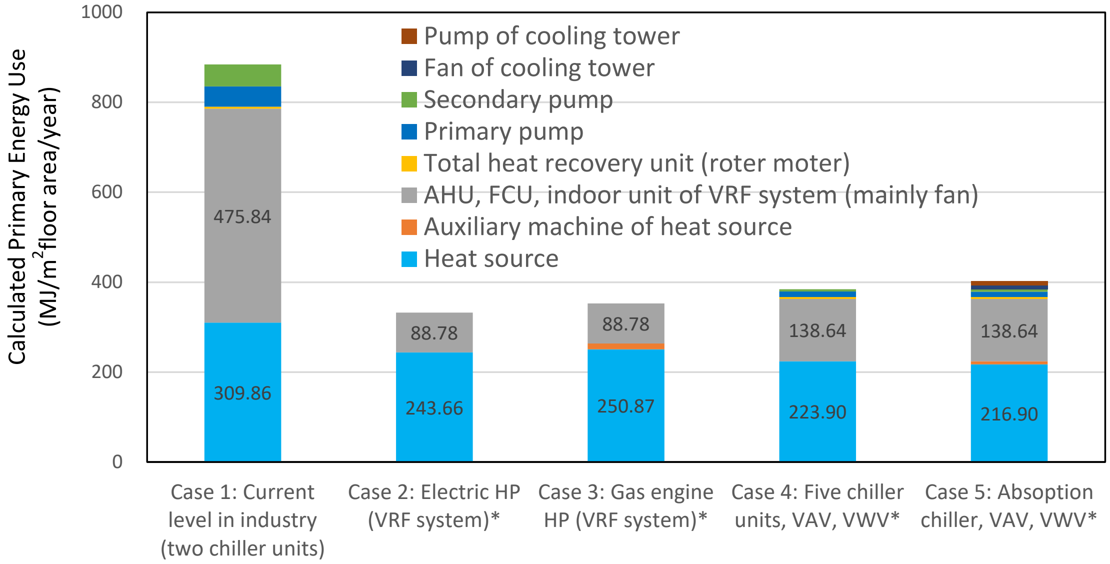


Figure 3.3.4-5. Examples of characteristic curves of heat pump systems for cooling

3.3.4.5.3 Example calculations input and results

In the example shown in Figure 3.3.4-6, energy uses for HVAC systems in an office building are calculated. Calculated energy uses for four types of HVAC systems (electric chiller, absorption chiller, electric VRF and gas engine VRF) are shown in the Figure 3.3.4-6 (BRI, 2021).



* For Case 2 to Case 5, improved building envelope is assumed, even though its contribution is not as large as HVAC systems, partly because climatic condition is rather mild.

Note. VAV: Variable Air Volume System, VWV: Variable Water Volume System, AHU: Air Handling Units, FCU: Fan Coil Units

Figure 3.3.4-6 Energy calculation of HVAC in an office building (10,000m^2, 7 stories, mild climate, Tokyo)

In Case 1, standard specifications are input in the program, while in other Cases more energy-efficient designs are reflected, such as sizing of fans, pumps and heat sources has been carried out according to the public design standard (MLITT, 2021). These examples demonstrated the importance of fulfilling the standardized sizing practice and the control of number of heat sources in operation, both of which contribute to higher part load ratio.

3.3.4.5.4 Known issues

The characteristic curves of heat generators including heat pumps have been used for energy calculation programs, but their evidences are not necessarily clear, even though monitoring projects (BRI, 2016) had been carried out to check their reliability as much as possible.

3.3.4.5.5 Foreseen developments

It is strongly recommended to develop testing standard(s) to certificate other characteristic curves for energy-efficient heat pump systems and other heat sources.

3.3.5 Italy UNI-TS 11300-4

3.3.5.1 Status

The energy performance calculation method for regulatory purpose is defined by the technical specification UNI-TS 11300 (UNI, 2016), which is issued by CTI (which is the historical Italian association in charge of standardization in the field of building comfort in Italy) and referenced by the regulation. The heat pump module is included in part 4, which deals with special heat generation sub-systems (other than combustion systems).

3.3.5.2 Context and background information

In Italy, the energy performance of buildings is regulated since 1976. An energy performance calculation is required for any application for a building permit since 1993. Since 2009 it is required also to issue EPCs and for deep renovations.

The whole calculation procedure of the energy performance of the building is monthly. The calculation of the heat pump is performed according to monthly bins. This is to check if the heat pump can cover the whole load and, if not, to evaluate the share of the load which is covered by the integrated back-up heater or of next generator in the priority sequence.

UNI-TS 11300 calculation method is used in the day-to-day workflow of designers and energy performance assessors in Italy. For regulatory purpose, an approved software shall be used. There are currently about 20 energy performance software in Italy, which are available by commercial entities and approved by CTI.

3.3.5.3 Output data

The output data of the heat pump module of UNI TS 11300-4 (UNI, 2016) is:

- the part of the required output that can be supplied by the heat pump;
- the required driving energy;
- the required auxiliary energy;
- the amount of heat captured from the environment;

No recoverable losses are considered.

The results of the monthly bin calculations are aggregated into monthly values.

3.3.5.4 Method (structure and rationale)

The calculation method is like path A of EN 15316-4-2 (CEN, 2017c).

The capacity and COP at full load of the heat pump ($\Phi_{100\%}$ and $COP_{100\%}$) shall be declared by the manufacturer at a set of predefined values of source and sink temperatures ($\theta_{src;ref,j}$ and $\theta_{snk;ref,i}$) which create a “grid” of reference values. The reference values for source and sink temperature are the usual ones already defined in EN 14511 (BSI, 2018). Table 3.3.5-1 shows the predefined source and sink temperature depending on source and sink type.

Table 3.3.5-1. Reference source and sink temperatures for UNI-TS 11300-4 (UNI, 2016), heating mode.

