CEN WORKSHOP AGREEMENT

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English version

Characterization of a hybrid heat pump module

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European foreword

This CEN Workshop Agreement (CWA 17954:2022) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations – Part 2. It was approved by a Workshop of representatives of interested parties on 2022-10-20, the constitution of which was supported by CEN following the public call for participation made on 2022-03-17. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

0.1 General

Industrial processes are often energy-intensive and the need for their efficient decarbonization is now at the forefront of governmental and corporate policies worldwide. However, solutions for the green transition of the industrial sector should be flexible, widely applicable, and reliable.

Two-thirds of industrial energy consumption is related to heating and cooling processes and is becoming a major environmental problem. The integration of renewable thermal energy sources at industrial sites is therefore crucial.

In this context, the EU co-financed project "Industrial Cooling through Hybrid system based on Solar Heat" aims to increase the use of solar heat in industrial processes by combining two key components: solar thermal collectors and hybrid adsorption-compression chillers to provide steam, heating, and cooling energy with greater efficiency.

Originally the above solution was addressed to industrial processes, but the content of this document is also relevant to other environments and can have industrial, residential, and commercial applications, no matter the size and resources of the project.

0.2 The hybrid heat pump

One of the key innovations that allows solar cooling for green and energy-efficient processes is the Hybrid chiller also referred to as hybrid heat pump since the working principle is the same as for heat pumps, but the useful effect is cooling not heating. The hybrid is composed of a vapour compression machine coupled to a sorption heat pump. The sorption heat pump can exploit low-temperature waste heat (i.e., 70-90 °C) that is generally unused or dumped to the ambient. It can also be powered by renewable sources, such as solar heat and biomass. The electrical heat pump can exploit electricity locally produced (i.e. from photovoltaic panels or other sources) and thus further increase the share of renewables. The hybridization consists in the configuration of the two heat pumps: they can work in series, in parallel or in cascade by just changing the hydraulic connections. This makes its configuration flexible and easily adaptable to different cases.

The hybrid heat pump will allow a step forward towards the exploitation of thermally driven cooling systems in industrial, residential, and commercial applications. It will take advantage of the renewable solar heat source to drive a sorption module, thus increasing the electrical energy efficiency of the whole cooling system.

To evaluate the performance of the technology, different performance parameters must be experimentally evaluated under controllable boundary conditions and following a standardized methodology. Some of the most relevant parameters to be considered are the cooling power, the Energy Efficiency Ratio (EER) and the thermal Coefficient of Performance (COP).

0.3 Verbal forms in the document

In this document, the following verbal forms are used:

— "shall" indicates a requirement;

— "should" indicates guidance and/or best practices;

— "may" indicates permission;

— "can" indicates a possibility or a capability.

Information marked as "NOTE" is for guidance in understanding or clarifying the associated requirements.

0.4 Acronyms

Along the text, the following abbreviations are used:

Cp	Specific heat, kJ/(kg K)
$\dot{m}$	Mass Flow, kg/s
P	Power, kW
$\dot{Q}$	Thermal Power, kW
ϑ	Temperature, °C
T	Temperature, K
t	Time, s

Subscripts

cool	cooling
ext	external
HEX	Heat exchanger
in	inlet
int	internal
out	outlet

Abbreviations

SHP	Sorption Heat Pump
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
HT	High temperature circuit
HHP	Hybrid Heat Pump
LT	Low temperature circuit
MT	Medium temperature circuit
VCHP	Vapour compression heat pump

1 Scope

This CEN Workshop Agreement specifies the experimental methodology to characterize a hybrid heat pump under real operating conditions to derive performance parameters, which can be also presented as a map of performance, and heat pump capacity as a function of operating conditions.

The characterization includes a definition of testing rig configuration, a testing methodology, the list and definition of relevant performance parameters and the procedure for calculating them. The characterization can be of help to make comparisons in terms of performance.

This CEN Workshop Agreement is valid to a vast range of industrial, commercial, and residential applications and to those wishing to:

— turn renewable heat and waste heat into useful cooling effect;

— minimize energy consumption;

— reduce operational costs; and

— lower CO_2 footprint.

2 Normative references

The following documents are referred to in the text in such a way that some or all their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 14511-3, *Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling — Part 3: Test methods*

3 Terms and definitions

For the purpose of this document, the following terms, definitions, and abbreviations apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
hybrid heat pump
assembly or assemblies designed as combination of *vapour compression heat pump* (3.3) and *sorption heat pump* (3.2), that may be connected in various layouts (i.e., cascade, parallel, in series) and are co-operating in an optimized manner managed by a dedicated control system

3.2
sorption heat pump
encased assembly or assemblies of refrigerant-containing parts designed as a closed circuit in which the refrigerant is circulated using a sorption cycle relying on external combustion of fuels and/or supply of heat for the purpose of extracting and delivering heat (i.e., cooling and heating)

Note 1 to entry: Heat extraction (cooling) is effected by evaporation of a refrigerant, the vapour then being absorbed by an absorbent (liquid) or adsorbent (solid) respectively, from which it is subsequently expelled at a higher partial vapour pressure by heating and then liquefied by re-cooling.

[SOURCE: EN 378-1:2016+A1, 3.1.5 modified and aligned with Commission Regulation (EU) 2016/2281]

3.3
vapour compression heat pump
encased assembly or assemblies of refrigerant-containing parts designed as a closed circuit in which the refrigerant is circulated using vapour compression cycle driven by an electric compressor for the purpose of extracting and delivering heat (i.e., cooling and heating)

[SOURCE: EN 14511-1:2022, 3.19 modified and completed with EN 378-1:2016+A1, 3.1.1]

3.4
Energy Efficiency Ratio (EER)
ratio of the net cooling capacity to the effective power input at any given set of rating conditions

Note 1 to entry: Expressed in units of watt per watt.

[SOURCE: ISO 13256-2:2021, 3.11]

3.5
Coefficient of Performance (COP)
ratio of the net heating capacity to the effective power input of the equipment at any given set of rating conditions. In this case used as thermal COP, namely, the ratio between cooling capacity of the sorption heat pump and the heating capacity needed to drive the process

Note 1 to entry: Thermal COP is expressed in units of watt-hour per watt-hour.

[SOURCE ISO 13256-2:2021, 3.12]

3.6
European Seasonal Energy Efficiency Ratio (ESEER)
Seasonal *EER* (3.4) calculated by considering both full and partial load operation for cooling provision, according to defined weighting factors

Note 1 to entry: Weighting factors are defined by Eurovent certification procedures.

4 Testing facility

The first step to guarantee proper testing conditions for a hybrid heat pump is the definition of the proper configuration for the testing rig. Since the sorption heat pump of the hybrid machine requires three different temperature levels to operate, namely, high driving temperature (HT), medium re-cooling temperature (MT) and low chilling temperature (LT), the testing rig configuration shall guarantee the possibility of independently setting these three temperature levels and to maintain the inlet temperature conditions to each component almost constant throughout the testing, with acceptable fluctuation range depending on the different circuits.

A possible layout is schematically represented in Figure 1. It consists of three different hydraulic circuits connected to a buffer tank, employed to setup the desired temperature and a fast-reacting mixing valve, used to mix the delivered and return heat transfer fluid flow thus properly setting the inlet temperature of each circuit.

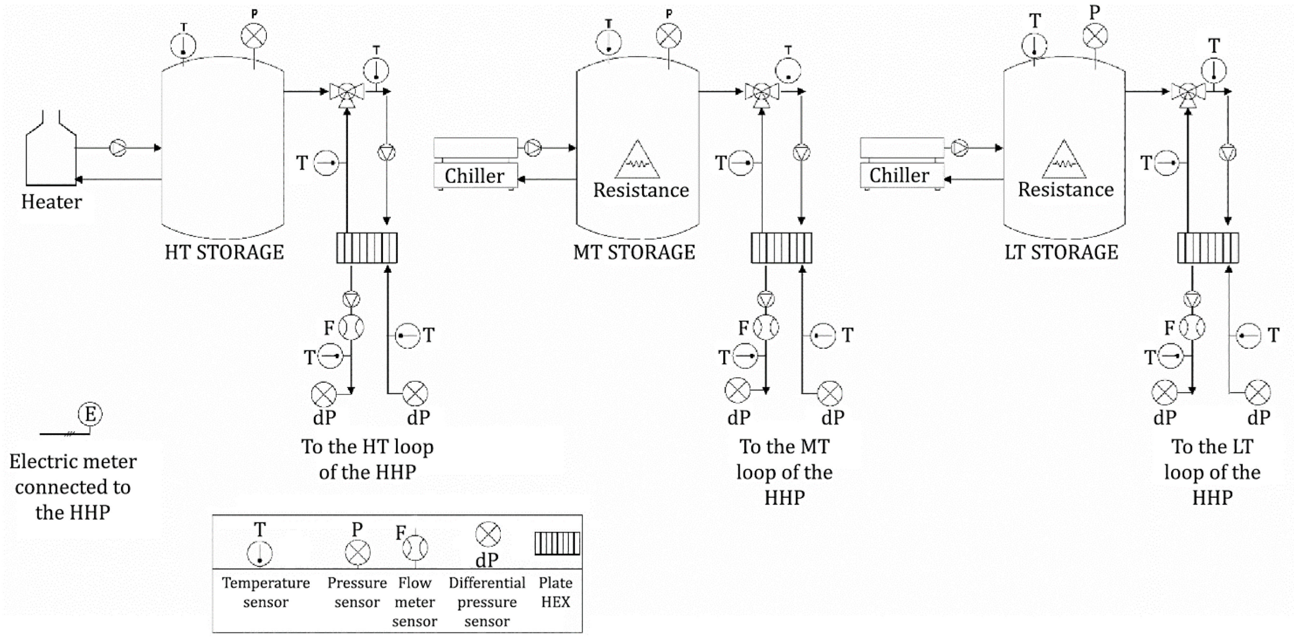


Figure 1 — Simplified schematic of the testing rig including all the pumps and sensors

