GUIDELINES FOR DESIGN AND INSTALLATION OF HEAT PUMPS IN LEBANESE BUILDINGS

JULY 2020

THE NATIONAL HEAT PUMP PROJECT OF LEBANON

MINISTERO DELL'AMBIENTE
E DELLA TUTELA DEL TERRITORIO E DEL MARE

LEBANESE REPUBLIC
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FOREWORD

Considered as main contributors to solve the problems of the electricity sector in Lebanon, renewable energy and energy efficiency are developing at a considerable fast pace in the country. With clear objectives to reach the target of 12% renewable energy and 5% energy demand savings by 2020, the two subsectors are expected to offer new job opportunities, increasing market momentum, and most importantly present environmentally-friendly solutions. Heat pumps are one of the most promising solutions.

Heat pump technology is capable of playing a key role in reducing fossil fuel and electricity dependency, improving quality of life in the Lebanese community and reducing CO_2 emissions. The "National Heat Pumps" project aims at supporting the Lebanese government in addressing the climate change mitigation challenges presented in the Intended Nationally Determined Contribution under the UNFCCC by introducing "heat pump" technologies in the heating, domestic hot water production and cooling sectors (for residential and tertiary applications mainly). The "National Heat Pumps" works on the know-how and technology transfer, in line with the European legislation and Montreal Protocol for the phasing out of the high global warming potential refrigerant gases (fluorinated greenhouse gases- including hydrofluorocarbons -HFCs).

The "National Heat Pumps" is one main component of the technical cooperation agreement on sustainable development that was signed on 7 July 2016 in Rome between the Italian Ministry for the Environment Land and Sea and the Lebanese Center for Energy Conservation. The objective of the agreement is to strengthen bilateral relations between Italy and Lebanon in the field of sustainable development and the fight against climate change.

The cooperation between Italy and Lebanon is not new. It started in January 2013 with the MEDiterranean DEvelopment of Support schemes for solar Initiatives and Renewable Energies (MED-DESIRE Project) MED-DESIRE that was co-funded by the European Union through the ENPI CBC MED Programme 2007-2013. As a result of this cooperation, The Lebanese Center for Energy Conservation finalized a national solar ordinance and proposed it to the Higher Council for Urban Planning.

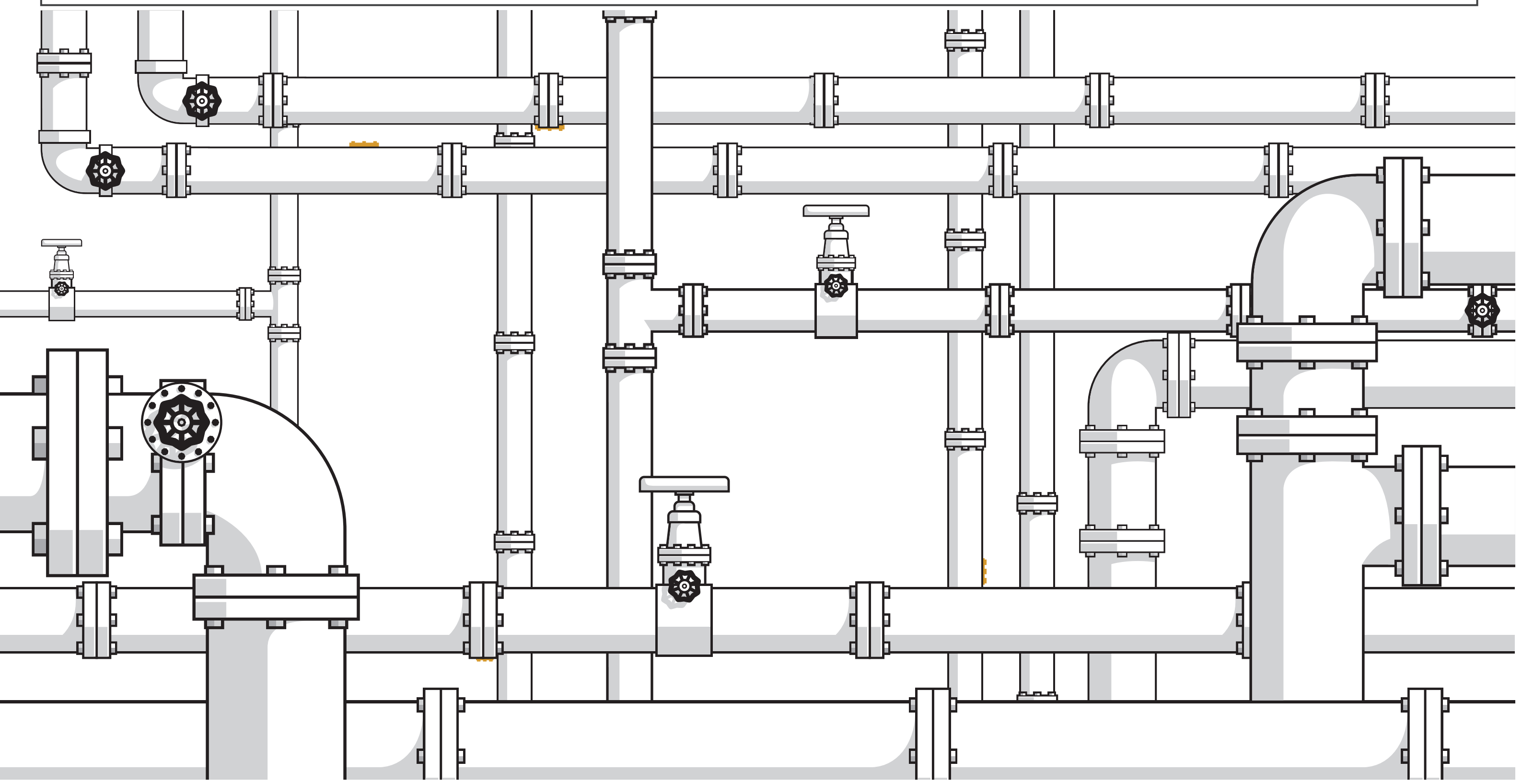
By substituting only 10% of electric boilers and heaters in existing buildings and new buildings with heat pumps technologies for hot water generation and space heating in the time frame 2017-2030, cumulative energy savings of over 1,000 GWh can be achieved. This is equivalent to approximately 70 million USD saving in electricity subsidies for the Lebanese government.

The Lebanese Center for Energy Conservation is glad to share this new report entitled "Guidelines for Design and Installation of Heat pumps in Lebanese Buildings", offering highly specialized and concrete engineering of heat pump systems. The Lebanese Center for Energy Conservation encourages all qualified entities to consult this report when installing heat pumps in Lebanon.

This report was published thanks to the support of the Italian Ministry for the Environment Land and Sea. The technical work of Politecnico di Milano was also essential in realizing this report. The Lebanese Center for Energy Conservation is thankful to both entities.

The Lebanese Center for Energy Conservation stands ready to coordinate with all interested parties in order to further understand and develop heat pumps technologies and projects in the country. It is true that the sustainable energy market in Lebanon faces uncertainties and challenges, but it is also true that this market offers huge opportunities for development. With the support of our local and international partners and friends, let us all look forward for a prosperous and sustainable future for our country and the environment.

LCEC Team
July 2020



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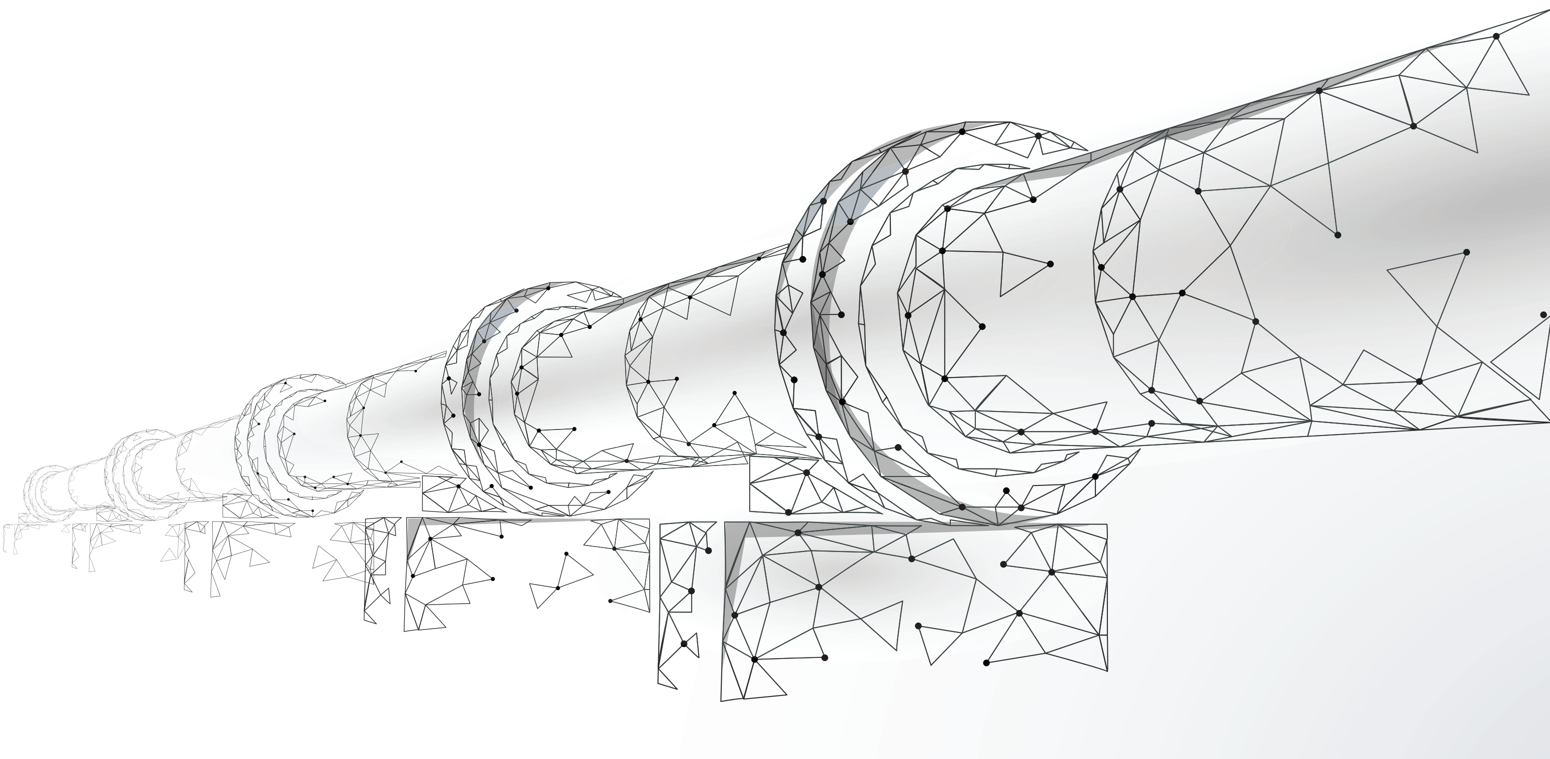

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ABBREVIATIONS

A/W HP	air-to-water heat pump
CEDRO	Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon
CFC	chlorofluorocarbon
Cc	degradation coefficient of the heat pump coefficient of performance
CO_2	carbon dioxide
COP	heat pump coefficient of performance
COP_{DC}	coefficient of performance at the heat pump declared capacity
COP_{MAX}	theoretical maximum coefficient of performance
$COP_{N,bin,m}$	nominal coefficient of performance at supply temperature, θ_H, and source temperature (θ_{bin} for air source heat pump) of bin on a specific month
$COP_{PL,bin,m}$	actual coefficient of performance at capacity ratio of bin on a specific month
CR	capacity ratio
$CR_{bin,m}$	heat pump capacity ratio of bin on a specific month
DC	declared capacity
$DC_{bin,\ m}$	heat pump declared capacity at supply temperature, θ_H, and source temperature (θ_{bin} for air source heat pump) of bin on a specific month
$DH_{bin,m}$	degree hours of bin on a specific month
DHW	domestic hot water
EER	energy efficiency ratio
EN	European Standard
F_{COP}	correction factor
$F_{COP,bin,m}$	corrective factor of coefficient of performance of bin on a specific month
GSHP	ground source heat pump
GWP	global warming potential
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HVAC	heating, ventilation and air conditioning
IMELS	Italian Ministry for the Environment Land and Sea
ISO	International Organization for Standardization
K	kelvin
kPa	kilopascal
kW	kilowatt
LCEC	Lebanese Center for Energy Conservation
LFL	lower flammability limit
n.d.	no date
NEEAP	National Energy Efficiency Action Plan
NREAP	National Renewable Energy Action Plan
ppm	parts per million

POLIMI	Politecnico di Milano
$Q_{el,HP}$	electrical energy input to the heat pump
$Q_{el,HP+AUX}$	electrical energy input to the generation system (composed of the heat pump and the auxiliary generation system)
Q_H	monthly thermal needs
$Q_{H,aux,out,bin,m}$	thermal energy ratio, to be provided by the auxiliary generation system, of bin on a specific month
$Q_{H,aux,out,m}$	total energy input of the auxiliary generation system on a specific month
$Q_{H,aux,out,s}$	seasonal energy input of the auxiliary generation system
$Q_{H,hp,el,bin,m}$	heat pump energy input of bin on a specific month
$Q_{H,hp,el,m}$	total heat pump energy input on a specific month
$Q_{H,hp,el,s}$	seasonal heat pump energy input
$Q_{H,hp,out,bin,m}$	heat pump thermal energy output of bin on a specific month
$Q_{req,bin,m}$	share of energy needs of bin on a specific month
$Q_{req,m}$	total energy needs of a specific month
$Q_{req,s}$	seasonal energy needs
RH	relative humidity
SCOP	seasonal coefficient of performance
$SCOP_{HP}$	seasonal coefficient of performance of the heat pump
$SCOP_{HP+AUX}$	seasonal coefficient of performance of the system composed of the heat pump and the auxiliary generation system
SPF_{HP+AUX}	seasonal performance factor of the system composed of heat pump and auxiliary generation system
T_A	ambient temperature
t_{bin}	number of hours for the specific bin
$T_{bivalent}$	bivalent temperature
T_d	design temperature
T_{ext}	external ambient temperature
$T_{set\ point}$	set-point temperature
T_{supply}	monthly heat pump supply temperature
T_t	target temperature
UNI	Ente Nazionale Italiano di Unificazione
VRF	variable refrigerant flow or variable refrigerant volume
ΔT	temperature difference
η_{II}	second law efficiency
η_{el}	electric efficiency
$\Phi_{gn,out,bin,m}$	heat pump thermal power output of bin on a specific month
$\Phi_{req,bin,m}$	requested thermal power of bin on a specific month
θ_{bin}	external temperature of bin on a specific month
θ_C	temperature (°C) of the cold source
θ_H	heat pump supply temperatures, which can be defined as a constant value or not
$\theta_{H,off}$	external temperature over which the heating system is switched off by the control system

INTRODUCTION

Energy efficiency and renewable energy have gained huge interest in Lebanon since 2010. The 2010 Policy Paper for the Electricity Sector (Bassil, 2010) mentioned Lebanon's need to develop action plans for both energy efficiency and renewable energy. The first National Energy Efficiency Action Plan for the Republic of Lebanon-NEEAP 2011-2015 (Lebanese Center for Energy Conservation [LCEC], 2012) was adopted by the Council of Ministers of Lebanon on November 10, 2011 (Decision No 26). It includes 14 initiatives that tackle energy efficiency and renewable energy. The Second National Energy Efficiency Action Plan for the Republic of Lebanon-NEEAP 2016–2020 (LCEC, 2016b) is a 5-year plan that covers 2016–2020. It was published in March 2016 and includes 26 sectoral measures. The second NEEAP was followed by The National Renewable Energy Action Plan for the Republic of Lebanon 2016-2020 (NREAP) (LCEC, 2016a). NREAP details the measures to be implemented in Lebanon to achieve 12% renewable energy in the national energy mix.

The First Energy Indicators Report of the Republic of Lebanon (LCEC, 2018) specified the most consuming sectors and usages. The residential sector has been the largest consumer of electricity, generating approximately 30% of Lebanon's overall electricity demand in 2014. Total thermal consumption showed an average of 5,146 gigawatt-hours between 2009 and 2014. The thermal demand for the industrial sector was shown to be 74% of the total followed by the residential sector at 15%.

To reach both NEEAP (2016-2020) and NREAP (2016-2020) targets in reducing energy consumption and increasing renewable energy share in the Lebanese energy mix, heat pump technology is being introduced to the Lebanese market. This technology can be used for space heating, domestic hot water generation, swimming pool water heating, and many other applications.

A technical cooperation agreement on sustainable development was signed on July 7, 2016 in Rome between the Italian Ministry for the Environment Land and Sea and LCEC. The objective of the agreement is to strengthen bilateral relations between Italy and Lebanon in the field of sustainable development and the fight against climate change. The cooperation between Italy and Lebanon is not new. It started in January 2013 with the MEDiterranean DEvelopment of Support schemes for solar Initiatives and Renewable Energies (MED-DESIRE Project) MED-DESIRE that was co-funded by the European Union through the European Neighbourhood and Partnership Instrument Cross-Border Cooperation in the Mediterranean Programme 2007-2013. As a result of this cooperation, LCEC finalized a national solar ordinance and proposed it to the Higher Council for Urban Planning.

The National Heat Pump project aims at supporting the Lebanese government in addressing the climate change mitigation challenges presented in the Intended Nationally Determined Contributions under the United Nations Framework Convention on Climate Change by introducing heat pump technology to the heating, domestic hot water production, and cooling sectors (for residential and tertiary applications mainly) through know-how and technology transfer, in line with the European legislation and Montreal Protocol for the phasing out of the high global warming potential (GWP) refrigerant gases (fluorinated greenhouse gases- including hydrofluorocarbons [HFCs]).

Heat pump technology is capable of playing a key role in reducing fossil fuel and electricity dependency, improving quality of life in the Lebanese community, and reducing carbon dioxide (CO_2) emissions.

This report introduces best practices for design and installation of heat pumps, specifically air-to-water heat pumps.

1. OVERVIEW OF THE HEAT PUMP TECHNOLOGY

A heat pump is a high performance technology, capable of exploiting renewable energy (e.g., from air, water, and ground) for the generation of useful heating and cooling energy.

For example, an electric heat pump is able to generate four times more thermal energy than the electrical energy it consumes (e.g., by recovering heat from renewable sources). Also, since an electric driven, vapor-compression heat pump burns no fossil fuel, it does not generate CO_2 emissions on site.

Heat pumps can be used for space heating, domestic hot water (DHW), and air conditioning systems. They can be used individually or in hybrid systems, where integrated with other heating devices (e.g., electrical heater or gas boiler).

Heat pumps can be coupled with other renewable energy technologies, such as solar water heating collectors or photovoltaic panels, to provide even higher performance solutions.

They are also suitable for different applications:

- New residential buildings
- Refurbishment of existing residential buildings, by replacement or integration in the existing heating system
- Commercial and tertiary buildings and applications
- Public buildings (e.g., hospitals, schools, and town halls)

Heat pump systems vary in terms of: (a) renewable energy source (e.g., air, ground, or water), (b) heat transfer medium (e.g., water, or air), (c) end use of the system (e.g., space heating, DHW, or both), and (d) capacity (e.g., systems for a single residential unit to centralized systems for multi-family units and commercial spaces). The range of possible heat pump systems is wide, and each particular configuration has its specific issues.

1.1. Vapor-compression thermodynamics

A heat pump cycle comprises a circuit, filled with refrigerant that, depending on the actual temperature and pressure conditions, is in either a gaseous or liquid state. Figure 1 shows the main components (a compressor, a condenser, an expansion valve, and an evaporator) in a vapor-compression heat pump cycle.