Type of source	Reference source temperatures $\theta_{src;ref,j}$				Reference sink temperatures, $\theta_{snk;ref,i}$					
					Air	Water			Domestic hot water	
External air	-7	2	7	12	20	35	45	55	45	55
Surface water and ground water		5	10	15						
Ground heat exchanger	-5	0	5	10						
Domestic hot water heaters, air source only	7	15	20	35	Not applicable				45	55

The full load capacity for the actual source and sink temperature (θ_{src} and θ_{snk} respectively) $\Phi_{100\%}(\theta_{src}; \theta_{snk})$ is calculated by linear interpolation between the nearest points.

The part load LR is calculated as the ratio of the required capacity to the full load capacity at the same source and sink temperature:

$$LR = \frac{Q_{H;gen;out;req}}{\Phi_{100\%}(\theta_{src};\theta_{snk}) \cdot t_{ci,H}} \qquad (3.3.5.1)$$

where:

- $Q_{H;gen;out;req}$ is the required heat output for heating in the calculation interval (temperature bin);
- $t_{ci;H}$ is the available time for space heating operation during the calculation interval (this is less than the entire calculation interval if the heat pump must provide other services, too).

The full load COP for the actual source and sink temperature $COP_{100\%}$ (θ_{src}; θ_{snk}) is calculated by linear interpolation (or extrapolation) of the exergetic efficiency from the values at the nearest available reference points. The extrapolation according to source and/or sink temperature is limited to 5 °C. Example: if performance data are declared for leaving water temperature of 35 and 45 °C, the calculation can be performed only in the range 30 to 50 °C (interpolation between 35 and 45 °C plus 5°C extrapolation on both sides).

A correction factor is then applied to the full load COP to consider the effect of part-load operation.

$$\boldsymbol{COP = COP_{100\%}(\theta_{src};\theta_{snk}) \cdot f_{corr;COP}(LR)} \tag{3.3.5.2}$$

There are several options to establish the correction function $f_{corr;COP}(LR)$ depending on the type of heat pump and on the availability of product data:

- a calculation based on a set of declared values of COP at full load and part load with the same sink and source temperatures, which was intended to leverage the use of data according to EN 14825;
- default correction functions;
- a correction function declared by the manufacturer;
- a recently proposed method based on the estimation of the change in evaporation and condensation temperature due to part load operation and constant exergetic efficiency.

The basic assumption is that the function $f_{corr;COP}(LR)$ does not depend on source and sink temperatures. The default correction functions $f_{corr;COP}(LR)$ in use with UNI-TS 11300-4 (UNI, 2016) are given in Figure 3.3.5-1.

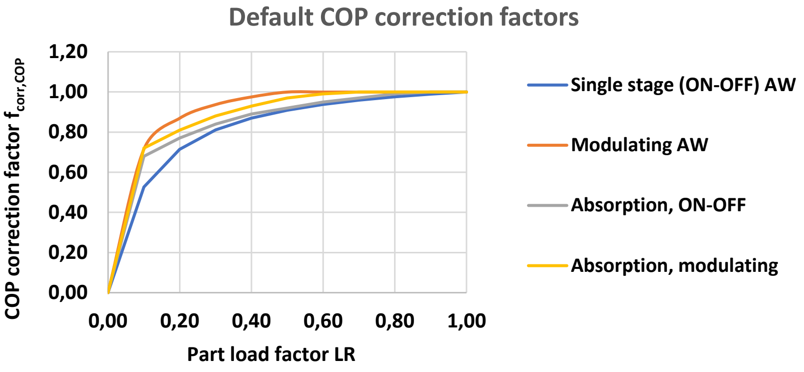


Figure 3.3.5-1. Default values of $f_{corr;COP}(LR)$ for UNI-TS 11300-4 (UNI, 2016)

The required leaving water temperature (sink temperature) for hydronic systems is calculated explicitly for each month in other parts of UNI-TS 11300-4 (UNI, 2016) and then interpolated to get the conditions in each bin. The following influence factors are considered:

- the actual size of the heat emitters (nominal power at a given average water temperature);
- the required heat emission in the calculation interval;
- the type of hydraulic circuit (e.g. direct, mixed, by-pass);
- the type of heat emission control (e.g. constant versus variable flow rate, constant versus variable flow temperature);
- the type of hydraulic connection of the generator (e.g. direct connection versus hydraulic decoupling).

Little information is provided for other sources than air (e.g. ground coupled loops, groundwater, surface water). This information shall be provided by the assessor, depending on the system's design.

3.3.5.5 Required input data

The minimum required input data is a full load performance map (capacity and COP), according to EN 14511 for the set of reference source and sink temperatures.
Optionally, the manufacturer may supply suitable information to determine the function $f_{corr;COP}(LR)$.

3.3.5.6 Known issues

UNI-TS 11300-4 (UNI, 2016) was developed having in mind water-based heating systems. Thus, this calculation method is not suitable for air-to-air heat pumps, whose efficiency is strongly linked to part load operation.
An attempt has been made to extract the information of the impact of part load on COP using data declared according to EN 14825 (BSI, 2022). The result was not satisfactory because data about the test conditions of EN 14825 (BSI, 2022) also incorporate the effect of changing both source and sink temperature, making it very difficult to isolate the effect of part-load only. Also, the connection with domestic hot water heaters product data is not clear.

3.3.5.7 Foreseen developments

Italian experts are contributing to the development of EN 15316-4-2 (CEN, 2017c), in the view of referencing it in the future major revision of the UNI-TS 11300-4 (UNI, 2016) calculation method. The next major revision is expected to include the switch from monthly to hourly calculation intervals. Some years are still needed before the hourly procedure for the whole building is established and tested.

3.3.6 UK SAP 10.2

3.3.6.1 Status

The Standard Assessment Procedure (SAP) is the mandatory calculation method in force in the United Kingdom for the assessment of energy performance of residential buildings for regulatory purpose. It is therefore used in the day-to-day workflow of energy performance assessors.
SAP was developed by the Building Research Establishment (BRE) for the former Department of the Environment and was based on the BRE Domestic Energy Model (BREDEM). SAP was first published in 1993. It has been regularly updated and the current version 10.2 was published in 2022.