Each hydraulic loop should be designed according to the following specifications:

a) High temperature loop: A buffer tank with an overall volume in the range of 50 l/kW of heating power shall be provided to the heat pump under testing. The buffer shall be connected to a heating source (e.g., electric heater, gas boiler), able to reach a temperature up to 95 °C. The heater capacity depends on the size of the hybrid heat pumps to be tested. The suggested rule is to have an available heating capacity as high as the expected heating power needed to drive the sorption heat pump. On the delivering side, a motorised 3-way valve connected to a PID regulator should be installed to guarantee the mixing between delivering and return heat transfer fluid flow, thus finely tuning the input driving temperature to the sorption heat pump. A variable speed pump should be integrated as well in case the machine under testing is not equipped with on-board pumping. The integration of a separation plate heat exchanger between testing rig loop and hybrid heat pump shall be foreseen in case of specific needs. The size of the heat exchanger shall guarantee the minimum temperature difference between primary and secondary side.

b) Medium temperature loop: A buffer tank with an overall volume in the range of 50 l/kW shall be extracted from the heat pump under testing. The buffer shall be connected to a heat rejection system (e.g., air-to-water chiller, geothermal chiller), able to keep the buffer temperature as close as possible to the heat rejection temperature (i.e., external ambient temperature). The cooling capacity depends on the size of the hybrid heat pumps to be tested. The suggested rule is to have an available cooling capacity as high as the expected cooling power needed to dissipate condensation and adsorption heat coming from the HHP. Furthermore, the integration of submersed electrical resistance inside the buffer tank should be considered, to increase the degree of flexibility in operating the testing rig. It should help in quickly fixing the right temperature level inside the tank before starting the tests. On the delivering side, a motorised 3-way valve connected to a PID regulator should be installed to guarantee the mixing between delivering and return heat transfer fluid flow, thus finely tuning the input driving temperature to the HHP. A variable speed pump should be integrated as well in case the machine under testing is not equipped with on-board pumping. The integration of a separation plate heat exchanger between testing rig loop and hybrid heat pump shall be foreseen in case of specific needs. The size of the heat exchanger shall guarantee the minimum temperature difference between primary and secondary side.

c) Low temperature loop: A buffer tank with an overall volume in the range of 50 l/kW of chilling power shall be provided to the chiller under testing. The buffer shall be connected to a controllable heating system (e.g. submersed electrical heaters), able to compensate the power extracted by the hybrid heat pump evaporator(s) during the operation, thus keeping the buffer temperature as close as possible to the evaporation temperature (i.e. end-user temperature). The heating capacity of the installed heater depends on the size of the hybrid heat pumps to be tested. The suggested rule is to have an available heating capacity as high as the expected chilling power provided by the heat pump under testing. The installation of an external chiller connected to the buffer tank is also suggested, to pre-condition the buffer down to the target temperature, before starting the testing phase. On the delivering side, a motorised 3-way valve connected to a PID regulator should be installed to guarantee the mixing between delivering and return heat transfer fluid flow, thus finely tuning the input driving temperature to the HHP. A variable speed pump should be integrated as well in case the machine under testing is not equipped with on-board pumping. The integration of a separation plate heat exchanger between testing rig loop and hybrid heat pump shall be foreseen in case of specific needs. The size of the heat exchanger shall guarantee the minimum temperature difference between primary and secondary side.

The testing rig shall be equipped with temperature sensors, flow meters, differential pressure transducers and electric meters to properly evaluate the performance. A list of parameters to be evaluated, sensors needed and acceptable uncertainty to evaluate each parameter, is reported in Table 1.

NOTE ISO/IEC Guide 98 *Uncertainty of measurement — Part 1: Introduction to the expression of uncertainty in measurement* can be used for this purpose.

Table 1 — Parameters to monitor, sensors and acceptable uncertainties

Monitored parameter	Sensors needed	Acceptable uncertainty
Heating/cooling power	Temperature inlet/outlet circuits Flow meter	±0,2 kW
Electric power	Voltage sensor Current sensor	±0,05 kW
Pressure losses	Differential pressure sensors	±1,5 kPa

Table 2 includes a list of parameters to be monitored, the unit and its description.

Table 2 — List of parameters to be monitored

Name of parameter	Unit	Description
ϑ_{HTin}	°C	Inlet temperature of the hot water in the sorption heat pump
ϑ_{HTout}	°C	Outlet temperature of the hot water from the sorption heat pump
ϑ_{MTin}	°C	Inlet temperature of the re-cooling water in the sorption heat pump
ϑ_{MTout}	°C	Outlet temperature of the re-cooling water from the sorption heat pump
ϑ_{LText_in}	°C	Inlet temperature of the chilled water/glycol solution to the evaporator
ϑ_{LText_out}	°C	Outlet temperature of the chilled water/glycol solution from the evaporator
$\vartheta_{HTstorage}$	°C	Temperature of HT storage
$\vartheta_{LTstorage}$	°C	Temperature of MT storage
$\vartheta_{LLTstorage}$	°C	Temperature of LT storage
$\dot{m}_{LPM\_HT}$	kg/s	Flow rate in HT circuit

Name of parameter	Unit	Description
$\dot{m}_{LPM\_MT}$	kg/s	Flow rate in MT circuit
$\dot{m}_{LPM\_LTint}$	kg/s	Flow rate in LTint circuit (circuit connecting the two units)
$\dot{m}_{LPM\_LText}$	kg/s	Flow rate in LText circuit
V	V	Supply voltage
F	Hz	Supply frequency
P_el	W	Electric energy consumption of the two units and their auxiliaries

5 Testing procedure

5.1 System boundaries

An important part of the testing procedure is the definition of system boundaries. Comparison of different systems or individual hybrid heat pumps is only possible if both were tested with the use of the same boundaries. The following suggestions are based on the balance areas and measuring points of VDMA 24247-7 and VDMA 24247-9.

— Boundary I is the hybrid heat pump including both sorption and vapour compression unit, power consumption of:

  — circulation pumps needed to transport the heat transfer medium through and between both units,

  — controller(s),

  — valves actuation.

— Boundary II additionally includes the heat sink (e.g., cooling tower, dry cooler) needed to dissipate the MT heat.

— Boundary III additionally includes the cooling distribution circuit, which consists of all components needed to exploit the cooling effect supplied by the hybrid heat pump.

— Boundary IV additionally includes the heat source system, which consists of all components needed to transfer the hot water from the driving source to the hybrid heat pump.

As shown in Figure 2, the test procedure described in this document focuses on Boundary I. Additionally, Clause 6 presents the range of power consumption of the heat sink so that an indicative performance evaluation can be done also for Boundary II.