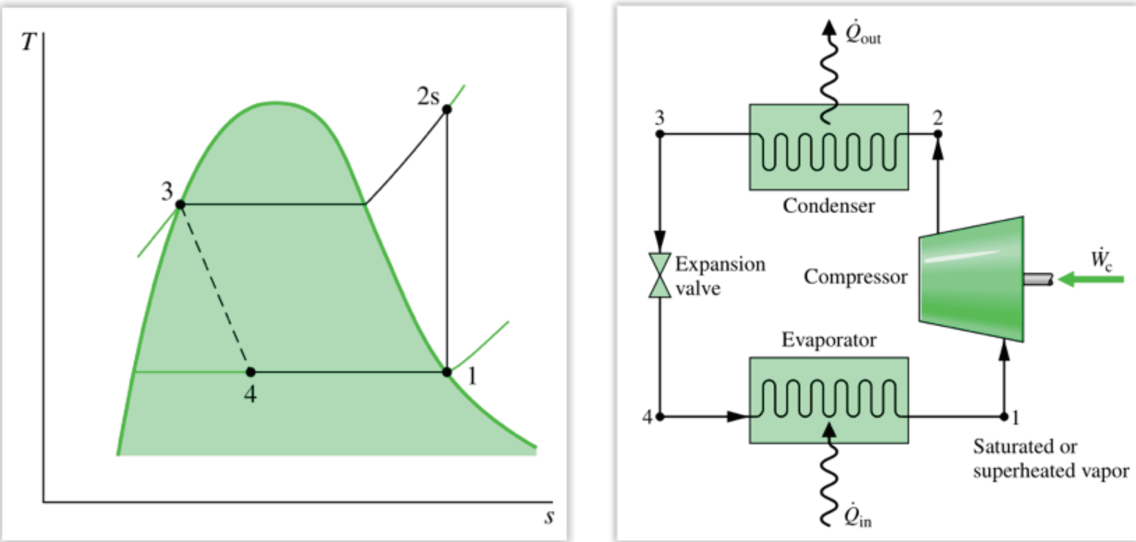


Figure 1. Vapor-compression heat pump thermodynamic cycle and temperature-entropy (T-S) diagram. Reprinted from Fundamentals of engineering thermodynamics (p.457), by M.J. Moran and H.N. Shapiro, 1992, John Wiley & Sons. Copyright 1992 by John Wiley & Sons

Starting from the compressor inlet (Figure 1, point 1), the refrigerant is in a gaseous state (saturated vapor, or slightly superheated gas to ensure a good function of the compressor). Then, it is compressed and is therefore hotter and at higher pressure (Figure 1, point 2s). The refrigerant passes into the condenser where it exchanges most of its heat to the sink (surroundings). As it cools, the refrigerant changes state (condenses) to a liquid that is still warm and at higher pressure (Figure 1, point 3). This warm liquid refrigerant then passes through a pressure-reducing device (the expansion valve). Dropping the pressure causes a decrease in refrigerant temperature (Figure 1, point 4). Next, the refrigerant passes to another heat exchanger (the evaporator), where it absorbs heat and fully evaporates into a low-pressure gas. In this gaseous state, the refrigerant, passes to the compressor where it is pressurized, heated, and recirculated through the system. The heat pump is giving heat out in the condenser and is absorbing heat from a source (surrounding air, ground, water…) in the evaporator.

The key performance indicator for heat pumps is the coefficient of performance (COP)—the ratio between the heating capacity at the condenser ($\dot{Q}_{condenser}$) and the electricity absorbed at the compressor ($\dot{W}_{compressor}$):

$$COP = \frac{\dot{Q}_{condenser}}{\dot{W}_{compressor}}$$

The heat pump cycle can be seen also as a chiller cycle considering the cooling capacity available at the evaporator. Similar to the COP, in this case, the key performance indicator is the energy efficiency ratio (EER)—the ratio between the cooling capacity at the evaporator ($\dot{Q}_{evaporator}$) and the electricity absorbed at the ($\dot{W}_{compressor}$):

$$EER = \frac{\dot{Q}_{evaporator}}{\dot{W}_{compressor}}$$

1.2 Renewable energy sources

As shown in Figure 2, the typical renewable sources used by heat pumps are air, ground, or water.

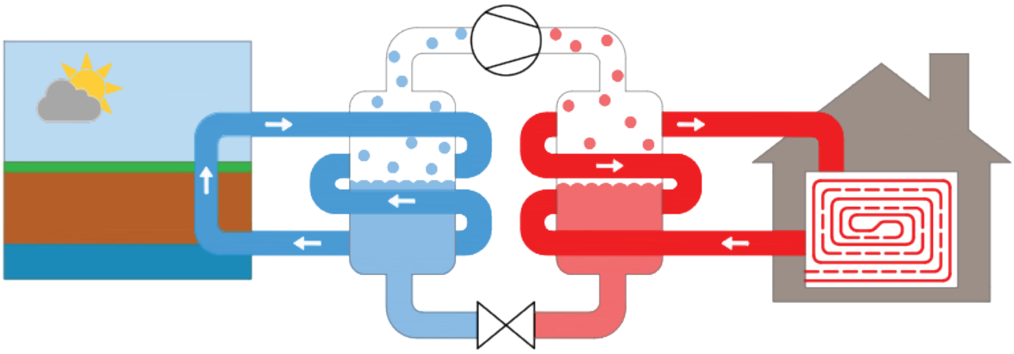


Figure 2. Heat pump renewable energy sources

Air has the advantage of being available at all times but the temperature is not constant. When the ambient temperature is close to or below 0 °C, removal of heat will cause the evaporator to freeze, and it becomes necessary to incorporate a defrost system to clear the frost accumulated. The defrost cycle uses energy from the heat pump, energy from the condenser, that is not released into the sink at the end-user side (e.g., hot water circuit), thereby temporarily reducing the output.

Ground energy is recovered by pipes through which brine (a water and glycol mixture that has a lower freezing temperature than water alone) is circulating. The pipes can be installed either vertically or horizontally. Ground source heat pumps (GSHPs) have the advantage of a relatively constant COP and heating capacity, as they are less affected by changes in external climatic conditions. However, there is a substantial extra initial cost related to the low temperature source heat exchanger. For more information on ground heat pump systems and requirements, see Ground Source Heat Pumps (GSHPs) - A Guideline Report by Country Energy Efficiency and Renewable Energy Demonstration Project for the Recovery of Lebanon (CEDRO) and LCEC (Casals, Anzizu, & Lazopoulou, 2017).

Water can provide good performance and is not subject to variations caused by climate variations. However, water is not always available, groundwater extraction requires a license and additional costs are incurred in the assembly of an external hydraulic circuit.

1.3. Refrigerants

In 2016, the Kigali Amendment to the Montreal Protocol required the phase-down of HFC refrigerants to combat global warming. The GWP of a refrigerant is defined as the global warming potential of one ton of a greenhouse gas relative to one ton of CO_2, over a period of 100 years. The GWP reference value for CO_2 is 1. The most common refrigerants in heat pump applications have quite high GWP values (GWP_{R134a} = 1,430, GWP_{R410A} = 2,088). To comply with the Kigali Amendment, the heat pump market will have to move towards low GWPs refrigerants.

Figure 3 shows the lower GWP alternatives to refrigerants commonly used for hydronic heat pumps, related to GWP and flammability (Emerson, 2017). Most low-GWP refrigerants currently available on the market are flammable (e.g., propane) or are characterized by operating pressures higher than those commonly used (e.g., CO_2). Refrigerant manufacturers are studying new low-GWP refrigerants, suitable to replace the most common ones (e.g., R134a and R410A).

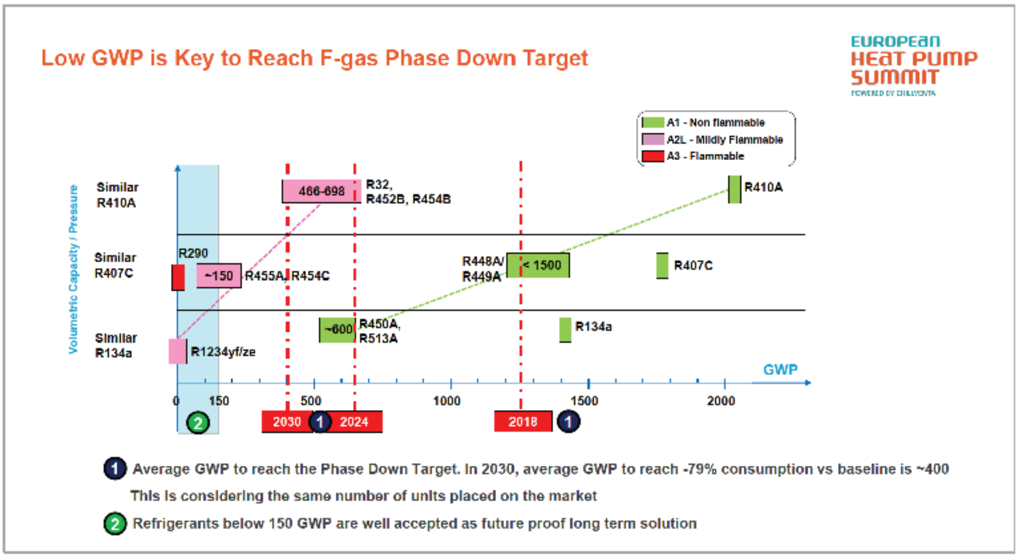


Figure 3. Actual and future scenario of the refrigerant market. F-gas = fluorinated greenhouse gases; GWP = global warming potential. Reprinted from Propane and A2L solutions for heating applications (p. 7), presentation by Emerson, European Heat Pump Summit Congress, Nuremberg, Germany (2017)

Table 1 shows the GWP of the most commonly used refrigerants.

Table 1. Global warming potential of common refrigerants

Refrigerant number	Global warming potential
Chlorofluorocarbon (CFC)	
R502	4,657
R12	10,900
Hydrochlorofluorocarbon (HCFC)	
R123	77
R401A	1,182
R401B	1,288
R22	1,810
R409A	1,909
R402B	2,416
R402A	2,788
R408A	3,152
Hydrofluorocarbons (HFC)	
R32	675
R134a	1,430
R407C	1,774
R437A	1,805
R407F	1,825
R442A	1,888
R410A	2,088
R407A	2,107
R427A	2,138
R438A	2,265
R423A	2,280
R417A	2,346
R424A	2,440
R422D	2,729

Refrigerant number	Global warming potential
R422A	3,143
R434A	3,245
R428A	3,607
MO89	3,805
R404A	3,922
R507A	3,985
R508B	13,396
R23	14,800
Hydrofluoroolefin (HFO)	
R1234yf	4
R1234ze	6
Natural	
R744 (carbon dioxide)	1
R1270 (propylene)	2
R290 (propane)	3
R600a (isobutane)	3
R1150 (ethylene)	4
R170 (ethane)	6

Several international standards address the safety of refrigerants used by heat pumps.

International Organization for Standardization (ISO) standard ISO 817:2017 (ISO, 2017) defines the safety classification of refrigerants, which consists of two capitalized alphanumeric characters (e.g., representing the toxicity (based on allowable exposure) and an Arabic numeral denoting flammability (e.g., A2 or B1). A third character "L" designates low burning velocity. Class A (lower chronic toxicity) refrigerants have an occupational exposure limit of 400 ppm or greater. Class B (higher chronic toxicity) refrigerants have an occupational exposure limit of less than 400 ppm. Refrigerant flammability is represented by four classes:

1. Class 1 (no flame propagation)
2. Class 2L (lower flammability)
3. Class 2 (flammable)
4. Class 3 (higher flammability)

For class 2L, 2 or 3 refrigerants, a lower flammability limit (LFL) is determined. LFL is the minimum concentration of the refrigerant that is capable of propagating a flame through a homogeneous mixture of the refrigerant and air under the specified test conditions at 23 °C and 101.3 kilopascal (kPa). It is expressed as a refrigerant percentage by volume. LFL is an important parameter on which many safety recommendations depend. Examples of refrigerant safety classifications are shown in Table 2. See ISO 817:2017 tables 5–7 for the safety classification of most refrigerants.

Table 2. Examples of refrigerant safety classifications

Refrigerant number	Composition designating prefix	Chemical name	Chemical formula	Safety group	LFL (ppm by volume)
R32	HFC	difluoromethane (methylene fluoride)	CH_2F_2	A2L	144,000
R134a	HFC	1,1,1,2 - tetrafluoroethane	CH_2FCF_3	A1	—
R717	n/a	ammonia	NH_3	B2L	167,000
R744	n/a	carbon dioxide	CO_2	A1	—
R1234yf	HFO	2,3,3,3 - tetrafluoro-1-propene	$CF_3CF{=}CH_2$	A2L	62,000
R1234ze(E)	HFO	trans-1,3,3,3-tetrafluoro-1-propene	$CF_3CH{=}CHF$	A2L	65,000
R1270	HC	propene (propylene)	$CH_3CH{=}CH_2$	A3	27,000

Notes: A = lower chronic toxicity; B = higher chronic toxicity; HC = hydrocarbon; HFC = hydrofluorocarbon; HFO = hydrofluoroolefin; LFL = lower flammability limit; n/a = not applicable; ppm = parts per million; R = refrigerant; — = no data. Adapted from ISO 817:2014 Refrigerants -- Designation and safety classification (Table 5: Refrigerant Designations)

European Standard (EN) 378:2016, covering safety and environmental requirements for refrigerating systems and heat pumps, provides specific recommendations for flammable refrigerants used in appliances.

EN 378-3:2016 (European Standard, 2016b) gives design specifications for machinery rooms for groups A2L, A2, A3, B2L, B2, and B3 refrigerants, in terms of location, emergency exhaust ventilation, maximum surface temperature, openings, and electrical equipment to be installed to detect refrigerant leakage.

EN 378-4:2016 (European Standard, 2016c) provides guidelines for operating equipment using flammable refrigerants, whose main points are summarized below.

Only competent persons, trained in the use of flammable refrigerants, are permitted to open equipment housings or to break into the refrigerant circuit.

When repairing sealed components on the refrigerant circuit, it is required that the following actions be taken:

- The power supply should be switched off before the sealed components are opened. If it is not necessary to switch off the relevant electrical components for repair work, the concentration in the atmosphere in the concerned area should be monitored continuously in order to be able to warn people about a potentially dangerous situation.

- Leak detection equipment shall be set at 20% of the LFL of the refrigerant within the equipment and should be calibrated for the refrigerant in question.

- The protective conductor connections should be checked according to the national rules and regulations each time a repair is made. The wiring and cabling should also be checked to make sure they are not damaged.

While working on the refrigerant circuit, it is recommended that the technician takes the following actions:

- Ensure that no flammable materials are stored in the work area and no ignition sources are present anywhere in the work area.

- Ensure suitable fire extinguishing equipment is available.

- Ensure the work area is properly ventilated before working on the refrigerant circuit or before welding, brazing, or soldering work.
- Ensure the leak detection equipment being used is non-sparking, adequately sealed or intrinsically safe.
- Check the concerned area with an appropriate refrigerant detector prior to and during any hot work to detect any potentially flammable atmosphere.
- Ensure the lubricant has been evacuated to an acceptable level if compressors or compressor oils are to be removed in order to guarantee that there is no flammable refrigerant remaining within the lubricant.
- Only use refrigerant recovery equipment designed for use with flammable refrigerants
- Avoid sources of ignition when searching for a refrigerant leak.

1.4. Hydronic heating systems

Hydronic heat pumps use water to transfer heat. They can be used for domestic hot water, space heating, or both. They come in two types: monobloc or split unit. As shown in Figure 4, for monobloc heat pumps, all the components of the vapor compression cycle are installed in the same unit, while split heat pumps are composed of an external unit and an internal unit (where the condenser is located), connected to each other by the refrigerant circuit.

The main advantage of monobloc heat pumps lies in an easier installation. The refrigerant circuit is already inside the heat pump, thus, the installation can be performed by a normal plumber (no need of expertise in handling refrigerant gas). While split units have the advantage of avoiding or reducing the effects of heat pumps on the indoor space, in terms of (a) noise (since the compressor is installed inside the external unit), (b) occupied space, and (c) reduction of indoor temperature (that occurs in case of monobloc heat pump which recovers thermal energy from indoor ambient temperature).

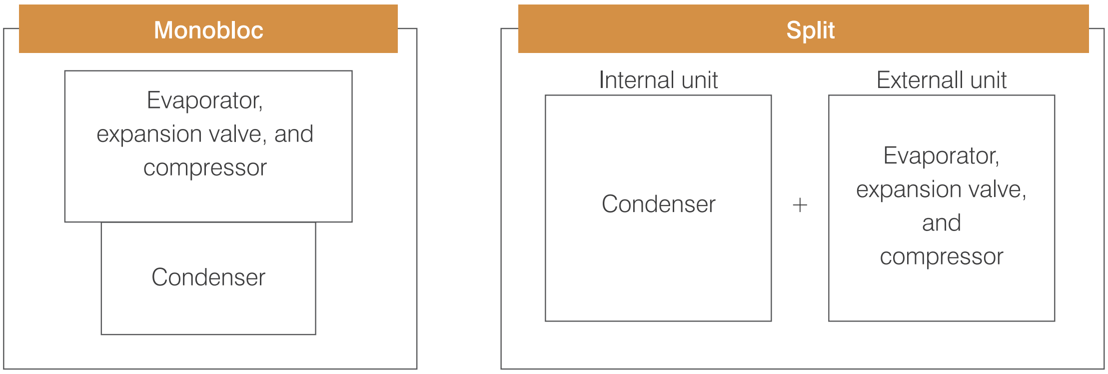


Figure 4. Monobloc and split heat pump systems

Unlike hydronic heat pumps, variable refrigerant flow (VRF), also called variable refrigerant volume, heat pumps use the refrigerant gas as heat transfer fluid; the refrigerant is conditioned by a single unit and is circulated within the building to multiple indoor units, modulating the amount of refrigerant sent to each zone in accordance with its heating demand. VRF systems require a higher amount of refrigerant than hydronic systems, flowing inside all branches of the circuit. This technology is not covered by these guidelines.

1.4.1. Domestic hot water

Heat pumps can be high-efficiency alternatives to traditional DHW heaters. Often DHW heat pumps available on the market are already integrated with thermal storage. Typically, the production of hot water for a dwelling with four occupants can be covered by a heat pump with storage of 80 liters. The heat pump can heat the DHW tank up to about 55 °C.

The unit is always equipped with an electrical back-up heater, which contributes to the thermal input only when the heat pump is not able to cover it by itself or in case of failure. Furthermore, the electrical back-up heater is used for anti-Legionella disinfection by heating the water up to 80 °C.

Usually DHW heat pumps are installed indoors and can easily replace existing electrical boilers, having compact dimensions and requiring the same connection to the electricity supply. The heat pump can get energy from the air source directly from the room where the unit is installed or from external air through an air duct system.

1.4.2. Space heating

Heat pumps can be used for residential space heating, both for new buildings and in case of refurbishment of existing buildings. This high-performance technology can reduce energy costs and emissions, but, due to its sensitivity to the operating conditions, its integration into a heating system requires special attention.

It is crucial to choose accurately the heat pump size and compressor type. Since energy needs for residential space heating can vary widely during the heating season, according to outside air temperatures, a multiple compressor or an inverter compressor heat pump can be suggested to cover a wide range of capacity ratio, without a noticeable reduction in energy performance that could be caused by on-off cycle working mode.

Moreover, considering that heat pump performance drops as the source temperature decreases, heat pumps, especially air source ones, can be integrated with an auxiliary heating system, which works at the lowest outdoor temperatures. This approach is suggested to optimize the cost-benefit analysis of a heat pump system.

The type of terminal unit determines the minimum temperature level at which the water inside the heat pump has to be heated in case of air-to-water or water-to-water systems. The lower the temperature of the water, the higher the efficiency of the heat pump. For this reason, it is better to couple heat pumps with terminal units able to work with low temperatures, such as floor heating (e.g., 35 °C). In case of refurbishment of existing buildings with radiators, which typically work with supply temperatures around 60-70 °C, the heating exchange surface of the heating devices should be increased in order to reduce the supply temperature. Figure 5 shows typical supply water temperatures for different heating terminal units.