3.3.6.2 Context and background information

SAP procedure covers the entire calculation of the energy performance of a building. It covers heating, cooling, ventilation, domestic hot water and lighting services. The calculation interval is monthly. The overall calculation is guided by a worksheet which is presented in annex U of SAP 10.2. Intermediate results for each calculation module shall be filled in into this worksheet.
Heat pumps, as well as other emerging technologies, were included at a later stage. The details about the heat pumps calculation method are presented in appendix N of SAP 10.2.

3.3.6.3 Output data

The heat pump module provides a seasonal efficiency which is fed into the building energy performance calculation worksheet.

3.3.6.4 Method (structure and rationale)

The seasonal efficiency of any heat pump introduced on the UK market shall be pre-calculated for a number of installation options and for a set of values of the so called “Plant Size Ratio” (PSR) (BRE, 2022).

The PSR is the ratio:
- of the nominal maximum output of the heat pump,
- to the design heat loss of the building.

The PSR is an indicator of the sizing of the heat pump relative to the space heating needs. The considered values are in the range from 0,2 (undersized heat pump) to 2,0 (highly oversized heat pump).

The installation and control options include:
- the type of heat pump (air source, water source, exhaust air source),
- the emitter temperature category (35 to 70°C and warm air),
- the services provided (space heating, domestic hot water preparation and combinations thereof).

For each heat pump, identified by brand name, model name and model qualifier, the seasonal efficiency (SPF, seasonal performance factor) is calculated using an hourly method (not described in SAP 10.2) for each desired combination of PSR and installation and control option. The resulting SPF is stored in the official Product Characteristics Data-Base (PCDB). An example of such data is given in Table 3.3.6-1. (PCDB, 2024).

Table 3.3.6-1. Data found in the PCDB for a sample heat pump.

PSR (Plant Size Ratio)	0,2	0,5	0,8	1,0	1,2	1,5	2,0
Floor heating							
Heating SPF	3,855	3,926	4,173	4,217	4,241	4,191	4,108
Running hours	4925	2716	1770	1447	1231	1016	800
Radiators							
Heating SPF	3.502	3.413	3.607	3.665	3.698	3.657	3.585
Running hours	4699	2516	1643	1345	1146	947	749
Convectors							
Heating SPF	3.930	3.89	4.133	4.186	4.215	4.166	4.081
Running hours	4776	2577	1682	1376	1172	968	764

For a specific calculation, the seasonal efficiency SPF found in the PCDB is interpolated linearly according to the PSR of the specific building.

The technical documents declare compliance of the underlying hourly calculation procedure with EN 15316-4-2:2017, path B (CEN, 2017c).

The pre-calculated efficiencies are stored in the Product Characteristics Data Base (PCDB, 2024a) for use by the assessors. This approach simplifies a lot of the tasks of the assessor and guarantees the availability of suitable product data for the calculation method.

3.3.6.5 Required input data

Little input data is required: qualitative information and then model and make of the heat pump are enough to find the efficiency as a function of the PSR in Product Characteristics Data Base (SAP, 2017; SAP, 2024a; SAP, 2024b; PCDB, 2024b).

3.3.6.6 Known issues

The pre-calculated values make the calculation simple for the assessor. The downside is that the method relies on extensive assumptions (e.g. load and operation profiles) and there are few rough options to adapt the calculation to the specific case. The result is little sensitivity to the specific conditions of the evaluated building.

The calculation of heating and domestic hot water needs is monthly, but a unique seasonal efficiency is used for heat pumps. The change of COP during the heating season is not considered.

3.3.6.7 Foreseen developments

The UK government is developing a new method to increase the accuracy and robustness of the energy performance calculation of buildings: the so-called Home Energy Model (DESNZ, 2023a).
The Home Energy Model is still under development and its first version will be implemented alongside the Future Homes Standard in 2025. The heat pump module is based on EN 15316-4-2:2017 (CEN, 2017c), path B.
The Home Energy Model documentation can be found in (DESNZ, 2023a) and the specific document about heat pumps can be found in (DESNZ, 2023b).

3.3.7 Germany DIN V 18599

3.3.7.1 Germany DIN V 18599

DIN V 18599 is the German standard for the calculation of primary and final energy demand (use) for heating, cooling, ventilation, domestic hot water and lighting in buildings. The development of the standard commenced in 2002 by the committee formed by the German Federal Ministry of Transport, Building and Urban Affairs in response to European Directive 2002/91/EC on the energy performance of buildings (EPBD). The first version of DIN V 18599 was published in 2005.

3.3.7.2 Method (structure and rationale)

Calculation of energy demand (use) for heat generators for space heating differs greatly from that for space cooling. Because of the space limitation in this report, only the calculation method for space heating by heat pumps is introduced here.
The relevant calculation method for energy use for space heating is described in 6.5.3 (motor-driven heat pumps) of DIN V 18599-5 (DIN, 2016a). The calculation method for space cooling is described 7.1.3 (chillers) in DIN V 18599-7 (DIN, 2016b).

As for the motor-driven heat pumps, the following factors are considered:

- Type of heat pumps (air-water, brine-water, water-water, direct condensation, etc.);
- System configuration (priority switching of domestic hot water heating before space heating, combined operation with simultaneous domestic hot water and room heating);
- Operation in bivalent operation combined with boilers depending on outdoor temperature;
- Running time for space heating, domestic hot water heating and combined operation;
- Effects of variation of source and sink temperature on the capacity and COP;
- Effects of part-load operation of single-stage, multi-stage and continuously controlled heat pumps on the COP;
- Required auxiliary power for operation of the heat pump, which is not considered in test conditions (external auxiliaries);
- System losses due to built-in storage.

Heating energy demand for heat pumps is calculated following DIN V 18599-5 (DIN, 2016a), while energy demand for cooling is calculated following DIN V 18599-7 (DIN, 2016b) differently.