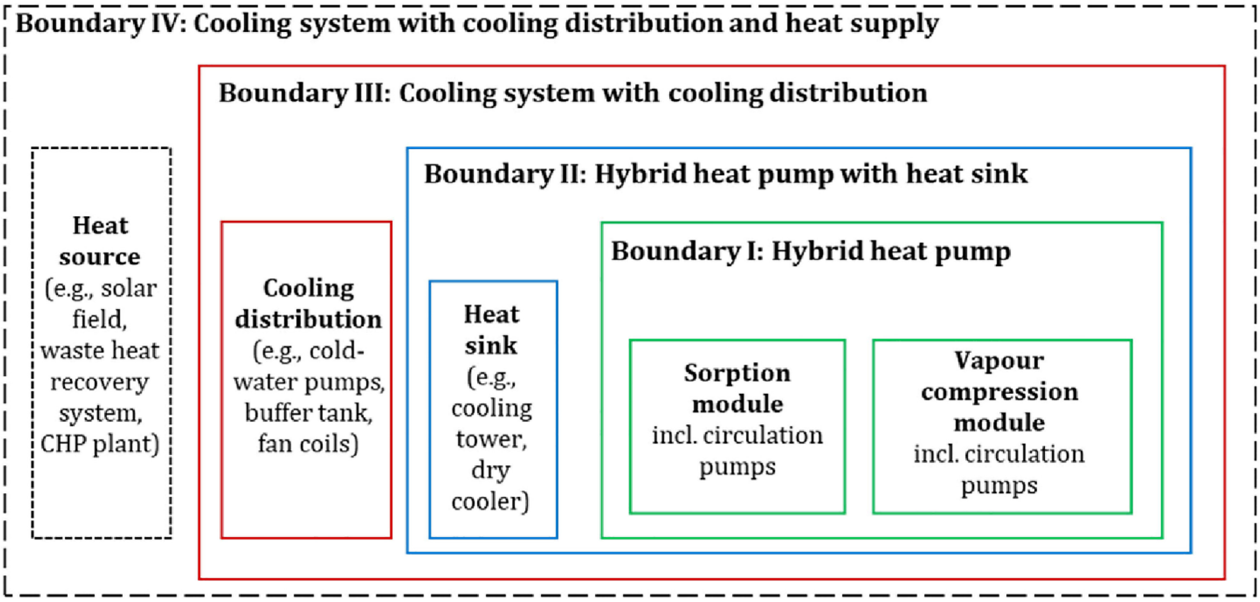


Figure 2 — System boundaries

5.2 Testing conditions

The preparation for tests shall include the definition of testing conditions. Since the hybrid heat pump may consist of a sorption heat pump based on different sorption cooling technologies (i.e. absorption or adsorption), the testing conditions shall be adjusted to the range of operating conditions given by the manufacturer. Moreover, the operating range of the hybrid heat pump depends on its layout. Different operating conditions may be allowed for a hybrid heat pump in cascade connection than in serial or parallel layout.

The following examples and suggestions included in Table 3 are partially based on the technologies and their operating ranges described in VDMA 24247-9.

Table 3 — Operating ranges of different HHPs

Technology	Hot water temperature range (inlet) °C	Re-cooling temperature range (inlet) °C	Cold-water (brine) temperature range (outlet) °C
Adsorption heat pump with working pair silica gel / water	50– 95	22 – 40	8 – 21
Adsorption heat pump with working pair zeolite / water	75 – 95	27 – 45	8 – 23
Absorption heat pump with working pair lithium bromide / water	50 – 180	20 – 35	-5 - 20
Absorption heat pump with working pair ammonia /	70– 180	5 – 50	-60 – 10

Technology	Hot water temperature range (inlet) °C	Re-cooling temperature range (inlet) °C	Cold-water (brine) temperature range (outlet) °C
water			
Hybrid heat pump in cascade layout (top: silica gel / water bottom: R290)	50 – 95	22 – 40	-10 – 20

If the HHP is intended for a particular application with different inlet chilled- water temperatures foreseen, this temperature should also be evaluated (if it lies within the operating range of the HHP).

5.3 Procedure for a standard test

The procedure for a standard test is summarised in Figure 3. In general, the controlled parameter shall be the inlet temperature provided to each component. After the desired temperature levels are set, the sorption unit in the hybrid heat pump shall be turned on followed by the compression chiller. Depending on the different hybrid configuration, the two modules can be also started at the same time.

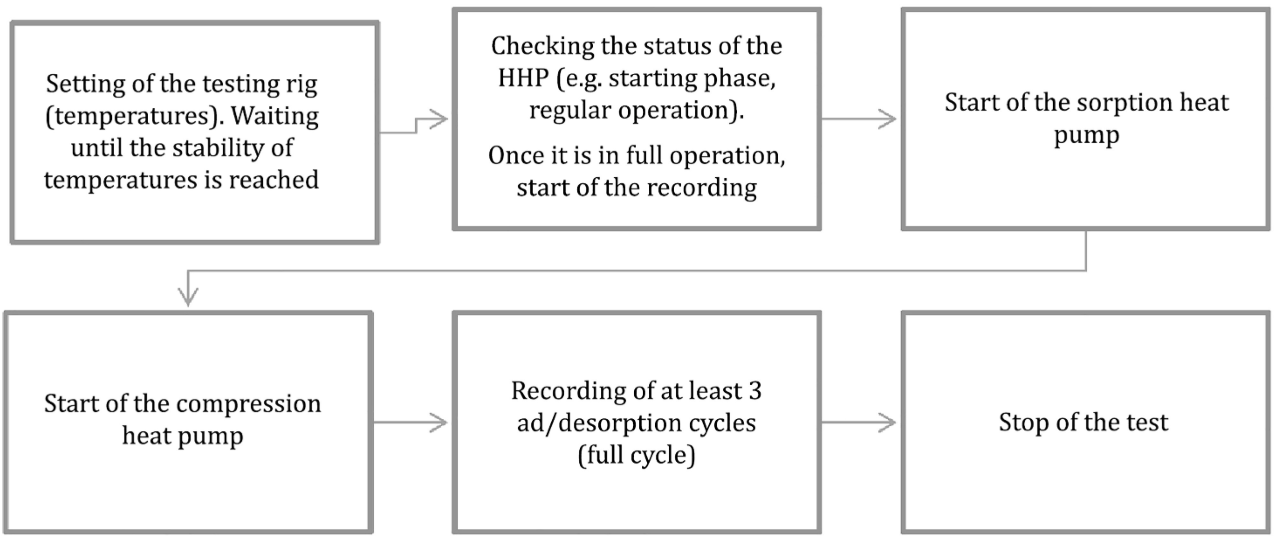


Figure 3 — Testing procedure

Each test shall be then recorded for a duration corresponding to at least three consecutive cycles of the sorption heat pump (this is especially relevant for adsorption technology where each cycle is easily identifiable during the operation). The inlet temperature fluctuations to different circuits should be the following: HT circuit ±5 °C, MT circuit ±3 °C, LT circuit ±2 °C.

6 Data reduction and performance evaluation

Performance of the hybrid heat pump can be evaluated by the following performance indicators:

1) Thermal COP

The thermal COP is defined as the ratio of the useful effect provided by the HHP (cooling capacity) and the heat input to its driving circuit (heating power). Higher COP means more effective use of the driving heat.

$$COP_{cooling} = \frac{\int_0^{\tau_{cycle}} \dot{m}_{LT} c_p \left(_{LTin} - _{LTout} \right) d\tau}{\int_0^{\tau_{cycle}} \dot{m}_{HT} c_p \left(_{HTin} - _{HTout} \right) d\tau} \quad (1)$$

If the HHP is used for heating purposes, the COP is also defined as the useful effect provided by the HHP and the heat input to its driving circuit. However, in this case the useful effect is not the cooling capacity but the heat rejection capacity (MT circuit).

$$COP_{heating} = \frac{\int_0^{\tau_{cycle}} \dot{m}_{MT} c_p \left(_{MTin} - _{MTout} \right) d\tau}{\int_0^{\tau_{cycle}} \dot{m}_{HT} c_p \left(_{HTin} - _{HTout} \right) d\tau} \quad (2)$$

2) Electrical EER of the HHP (Boundary I)

The EER is defined as the ratio between the useful effect provided by the HHP and the electric consumption needed to produce the said effect. This EER value considers the electric consumption of the HHP only ($P_{el,HHP}$), hence it is measured in system boundary I (see Clause 5).

$$EER_{HHP} = \frac{\int_0^{\tau_{cycle}} \dot{m}_{LT} c_p \left(_{LTin} - _{LTout} \right) d\tau}{\int_0^{\tau_{cycle}} P_{el,HHP} d\tau} \quad (3)$$

Measurements required for the evaluation of EER_{HHP} are the power consumption of the hybrid heat pump. The power consumption of the HHP shall be planned in such way, that it is possible to separately measure the energy consumed by the hydraulic pumps and the energy consumed by other consumers (controller, compressor, valve actuation). The proper methodology is schematically represented by Figure 2.

The overall electric consumption of the HHP is directly measured by connecting the electric meter to the supply of the electric cabinet. It accounts for all the electric consumption of the HHP (i.e., valves, controllers, compressor of the VCHP, pumps etc.). To evaluate only the pumping energy consumption inside the HHP, differential pressure meters shall be connected, for each hydraulic circuit, at the inlet of the HHP and at the end of each pipe connected to the testing rig.

Since the EER_{HHP} shall account only for the part of the energy consumption of the hydraulic pumps, which is needed to overcome the internal pressure losses of the HHP, the energy consumption due to external pressure losses of the testing rig shall be excluded from the evaluation, by subtracting from the external pressure losses the ones measured for the entire hydraulic circuit. Consequently, the electric consumption due to the internal pumping shall be calculated as described in subclauses 4.1.4.4.1 and F.2.1 Power input correction for integrated liquid pumps of EN 14511-3.

Figure 4 shows the schematic of the installation of differential pressures in the system under testing.