Figure 5. Typical supply temperatures of different heating terminal units

With regard to all these issues, evaluating the seasonal performance of the system is necessary to assess the proper design of the heat pump system according to the specific boundary conditions and to set the heat pump capacity, the supply temperature and the integration of an auxiliary heating system. In section 2, a methodology for the evaluation of the seasonal performance of the system is suggested and explained.

For large heat pump systems, the evaluation of the integration of thermal storage is suggested. Thermal storage reduces the heating request peaks and, therefore, allows installation of smaller heat pumps. It also allows the thermal energy to be available when it is more convenient and whenever requested by the facility. For example, it is possible to take advantage of times when electrical energy is cheaper or photovoltaic panels are overproducing. Thermal energy storage guarantees that the facility will be autonomous even when the heat pump is used to satisfy other needs (e.g., DHW production) or when the electrical energy is not available.

1.4.3. Heat pump for space heating and DHW generation

A heat pump system can be used for the combined production of hot water for space heating and DHW. Heat pumps combining both functions in one heating unit exist on the market.

As shown in Figure 6, since the temperature set points for space heating and DHW are different, this kind of heat pump is provided with an internal three-way valve, which diverts the hot water between DHW and space heating circuits, with priority on the DHW circuit. Usually, there is internal thermal storage for DHW. Similar to DHW-only heat pumps, a heat pump used for both space heating and DHW is always equipped with an electrical back-up heater

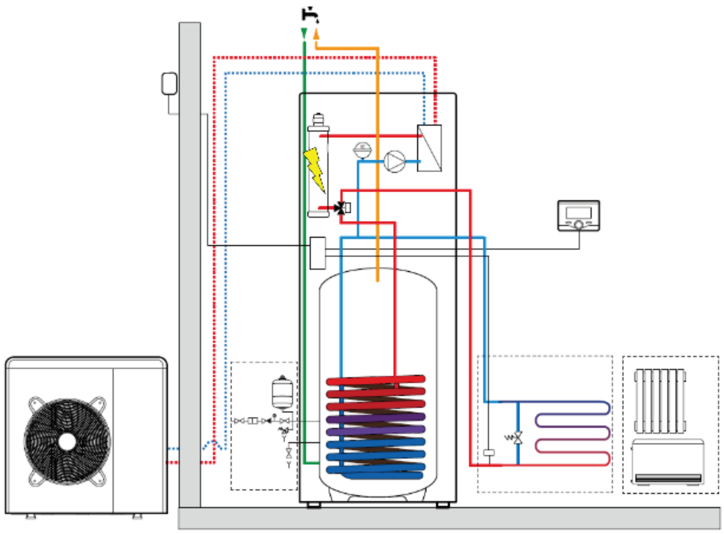


Figure 6. Example of a combined space heating and domestic hot water scheme. Reprinted from Product Guide of Nimbus M (p. 85), by Ariston, 2017

For an application with high energy needs both for space heating and DHW, it can be more suitable to have one heat pump for space heating and one for DHW. In this way, each heat pump is optimized for producing hot water at the related set-point temperature. Moreover, space heating load and DHW load can be fulfilled simultaneously.

1.4.4. Four-pipe systems

Because sometimes in a single building there are areas dedicated to different functions with very variable heat loads, there could be a simultaneous demand for heating and cooling, especially for commercial and tertiary applications (e.g., shopping centers, large business centers, hotels, swimming pools, and wellness centers). In these cases, a four-pipe heat pump system can be used to fulfill simultaneous heating and cooling needs (see Figure 7).

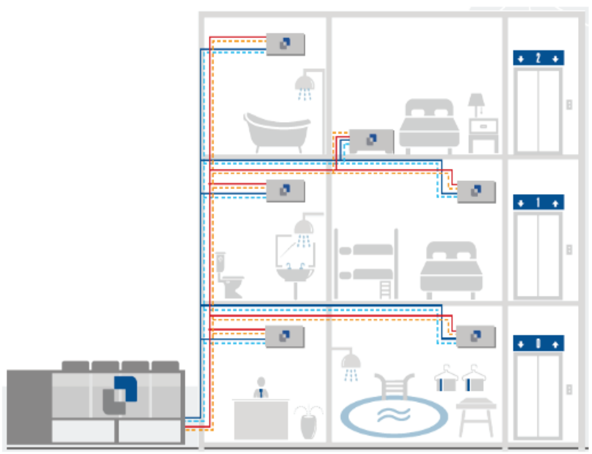
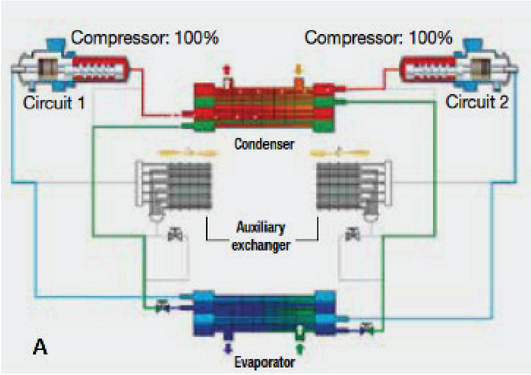


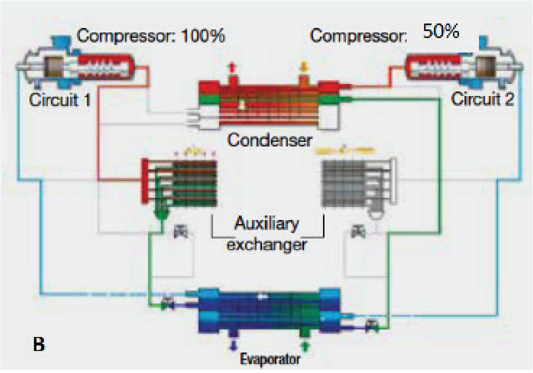
Figure 7. Example of a four-pipe heat pump system for a multipurpose building (residential, office, and hotel). Reprinted from Product Guide of Integra (four-pipe heat pump) (p. 5) by Climaveneta, Mitsubishi Electric Hydronics & IT Cooling Systems, 2018

A four-pipe system is made of two separate circuits (one for cooling and one for heating) that share the same condenser and evaporator. In this way, when there is simultaneous production of heating and cooling, the energy that usually would be exchanged with the energy source (e.g., air, water, or ground) by the single circuit is recovered by the other circuit and vice versa.

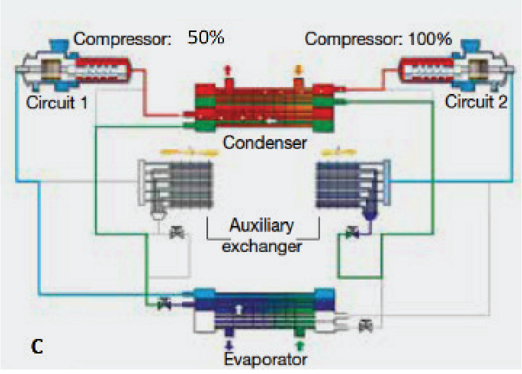
A four-pipe system also includes two auxiliary heat exchangers, which work, as evaporator and condenser, when there is no balance between heating and cooling needs. Figure 8 shows possible operating conditions. For example, as shown in Figure 8B), in case of cooling needs much higher than heating needs, the auxiliary condenser of the cooling cycle exchanges with the external sink (e.g., air) the ratio of energy not recovered by the evaporator of the heating circuit. While in case of heating needs much higher than cooling needs, Figure 8 C), the auxiliary evaporator of the heating cycle exchanges with the external sink (e.g., air) the ratio of energy in excess of the one already subtracted from the cooling circuit.



100% cold side, 100% heat side



100% cold side, 50% heat side



50% cold side, 100% heat side

Figure 8. Possible operating conditions of a four-pipe system. A shows balance between heating and cooling energy needs. B shows cooling needs higher than heating needs. C shows heating needs higher than cooling needs. Reprinted from Product Guide of Integra (four-pipe heat pump) (p. 5), by Climaveneta, Mitsubishi Electric Hydronics & IT Cooling Systems, 2018

Thus, when there is perfect balance between heating and cooling demand, there is maximum recovery of energy as shown in Figure 9.

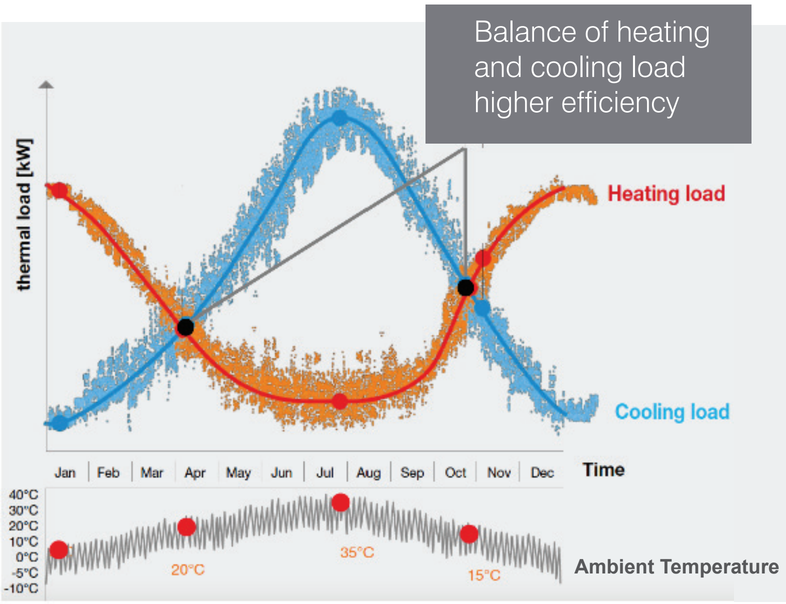


Figure 9. Example of yearly heating and cooling needs. Reprinted from Product Guide of Integra (four-pipe heat pump) (p. 5), by Climaveneta, Mitsubishi Electric Hydronics & IT Cooling Systems, 2018

The advantages of this four-pipe system are a simpler system configuration (one appliance satisfies the demand that is usually covered at least by two appliances) and higher energy performance.

1.5. Control strategies

The implementation of control logics and control devices plays a key role in achieving expected performance and optimizing management of the system, according to the external conditions and the users' habits.

In general, the regulation chain contains a sensor, a controller, an actuator, and a control variable (see Figure 10 and Figure 11).

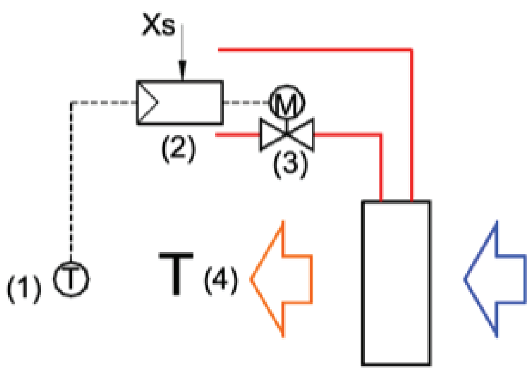


Figure 10. Example of control system of the heating fluid temperature based on the ambient temperature value. M = motorized Valve, T= temperature; Xs = controlled parameter; 1 = sensor; 2 = controller; 3 = actuator; 4 = control variable

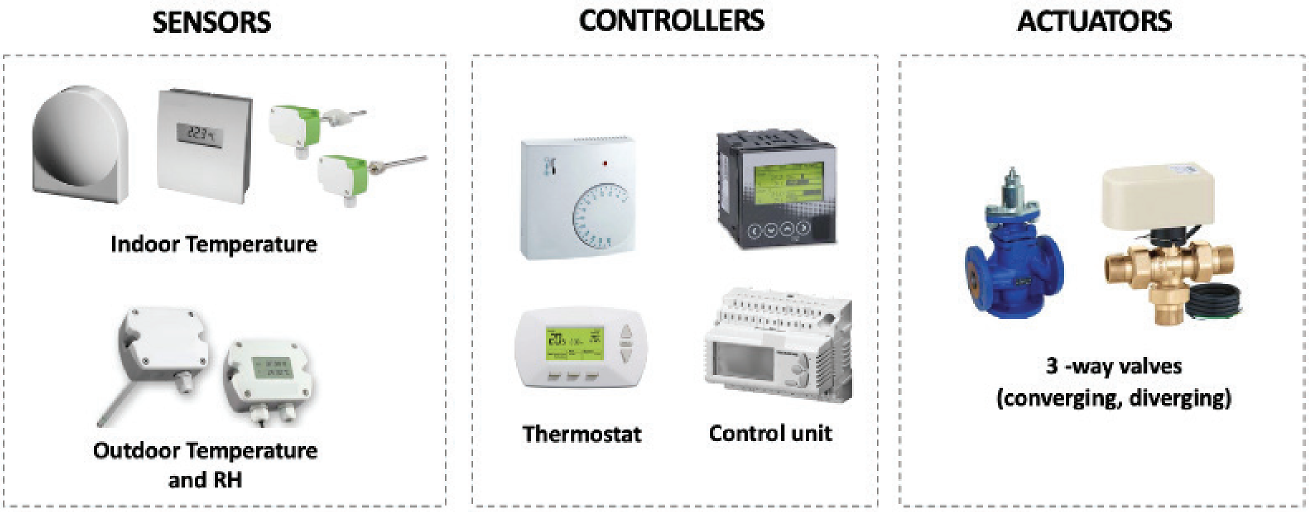


Figure 11. Components of a heat pump control system. RH = relative humidity

The control unit shall regulate different levels of the system, for example:

- The generation subsystem which produces the useful thermal energy via the heat pump and, if present, the auxiliary heating system.
- The distribution subsystem, composed of pipes, circulation pumps and other components of the circuit, which carries the heating fluid from the generation system to the heating devices.
- The emission subsystem, composed of the heating devices (e.g., fan coils, radiators, and heating floor), which is used for space heating.

1.5.1. Control logics for the generation subsystem

The supply temperature set point of a heat pump depends on the use of the system (e.g., space heating, DHW, or combined) and the operating temperature of the heating devices. If the space heating system is made of different types of heating devices with different operating temperature levels (e.g., high temperature radiator for bathrooms and low temperature floor heating for the other rooms), then different set-point temperatures shall be set on the control unit and a three-way valve shall be installed. The three-way valve will mix the heat pump supply temperature with the return temperature from the system to provide the low set-point temperature.

For heat pumps that can cover both space heating and DHW requests, at least two set-point levels shall be set, to provide energy on the two circuits, with priority on the DHW circuit.

To improve the control of the heat pump supply temperature for space heating, an external temperature sensor can be installed and connected to the control unit, for the compensation of the hot water set point with respect to the variation of outdoor ambient temperature (see Figure 12).

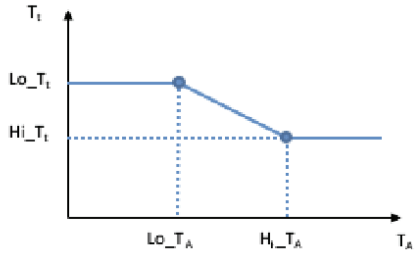


Figure 12. Regulation of the supply temperature according to external temperature variation. Tt = target temperature; TA = outdoor ambient temperature; Lo_TA = low ambient temperature; Lo_Tt = heat pump set-point temperature at Lo_TA; Hi_TA = high ambient temperature; Hi_Tt = heat pump set-point temperature at Hi_TA

If an auxiliary heating system is present, it is really important to set the control logics for the heat pump and auxiliary system coupling. For example, the bivalent temperature should be set. The bivalent temperature corresponds to the outdoor temperature value below which the back-up heating system is enabled. In these conditions, the heat pump has worse performance.

1.5.2. Control logics for the distribution subsystem

To optimize the energy consumption of the circulation pump on the distribution system, some heat pumps are provided with a water temperature sensor, which can be used to stop the circulation pump from being used during periods of stand-by, when the water temperature reaches the set point. This feature can greatly reduce the unit's power consumption.

1.5.3. Control logics for the emission subsystem

Indoor conditions can be controlled by thermostats, setting the time schedule and temperature set point as well as set-back temperature. Set-back temperature is the minimum indoor temperature to be guaranteed in the room even when there are no occupants. Figure 13 shows a sample time schedule for winter during weekdays and weekends. It also shows the temperature set point and the set-back temperature.

Sample heat pump system schemes can be found in Annex B.

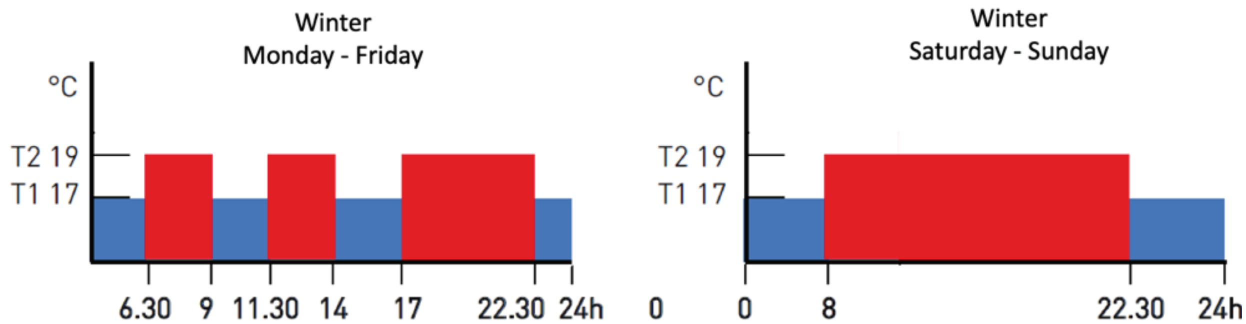


Figure 13. Sample thermostat configuration for week days and weekend. T1 = set-back temperature; T2 = set-point temperature, h = hours

2. EVALUATING DESIGN AND PERFORMANCE OF SPACE HEATING SYSTEMS

For space heating systems, the influence of the variation of the boundary conditions and, consequently, of building energy needs on the efficiency of the heat pump should be analyzed. Thus, this section focuses on the design of a heat pump system for space heating and evaluation of the seasonal performance.

2.1. Designing systems for space heating

The design of the heat pump system for space heating starts from the evaluation of a building's energy needs, on the basis of the boundary conditions (e.g., outdoor conditions), and design conditions (e.g., indoor set-point temperatures, end-user needs). The heating system shall be designed to satisfy the peak load, at the corresponding conditions (e.g., lowest external temperature and needed supply temperature).

Focusing on the design of heat pump systems, it is necessary to define the system configuration. In particular, the heat pump can be sized to (a) provide the peak demand entirely, without any other auxiliary generation system or (b) cover the peak demand partially, with the integration of an auxiliary generation system (e.g., electrical resistance). In case (b), the bivalent temperature ($T_{bivalent}$) has to be defined as the lowest outdoor temperature point at which the heat pump is able to meet 100% of the heating load without a back-up heater. For external temperatures below this point, the heat pump can still deliver capacity, but an additional back-up heating system is necessary to fulfill the full heating load. At the $T_{bivalent}$ the capacity ratio (CR), corresponding to the heating load divided by the declared heating capacity of the heat pump in full load at the same temperature conditions, is equal to 1.

Figure 14 line 1 represents building energy needs, while line 2 corresponds to the heat pump's full load capacity according to the external temperature. This is a fixed capacity type heat pump. The operating external temperature range goes from the design temperature (T_d) (the lowest outdoor temperature) to the temperature over which the heating system is switched off by the control system ($\theta_{H,off}$). The intersection point between line 1 and line 2 corresponds to the $T_{bivalent}$, at which the heat pump CR is equal to 1. For external temperatures higher than the $T_{bivalent}$, CR is always less than 1. Note that if the $T_{bivalent}$ is set equal to T_d, the building heat demand has to be fulfilled only by the heat pump. Thus, the heat pump will work mainly with partial load capacity, and, especially for units with fixed capacity, this could be detrimental to its energy performance. Whereas, Figure 15 shows the operation of a heat pump with inverter. In the latter case, the heat pump is able to fulfill better the energy needs with higher performance than the fixed-capacity heat pump specifically for CR lower than 1.