The basic procedure for calculating the energy demand for heating is divided into the following steps:

- Evaluation of source temperature (determination of outdoor temperature classes and their heating degree hours);

- Reduction of the heat output by the heat pump;
- Allocation of the heat output to the temperature classes;
- Correction of the source (e.g. outdoor temperature) and sink (e.g. room temperature) temperatures for adjusting test results of the heat pump;
- Consideration of the partial load behaviour of the heat pump;
- Calculation of running times;
- Calculation of the actual heat output, auxiliary energy use and total energy demand.

Necessary heat pump monthly heat outputs ($Q_{h,\ outg}$) are divided into temperature class i, which are defined as shown in Table 3.3.7-1, commonly used for all areas in Germany, by using the following equation:

$$Q_{h,outg,i} = Q_{h,outg} \cdot \left(\frac{DH_{TK,i,mth}}{HDH_{t,mth}} - k\right) \tag{3.3.7.1}$$

Where

- $Q_{h,outg,i}$ is necessary heat pump heat output for the temperature class i in the month mth,
- $DH_{TK,i,mth}$ is the degree hours of the temperature class i in the month mth,
- $HDH_{t,mth}$ is the total degree hours of all temperature classes in the month mth and
- k is the coverage of the second heat generator for bivalent operation.

Table 3.3.7-1. Default values for the monthly hours and the degree hours in the individual temperature classes, which are divided into the test points according to EN 14511-2 (BSI, 2018).

temperature class	W-7	W2	W7	W20	Monthly sum
Checkpoint, °C	-7	-2	7	20	
BIN temperature limits, °C	-15 to -3	-2 to 4	5 to 15[a]	15[a] to 32	
month	monthly hourly rate in h / degree hours in Kh				
January	156/4,103	392/7,705	196/2,335	0/0	744/14,143
February	90/2,208	436/8,239	140/1,724	6/0	672/12,171
March	41/975	337/6,172	349/4,219	17/0	744/11,366
April	4/83	142/2,527	463/4,920	111/0	720/7,530
May	0	13/224	425/3,920	306/0	744/4,144
June	0	0	301/2,470	419/0	720/2,470
July	0	0	131/921	613/0	744/921
August	0	0	146/986	598/0	744/986
September	0	0	411/3,584	309/0	720/3,584
October	0	93/1,692	597/5,955	54/0	744/7,647
November	34/824	317/6,032	369/4,606	0/0	720/11,462
December	154/3,793	424/8,171	166/2,231	0/0	744/14,195
Year	479/11,986	2,154/40,762	3,694/37,871	2,433/0	8,760/90,619
[a] The temperature BIN 15 °C is split in half.					

By using heat pump test results, the maximum heat output, the power consumption and the coefficient of performance of the heat pump under the checkpoint temperatures in the second line of the above table are calculated through interpolation. If such test results are not available, default values given in Appendix C of DIN V 18599-5 (DIN, 2016a) can be used.

In the next step, the load factor of temperature class i in each month (FC) is calculated as the ratio of $Q_{h,outg,i}$ to the maximum heat output of the heat pump, and the partial load factor (f_{Pint}) for each range of FC is determined by referring to the tables also given in Appendix C (Correction factors and performance figures). For electrically driven air-air heat pumps, the following table is used to determine the partial load factor (f_{Pint}). The default values for COP at outdoor temperature ranges are also provided, such as in Table 3.3.7-2 and 3.3.7-3 for VRF systems.

Finally, the coefficient of performance ($COP_{Pint,i}$) under the load factor (FC) and the temperature class *i* is calculated using the following equation, and the heat pump energy use ($Q_{h,f}$) is also calculated.

$$COP_{Pint,i} = f_{Pint} \times COP_{hp,\theta_{source},max} \tag{3.3.7.2}$$

$$Q_{h,f} = \sum_{i=1}^{n_{class}} \frac{Q_{h,outg,i}}{COP_{Pint,i}} \tag{3.3.7.3}$$

where,

- $COP_{hp,\theta source,max}$ is the coefficient of performance at maximum heat output of the heat pump under the source temperature (checkpoint temperature representing each temperature class);
- n_{class} is 4, the number of temperature classes.

Table 3.3.7-2. Correction factor for partial load operation (f_{Pint}) for electrically driven outside air-room air heat pumps with direct condensation

system	Load factor FC %									
	10	20	30	40	50	60	70	80	90	100
Compact devices (window or wall)	0.39	0.6	0.7	0.75	0.78	0.82	0.85	0.88	0.93	1.0
Split systems (also simultaneous multi)	0.4	0.65	0.75	0.78	0.81	0.85	0.9	0.92	0.95	1.0
Multi-split systems	0.54	0.85	0.94	0.98	1.02	1.02	1.0	1.0	0.99	0.98
VRF systems (variable refrigerant mass flow)	0.65	1.07	1.15	1.15	1.17	1.15	1.10	1.07	1.01	0.98

Table 3.3.7-3. Default COP values for each outdoor temperature range for products

Outside temperature (inlet source temperature)	Constantly performance-regulated			
	-7 ° C	2 ° C	7 ° C	10 ° C
	w-7	w2	w7	w10
COP from 2003	3.0	3.3	3.5	3.7
COP from 1998 to 2002	2.7	2.9	3.0	3.3
COP before 1998	2.5	2.9	3.1	3.2
Utilization 100%	0.81	0.96	1.00	1.00

3.3.8 France RE 2020

3.3.8.1 France RE 2020

In France, the supporting calculation method for regulatory purpose is developed by the "Centre Scientifique et technique du Batiment" (CSTB) and adopted as a French regulation. The version currently in force is the "RE 2020", which was published in the Official Journal of the French Government on the 15th of August 2021[7].

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[7] Arrêté du 4 août 2021 relatif aux exigences de performance énergétique et environnementale des constructions de bâtiments en France métropolitaine et portant approbation de la méthode de calcul prévue à l'article R. 172-6 du code de la construction et de l'habitation – 15th of August 2021 - Journal officiel de la République Française

3.3.8.2 Context and background information

In France, the energy performance of buildings is regulated since 1974. An energy performance calculation is required for any application for a building permit, to issue EPCs and for deep renovations.