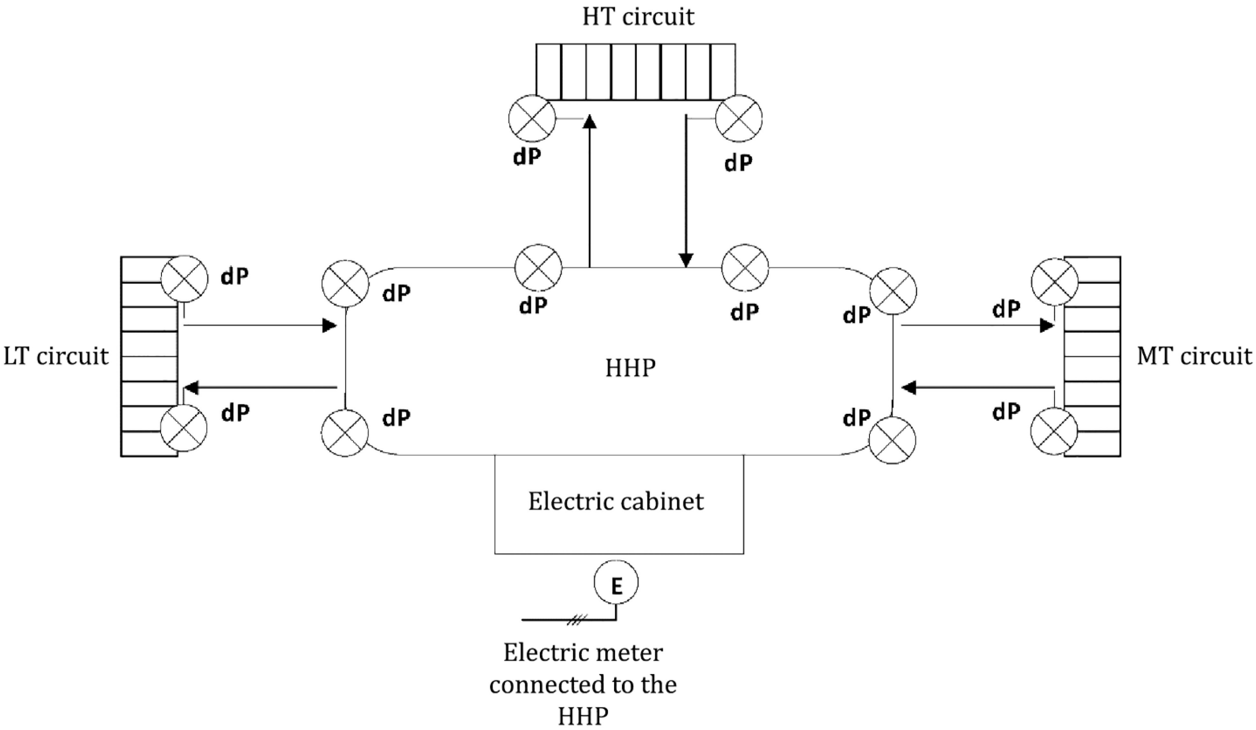


Figure 4 — Schematic of the installation of differential pressures in the system under testing

3) EER of the HHP including heat sink (Boundary II)

For proper operation, the hybrid heat pump needs some peripheral components. The main one is a heat dissipation device (also called re-cooler). The power consumption of the heat sink (e.g., a dry cooler or a cooling tower) can be described as high in comparison to the power consumption of sorption heat pump alone. Therefore, this consumption ($P_{el,HS}$) shall be considered while evaluating the performance of the system. There may be also other peripheral consumers, for example an external hydraulic pump in the re-cooling water circuit ($P_{el,PumpHS}$).

This type of EER is the one calculated for the system boundary II (see Clause 5).

$$EER_{HHP+HS} = \frac{\int_0^{\tau_{cycle}} \dot{m}_{LT} c_p \left(_{LTin} - _{LTout} \right) d\tau}{\int_0^{\tau_{cycle}} P_{el,HHP} + P_{el,HS} + P_{el,PumpHS} d\tau} \quad (4)$$

This document does not concern measuring the energy consumption of the heat sink. Instead, to evaluate the performance of the system in boundary II indicative values of heat sinks' power consumption should be used.

For the absorption heat pumps, which use typically wet cooling towers, the indicative values are given in VDMA 24247-9. The energy consumption of the heat sink lies in the range of 80 W to 120 W per 1 kW of supplied cooling capacity (fans + pumps).

For the adsorption heat pumps, which can be operated with dry coolers, the energy consumption of the heat sink lies within a broader range of 50 W to 130 W per 1 kW of supplied cooling capacity (fans + pump).

The indicative values for the vapour compression heat pumps are given in VDMA 24247-9 as well. It lies in the range of 42 W to 59 W per 1 kW of supplied cooling capacity (fans + pump).

4) Primary energy ratio

The HHPs consume two types of energy: heat and electrical energy. It is impossible to directly consider the consumption of both types of energy in one performance indicator. Therefore, the heat and electricity consumption should be re-calculated into primary energy consumption, which can be defined as primary energy ratio, PER.

$$PER_{HHP} = \frac{\int_0^{\tau_{cycle}} \dot{m}_{LT} c_p \left(_{LTin} - _{LTout} \right) d\tau}{\int_0^{\tau_{cycle}} P_{el,HHP} d\tau \ PEC_{El} + \int_0^{\tau_{cycle}} \dot{m}_{HT} c_p \left(_{HTin} - _{HTout} \right) d\tau \ \eta_{Gen} PEC_{Heat}} \quad (5)$$

Where PEC_{El} [kWh/kWh], represents the energy conversion factor from primary energy to electric energy and depends on the specific energy mix for electricity generation in each country; η_{Gen} [-], represents the generator efficiency in case of heat supplied by an external source; PEC_{Heat} [kWh/kWh], represents the energy conversion factor from primary energy to the energy source used to provide heating energy to the system (e.g. natural gas, fuel etc.).

The primary energy consumption can be neglected if the heat comes from a renewable or waste heat source. In other cases, it should be accounted for in the evaluation.

System performance should be estimated after the calculation of the following parameters:

— Heating power provided to the HHP Q_{HT}.

— Heat rejection power of the HHP Q_{MT}.

— Cooling energy provided by the HHP Q_{LText}.

— Electrical energy input for the operation of the HHP $P_{el,HHP}$.

Instantaneous power for each component should be calculated from the power balance of each component as:

$$\dot{Q} = \dot{m} c_p \left(T_{in} - T_{out} \right) \quad (6)$$

where

$\dot{Q}$	is the instant power in kW;
$\dot{m}$	is the mass flow rate in the circuit in kg/s;
c_p	is the specific power of the heat transfer fluid;
T_{in} and T_{out}	are the inlet and outlet temperatures of the circuit considered.

5) European Seasonal Energy Efficiency Ratio

The evaluation of the HHP's seasonal performance can be done using the European Seasonal Energy Efficiency Ratio (ESEER) as benchmarking parameter. The ESEER defined by Eurovent, considers different part load occurring at different ambient temperatures and is calculated as follows:

$$ESEER = 0.003 EER 100\ \% + 0.33 EER 75\ \% + 0.41 EER 50\ \% + 0.23 EER 25\ \% \quad (7)$$

where

EER is the Energy Efficiency Ratio at different part loads. Each part load ratio corresponds to a different air temperature, as shown in Table 4.

Table 4 — Correspondence between part load ratio, air temperature and weighing coefficients according to Eurovent standard

Part load ratio	Air temperature	Weighing coefficient
100 %	35 °C	0,03
75 %	30 °C	0,33
50 %	25 °C	0,41
25 %	20 °C	0,23

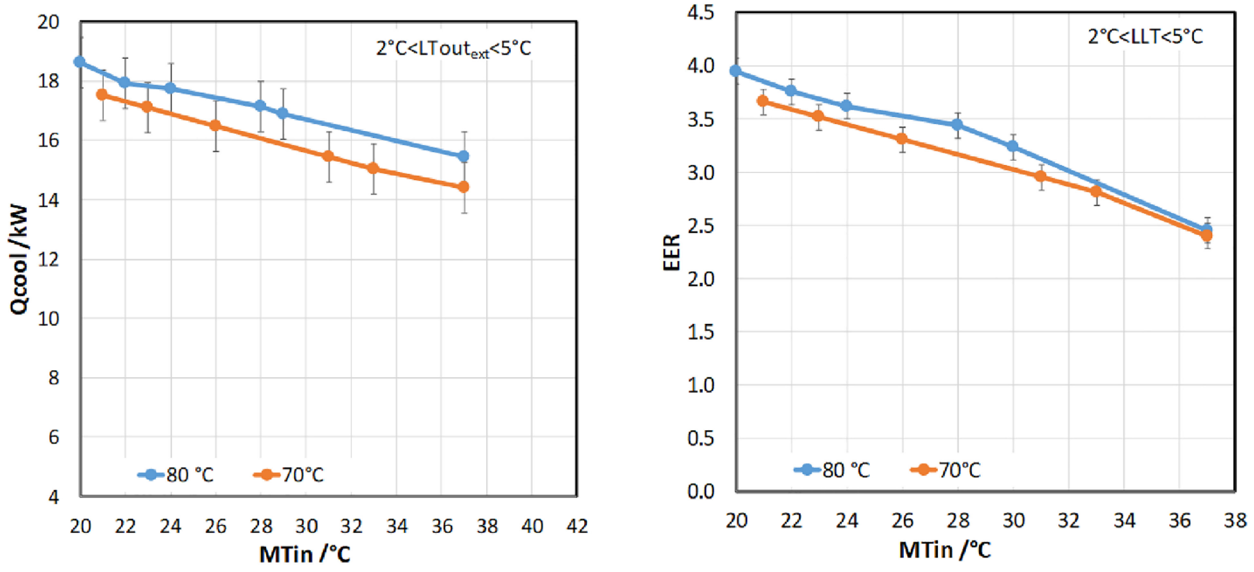
The above-mentioned parameters [i.e. thermal COP, Electrical EER of the HHP (Boundary I), EER of the HHP including heat sink (Boundary II), Primary energy ratio and ESEER] shall be used for the evaluation of the chiller's performance.