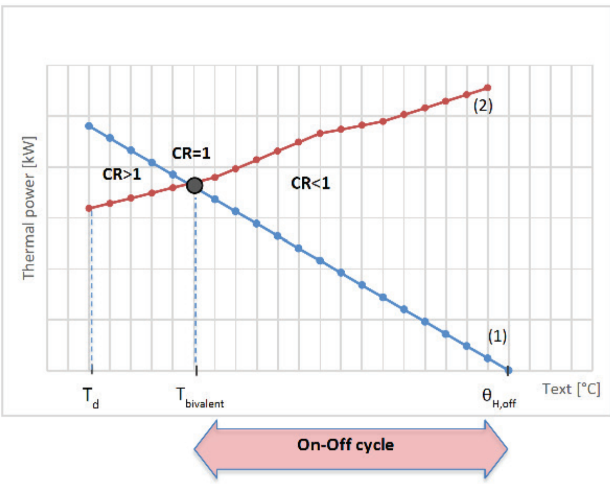


Figure 14. Building energy load and heat pump thermal capacity according to external temperature for a fixed-capacity heat pump. CR = capacity ratio; $\theta_{H,off}$ = temperature over which the heating system is switched off by the control system; T_d = design temperature; $T_{bivalent}$ = bivalent temperature; (1) = building energy needs; (2) = heat pump's full load capacity according to the external temperature

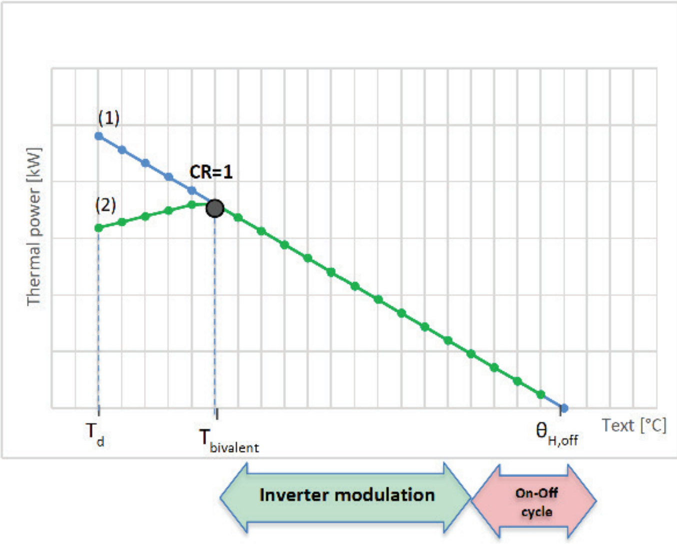


Figure 15. Building energy load and heat pump thermal capacity according to external temperature for an Inverter compressor heat pump. CR = capacity ratio; $\theta_{H,off}$ = temperature over which the heating system is switched off by the control system; T_d = design temperature; $T_{bivalent}$ = bivalent temperature; (1) = building energy needs; (2) = heat pump's capacity according to the external temperature

2.2. Evaluating energy consumption and seasonal performance of space heating systems

The performance of the heat pump system can be evaluated starting from the technical data provided by the heat pump manufacturer at specific operating conditions, in terms of source temperature, outlet temperature, and partial load ratio.

2.2.1. Calculating coefficient of performance and capacity at different conditions for air-to-water and water-to-water units

To calculate the seasonal coefficient of performance (SCOP) of a heat pump system, it is necessary to evaluate its performance in operating conditions different from those declared by the manufacturer, according to standards EN 14825 and EN 14511 (European Standard 2016a, 2018), which define the specific test conditions to measure the COP of heat pumps used for space heating.

Below, a methodology is described for deriving the COP, at different values of source and supply temperatures and CR, for air-to-water and water-water vapor-compression units, according to EN 14825 and UNI TS 11300-4 (Ente Nazionale Italiano di Unificazione, 2015)[1] .

This method is based on the second law of efficiency (η_{II}), which is the ratio between the COP and the theoretical maximum COP (COP_{MAX}) (Carnot cycle), according to the second law of thermodynamics, at the same temperature conditions:

$$COP_{MAX} = (\theta_H + 273.15)/(\theta_H - \theta_C),$$

$$\eta_{II} = COP/COP_{MAX}$$

[1] *The Italy standard UNI TS 11300-4:2015 (Ente Nazionale Italiano di Unificazione, 2015) provides methods to evaluate primary energy consumption for space heating and DHW production from generation systems that use renewable energy sources. In particular, with regard to electrically-driven compressor heat pumps used for space heating, it transposes European Standard (EN) 14825, which provides partial load conditions and calculation methods for calculating the seasonal energy efficiency ratio (SEERon) and seasonal coefficient of performance (SCOPon and SCOPnet) of electrically-driven compressor heat pumps for space heating and cooling.*

where θ_C is temperature (°C) of the cold source and θ_H is the temperature (°C) of the hot sink, corresponding to the heat pump supply temperature.

Note: In this document all temperature values are expressed in (°C).

Correction of coefficient of performance for a different supply temperature

To interpolate between different supply temperatures ($\theta_{H,x}$), $\theta_{H,1}$ and $\theta_{H,2}$, for a given source temperature θ_C, the second law of efficiency for each supply temperature has to be defined:

$$\eta_{II,1} = COP1 / [(\theta_{H,1} + 273.15)/(\theta_{H,1} - \theta_C)]$$

$$\eta_{II,2} = COP2 / [(\theta_{H,2} + 273.15)/(\theta_{H,2} - \theta_C)]$$

Where COP_1 and COP_2 are the COP declared by the manufacturer respectively at supply temperatures $\theta_{H,1}$ and $\theta_{H,2}$ and source temperature θ_C.

$$\eta_{II,x} = \eta_{II,1} + (\eta_{II,2} - \eta_{II,1}) \times (\theta_{H,x} - \theta_{H,1})/(\theta_{H,2} - \theta_{H,1})$$

Then, the second law efficiencies for the new supply temperature $\theta H,x$ are interpolated:

And then the corrected COP for $\theta_{H,x}$ is derived:

$$COP_x = \eta_{II,x} \times (\theta_{H,x} + 273.15)/(\theta_{H,x} - \theta_C)$$

Correction of coefficient of performance for a different source temperature

The same method of interpolation on the basis of the second law of efficiency is used to calculate the COP for a different source temperature ($\theta_{C,x}$), between $\theta_{C,1}$ an $\theta_{C,2}$ for a given supply temperature θ_H:

$$\eta_{II,x} = \eta_{II,1} + (\eta_{II,2} - \eta_{II,1}) \times (\theta_{C,x} - \theta_{C,1})/(\theta_{C,2} - \theta_{C,1})$$

$$COP_x = \eta_{II,x} \times (\theta_H + 273.15)/(\theta_H - \theta_{C,x})$$

where COP_x is the coefficient of performance at the source temperature ($\theta_{C,x}$)

Correction of heat pump capacity for a different source temperature

The heat pump capacity in full load conditions for an $\theta_{C,x}$, between $\theta_{C,1}$ an $\theta_{C,2}$, is calculated through linear interpolation:

$$DC_x = DC_1 + (DC_2 - DC_1) \times (\theta_{C,x} - \theta_{C,1})/(\theta_{C,2} - \theta_{C,1})$$

where DC_1 and DC_2 are the declared capacities in full load conditions, provided by the manufacturer respectively at source temperatures $\theta_{C,1}$ and $\theta_{C,2}$, and a supply temperature θ_H.

Correction of heat pump capacity for a different supply temperature

The heat pump capacity for a different supply temperature ($\theta_{H,x}$), between $\theta_{H,1}$ and $\theta_{H,2}$, is calculated through linear interpolation:

$$DC_X = DC1 + (DC\ 2 - DC\ 1) \times (\theta_{H,x} - \theta_{H,1})/(\theta_{H,2} - \theta_{H,1})$$

Correction of coefficient of performance for different capacity ratio

When the heat pump CR is less than 1, it is necessary to define a correction factor (F_{COP}), to calculate the COP according to the following equation:

$$COP_X = COP_{DC} \times F_{COP}$$

$$F_{COP} = \frac{CR}{((1 - C_C) \times CR + C_C)}$$

Where COP_{DC} is COP at full load conditions (when CR = 1) and CR is heating load/heat pump full load capacity.

The degradation coefficient (Cc), due to the cycling of the heat pump unit, can be provided by the manufacturer data. If this information is missing, consider

- for fixed-capacity heat pump, $C_C = 0.9$;

- for variable-capacity heat pump

- if $0.5 \leq CR < 1$, $CC = 1$

- if $CR < 0.5$, $CC = 0.9$

2.2.2. Calculating seasonal coefficient of performance and seasonal primary energy needs

The bin-method is a methodology that can be used to evaluate the SCOP and seasonal primary energy needs, starting from the monthly energy needs and the bin hours, which correspond to the total hours occurring for each external temperature interval (of 1 K), evaluated on the typical meteorological year. The evaluation is done monthly. The share of monthly energy needs is calculated on each bin, and for each bin. The SCOP and seasonal primary energy needs are determined on the basis of the values of (a) external temperature (corresponding to the temperature of the cold source for an air-to-water heat pump), (b) supply temperature (which can be defined as a function of external temperature), and (c) a heat pump's CR. This method is useful to estimate the impact of the design choices of the heating system on its seasonal energy consumption.

To begin, define the design conditions:

- θ_H: heat pump supply temperatures, which can be defined as a constant value or as a function of external temperature

- $\theta_{H,off}$: external temperature over which the heating system is switched off by the control system

- $T_{bivalent}$

For each month, starting from the monthly energy needs ($Q_{req,m}$), the following calculations should be performed:

1. Calculate for each bin the degree hours (excluding bins with $\theta > \theta_{H,off}$):

$$DH_{bin,m} = (\theta_{H,off} - \theta_{bin}) \times t_{bin}$$

where $DH_{bin,m}$ is the heat pump declared capacity at supply temperature, θ_H, and source temperature (θ_{bin} for air source heat pump) of bin on a specific month and t_{bin} is the number of hours for the specific bin.

2. Calculate the share of the monthly energy needs on each bin:

$$Q_{req,bin,m} = Q_{req,m} \times DH_{bin,m} / \Sigma(DH_{bin,m})$$

where $Q_{req,bin,m}$ is share of energy needs of bin on a specific month, $Q_{req,m}$ is total energy needs of a specific month, and $\Sigma(DH_{bin,m})$ is the sum of $DH_{bin,m}$ calculated in the first step.

3. Calculate for each bin the requested thermal power:

$$\Phi_{req,bin,m} = Q_{req,bin,m} / t_{bin}$$

where $\Phi_{req,bin,m}$ is requested thermal power of bin on a specific month.

4. Determine for each bin the heat pump declared capacity ($DC_{bin,m}$) and nominal performance ($COP_{N,bin,m}$) at the specific supply temperature, θ_H, and source temperature (θ_{bin} for air source heat pump), as explained in the previous paragraph;

5. Calculate for each bin the heat pump CR:

$$CR_{bin,m} = \Phi_{req,bin,m} / DC_{bin,m}$$

6. Calculate for each bin the corrective factor ($F_{COP,bin,m}$) at the specific CR, according to the methodology explained in the previous paragraph.

7. Calculate for each bin the actual COP:

$$COP_{PL,bin,m} = COP_{N,bin,m} \times F_{COP,bin,m}$$

8. Calculate for each bin the heat pump power output:

$$\Phi_{gn,out,bin,m} = DC_{bin,m} \times CR_{bin,m}$$

where $\Phi_{gn,out,bin,m}$ is the heat pump thermal power output of bin on a specific month.

9. Calculate for each bin the heat pump energy output:

$$Q_{H,hp,out,bin,m} = \Phi_{gn,out,bin,m} \times t_{bin}$$

where $Q_{H,hp,out,bin,m}$ is heat pump thermal energy output of bin on a specific month.

10.Calculate for each bin the share of energy that should be provide by an auxiliary generation system when $Q_{H,hp,out,bin,m} < Q_{req,bin,m}$:

$$Q_{H,aux,out,bin,m} = Q_{req,bin,m} - Q_{H,hp,out,bin,m}$$

where $Q_{H,aux,out,bin,m}$ is seasonal energy input of the auxiliary generation system.

11. Calculate for each bin the heat pump input energy:

$$Q_{H,hp,el,bin,m} = Q_{H,hp,out,bin,m} / COP_{PL,bin,m}$$

where $Q_{H,hp,el,bin,m}$ is heat pump energy input of bin on a specific month and $COP_{PL,bin,m}$ is the actual COP at CR of bin on a specific month.

12. Calculate the monthly heat pump input energy:

$$Q_{H,hp,el,m} = \Sigma(Q_{H,hp,el,bin,m})$$

where $Q_{H,hp,el,m}$ is total heat pump energy input on a specific month and $Q_{H,hp,el,bin,m}$ is heat pump energy input of bin on a specific month.

13. Calculate the monthly electrical energy input of auxiliary generation system:

$$Q_{H,aux,out,m} = \Sigma(Q_{H,aux,out,bin,m})$$

Once the energy inputs and outputs have been defined for each month, the following calculations should be performed:

1. Calculate the seasonal energy needs of the building:

$$Q_{req,s} = \Sigma(Q_{req,m})$$

2. Calculate the seasonal electrical energy input of heat pump:

$$Q_{H,hp,el,s} = \Sigma(Q_{H,hp,el,m})$$

3. Calculate the seasonal electrical energy input of auxiliary generation system:

$$Q_{H,aux,out,s} = \Sigma(Q_{H,aux,out,m})$$

Once the seasonal energy inputs and outputs have been defined, calculate SCOP for heat pump and seasonal performance factor of the system composed of heat pump and auxiliary generation system ($[SPF_{HP+AUX}]$):

$$SCOP_{HP} = Q_{req,s} / Q_{H,hp,el,s}$$

$$SPF_{HP+AUX} = Q_{req,s} / (Q_{H,hp,el,s} + Q_{H,aux,out,s})$$

Once the energy inputs have been defined for each month, the SCOP and the performance of the integrated system (heat pump and auxiliary generation system) can be defined, as the ratio between the sum of the monthly energy needs and the sum of the monthly energy inputs.

If the auxiliary generation system has not the same energy carrier of the heat pump (e.g., gas, fuel), the performance of the integrated system has to be calculated in terms of primary energy, considering the conversion factors for each different energy carrier.

2.3. Analyzing the impact of design parameters on the seasonal coefficient of performance

A reference case has been studied to analyze the impact of the heat pump sizing and the integration with an auxiliary generation system on the seasonal performance of the heat pump system, using the method described in the previous paragraph.

The input variables were the building's monthly energy needs and monthly bin hours. The design parameters included:

- θ_H ,the heat pump supply temperature;
- $\theta_{H,off}$, the temperature over which the heating system is switched off by the control system
- $T_{bivalent}$
- the external temperature (T_{ext})
- heat pump nominal capacity (chosen on the basis of the heating load for $T_{ext} = T_{bivalent}$)

The reference case is based on a heat pump system for space heating, located in Qartaba (Lebanese climatic zone 2). The climatic data in Table 3 are taken from the typical meteorological year provided by Meteonorm. The coldest month is January, with a lowest external temperature of -4 °C, thus, the reference T_d = -4 °C. $\theta_{H,off}$ has been set equal to 16 °C (the system is considered switched off for external temperature ≥ 16 °C).

Table 3. Bin hours for Qartaba (Lebanese climatic zone 2) for heating season

	Bin hours Text (°C)																			
Month	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Jan	5	15	18	27	58	60	73	65	70	61	77	57	45	35	33	24	16	2	3	0
Feb	0	0	7	12	27	38	48	44	60	76	71	73	43	43	36	25	24	20	14	9
Mar	0	0	0	0	0	7	10	16	36	38	48	66	62	59	64	48	61	53	41	36
Apr	0	0	0	0	0	0	0	0	0	0	11	19	42	53	53	58	62	59	52	59
May	0	0	0	0	0	0	0	0	0	0	0	0	2	15	12	16	19	35	51	65
Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	7	14
Jul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	15	22
Oct	0	0	0	0	0	0	0	0	0	0	0	0	4	20	27	40	37	39	46	52
Nov	0	0	0	0	0	0	8	17	20	37	43	53	63	61	71	65	52	58	42	46
Dec	0	0	7	10	24	31	36	45	59	84	77	84	64	57	45	45	21	19	16	8
TOTAL	5	15	32	49	109	136	175	187	245	296	327	352	325	343	341	321	292	294	287	311

Note: Heating season = Jan–Apr and Oct–Dec.

Table 4 shows the monthly thermal needs Q_H (kWh) and the monthly heat pump supply temperature T_{supply} (°C), which varies between 37 °C and 43 °C.

Table 4. Example of variation of required supply temperature

Month	T_{supply}	Q_H
January	43	10,400
February	40	9,600
March	40	7,200
April	37	3,440
October	37	3,200
November	40	6,520
December	40	8,800

Notes: Tsupply = monthly heat pump supply temperature; Q_H = monthly thermal needs.

To analyze the impact of $T_{bivalent}$ choice four cases have been analyzed:

1. No integration of auxiliary generation system ($T_{bivalent}$ = Td = -4 °C)

2. $T_{bivalent}$ = 0 °C

3. $T_{bivalent}$ = 2 °C

4. $T_{bivalent}$ = 4 °C

The heat pump capacity has been chosen to satisfy the heat load of January for $T_{ext} = T_{bivalent}$.

For demonstration purposes, the reference values of COP from datasheet are based on the same model of heat pump, and, to vary the heat pump size (according to $T_{bivalent}$ of the specific case), those values have been multiplied by a coefficient.

The considered auxiliary generation system is an electrical resistance, with an efficiency $\eta_{el}=1$.

Applying the method explained in the previous paragraphs, seasonal COP (SCOP) and primary energy needs of the single heat pump and of the system (heat pump) HP+AUX have been calculated.

Figure 16 and Table 5 and Table 6, show that the best results in terms of total primary energy needs and SCOP of the entire heating system, are obtained for case 2, with $T_{bivalent}$ = 0 °C.

For case 1, with $T_{bivalent} = T_d$, the single heat pump has to fulfill the heat load in every climatic condition (also for low values of external temperature, which has a negative impact on air source heat pump performance), thus, most of the time it has to work in partial load, with low capacity ratio, which damages heat pump performance.

For increasing $T_{bivalent}$ (cases 3 and 4), the SCOP of the single heat pump is increasing, because of more favorable external conditions and capacity ratio closer to 1, but the energy ratio provided by the electrical resistance gets higher, therefore, $SCOP_{HP+AUX}$ decreases.