The text of RE2020 is written like an analysis of a calculation software because CSTB is also in charge of providing and maintaining a software kernel for the calculation of energy performance of buildings according to RE 2020. Software houses providing professional software to practitioners must incorporate the official kernel into their software (they develop only the user interface) and submit their software to a validation test.

RE 2020 applies similar (and sometimes identical) concepts and methods, but it is not directly linked to national and international technical standards (AFNOR, EN and ISO standards).

RE 2020 covers the whole building energy performance calculation for space heating, space cooling, domestic hot water preparation, ventilation, lighting, and people transport (elevators and travelators). The calculation interval is hourly. Section 8.23 of RE 2020 is dedicated to “thermodynamic generators for heating and cooling”, that is heat pumps and chillers.

RE 2020 also covers the assessment of the building environmental performance over its whole life cycle.

3.3.8.3 Output data

The module for heat pumps provides the usual results for each calculation interval:

- the part of the required heat output that can be supplied by the heat pump;
- the required driving energy, per energy carrier;
- the required auxiliary energy;
- the amount of heat captured from the environment;
- the efficiency and load factor;

No recoverable losses are considered.

3.3.8.4 Method (structure and rationale)

RE2020 covers also extensively the calculation of the temperature of the following sources (or sinks for cooling):

- external air;
- extracted air;
- indoor air of an unheated space (for domestic hot water preparation only);
- ground water;
- brine;
- water loop (a common loop to act as source and/or sink of multiple heat pumps);
- ground heat exchanger with direct expansion (heating and domestic hot water only).

The method considers a total of:

- 9 combinations of source and sinks for heating,
- 7 combinations of source and sinks for cooling,
- 6 possible sources for domestic hot water heaters.

The method is the same as path A of EN 15316-4-2:2017 (CEN, 2017c) and it is applied for both heating and cooling. The calculation of the COP or EER is performed in two basic steps:

- calculate the COP or EER at full load, with the same source and sink temperature;
- correct the full load COP or EER according to part load LR.

The full load performance map of the heat pump (both capacity and COP_{LR100} or EER_{LR100} at full load) may be generated from a single value at full load and a given source and sink temperature (the “pivot” value). All other values in the grid are calculated by applying default multiplying factors that depend on the heat pump type. Optionally, the manufacturer can declare additional pivot values.

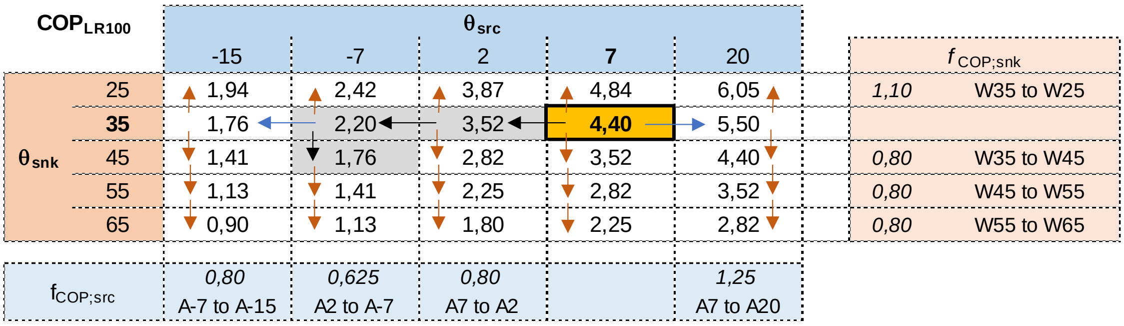
The pivot value provided by the manufacturer is evaluated according to the following criteria:

- it is taken as is, if the value is “certified” by an accredited organism;

- it is reduced by 10%, if the value is “justified”, that is “measured” by an accredited organism;
- it is reduced by 20%, if the value is simply declared by the manufacturer;
- otherwise, a default value is provided, depending on the technology.

Figure 3.3.8-1 shows an example of filled in values of full load COP_{LR100} for an AW heat pump with a certified pivot value of COP=4,2 at air 7°C and water 35 °C (A7W35). Since it is certified, the starting value is 4,20. Then:

- values in the next columns are obtained by multiplying the COP by factors $f_{COP;src}$;
- values in the next rows are obtained by multiplying the COP by factors $f_{COP;snk}$.



COP_{LR100}		θ_{src}					$f_{COP;snk}$	
		-15	-7	2	**7**	20		
θ_{snk}	25	1,94	2,42	3,87	4,84	6,05	*1,10*	W35 to W25
	35	1,76	2,20	3,52	**4,40**	5,50		
	45	1,41	1,76	2,82	3,52	4,40	*0,80*	W35 to W45
	55	1,13	1,41	2,25	2,82	3,52	*0,80*	W45 to W55
	65	0,90	1,13	1,80	2,25	2,82	*0,80*	W55 to W65
$f_{COP;src}$		*0,80* A-7 to A-15	*0,625* A2 to A-7	*0,80* A7 to A2		*1,25* A7 to A20		

Figure 3.3.8-1. Sample COP calculation table for an air to water heat pump

The COP at A-7W45 is given by: 4.40 (pivot value) x 0.80 (A7 to A2) x 0.625 (A2 to A-7) x 0.80 (W35 to W45) = 1.76

The correction of the COP or EER for part load to get COP or EER at actual load is performed with the method at constant auxiliary power of EN 15316-4-2:2017 (CEN, 2017c) and considering a multiplication factor of COP at minimum load. The default values are:

- fraction of auxiliary energy: 2%;
- minimum continuous operating load: 40% of full load (turndown ratio = 2.5);
- default increase of COP a minimum continuous load: 0%.

The manufacturer can provide certified, justified or declared values to replace the default values. Dedicated calculation procedures are provided to calculate the heat capture and/or rejection temperature.