7 Reporting of the results

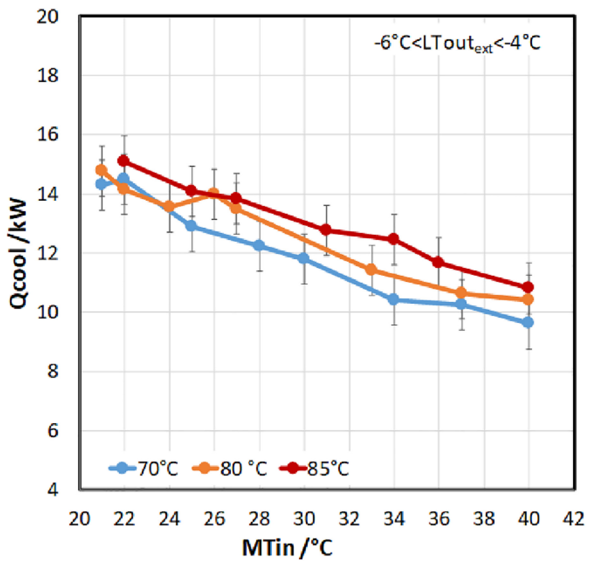
The obtained results can be reported in different ways, basically representing characteristic curves, performance maps and simplified linear regression, which can be useful for system simulations.

7.1 Characteristic curves

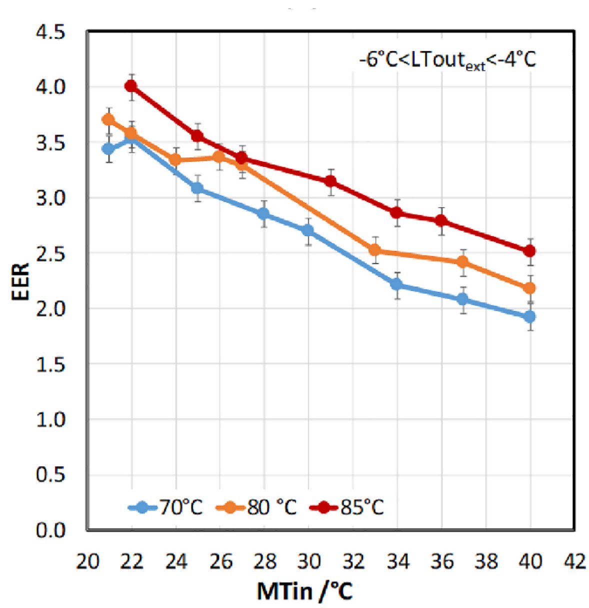
A first option is to represent the different performance parameters above defined as function of the different operating conditions tested, i.e. heat source temperature, ambient temperature and set point for chilled fluid as exemplary presented in Figure 5.



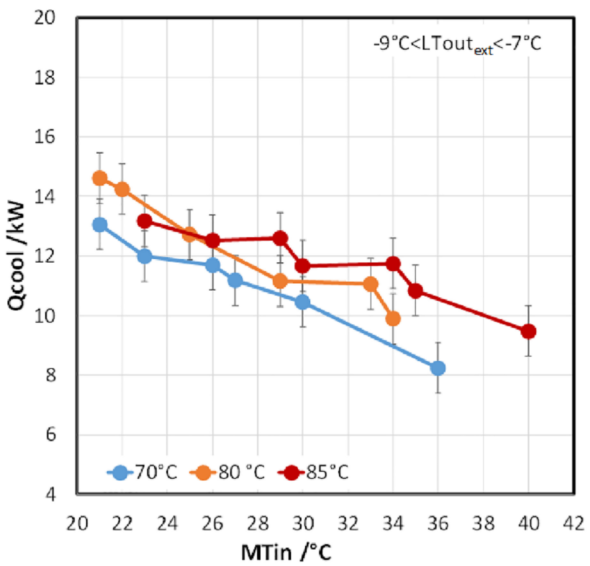
a) b)


-6°C<LTout$_{ext}$<-4°C
Qcool /kW
MTin /°C
70°C
80 °C
85°C

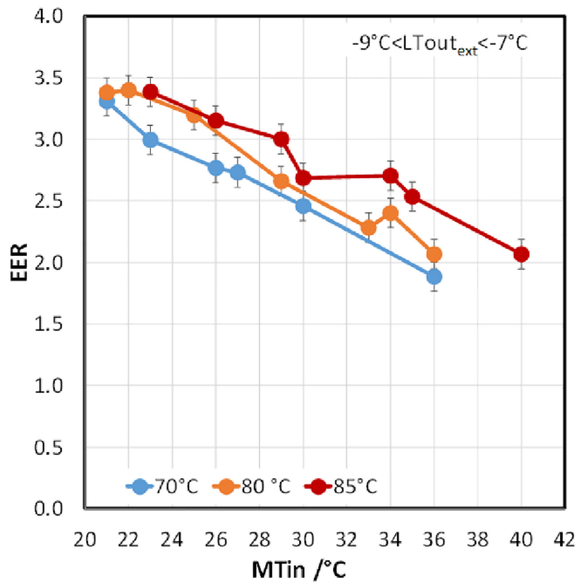
c)


-6°C<LTout$_{ext}$<-4°C
EER
MTin /°C
70°C
80 °C
85°C

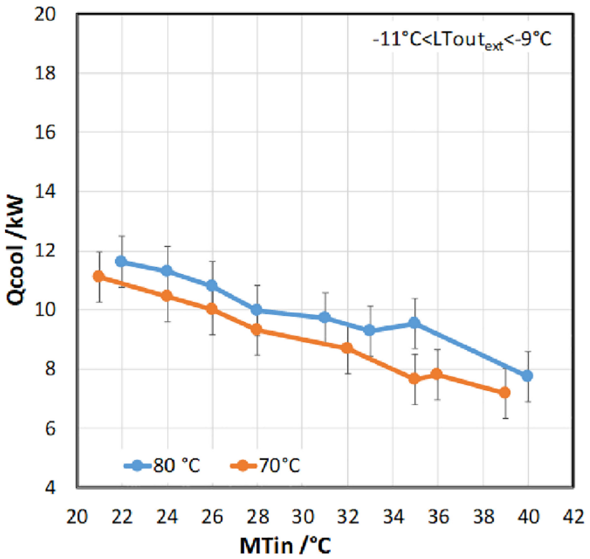
d)


-9°C<LTout$_{ext}$<-7°C
Qcool /kW
MTin /°C
70°C
80 °C
85°C

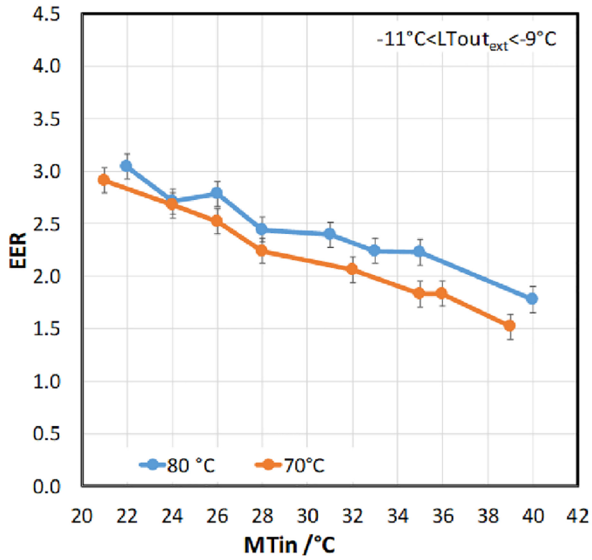
e)


-9°C<LTout$_{ext}$<-7°C
EER
MTin /°C
70°C
80 °C
85°C

f)



g)



h)

Figure 5 — Effect of operating conditions on the cooling power and EER_{HHP}

7.2 Performance maps

Another option is to represent the test results as a performance map, useful for the easy visualization and identification of the expected performance of the system for different conditions and different performance parameters.

Examples of possible performance maps reporting cooling power and EER_{HHP} are reported in Figure 6 and Figure 7, respectively.