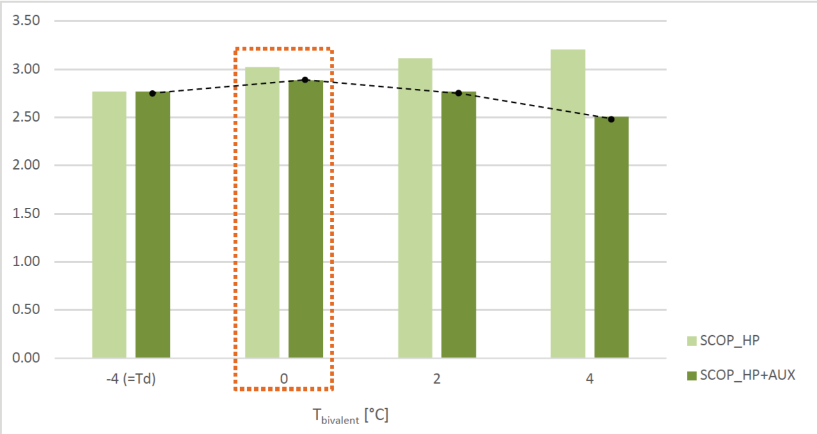


Figure 16. Seasonal coefficient of performance of the single heat pump and of the system heat pump and auxiliary generation system, for different values of $T_{bivalent}$. $SCOP_{HP}$ = seasonal coefficient of performance of the heat pump; $SCOP_{HP+AUX}$= seasonal coefficient of performance of the heat pump and auxiliary generation system $T_{bivalent}$ = bivalent temperature

Table 5. Monthly values of performance of the single heat pump and of the generation system (composed of the heat pump and the auxiliary generation system), by varying values of the bivalent temperature

	$T_{bivalent}$ = Td = -4°C		$T_{bivalent}$ = 0°C		$T_{bivalent}$ = 2°C		$T_{bivalent}$ = 4°C	
Month	COP_{HP}	COP_{HP+AUX}	COP_{HP}	COP_{HP+AUX}	COP_{HP}	COP_{HP+AUX}	COP_{HP}	COP_{HP+AUX}
Jan	2.56	2.56	2.74	2.58	2.81	2.40	2.87	2.13
Feb	2.82	2.82	3.03	2.76	3.10	2.57	3.17	2.25
Mar	2.84	2.84	3.12	3.03	3.21	2.96	3.31	2.70
Apr	2.78	2.78	3.19	3.19	3.34	3.34	3.50	3.49
May	—	—	—	—	—	—	—	—
Jun	—	—	—	—	—	—	—	—
Jul	—	—	—	—	—	—	—	—
Aug	—	—	—	—	—	—	—	—
Sep	—	—	—	—	—	—	—	—
Oct	3.31	3.31	3.63	3.60	3.74	3.45	3.84	3.02
Nov	2.80	2.80	3.10	3.06	3.20	3.04	3.31	2.84
Dec	2.75	2.75	2.99	2.89	3.07	2.79	3.16	2.55
SCOP	2.77	2.77	3.02	**2.89**	3.11	2.77	3.20	2.51

Notes: COP_{HP} = coefficient of performance of the heat pump; COP_{HP+AUX} = coefficient of performance of the heat pump with an auxiliary generation system; SCOP = seasonal coefficient of performance; $T_{bivalent}$ = bivalent temperature; T_d = design temperature; — = no data.

Table 6. Monthly values of electrical energy input to the single heat pump and to the generation system (composed of the heat pump and the auxiliary generation system), by varying values of the bivalent temperature

	$T_{bivalent} = T_d = -4°C$		$T_{bivalent} = 0°C$		$T_{bivalent} = 2°C$		$T_{bivalent} = 4°C$	
Month	$Q_{el,HP}$ (kWh)	$Q_{el,HP+AUX}$ (kWh)	$Q_{el,HP}$ (kWh)	$Q_{el,HP+AUX}$ (kWh)	$Q_{el,HP}$ (kWh)	$Q_{el,HP+AUX}$ (kWh)	$Q_{el,HP}$ (kWh)	$Q_{el,HP+AUX}$ (kWh)
Jan	4,069	4,069	3,654	4,031	3,362	4,330	2,948	4,888
Feb	3,407	3,407	3,023	3,473	2,792	3,739	2,458	4,265
Mar	2,539	2,539	2,280	2,378	2,153	2,436	1,962	2,665
Apr	1,235	1,235	1,079	1,079	1,030	1,030	980	987
May	—	—	0	0	0	0	0	0
Jun	—	—	0	0	0	0	0	0
Jul	—	—	0	0	0	0	0	0
Aug	—	—	0	0	0	0	0	0
Sep	—	—	0	0	0	0	0	0
Oct	968	968	877	890	829	928	753	1,061
Nov	2,330	2,330	2,091	2,133	1,986	2,146	1,828	2,296
Dec	3,205	3,205	2,898	3,042	2,726	3,151	2,476	3,448
Qseason	17,753	17,753	15,902	17,026	14,878	17,760	13,405	19,610

Notes: kWh = kilowatt hour; $Q_{el,HP}$ = electrical energy input to the single heat pump; $Q_{el,HP+AUX}$ = electrical energy input to the generation system (composed of the heat pump and the auxiliary generation system); $T_{bivalent}$ = bivalent temperature; T_d = design temperature; — = no data.

2.4. Domestic hot water systems with integrated thermal storage

The $SCOP_{DHW}$ is to be considered equal to the COP_{DHW}, evaluated according to the European Standard EN 16147[2] , for the specific conditions (e.g., outdoor or indoor installations, climatic zone of the installation site). Therefore, primary energy consumptions of the heat pump system can be calculated as DHW energy needs multiplied per $COP_{DHW,EN16147}$.

2.5. Space heating systems integrated with domestic hot water storage

For heat pump systems for space heating and DHW, with an integrated storage for DHW, the SCOP is calculated separately for space heating and DHW. SCOP and primary energy consumptions for space heating are calculated

2 EN 16147 (European Standard, 2017) fixes a testing procedure to evaluate COP of heat pumps for DHW with integrated thermal storage, on basis of a tapping cycle.

according to the method explained in section 2.2, on the basis of space heating energy needs and COP declared by the manufacturer according to EN 14511 (2018). While for DHW, $SCOP_{DHW}$ is to be considered equal to the COP_{DHW} declared by the manufacturer according to EN 16147 (2017), and primary energy consumptions are calculated as DHW energy needs multiplied per $COP_{DHW,EN16147}$. Total primary energy consumptions are the sum of primary energy consumptions for space heating and DHW.

2.6. Space heating systems coupled with external domestic hot water storage

For buildings with high DHW energy needs, the heat pump could be coupled with external DHW thermal storage. In this case the SCOP and primary energy consumption for DHW production can be calculated with the same method used for space heating, as explained in section 2.2, considering the COP provided by the manufacturer according to EN 14511 (2018).

3. INSTALLATION GUIDELINES

3.1. Heat pump location

In general, the heat pump should not: (a) be exposed to particular environmental conditions, to aggressive atmosphere, or to direct sunlight; and (b) not be near any heat source. To facilitate access for installation and ordinary and extraordinary maintenance, it is important to leave a minimum clearance (per manufacturer requirements) around the heat pump. The unit should be placed on a flat surface capable of supporting the weight of the product and its contents. The appliance should be installed as close as possible to the points of use to limit heat dispersion along the piping. Special attention shall be attributed to air source heat pump systems.

3.1.1. Outdoor air source heat pump systems

The external unit of an outdoor air source heat pump should be protected from particular weather conditions (e.g., in case of strong wind, the use of wind breaker barriers is recommended; for location with abundant snowfall, the unit needs to be installed above the usual level of fallen snow).

A large space, ventilated and free from obstacles is required to enable smooth flow of air to the finned coil and free air outlet above the air inlet of the fan, with no air recirculation. The minimum clearance declared by the manufacturer shall be respected (see Figure 17).

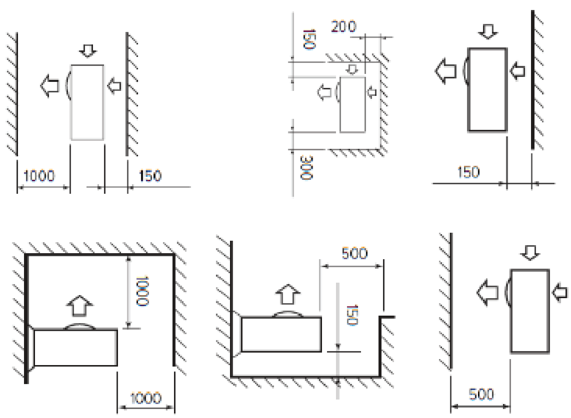


Figure 17. Example of minimum clearance distance (in mm) for the external unit of an outdoor air source heat pump. Reprinted from Product Guide of Nimbus Pocket M Net Heat Pump (p. 52), by Ariston Thermo Group, 2018

3.1.2. Indoor air source heat pump systems

If the product is designed for indoor installations, product safety and performance levels are not guaranteed in the event of outdoor installation.

The air vents shall be free from obstacles. The minimum clearance declared by the manufacturer shall be respected.

In case of installation without air canalization, the room where the heat pump is to be installed should respect the minimum volume declared on the data sheet and shall be adequately ventilated.

It is important to consider that, the heat pump outlet air may reach temperatures that are 5-10 °C lower compared to that of the inlet air and, if not ducted, the temperature of the room where the heat pump is installed may drop.

The heat pump should not be installed in a room containing an appliance that requires air to function (e.g., an open-chamber gas boiler, an open-chamber gas water heater, etc.).

3.2. Acoustics

The heat pump shall be installed on an anti-vibration support. Anti-vibration joints between the appliance and water pipes shall be provided.

For air source heat pumps, especially ones located outdoors, the heat pump should be installed where the noise and the air discharged do not disturb the neighbours. To reduce noise levels, the unit could be shielded by a fence or solid barrier that can reduce noise propagation but avoid materials that could reflect sound waves. Installers shall remember to ensure the minimum clearance required by the manufacturer.

Installers shall also assure that the heat pump noise level respects the maximum allowable levels, according to Lebanese Ministry of Environment Decision 1/52 (1996) (see Table 7).

Table 7. Maximum allowable acoustic levels

	Maximum allowable level (decibel)		
	Day	Evening	Night
Type	7:00–18:00	18:00–22:00	22:00–7:00
Commercial areas	55–65	50–60	54–55
Residential areas in cities	45–55	40–50	35–45
Residential areas in suburbs	40–50	35–45	30–40
Residential rural areas and hospitals	35–45	30–40	25–35

Adapted from Lebanese Ministry of Environment Decision 1/52 (1996)

3.3. Water quality (hydronic heat pump system case)

For hydronic heat pump systems, the water quality shall comply with the chemical-physical parameters specified in the heat pump installation manual. Water with inadequate characteristics can reduce energy efficiency and increase drops in pressure and potential for corrosion. If the hardness of the water exceeds the required limit, the use of a water softener is recommended.

3.4. Hydraulic connections (hydronic heat pump system case)

This section includes recommendations for the installation of hydraulic circuits for hydronic heat pump systems.

To limit heat dispersion, all pipes need to be well insulated and protected.

Before activating the heat pump system, carefully wash the system pipes to remove any residues of screw thread, welding, or dirt that may hamper the correct operation of the appliance.

If the heat pump is integrated with a water tank or if there is external storage, fill it with water and drain it completely to remove residual impurities.

The following components should be installed on the primary hydronic circuit to protect the system and to allow easy maintenance (not all of these components are required for a small-capacity heat pump) (see Figure 18):

1. Two anti-vibration joints on output and input water piping
2. Two shut-off valves on output and input water piping to facilitate service and maintenance
3. Two temperature sensors on output and input water piping
4. One pressure gauge
5. Drain taps to permit complete drainage of the circuit during maintenance
6. One non-return valve, to be installed directly downstream of the pump in order to not allow backflow, which can cause the pump to spin in the reverse direction and cause severe damage
7. One separator filter on the input water piping
8. One expansion tank of the individual unit, to protect the circuit from pressure variations
9. One safety valve to protect the circuit against excessive pressure
10. Automatic air vent valves to be installed at the highest elevation points of the system to evacuate air. Note: Air present in the water circuit might cause malfunctioning (e.g., heat transfer penalization) and disturbing noise.

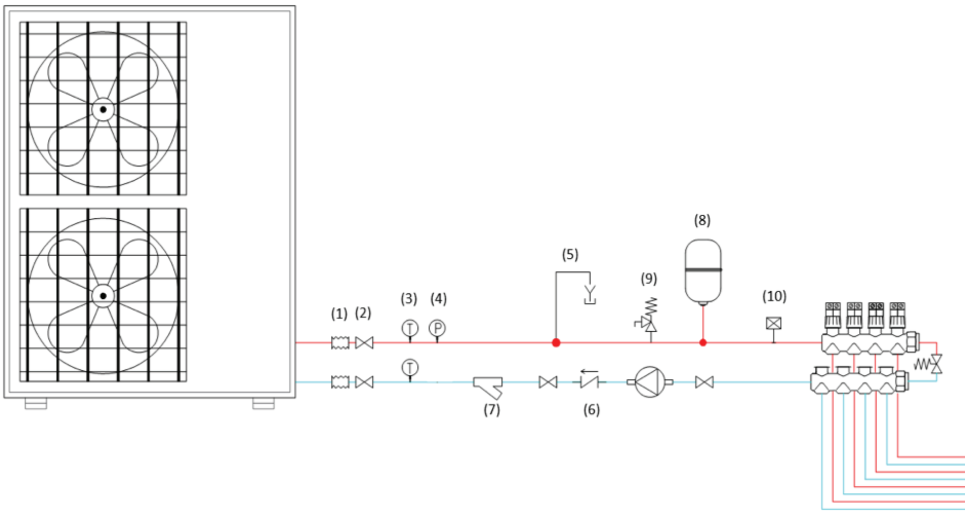


Figure 18. Example of main components to be installed on the primary hydraulic circuit. (1) = anti-vibration joints on output and input water piping; (2) = shut-off valves on output and input water piping; (3) = temperature sensors on output and input water piping; (4) = pressure gauge; (5) = drain taps; (6) = non-return valve; (7) = separator filter on the input water piping; (8) = expansion tank; (9) = safety valve; (10) = automatic air vent valve

For air source heat pumps, it is important to ensure that drain water coming from the evaporator during heating operation and defrost operation can be properly evacuated. To eliminate the condensate and avoid wetting pedestrian areas, a condensation collection basin and a drain channel should be available under the unit. Be sure that drain water in the drain channel does not freeze, causing blockage by ice accumulation. An anti-freeze electric resistance should prevent the ice from forming inside the tray.

3.5. Aeraulic connections (air source heat pump case)

Indoor air source heat pump can get the energy from the air directly from the room where the unit is installed or from external air through an air duct system. Figure 19 represents some examples of heat pump aeraulic connections. In Figure 19A, the heat pump exchanges thermal energy directly with the indoor environment. In this way the temperature of the inlet air is higher than the external temperature. On the other side, the outlet air will reduce the ambient temperature. In Figure 19B, there is an air duct system that takes and returns air to the external environment. In Figure 19C, the heat pump takes the air from the room and returns it to the external environment through an air duct. In this case, an air vent shall be installed in the room where the heat pump is installed to avoid a decrease of the ambient pressure.

If there is an air duct system, it is important to protect air ducts to prevent accidental intrusion of materials inside the unit, but do not use external grills with high pressure drop. The grills used should guarantee a good air flow.

Moreover, the distance between inlet and outlet ducts should respect the recommendation of the manufacturer to avoid the recirculation of air between the two ducts.

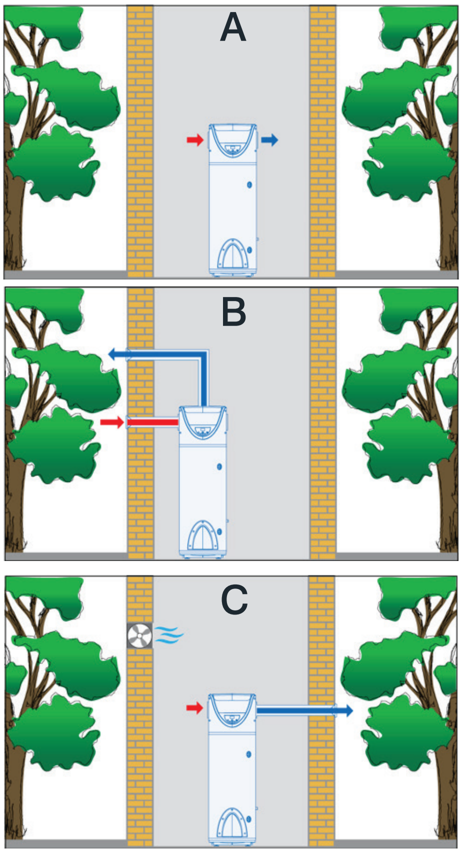


Figure 19. Example of aeraulic connections for indoor air source heat pump. A shows no aeraulic connections, the heat pump exchanges thermal energy directly with the indoor environment; B shows an air duct system that takes and returns air to the external environment, C shows the heat pump taking air from the room and returning it to the external environment through an air duct. Reprinted from Product Guide of Heat Pump Water Heaters (p. 36), by Ariston Thermo Group, 2018

3.6. Additional regulation components

The heat pump can be provided with an external temperature sensor that enables compensation of the hot water set point in winter mode with respect to the variation of outdoor ambient temperature. This probe shall be installed outside, away from sources of heat and from the heat pump external unit, not exposed to the direct radiation.

Some heat pumps are provided with a water temperature sensor, to be installed into the inlet pipe, which can be used to stop the pump during periods of stand-by, when the water temperature reaches the set point. When the probe is installed the power consumption of the unit is strongly reduced.

For space heating heat pump systems, a room thermostat can be connected to the unit. The thermostat must be placed away from sources of heat (e.g., radiators and direct exposure to sunlight) as well as from drafts or openings to the outside, both of which may affect the proper control of the system.

For domestic heat pump systems with integrated storage, an anti-Legionella system is needed to prevent the growth of Legionella bacteria. The conditions for Legionella growth are: water temperature between 25 °C and 50 °C and stagnant water. To prevent Legionella growth, the unit has to perform thermal disinfection cycles, that increase and keep the temperature of the stored water to the thermal shock temperature (65–70 °C) for a preset time.

The anti-Legionella function cannot be enabled by default. Enabling the function is strongly recommended.

3.7. Refrigerant charge

The refrigerant charge should be carried out by qualified technical personnel. For first installations, the refrigerant charge on-site is required only for heat pump systems composed of external and internal units.

Monoblock heat pump units are provided by the manufacturer already charged. However, in case of failures (e.g., gas leakage), the evacuation and recharging of the refrigerant could be required.

In general, given the high GWP of many refrigerants, it is really important to carefully carry out this operation to avoid leakage of refrigerant into the atmosphere. If any refrigerant gas leaks while working on the unit, it is important to ventilate the room thoroughly.

3.7.1. Procedure and tools

The procedure for the refrigerant charge consists of the following steps:

1. Installing the refrigerant pipes between the external and internal units, according to the manufacturer recommendations (e.g., maximum length of refrigerant pipes).

2. Testing for leakage test by pressurizing the refrigerant circuit with nitrogen at the nominal pressure declared by the manufacturer and watching the pressure gauge for any drop-off in pressure. This phase should last as long as possible, up to one day, to be sure there is no refrigerant leakage. At the end, nitrogen can be evacuated into the atmosphere.

3. Discharging the circuit through a vacuum pump, to remove impurities and assure that the refrigerant is not contaminated by other substances. Absolute pressure inside the circuit should reach approximately 0.01 bar.

For new installations, this phase can last about 40 minutes; for existing refrigerant pipes, it should last as long as possible (up to one day), to evaporate all the oil and impurities.

4. Charging the refrigerant, already present in the external unit, to the internal one.

5. If the refrigerant piping length exceeds the maximum length declared by the manufacturer, determining the additional amount of refrigerant to be charged.

6. Within one month from the refrigerant charge, verifying if there are refrigerant leakages, through electronic leak detector, is suggested.

Figure 20 shows the tools needed to complete a refrigerant charge.