3.3.8.5 Required input data

The method can be used with the default values only. Input values can also be declared by the manufacturer but they are derated according to the supporting evidence (certified, justified and declared values). The possible input data are:

- full load performance grid (COP and capacity) for the relevant source and sink temperature;
- fraction of auxiliary energy;
- minimum continuous operating load;
- increase of COP at minimum load.

3.3.8.6 Known issues

The derating of data according to the level of supporting documentation is introducing a bias in the calculation. Like all other methods based on full load data and then correction according to part load, the method is not suitable for air-to-air heat pumps.

3.3.8.7 Foreseen developments

French experts from CSTB are actively participating in the development of EN 15316-4-2 (CEN, 2017c). This should ensure alignment between the French method and EN standards.

3.3.9 UK SBEM for non-residential buildings

3.3.9.1 Status

SBEM is a computer program that provides an analysis of a building's energy use (UK, 2015). It was developed for the UK National Calculation Method (NCM), which is defined by the Department of Communities and Local Government (DCLG) in consultation with the Devolved Administrations (DAs-England, Wales, Scotland and Northern Ireland). The procedure for demonstrating compliance with the Building Regulations for buildings other than dwellings involves calculating the annual energy use for a proposed building and comparing it with the energy use of a "notional building". The "notional building" (or "reference building") is a building having the same size, location, orientation and operating conditions of the actual evaluated building and predefined energy efficiency properties like e.g. building envelope transmittance, HVAC system efficiency. The calculated energy performance of the notional building is assumed to be the regulatory requirement for the actual building under evaluation.
The NCM allows the calculation either by an approved simulation software or by a simplified tool based on CEN standards. The simplified tool, SBEM – Simplified Building Energy Method, was developed for DCLG by BRE.

3.3.9.2 Context and background information

The Building Regulations compliance calculation generally compares the total energy use of the building and its systems (in kWh/m^2/year), expressed as carbon dioxide emissions of the building being evaluated (its "Building Emission Rate" or BER) with a target value ("Target Emission Rate" or TER) derived from similar calculations for a "notional building" (where both emission values are in kgCO$_2$.m^2/year).

The purpose of SBEM and its basic user interface iSBEM is to produce consistent and reliable evaluations of energy use in non-residential buildings for Building Regulation Compliance and also for Building Energy Performance Certification. In introductions of relevant documents, the following caution is described:
"SBEM is a compliance procedure and not a design tool. If the performance of a particular feature is critical to the design, even if it can be represented in SBEM, it is prudent to use the most appropriate modelling tool for design purposes. In any case, SBEM should not be used for system sizing." (p.11 in User Guide iSBEM (1) Basics – UK, 20 November 2015)
"The need is to ensure that comparisons with the notional and other buildings are made on a standardized, consistent basis. For this reason, the energy and CO$_2$ emission calculations should not be regarded as predictions for the building in actual use." (p.20 in A Technical Manual for SBEM, UK volume, 20 November 2015)

3.3.9.3 Method (structure and rationale)

For the calculation of heating and cooling demand (load), a monthly calculation under ISO 52016-1 "Energy performance of buildings – Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads – Part 1: Calculation procedures" is conducted.
Heating energy consumption is determined on a monthly basis for each HVAC system defined in the building[34]. Having calculated the energy demand (load) for heating in each zone of the building ($Q_{NH,yr}$) as described above, the heating energy demand (load) for the HVAC system is the sum of the demands of all the zones serviced by that HVAC system (H_d in the following equation). The heating energy consumption for the HVAC system (H_e) is then calculated as follows:

$$H_e = \frac{H_d}{SCOP} \tag{3.3.9.1}$$

where *SCOP* is the Seasonal System Coefficient of Performance of the heating system, which is the ratio of the total heating need in zone(s) serviced by the HVAC system to the energy input into the heat generator(s). The SCoP includes generator (e.g., heat pump) efficiency, heat losses in pipework and ductwork, and duct leakage, but does not take account of energy use for fans and pumps (but does include the proportion of that energy which reappears as heat within the system).The building heating energy use will be the addition of the heating energy use of all the HVAC systems included in the building.

The SCOP is measured under the procedures in BS EN 14825:2013 Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling. Testing and rating at part load conditions and calculation of seasonal performance. As of 2013, European Commission Regulation No 206/2012 sets standards only for SCOP of electrically-driven air-to-air heat pumps with an output =< 12 kW. There was no European test standards for part-load testing of air-to-air heat pumps with an output > 12 kW or for other types of heat pumps, and so the performance of these must be specified using COP obtained at the heating system rating conditions.

Cooling energy consumption is also determined on a monthly basis for each HVAC system defined in the building. Having calculated the energy need (load) for cooling in each zone of the building ($Q_{\mathrm{NC,yr,z}}$) as described above (according to ISO 52016-1), the cooling energy demand for the HVAC system is the sum of the demands of all the zones serviced by that HVAC system (C_d in the following equation). The cooling energy consumption for the HVAC system (C_e) is then calculated as follows:

$$C_e = \frac{C_d}{SEER} \tag{3.3.9.2}$$

where *SSEER* is the Seasonal System Energy Efficiency Ratio of the cooling system, which is the ratio of the total heating need in zone(s) serviced by the HVAC system divided by the energy input into the cold generator(s) of the system. The SSEER takes account of the efficiency of the cold generator(s), heat gains to pipework and ductwork, and duct leakage, but does not consider energy consumption for fans and pumps. The building cooling energy consumption will be the addition of the cooling energy use of all the HVAC systems included in the building.

The value of SEER to be used in the SBEM tool can be calculated in several ways, according to the availability of information and the application (CEN, 2017e). In general, where an industry approved test procedure for obtaining performance measurements of cooling units at partial load conditions exists, and the cooling load profile of the proposed building is known, the SEER of the cooling unit is given by:

$$SEER = a(EER_{100\%}) + b(EER_{75\%}) + c(EER_{50\%}) + d(EER_{25\%}) \tag{3.3.9.3}$$

where EER_X is the EER measured at the load conditions of 100%, 75%, 50% and 25% at the operating conditions detailed under the part load energy efficiency ratio in Table 3.3.9-1.