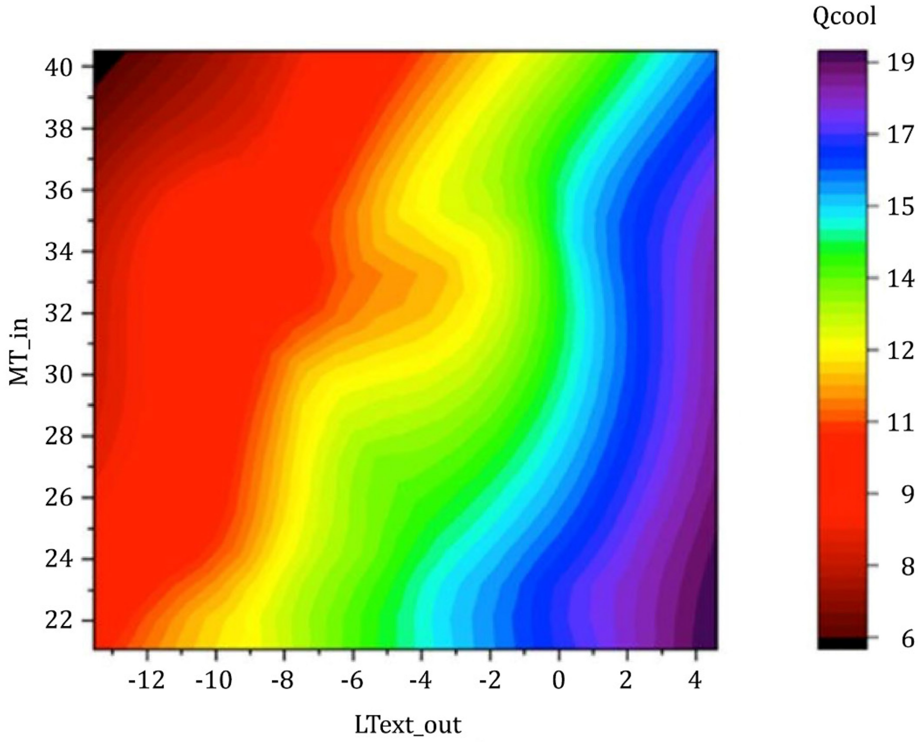


Figure 6 — Cooling power in different condensation and evaporation conditions

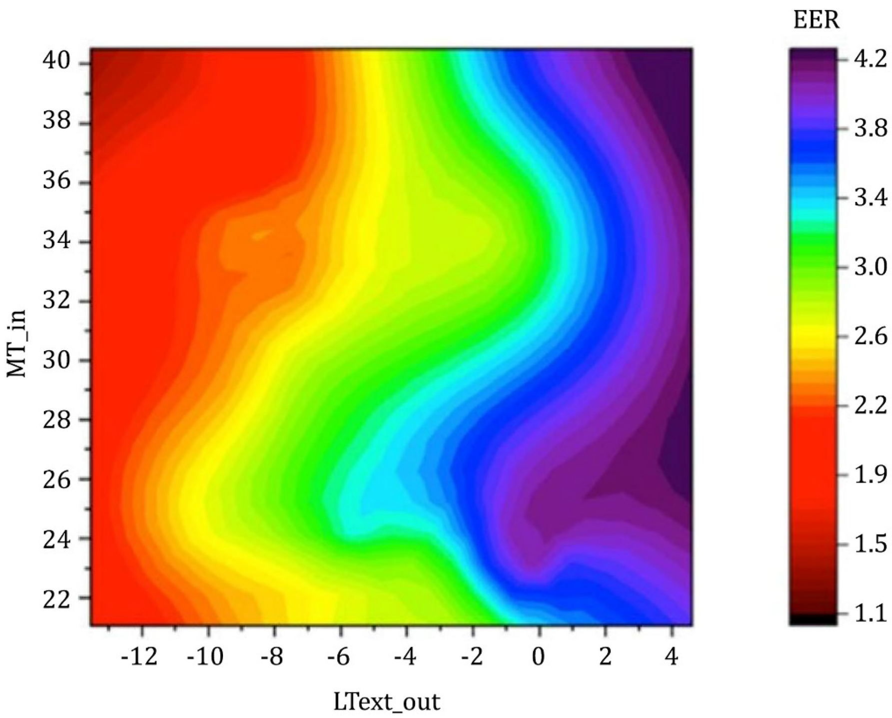


Figure 7 — EER_{HHP} in different condensation and evaporation conditions

7.3 Linear regression of data for implementation in control models

The results of the tests can be further elaborated, to get a simplified expression. Such an approach is particularly useful for embedding experimental data in Energy Management Systems that make use of Model Predictive Controls or other predictive techniques to optimise energy flow and the benefits arising from the use of an HHP. To this aim, a statistical analysis shall be carried out to correlate, for instance, the cooling power Q_{cool} and the EER_{HHP}, directly to the three fundamental parameters: HTin, MTin, $LTout_{ext}$. The resulting equations can have the following form:

$$Q_{cool} = a_0 + a_1 \cdot LText_{out} + a_2 \cdot MTin + a_3 \cdot HTin \quad (8)$$

$$EER = a_4 + a_5 \cdot LText_{out} + a_6 \cdot MTin + a_7 \cdot HTin \quad (9)$$

The equations can also include the flow rates in each circuit if the HHP is equipped with variable speed pumps. When this analysis is performed, it shall be specified which experimental operating conditions range have been considered to perform the evaluation, as represented in Table 5.

Table 5 — Range of the experimental operating conditions used for statistical elaborations

	Minimum	**Maximum**
HT [°C]		
MT [°C]		
LLT [°C]		
Q_{cool} [kW]		
EER		

An example of this kind of data reduction is reported in Figure 8, where a good agreement is achieved over a wide range of operating conditions.

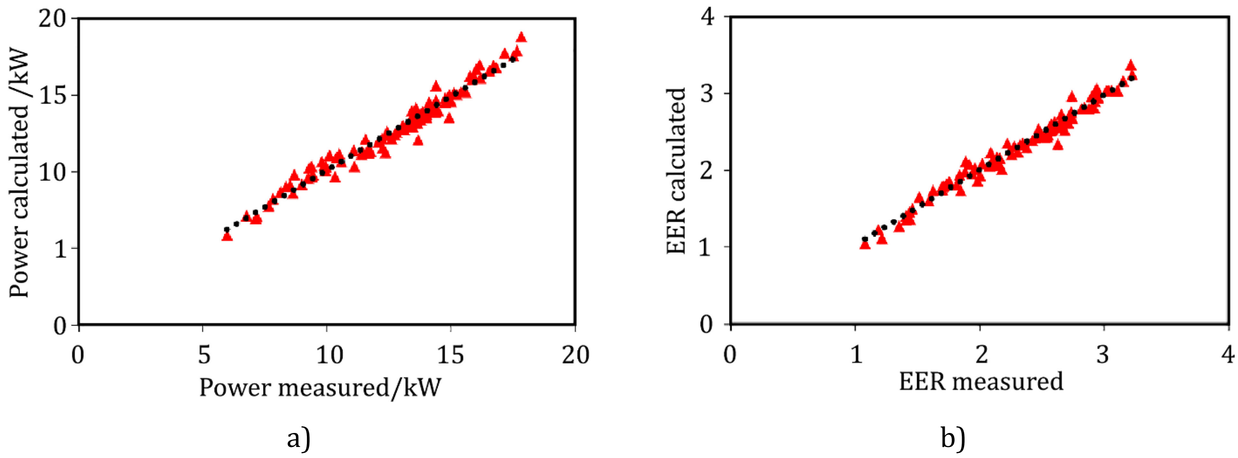


Figure 8 — Comparison between experimental and calculated data

7.4 Seasonal energy efficiency ratio

The outcomes of the tests can be also summarised and presented by seasonal performance indicator such as the ESEER described in Clause 6.

Annex A

(informative)

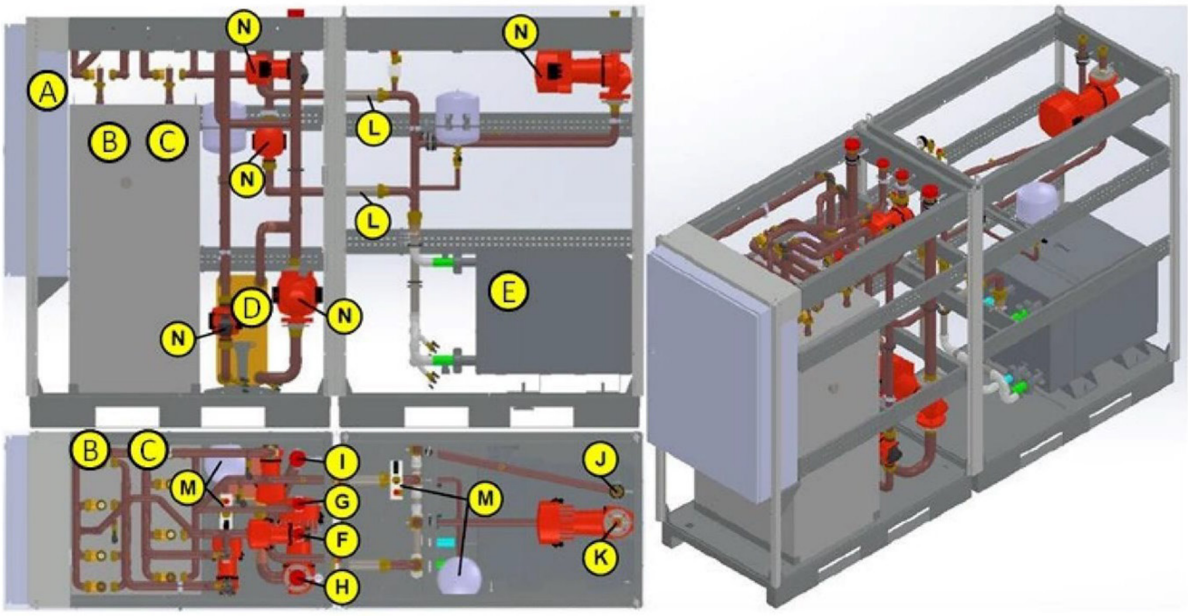
Example of application for a cascading HHP prototype

A.1 General

In the following, an example of testing of a hybrid (cascading) heat pump module is reported. This example is derived from the EU project "Industrial Cooling through Hybrid system based on Solar Heat" which is presented here as a case study.