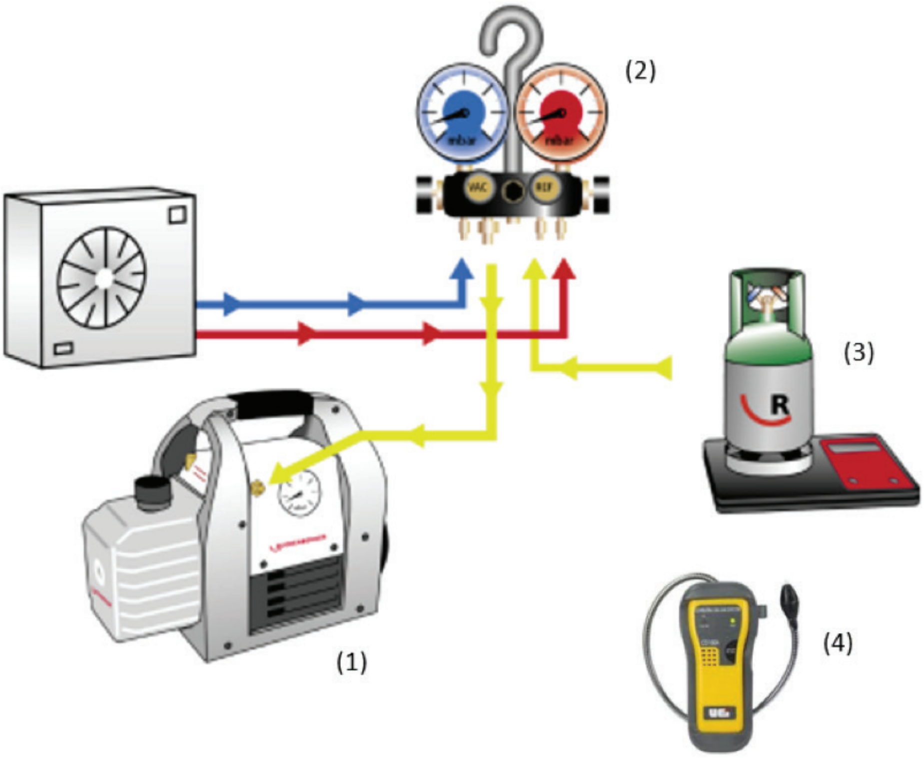


Figure 20. Required tools for heat pump refrigerant charge. (1) = a vacuum pump; (2) = pressure gauges, for low and high pressures; (3) electronic scale to measure the required amount of refrigerant (where additional charge is required); (4) = electronic leak detector. Flexible pipes are also needed

3.7.2. Safety considerations

It is strictly forbidden to discharge refrigerant into the atmosphere, in case of evacuation of the refrigerant circuit, the refrigerant should always be recovered into an appropriate gas tank, through a refrigerant recovery unit, which integrates a filter-drier to reduce contaminants (e.g., oil and moisture) inside the refrigerant.

During normal heat pump running cycles, the refrigerant, by flowing inside the compressor, may get mixed with compressor oil. Thus, during the refrigerant evacuation, also a small ratio of compressor oil is removed. Usually the compressor is provided with enough oil, therefore, the refrigerant technician shall not fill it up with additional oil. In any case, operations on compressor will be carried out by technician in charge of the heat pump ordinary maintenance.

Contaminated refrigerants (e.g., refrigerant coming from a system that has suffered a compressor burn-out) cannot be reused directly after recovery. In this case, the refrigerant shall be reclaimed by specialized centers, which process used refrigerant to new product specifications and verify by chemical analysis that new product specifications have been met.

3.8. System water filling (for hydronic heat pump system)

Once all the connections are completed in the hydronic heat pump system, the hydraulic circuits should be filled with water as follows:

1. Carefully wash the system with clean water by filling and draining the system several times.

2. Check and clean the filter on the inlet pipe.

3. Fill the circuit with water until the manometer indicates the pressure declared in the heat pump datasheet.

4. Determine if there are water leaks.

5. Remove air in the circuit as much as possible using the air purge valves; air present in the water circuit might cause malfunctioning.

6. Cover the pipes with insulation to avoid heat dispersions and formation of condensate.

3.9. Start-up and configuration of system settings

Once the installation of the heat pump system has been completed, the heat pump control parameters shall be set for each specific use of the system (e.g., space heating and DHW).

3.9.1. Heat pump used for space heating

The heat pump supply temperature has to be set, according to the specific heating device (referring to the technical requirements of the specific heating device installed on site).

If there is an external temperature probe sensor, that enables compensation of the hot water set point with respect to the variation of ambient temperature, the limit operating parameters of the climatic curve have to be set, according to the operating temperature range of the specific heating device (e.g., radiator, floor heating) (see Figure 21).

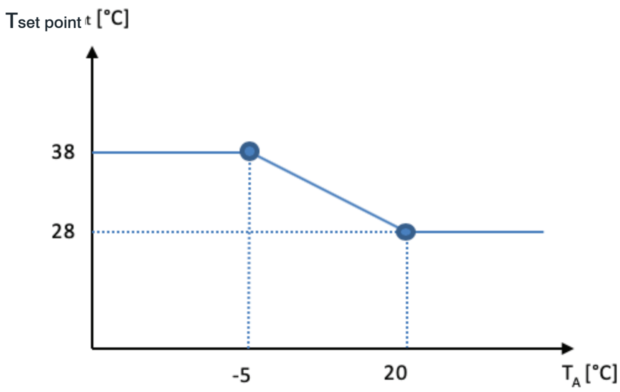


Figure 21. Example of supply temperature regulation according to external temperature, for a heating floor system. T_A = ambient temperature; $T_{set\ point}$ = required supply temperature

The thermostat has to be set, in terms of time schedule and temperature set points (the main one and the set-back value).

If the heat pump is integrated with an auxiliary generation system, the control strategy for the activation of the heat pump and auxiliary system shall be set; for example, the external temperature under which the back-up heating system is enabled.

3.9.2. Heat pump used for domestic hot water

The DHW set-point temperature has to be set (usually around 55 °C). For a heat pump with integrated storage, it is strongly recommended to enable the anti-Legionella function.

3.10. Acceptance and commissioning

At the initial start of the heat pump system, it is important to assure that it is working properly. The main checks are covered here. In any case, installers shall follow the instructions provided by the heat pump manufacturer inside the installation manual.

3.10.1. Heat pump installation

Ensure there are no damaged heat pump components, there is no gas leakage, and there are no strong vibrations.

For air source heat pumps, ensure the ventilation is good, there are no obstacles in front of the air intake and outlet, and the condensing discharge is properly installed.

3.10.2. Hydraulic circuit installation (for hydronic heat pump systems)

For hydronic heat pump systems, ensure the water pipes are fastened, there is no water leakage, and the water pipes have been insulated properly.

3.10.3. Wiring system installation

Ensure the power cable size is correct and it is connected to the earth line.
Ensure controller and sensor cables are separated from the power cables.

3.10.4. Controller

Ensure there is no error code on the controller display.
Ensure all controller buttons are working properly.

3.10.5. Regulation components

Ensure the external temperature sensor (if present) is located in the correct position (e.g., far from heat source or direct solar radiation).

Ensure the thermostat is located in the correct position (e.g., far from heat source or direct solar radiation).

3.10.6. Acoustic check

Ensure the noise level is within the range allowed by the Ministry of Environment, as specified previously in Table 7.

3.11. Troubleshooting and maintenance

3.11.1. Compressor

One of the most vulnerable parts of a vapor compression heat pump is the compressor. A common sign of compressor-related problems is noise coming from the compressor. Abnormal pressure readings may also signify that there is something wrong with the compressor. Heat pumps usually record pressure readings, especially for compressor output and input. Check if the input and output pressure measurements correspond to the values from the technical datasheet.

3.11.2. Refrigerant circuit

If the heat pump performance gets worse (e.g., heat pump cannot heat up to the set-point temperature), there could be a refrigerant leakage. There are indirect and direct methods to determine if there is a leak: (a) by checking the operating parameters on the refrigerant circuit (pressures and outlet temperatures from condenser and evaporator) to see if they meet manufacturer requirements, (b) by using an electronic gas leak detector, or (c) by applying a soapy water solution on the suspected leakage point. In any case, ordinary maintenance activities should include a refrigerant leakage test, especially for large heat pump systems with a significant amount of refrigerant characterized with a high GWP.

Note: It is strictly forbidden to discharge refrigerant into the atmosphere, because of its high GWP. In case of evacuation of the refrigerant system, the refrigerant should always be recovered into an appropriate gas tank.

3.11.3. Heat exchanger

Ensure the heat exchanger on the water side is free of dirt and incrustations to allow the optimal thermal exchange. If the appliance is provided with temperature sensors on board, check the difference between the temperature of the supply water and the condensation temperature; if the difference is over the value specified by the manufacturer (5–7 °C), it is advisable to clean the exchanger. Dirt or scale can give rise to clogging in the condensate discharge. Also, microorganisms and mold can flourish inside it. It is necessary to clean it periodically with suitable detergents.

3.11.4. Fan and ventilation grill (for an air source heat pump)

To assure that the evaporator in an air source heat pump gives the maximum thermal exchange, the front grill must be cleaned from dust and deposits. The deposits on the front grill could damage the air fan installed behind it; damage of the air fan may lead to heat pump stop.

3.11.5. Condensate discharge (for an air source heat pump)

For an air source heat pump, it is important to ensure the condensate discharge is clean and the water inside it is not frozen.

3.11.6. Hydraulic circuit (for hydronic heat pump systems)

For hydronic heat pump systems, the water piping may have some air inside; to avoid the air affecting the water flow rate, the air should be discharged regularly from the water. To assure proper heat pump operation, the pressure on the hydronic circuit shall satisfy the design value. If the pressure inside the circuit is lower than the design value, check the existence of impurities in the water filter, which prevent the correct passage of water. Moreover, check if there are leakages from valves or other components. It is also important to check and, if necessary, restore the air pressure inside of the expansion vessel.

4. MONITORING SYSTEMS

4.1. Purpose of monitoring

The purposes of the monitoring system are to quantify the real energy consumption of the system, to evaluate the heat pump efficiency in the field (considering COP as main performance indicator), to be aware of the real operating conditions, and to investigate the reasons for good or bad efficiency of the system. The required measurements are summarized below:

- Energy consumption of the heat pump
- Thermal energy output of the heat pump
- Heat pump supply and return temperatures
- Temperature and relative humidity for indoor and outdoor conditions

For complex system configurations (e.g., two or more heat pumps, integration of auxiliary generation systems, or integration with a buffer tank) or heat pump capacity higher than 20 kW, additional measurements are suggested:

- Energy consumption of the auxiliary generation system (if present)
- If the heat pump system covers space heating and DHW needs, thermal energy output, related supply and return temperatures, and water flow for each use
- Energy consumption of the auxiliaries (e.g., circulation pumps)
- Thermal energy after the buffer tank (if present), and related supply and return temperatures and water flow
- If present, temperature inside the buffer tank

4.2. Sensors and monitoring system architecture

4.2.1. Measurement instruments

The instruments used to monitor and measure heat pump performance include (a) heat meters, (b) electrical energy meters, (c) ambient relative humidity sensors, and (d) temperature sensors. Before selecting the set of measurement sensors, it is important to define their requirements as: the operating range of the variables to be measured, the measurement accuracy for each variable, the sample time, and the data resolution.

Heat meters

A heat meter (see Figure 22) measures thermal energy, by measuring the water flow rate and the change in temperature (Δ T) between the outflow and return pipes of the circuit. Usually the measured data outputs include (a) incremental thermal energy, (b) incremental water volume, (c) average values on the timestep of flow, and (d) return temperatures, ΔT.

Figure 22. Heat meter composition

A heat meter is composed of:

- a water flow meter;
- a couple of temperature sensors (e.g., thermoresistance, thermocouple,..) to measure the temperature difference between the outflow and the inflow;
- a computer for integrating the two measurements over a period of time and accumulating the total heat transfer in a given period.
- There are different types of flow meter technologies: ultrasonic, electromagnetic, volumetric, turbine, vortex, differential pressure, etc.

The main criteria to consider when choosing the most suitable flow meter technology for an application are:

- range of flow rate (e.g., vortex flow meter is not suitable for low flow rate)
- measurement accuracy
- pressure drop
- fast response to flow rate variation
- resistance to suspended solid particles (e.g., impurities that could be present inside the technical water)

One of the most common flow meter technologies in residential applications is the ultrasonic flow meter, which can have good accuracy, does not introduce relevant pressure drop, and can measure a wide range of flow rates. Also, mechanical flow meters can be used, as volumetric or turbine type; they are usually less expensive, but they introduce higher pressure drops and can be damaged by impurities in water.

Temperature sensor

To measure a single temperature, for example inside a thermal storage, a temperature sensor, as thermoresistance or thermocouple, can be installed. Usually thermal storage units are already provided with wells at different heights, in which the temperature sensor can be placed.

Electrical energy meter

An electrical energy meter measures the heat pump's electrical consumption in terms of incremental energy and average power on the timestep (e.g., of the heat pump, auxiliary generation system, and circulation pumps). Usually, the electrical energy meter needs to be coupled with a transformer, to reduce the input current to the meter. In this case, it is important to choose a transformer with the same accuracy of the electrical energy meter.

Ambient relative humidity and temperature sensor (indoor/outdoor)

These sensors can measure temperature and relative humidity of the ambient air. The outdoor sensors are designed to resist to weather conditions.

4.2.2. Monitoring system architecture

All the monitoring sensors shall be connected to an acquisition system for data collection. The measured data can be collected on a computer installed on site or can be sent to a remote server or a cloud server through internet connection (see Figure 23).

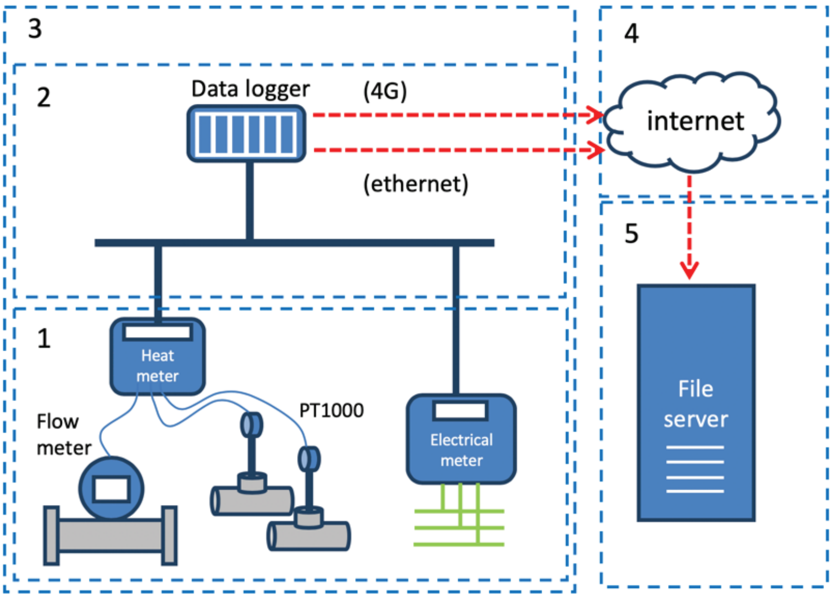


Figure 23. Architecture of the monitoring system. 1 = instrumentation; 2 = data logger; 3 =measurement system; 4 = internet connection; 5 = server

Some heat pump manufacturers offer monitoring integrated solutions, comprehensive of the set of measuring sensors (some of them could be already available on-board), data acquisition system and data elaboration and visualization service. Figure 24 shows a schematic of communication between a monitoring system on site and a data server.

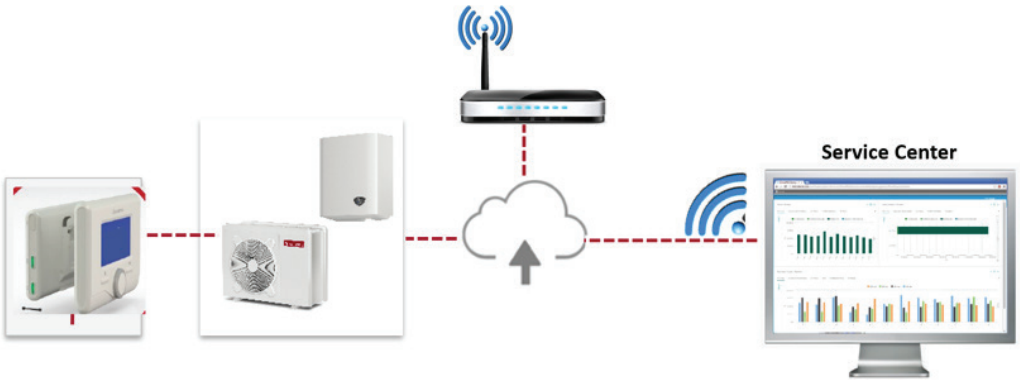


Figure 24. Example of communication scheme between monitoring system on site and data server and visualization system

4.3. Monitoring system reference schemes

Figure 25, Figure 26 and Figure 27 represent reference schemes of monitoring system components, for different heat pump system configurations.

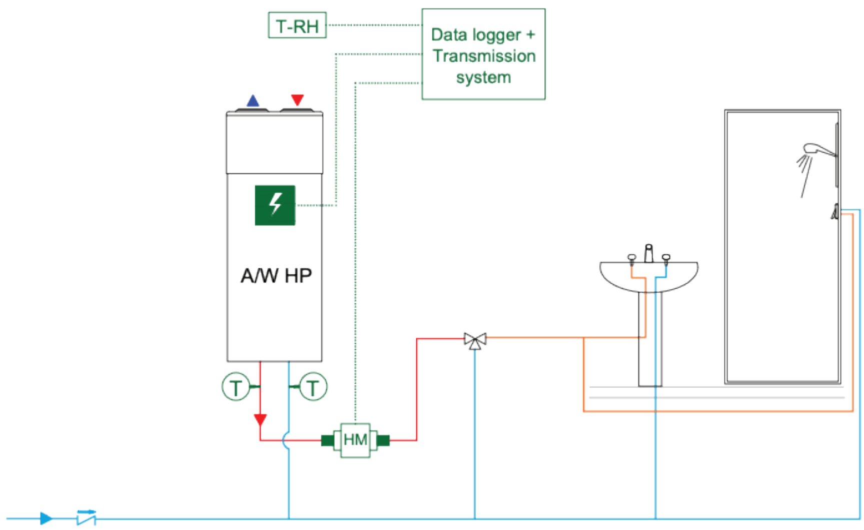


Figure 25. Example of monitoring scheme for a domestic hot water system. A/W HP = air-to-water heat pump; T= thermoresistance for water temperature; T-RH= ambient temperature and relative humidity sensors; HM= water flow meter with integrated heat meter

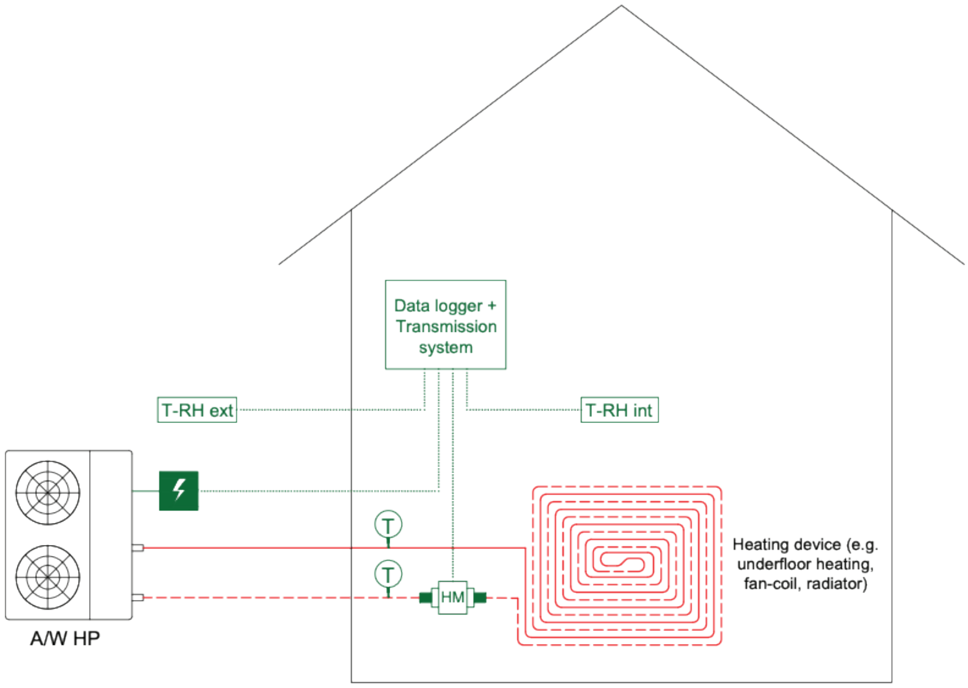


Figure 26. Example of monitoring scheme for space heating. A/W HP = air-to- water heat pump; T= thermoresistance for water temperature; T-RH= ambient temperature and relative humidity sensors; HM= water flow meter with integrated heat meter