Table 3.3.9-1. Operating conditions of cooling system for part load conditions

Percentage part load	25%	50%	75%	100%
Ambient air temperature (°C) for air-cooled chillers	20	25	30	35
Entering cooling water temperature (°C) for water-cooled chillers	18	22	26	30

Note: Chilled water temperatures are assumed at 7 °C out 12 °C in (at 100% load). For air cooled chillers, the relevant temperature is the outdoor temperature. For water cooled chillers, the relevant temperature is the inlet temperature of the cooling water (not the chilled water), which is assumed to be lower than air temperature because it is assumed that a cooling tower is used.

For cooling units that have no part load data, the SEER is the full load EER.

For applications where the load profile under which the cooling plant operates is not known but there is some data on chiller part load EER:

For chillers where the full and half load (50%) EERs are known, the 100% and 50% are equally weighted.

For chillers with four points of part load EER, the SEER is calculated using Equation (3.3.9.3) with each EER weighted equally, i.e., a, b, c and d each equal to 0.25.

For applications in general office-type accommodation, the following weighting factors can be taken as representative of the load profile:

a=0.03, b=0.33, c=0.41 and d=0.23

3.4 Discussion

The first evidence is the wide variety of calculation methods for the energy performance of heat pumps that have been developed independently in several countries. These methods are mostly used for regulatory purpose, as part of the energy performance calculation of the entire buildings, starting from the building envelope properties and providing the weighted energy use as primary energy and/or carbon emissions to provide comfort services (space heating and cooling, domestic hot water preparation, etc.).

None of the methods appears to be prominent: all have some to several shortcomings.

Several causes explain the current situation.

The activity of professionals involved in the installation, operation, maintenance, and renovation are mostly local as well as the building environment regulations that can be national, often regional and sometimes local to large municipalities. Products are distributed worldwide, whereas buildings stay where they are erected and the in-use energy performance of a heat pump is used as part of the characterisation of the building as a whole. This leads naturally to local developments about the in-use energy performance calculation.

Historically there has been a first interest on the performance of the building envelope. Heating and cooling needs calculation had the time to be standardised internationally and EN ISO 52016-1 (CEN, 2017a) (the new name of EN ISO 13790) is routinely used in several countries.

The standardisation on heating systems efficiency calculation started later and the massive use of heat pumps for heating is a recent development. Mechanical systems are very various and heat pumps are available and used in a wide range of different types that require different parameters for their characterisation. An additional complexity is the extreme sensitivity of the heat pump to operating conditions: an accurate and reliable calculation method of the in-use efficiency of a heat pump in a specific building with specific operating conditions must consider several parameters.

The result are substantial differences among the calculation methods related to the following aspects, which can be used as a basis for a classification:

- Calculation interval: this can be seasonal, monthly, hourly or based on temperature bins.
- Services considered: space heating, space cooling, domestic hot water preparation.
- Supported heat pump types, which are a combination of:
  - type of heat capture and/or heat rejection and related equipment: external air, exhaust air, ground heat exchanger, groundwater, surface water, cooling tower, solar assisted direct expansion, and more;
  - type of connection on the internal side of the building: indoor air (direct expansion or compression), technical water (i.e. non-domestic, just heat transfer fluid), domestic hot water;
  - type of heat pumping technology: vapor compression cycle (electric motor or combustion engine driven), absorption;

  - special devices such as heat recovery (de-superheater), simultaneous heating and cooling (VRV, VRF and 4 pipes heat pumps), by-pass for free cooling.
- influence parameters considered (source temperature, sink temperature, volume of water in the installation, flow temperature control, etc.);
- basic modelling concept (independent influence of parameters (or operating conditions parameters), …);
- connection with product data (fit for use of existing standardised product data).
- additional modelling criteria and energy performance concerns:
  - control options considered (type of capacity modulation, turndown ratio, etc.),
  - external auxiliaries calculation,
  - auxiliary calculation methods for heat capture and/or rejection devices,
  - calculation of back-up heater and checking the available capacity,
  - handling priorities between services,
  - any dynamic feature.

Table 3.4-1 summarises some features of the reviewed methods.

Table 3.4-1. Comparison of calculation methods

Method	**Coverage** (*)				**Calc. interval**	**Basic modeling concept**	**Product data**	**Notes**
	Services	HP type	Tech.	Other				
EN 15316-4-2	H, W	AW, WW, AA	E, A	-	M, H, B	A, B	EN 14511 EN 14825	On-going revision. Path A related to EN 14511 data, path B related to EN 14825 data.
EN 16798-13	C	AW, WW, AA	E, A	FC, M	M, H, B	A, B	EN 14511 EN 14825	
NECB	H							
BECS	C							
UNI TS 11300-4	H, W	AW, WW	E, A, C	-	B	A	EN 14511	Monthly bins UNI-TS 11300-3 for cooling
SAP 10.2	H, W	AW, AA, WW	E, A	-	S (H)	B	PDB EN 14825	Precalculated seasonal COP based on hourly calculation PDB = official Product Data Base
SBEM								
DIN V 18599	H, W, C	AW, WW, AA	E, A		M	C	EN 14511	
RE 2020	H, W, C	AW, WW, AA	E, A	Exh	H	A	EN 14511	
Energy plu	H, W, C	Any	Any		H	A		Requires modeling skills and efficiency curves.

Key
Services: H = heating C = cooling W = domestic hot water
HP type: A = air W = water/brine G = ground heat exchanger
Technology: E = electric compression. A = absorption C = combustion engine
Other FC = free cooling C = cascade Exh = Exhaust air heat pump
Interval: S = seasonal H = hourly B = Bin M = Monthly
Influence
Basic modeling A = Based on full load data and correction for part load B = Based on part load data processing C = Based on weighted average of test results

(*) Main intended and/or suitable coverage.