The testing consists of two units connected in cascade: an adsorption module employing silica gel/water as working pair and a compression chiller using R1270 as refrigerant. Therefore, one of the peculiarities of the hybrid machine is the use of natural and low Global Warming Potential (GWP) refrigerants: the adsorption unit makes use of R718 (water), with 0 GWP and 0 Ozone Depletion Potential (ODP); the compression unit makes use of R1270 (propylene) with GWP = 2 and 0 ODP. The two units work in cascade, meaning that the chilled water circuit (LTint) from the sorption heat pump constitutes the re-cooling circuit of the compression chiller. The connection between them is made through a hydraulic circuit.

A rendering of the hybrid system with the main components is shown in Figure A.1.



Key

A electric rack

B-C modules of the sorption heat pump

D intermediate heat exchanger re-cooling circuit

E compression chiller

F high temperature inlet

G high temperature outlet

H external re-cooling circuit inlet

I external re-cooling circuit outlet
J external chilled brine inlet
K external chilled brine outlet
L expansion joint
M expansion vessel and filling group
N variable speed pump

Figure A.1 — Schematics and main components of the hybrid system

The adsorption unit is made up of two modules, working with alternating phases, reaching up to 25 kW of cooling capacity. Each internal circuit is equipped with variable speed pumps and safety devices (pressure indicators, expansion vessels). In addition, the re-cooling circuit of the adsorption unit is hydraulically separated from the external re-cooling inlet/outlet, by means of a plate heat exchanger (HEX). In this way, it is possible to use water/glycol mixtures in the external circuit, allowing the operation also when ambient temperature is below zero. The vapour compression unit is directly connected to the evaporation circuit of the adsorption unit and a direct connection to the user circuit is considered as well. The main characteristics of the sorption heat pump and the compression chiller constituting the hybrid system to be tested are reported in Table A.1 and Table A.2, respectively.

Table A.1 — Main features of the adsorption unit

Refrigerant	R718 (water)
Sorbent	silica gel
Weight	550 kg
Dimensions (L×W×H)	875 × 765 × 2 500 mm
Max. pressure drop HT circuit	0,30 bar
Max. pressure drop MT circuit	0,32 bar
Max. pressure drop LTint circuit	0,50 bar
Nominal flow rate HT circuit	3,70 m^3/h
Nominal flow rate MText circuit	11,80 m^3/h
Nominal flow rate MTint circuit	7,65 m^3/h
Nominal flow rate LTint circuit	4,35 m^3/h

Table A.2 — Main features of the vapour compression unit

Refrigerant	R1270 (propylene)
Refrigerant charge	1 200 g
Expansion valve	electronic
Max. current	12,2 A
Max. consumption	3 kW
Weight	170 kg
Dimensions (L×W×H)	940 × 700 × 760 mm
Nominal flow rate Ltext circuit	m^3/h

A.2 Description of a typical test

Figure A.2 shows the typical trends in the temperature of the hybrid system for a test with the following parameters: HTin = 70 °C, MTin = 30 °C, LText set point = -2 °C. It is possible to notice, for the HT, MT and LTint circuits, the typical tendencies of a sorption unit that is intrinsically discontinuous. Therefore, their evolution is strongly dependent on the phase of the cycle and the cycle time. Nonetheless, curve trends are regular, thus indicating a steady-state behaviour.

On the contrary, the temperatures in the LText circuit (the evaporator circuit of the compression unit) are constant since this kind of units are characterised by a continuous operation. Figure A.3 shows the flow rates for the same test. In the adsorption unit, a PID regulation is implemented onto HT and MT pumps, whose speed is continuously regulated to keep a constant output set-point temperature. The flow rates in the other circuits are almost constant throughout the test.

Finally, Figure A.4 reports the thermal and electrical power measured during the same test. The desorption process, with the consequent condensation of water determines a strong increment in the temperature in the first seconds after each phase shift and a decreasing trend henceforth. A detail of the cooling power supplied by the compression chiller and the overall electric consumption of the hybrid system are reported in Figure A.5. It is possible to notice that the electric consumption follows the same cyclic trend of the cooling power output from the sorption heat pump (yellow line in Figure A.4): this is due to the fact that, during the first seconds of each phase, the cooling power produced by the sorption heat pump is maximum, and the inlet temperature to the condenser of the compression unit decreases correspondingly. During the last seconds of each phase, instead, the cooling power output from the sorption heat pump is lower and therefore the temperature inlet to the condenser of the compression unit is higher, which in turn causes a loss of performance and an increase in the electric consumption. However, as it is possible to notice from Figure A.5, such a fluctuation is in the range of ±0,4 kW, i.e., around 8 % of the overall electric consumption and consequently can be considered negligible.