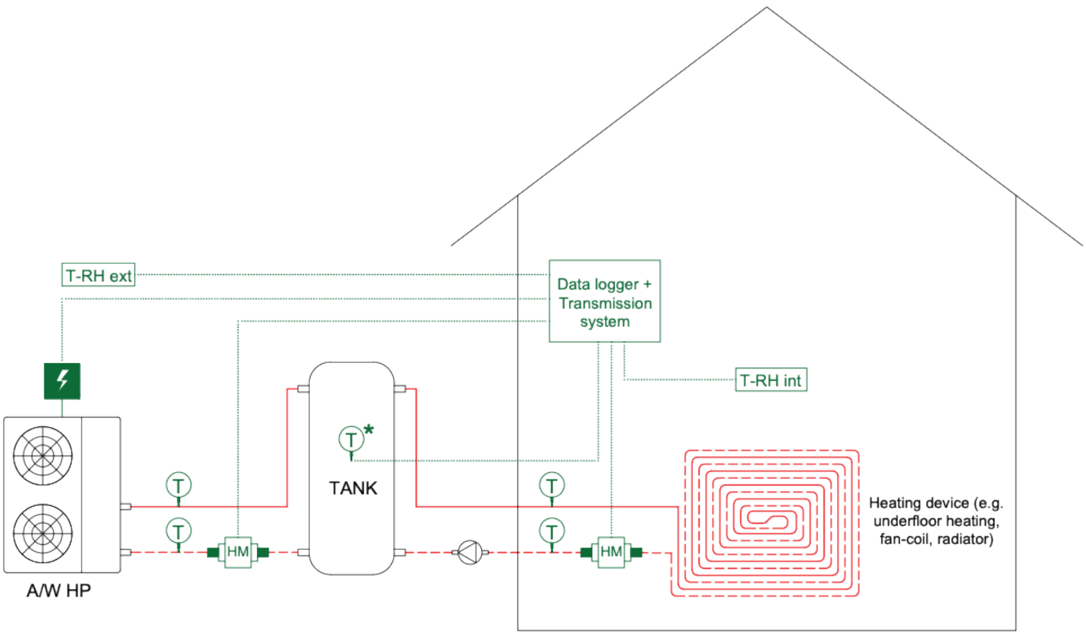


*Figure 27. Example of monitoring scheme for space heating with thermal buffer (tank). * = roughly 1 temperature sensor every 500 liters (e.g., for a volume of 1000 liters, 2 temperature sensors have to be installed at different heights, to characterize the temperature levels inside the buffer tank); A/W HP = air-to-water heat pump; T= thermoresistance for water temperature; T-RH= ambient temperature and relative humidity sensors; HM= water flow meter with integrated heat meter*

4.4. Data collection and post-processing

Once the monitoring system has been activated, the collected monitoring data need to be post-processed, according to the following steps:

1. Perform the preliminary conversion operation (e.g., conversion from sensor output signal, as impulse, current, resistance, to the desired measurement unit for each measured variable).

2. Resample for the desired timestep. Usually the output data are not all measured exactly at the same instant or with the same sample time, thus it is necessary to resample data to the same time index.

3. Validate data; define the validity range and exclude data that are out of range.

4. Process data; calculate performance indicators, as heat pump COP, and aggregate data for different time periods (e.g., daily, weekly, monthly, and seasonal) for: total energy consumption, total energy needs, energy needs for space heating, energy needs for DHW, average outdoor and indoor ambient temperature, average heat pump supply temperature, etc.

5. Visualize data.

4.5. Installation recommendations

To guarantee reliable measurements, it is very important to follow some suggestions for the proper installation of sensors.

4.5.1. General indications

In general, to ensure proper installation of sensors, technicians should:

- Clean the system by removing dirt and residuals from pipes before and after installation of the sensors.

- Clean the filters after the installations.

- Check for leakage from valves.

4.5.2. Flow meters

Flow meters that introduce low pressure drop (e.g., an ultrasonic flow meter) should be used. Since electromagnetic flow meters can attract iron particles present in fluid (e.g., water) and can settle on the electrodes and reduce the measuring sensitivity of the instrument, it is best to avoid their use in old systems with iron pipes.

To further ensure that flow meter sensors are installed properly, the following actions are recommended:

- Install the flow meter in the direction of the water flow (according to the arrow on the instrument).

- Install the flow meter on a straight pipe, according to the specific installation requirement of the sensor, without other devices installed upstream and downstream of it (to not disturb the flow and improve the accuracy of measurement) (see Figure 28).

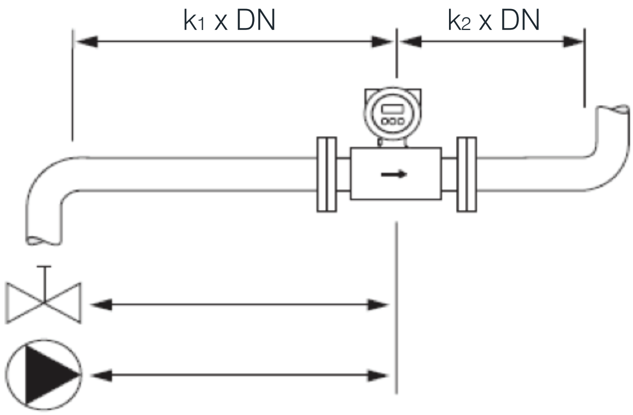


Figure 28. Example of recommended location for flow meter installation. DN = nominal diameter; k = coefficient of correction depending on the type of the flow meter

- Use a flow meter with a diameter smaller than that of the pipe on which it is installed, in order to increase the velocity of the flow and gain a higher sensor's accuracy. In this case provide a conical reduction, before and after the straight pipe length, the straight length shall be defined using the manufacturers' recommendations (see Figure 29).

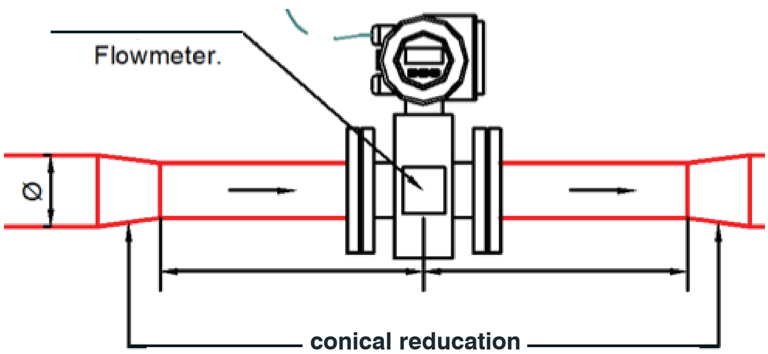


Figure 29. Example of using conical reduction to increase flow velocity

- Install the flow meter on the return circuit, to avoid high temperature stress.
- Install air vent valves in the circuit to avoid measurement errors due to entrained air or gas bubble formation in the measuring tube.
- Do not install the flow meter on a vertical pipe with flow going down (see Figure 30).

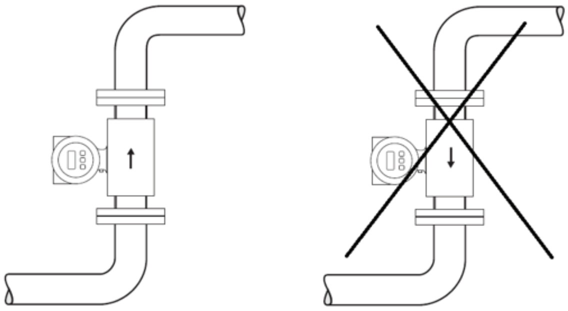


Figure 30. Recommendation for installing a flow meter on a vertical pipe

- Do not install the flow meter at the highest point of a pipeline to avoid the risk of air accumulating air in the instrument (see Figure 31).

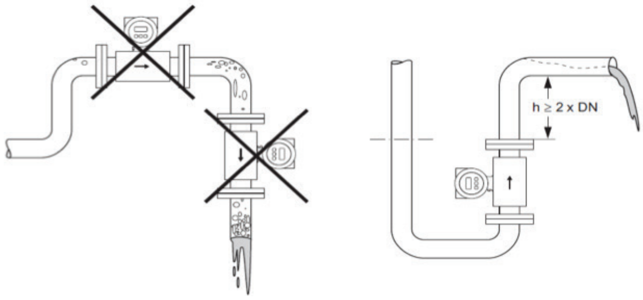


Figure 31. Recommendation on the best position to install a flow meter

- Install the flow meter downstream of the circulation pump to avoid low pressure conditions that could damage the meter (see Figure 32).

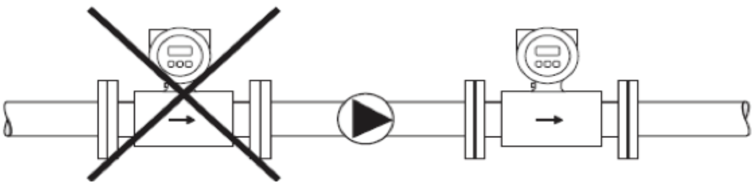


Figure 32. Recommendation on the best position to install a flow meter relative to the pump

- To protect the flow meter against vibrations, do not install it on a suspended section of the pipe that is too long (see Figure 33).

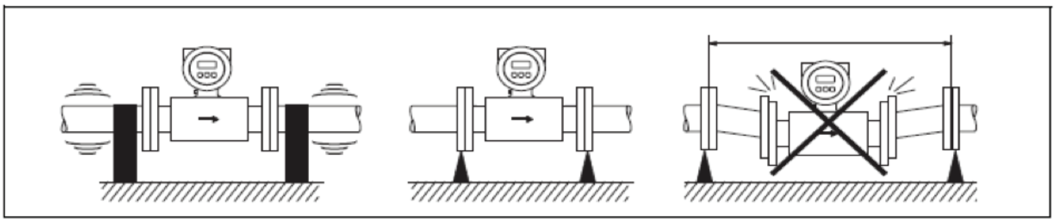


Figure 33. Recommendation for installing a flow meter on a suspended section of a pipe

4.5.3. Temperature sensors

To ensure that temperature sensors are installed properly, the following actions are recommended:

- Calibrate, in pairs, the two heat meter sensors to be installed on flow and return pipes of the same circuit to guarantee the measurement accuracy on the temperature difference. It is important to not mix them up with other sensor couples.
- Install the sensors in the same way (e.g., same depth in the pipe), to have comparable measurements.
- Install the sensors far from intersection with other pipes.
- Do not install sensors on pipe sections that contain stagnant water.
- The best position is in a curve and in counter flow or tilted at 45° (see Figure 34).

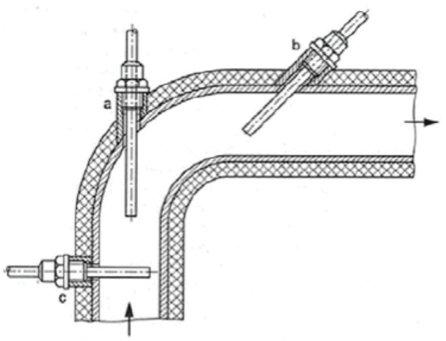


Figure 34. Recommendations for proper installation of temperature sensors

4.5.4. Electrical wiring

To ensure that wiring supports proper functioning of sensors, the following actions are recommended:

- Install cables that transmit data farther than 50 mm from power cables or shield them.
- Ensure cables between sensors and data loggers are continuous without junctions.

4.5.5. Ambient temperature and relative humidity sensors

To ensure that ambient temperature and relative humidity sensors function properly, the following actions are recommended:

- Install the sensors far from heat sources (e.g., exhaust pipes).
- For outdoor installation, install sensors specifically designed to resist weather conditions (e.g., water resistant).
- For outdoor installation, install sensors on the north side of the structure to avoid direct solar radiation.
- For outdoor installation, mount a weather guard on the sensor to protect it from the solar radiation and other atmospheric agents.

4.6. Commissioning the monitoring system

After the installation, it is necessary to verify the reliability of the collected data.

A first check shall be done just after installing the monitoring system to assure that each sensor is measuring the wanted physical quantity. This control consists of verifying that the collected data are understandable, for example: (a) to check if the flow and return temperature sensors are not twisted, (b) if the flow meter is installed in the direction of flow, or (c) if correspondence between input and output energies of the heat pump occurs.

After the initial check, a continuous validation procedure shall be set and applied on all monitored quantities, to determine, for example, whether:

- Data is missing
- Measured values are inside the validity range previously fixed for each specific quantity
- There is electric consumption of the circulation pump when there is flow
- The energy balance among output and input energies is verified.

Once data have been validated, performance indicators can be calculated and possible faults detected.

ANNEX A - BALANCING THE HYDRAULIC CIRCUIT

The main principles for hydraulic circuit balancing are presented here and are based on the guidelines about design principles of hydronic heating systems provided by Doninelli (1993).

Hydraulic circuit balancing is one of the most challenging aspects in hydronic system design, especially for systems with an extensive network. Balanced circuits are defined as those circuits that are capable of supplying their emitters with the flow rate required by design specification. The design and installation of balanced circuits is used:

- To ensure the correct performance of the emitters
- To prevent excessive water velocities, which can cause noise and abrasion
- To prevent circulating pumps from operating under low efficiency conditions, leading to overheating
- To limit the value of the differential pressures acting on the regulating valves, thus, preventing damage

For medium and small systems with a constant flow rate, proper sizing of the pipework will normally be adequate to ensure that the circuits are balanced.

Figure 35 shows an example of a hydraulic circuit, where circuit A and circuit B are two different branches of the same hydraulic network, which flow into node 1. In this node, the circuits have the same differential pressure. Usually, to size the circulation pump, the design differential pressure is chosen according to the circuit with the highest pressure drop, in this case circuit A, but also other values can be assumed. Different types of balancing are available, as detailed below:

- Balancing according to the highest pressure drop circuit, which guarantees good performance of emitters, but leads to excessive velocity inside circuits with lower pressure drop
- Balancing according to the lowest pressure drop circuit, which prevents high velocity flows, but the performance of heating devices on highest pressure drop circuit can decrease
- Balancing according to the average pressure drop, which can be a good compromise in the case of a small hydraulic circuit, where the pressure drops on circuits are quite similar

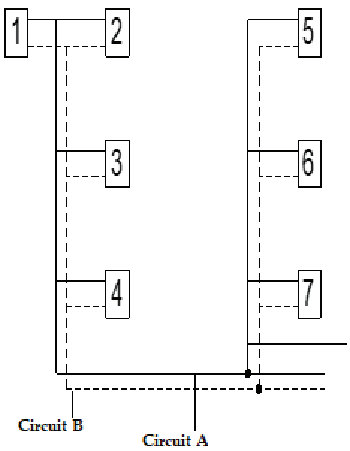


Figure 35. Example of hydraulic circuits, with higher and lower pressure drop branches. A hydraulic circuit, where circuit A and circuit B are two different branches of the same hydraulic network that flow into node 1. Circuit A = higher pressure drop branch; Circuit B = lower pressure drop branch

The degree of imbalance of flow rates through circuits depends on the number of branches served:

- If the number of branches is small, the differences between the required flow rates and the actual rates are generally within acceptable margins.
- If the number of branches is large, the imbalances in the flow rates can be considerable.

For systems with extensive networks or with variable flow rates, it is necessary to include equipment capable of regulating water flow. Three types of suitable equipment are listed below:

- Balancing valves can adjust the flow of water when there is a pressure drop. In this way it is possible to regulate the flow passing through the branches on which they are located. Each device needs to be calibrated, according to the specific pressure drop to be compensated. It is a static regulation, thus, it cannot be automatically adapted to new operating conditions.
- Auto flow regulators are valves capable of maintaining automatically a constant rate of water flow through the branches on which they are located. The advantage is that, in case of changing on the system configuration, the circuits can easily be adapted to the new operating conditions, since auto flow regulators are capable of maintaining constant flow rates at the emitters over a wide range of differential pressures.
- Automatic bypass valves are used to control water flowing into a bypass by means of differential pressure. A bypass may be necessary to prevent the differential pressure across a circuit exceeding the design value. This may occur when a number of emitters or a branch circuit shuts down.

Reference applications of balancing devices are shown in Figure 36, Figure 37, Figure 38, Figure 39, and Figure 40. Figure 36 shows a circuit with auto flow valves at the bottom of each branch. Auto flow regulators provide the required flow rates at the risers. Imbalances in flow rate distribution can however occur along the risers. For this reason, these circuits are normally used in buildings with no more than five or six floors. Additional information and practical examples can be found in the extended documentation provided in Doninelli (1993).

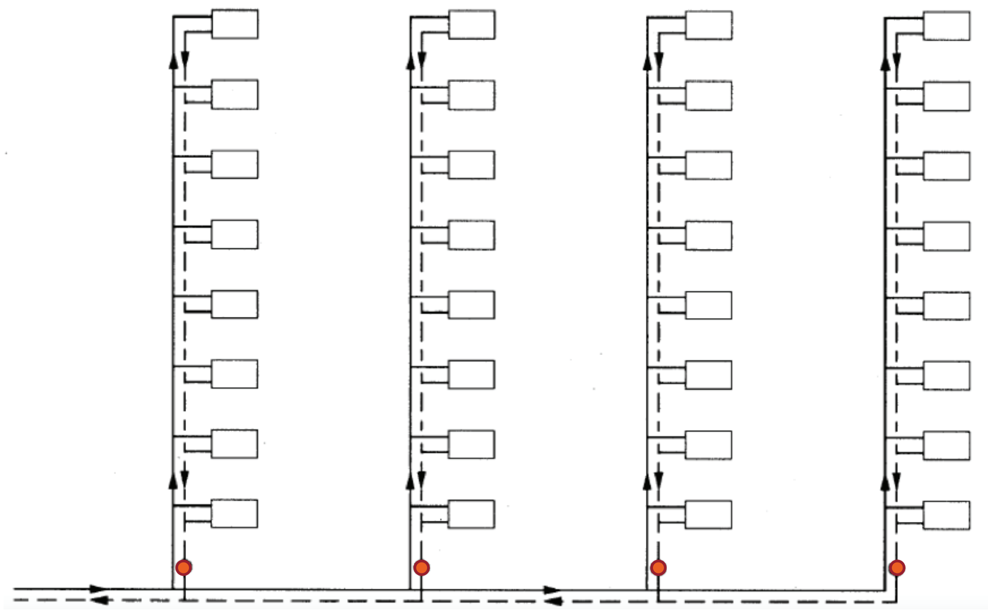


Figure 36. Hydraulic circuit with auto flow valves at the bottom of each riser. Reprinted from Design principles of hydronic heating systems (p54), by M. Doninelli, 1993, Gavirate, Varese, Italy: Handbooks Caleffi

Figure 37 shows a circuit with auto flow valves at each terminal. These circuits are capable of guaranteeing the required water flow through each emitter. In circuits using three-way valves, the flow rate or temperature of the fluid passing through the emitters can be varied by the action of the automatic three-way valves. The closing of valves, e.g. at the opening of their bypasses when the emitter is switched off, may determine changing of differential pressure distribution. For this reason, it is required to install balancing devices. For example, for zone systems it is always necessary to balance the bypasses of the valves (e.g., with valves or auto flow regulators). If this balancing is not carried out, then even a limited number of closed valves may reduce water flow through some heat emitters, still with their valves in the open position, because of the relatively low pressure drop through the uncalibrated open bypasses.