A critical issue is the connection between product data and related testing procedures and the energy performance calculation methods. The strong and non-linear sensitivity of the heat pump performance to several parameters makes it difficult to provide enough information to identify the full performance map of a heat pump with only a few testing points. The current calculation methods make strong assumptions to simplify the required input data or to adapt to available data. This inherently limits the reliability of calculation methods to the validity interval of the underlying assumptions, which can be quite small.

To avoid or overcome this issue:

- the definition of the “heat pump” and of its product data, that is the properties that characterise the heat pump;
- the product testing method, that is the method to evaluate the defined heat pump properties;
- the product rating method, that is the determination of a single figure that allows to evaluate a heat pump and compare it against regulatory limits and other products;
- and the energy performance calculation method, that is the determination of the efficiency of the heat pump in a specific use and operating condition, should be developed simultaneously and with a strong coordination between developers of the respective standards. This is also necessary to achieve a good balance between:
- testing effort on one side;
- and product qualification and energy performance prediction accuracy on the other side.

Coordination of the above-mentioned standardisation aspects of heat pumps was very limited so far and happened mostly about product data and product qualification. An example of this approach is EN 14825 (BSI, 2022) that defines both the calculation method to rate a heat pump and the required testing points.

The required data for product rating and for in-use energy performance calculation may be quite different:

- product rating means calculating the efficiency of all models of heat pumps in the same representative operating conditions;
- in use energy performance calculation means calculating the efficiency of a specific heat pump in any specific operating conditions (event the wrong ones to evaluate savings deriving from e.g. correct operation and sizing).

Due to lack of coordination with test methods development, developers of calculation methods of the in-use energy performance of heat pumps had to rely just on the available product data. As an example, EN 15316-4-2 (CEN, 2017c) includes two main calculation paths precisely to adapt to the available datasets according to EN 14511 (BSI, 2018) and EN 14825 (BSI, 2022). Physical and engineering assumptions are often used to cover a wide range of application cases. In some cases, developers of energy performance calculation methods apparently did not even try to adapt: EnergyPlus seems to let the responsibility to provide a suitable empirical model of the heat pump efficiency on the user. There is little guidance in the documentation for the user on how the model shall be made or chosen for heat pumps.

A good example of the required coordination is the current development of an EN standard on instantaneous drain water heat recovery. The main application of these products is preheating the incoming domestic cold water for a shower using the warm drain water. These products recently appeared on the market and product standards and testing standards were developed by national approaches. Now two EN standards are under development simultaneously for both product testing and energy efficiency calculation. The coordinated development resulted even in a simplification of the envisaged testing procedure.

The poor coordination between product data and in-use energy performance calculation may partly explain the gap which is often reported between calculated and measured energy performance. Another reason can be the poor commissioning and the misuse of this sensitive machine. Before investigating the gap between calculated and measured in-use performance, the calculation method should be stabilised and well connected to product data, which is not the case yet.

3.5 Perspectives of the future development of energy calculation methods for heat pump systems and harmonisation with their testing methods

Heat pumps comprise a wide and varied family of products that is far from being clearly and robustly standardised. A robust standardisation system should cover extensively and coherently:

- product definition and characterisation;
- product testing methods;
- product rating and related calculation methods;
- in-use energy performance calculation methods.

There is still a gap between tested and/or calculated efficiency and actual efficiency that can be measured in real life. This can partly be explained by the still frequent misuse and sub-optimal commissioning of heat pumps, but it is also caused by the poor coordination between product data and in-use energy performance calculations.

Several energy performance calculation standards have been developed in the different countries, but this happened independently, with little coordination with product standards, and with quite different approaches.

Based on the review of existing energy calculation methods in this Chapter, there seem at least the following three main basic modelling approaches.

a. Starting from tested performance data at one or several nominal conditions, interpolation, extrapolation and default correlations are applied to introduce the effect of changes in operating temperatures and/or part load operation and/or other influencing factors. The effects of the different influencing factors are assumed to be independent of each other and are applied one after the other.

   Examples of this approach are e.g. path A of EN 15316-4-2, EnergyPlus, NECB, BECS, UNI-TS 11300-4, RE2020, method 2 of EN 16798-13.

b. Test results from several conditions with changing part load and temperature conditions are pre-processed to identify a characteristic function that describes the efficiency of the heat pump. Then the characteristic function is used to evaluate the efficiency in the specific operating conditions of the calculation interval.

   Example: the dependency of exergetic efficiency on required heat output is determined according to several part load performance data. Then the Carnot efficiency is calculated based on operating temperatures and multiplied by the exergetic efficiency for the specific part load.

   Examples of this approach are e.g., path B of EN 15316-4-2, method 1 of EN 16798-13.

c. The seasonal efficiency is assumed to be a weighted average of heat pump efficiencies for different part load ratios.

   Example of this approach is SBEM.

The basic modelling assumption relate to the required and/or available product data.

None of the current in-use energy performance calculation methods looks fully satisfactory and provides full coverage of all heat pump types.

There are a lot of ongoing activities to further develop energy performance calculation standards, but it looks like there is not enough attention and effort to coordination with product standards.

A combined research effort to identify:

- the relevant influence factors of heat pumps efficiency;
- the product data set required to quantify the influence of each factor on a specific product;
- the test procedures to identify the product data;
- the energy performance calculation method to use the data-set;

would help increase the connection between product data and energy performance calculation. In this respect, a call for experts has been launched (spring 2024) by ISO/TC 86/SC 6/WG 16, to start the development of an ISO standard titled "Data from Air Conditioning and Heat Pumps for Energy Efficiency Simulation of Building Systems".

To further develop reliable in-use energy efficiency calculation methods for heat pumps, much more field monitoring results should be collected and referred to. Reasonable judgements on the choice of the factors to be included in the models should be based on monitoring evidence. Then the feasibility to obtain the product data to assess the impact of those factors should be taken into consideration.

It is also said that the load-based test methods for heat pumps, which are one of the focuses of Chapter 1, should be standardised and the best way to utilise the results should be searched for in the development of energy calculation methods.

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