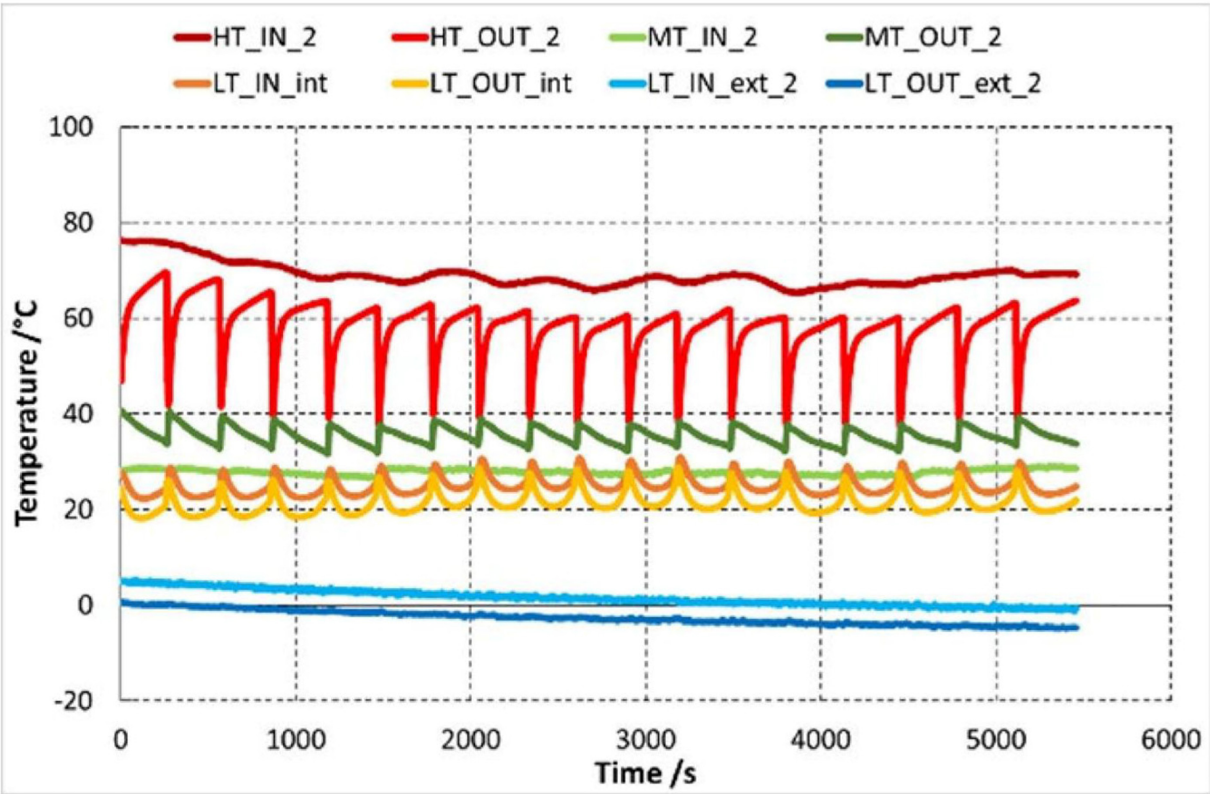


Figure A.2 — Temperature trends for a typical test

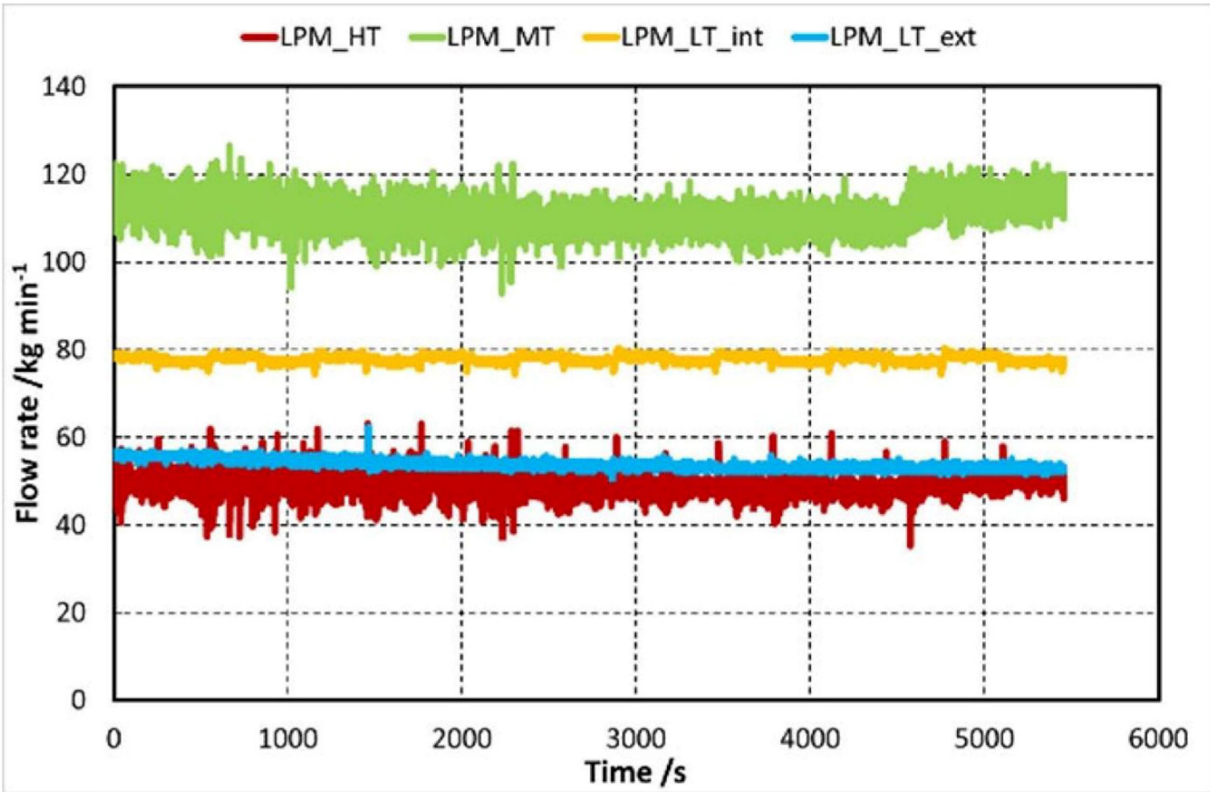


Figure A.3 — Flow rate trends for a typical test

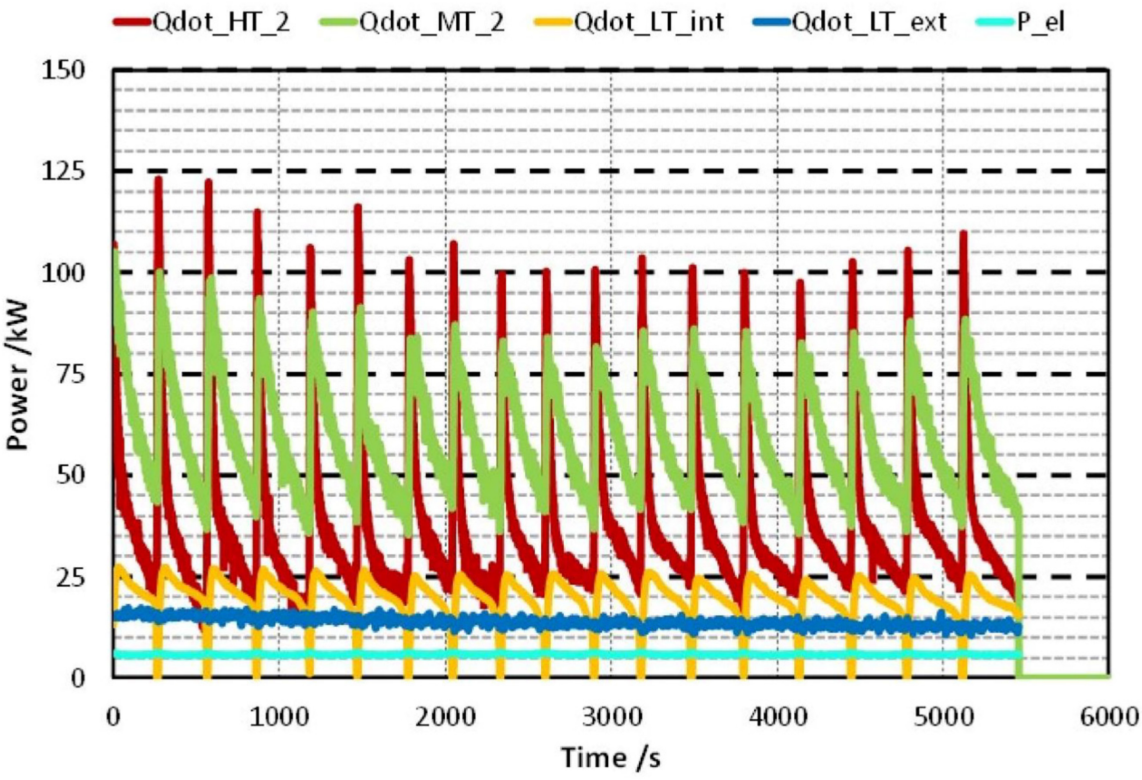


Figure A.4 — Power trends for a typical test

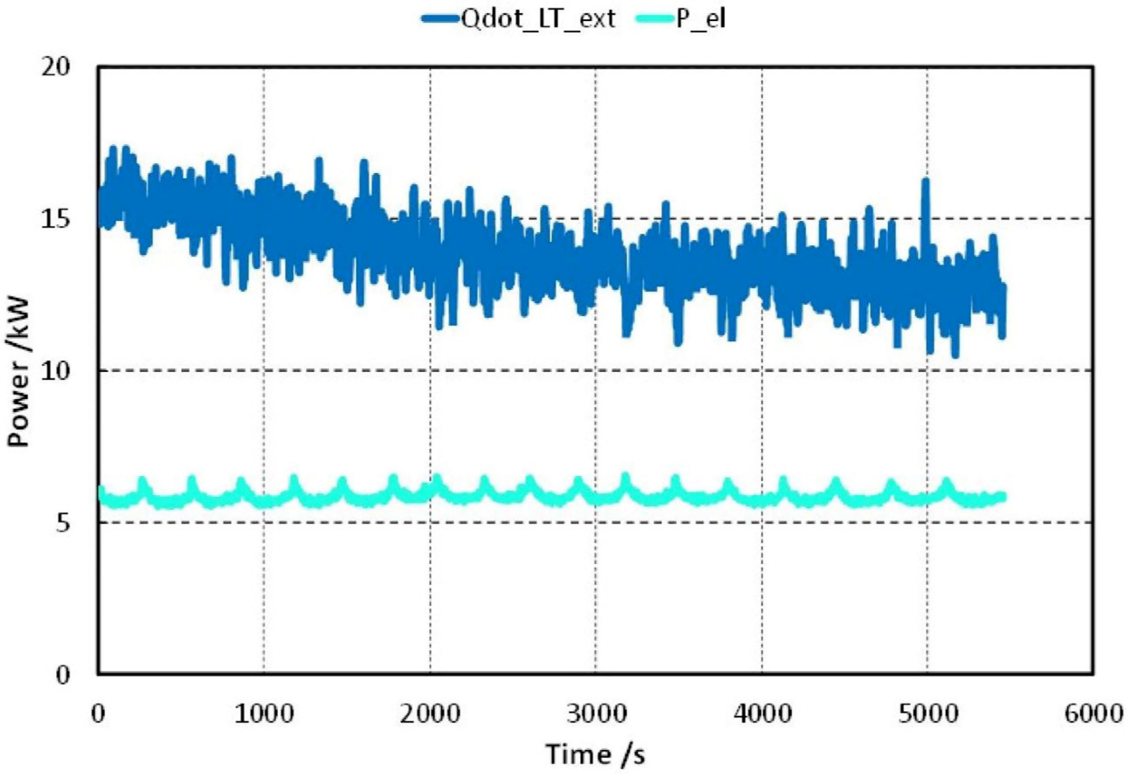


Figure A.5 — Detail of the cooling capacity and electric consumption of the hybrid system for a typical test

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