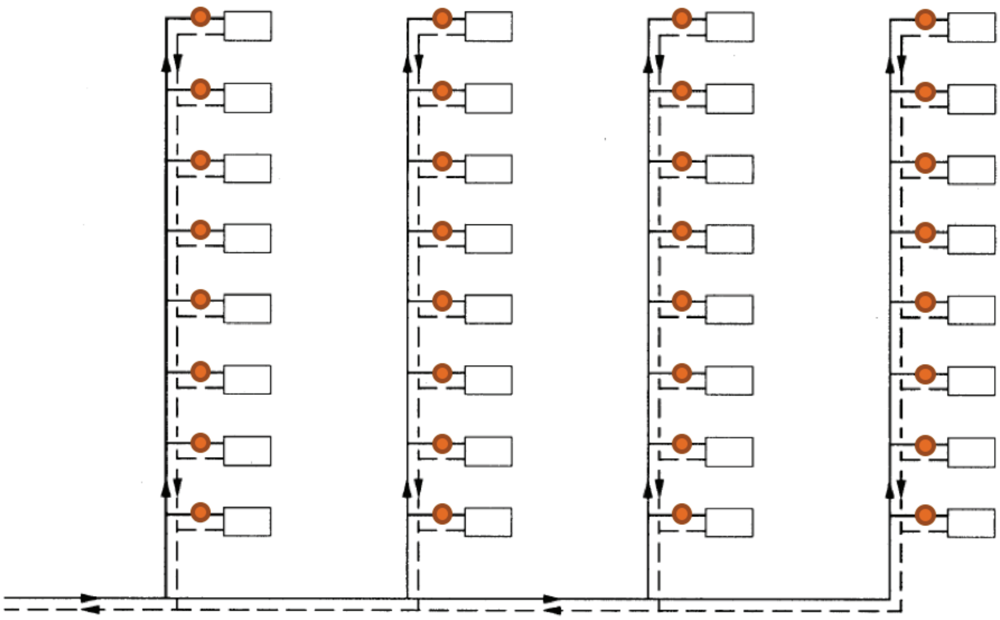


Figure 37. Hydraulic circuit with auto flow valves at each terminal. Reprinted from Design principles of hydronic heating systems (p. 55), by M. Doninelli, 1993, Gavirate, Varese, Italy. Handbooks Caleffi

Figure 38 shows zone systems with three-way valves, balanced by balancing valves. The balancing valves (located on bypasses) must be calibrated in order to oppose the same pressure drop as the related zone circuit, when the three-way valve is closed.

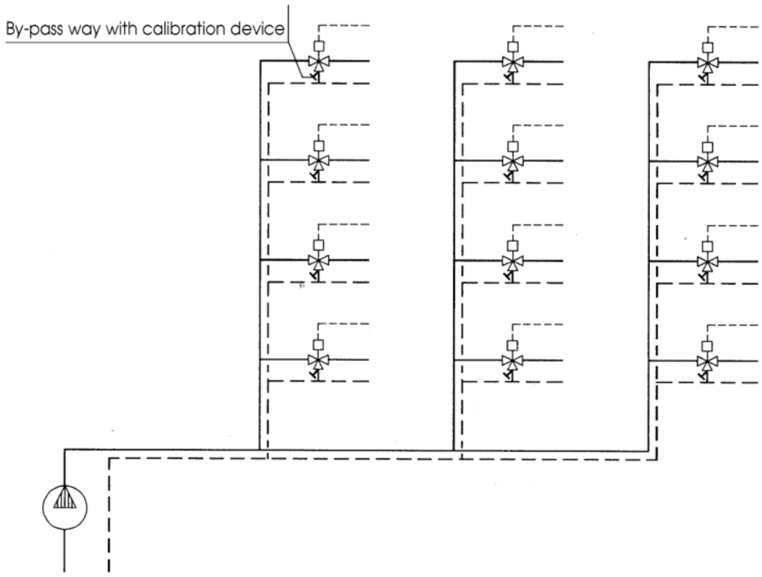


Figure 38. Scheme of hydraulic circuit with different heating zones with three-way valves, balanced by balancing valves. Reprinted from Design principles of hydronic heating systems (p. 59), by M. Doninelli, 1993, Gavirate, Varese, Italy. Handbooks Caleffi

Figure 39 shows zone systems balanced with auto flow valves. With auto flow devices, the flow rate of each zone can be kept at a constant level either with open valves or closed valves.

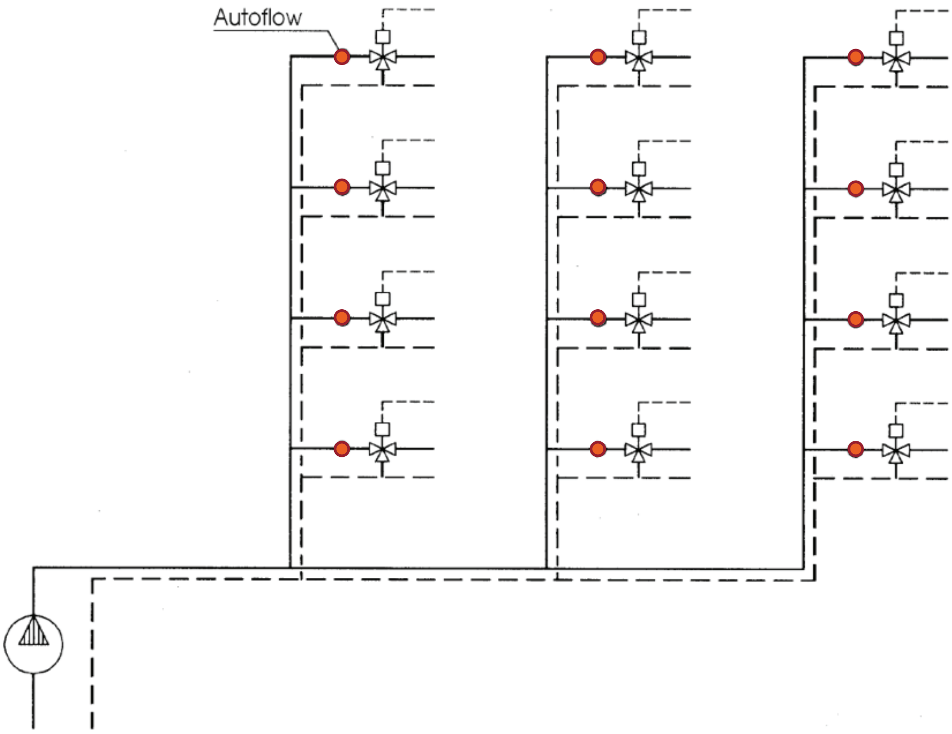


Figure 39. Hydraulic circuit with different heating zones with three-way valves, balanced by auto flow valves. Reprinted from Design principles of hydronic heating systems (p. 60), by M. Doninelli, 1993 , Gavirate, Varese, Italy.Handbooks Caleffi

Figure 40 shows an automatic bypass valve located at the base of the circuit.

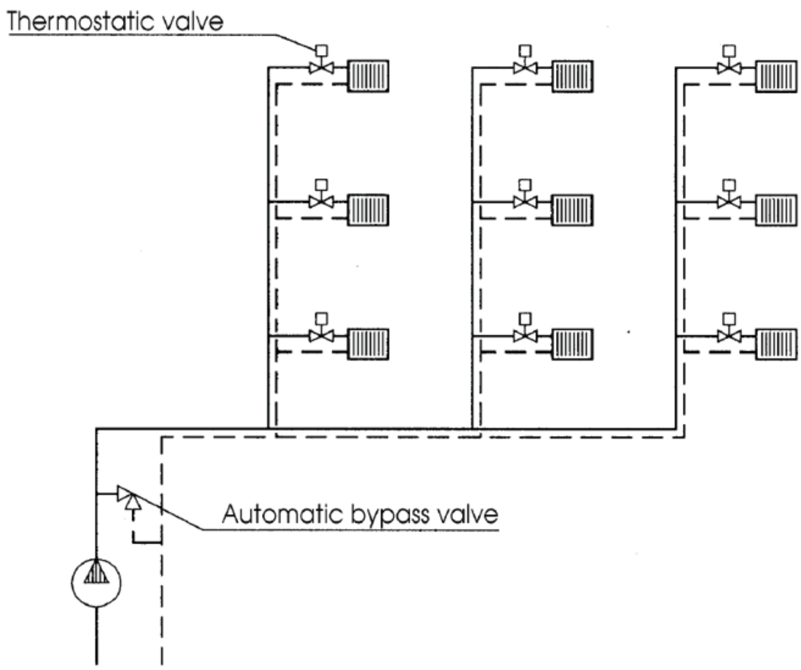


Figure 40. Hydraulic circuit with automatic bypass valve located at the base of the circuit. Reprinted from Design principles of hydronic heating systems (p. 68), by M. Doninelli, 1993, Gavirate, Varese, Italy. Handbooks Caleffi

For small systems, where there is no hydraulic separation between primary circuit, downstream of the generator, and distribution circuits, a bypass valve may be located at the base of the circuit to prevent from high pressure, which can occur when most or all valves of zone circuits are closed. It is recommended that the opening pressure of the bypass valve is approximately 10% greater than the differential pressures between the points of the circuit connected by the bypass when all valves are open.

ANNEX B - SAMPLE HEAT PUMP SYSTEM SCHEMES

Figure 41, Figure 42, Figure 43, Figure 44, Figure 45, Figure 46, and Figure 47 show different configurations of air-to-water heat pump systems.

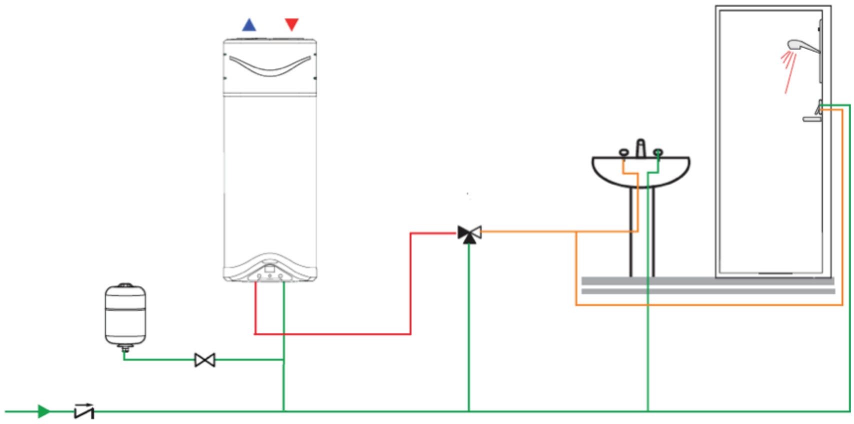


Figure 41. Indoor air-to-water heat pump with internal storage for domestic hot water. Reprinted from Ariston Thermo Group web site - Technical area

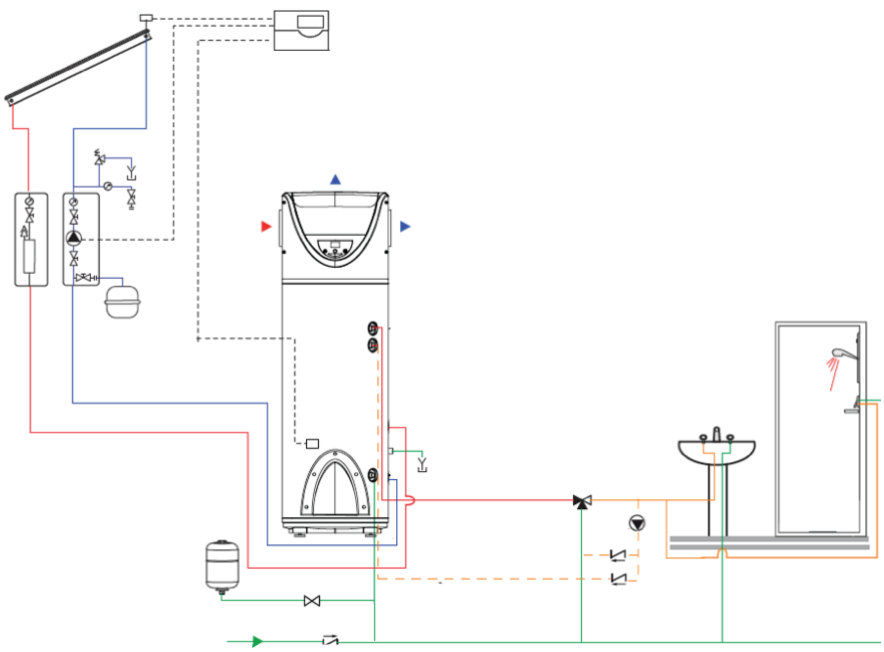


Figure 42. Indoor air-to-water heat pump with internal storage for domestic hot water with integration of solar water heating collector. Reprinted from Ariston Thermo Group web site - Technical area

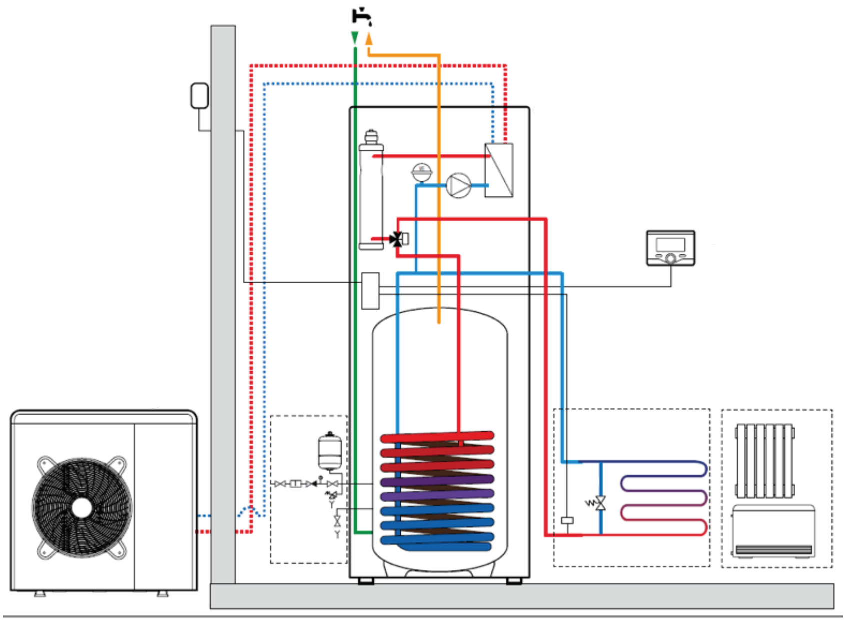


Figure 43. Air-to-water heat pumps with external and internal units and internal thermal storage for domestic hot water and space heating. Reprinted from Product Guide NIMBUS NET reversible air/water heat pumps (p. 55), by Ariston, 2018

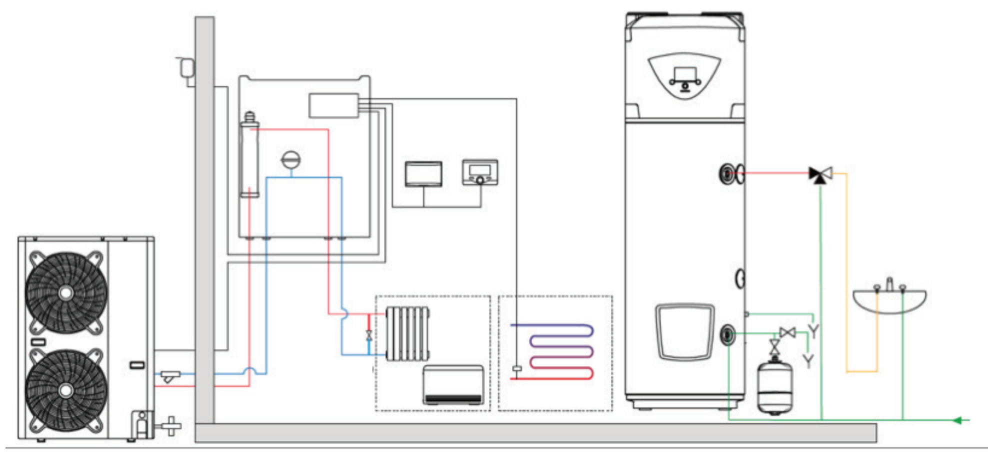


Figure 44. Air-to-water heat pump with external and internal units for space heating (high temperature zone and low temperature zone) and one indoor air-to-water heat pump for domestic hot water with internal thermal storage

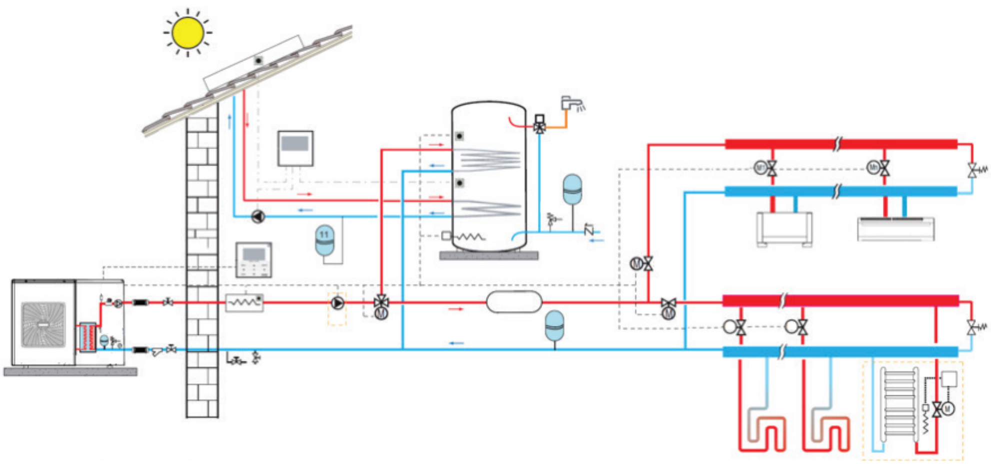


Figure 45. Air-to-water heat pump with external unit for space heating and domestic hot water and an external thermal storage for domestic hot water integrated with solar water heating collectors. Reprinted from Product Guide of RVL-I PLUS Heat Pump (p. 76), by Ferroli, 2018

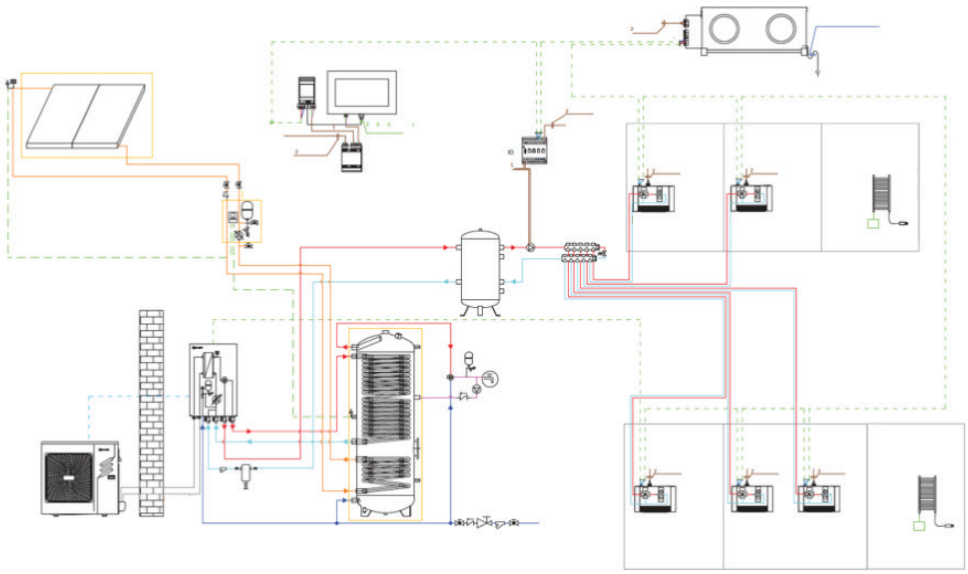


Figure 46. Air-to-water heat pumps with external and internal units for space heating, air conditioning and domestic hot water and an external thermal storage for domestic hot water integrated with solar water heating collectors. Reprinted from Product Guide: Sistemi residenziali autonomi in pompa di calore (p. 100), by Clivet, 2018

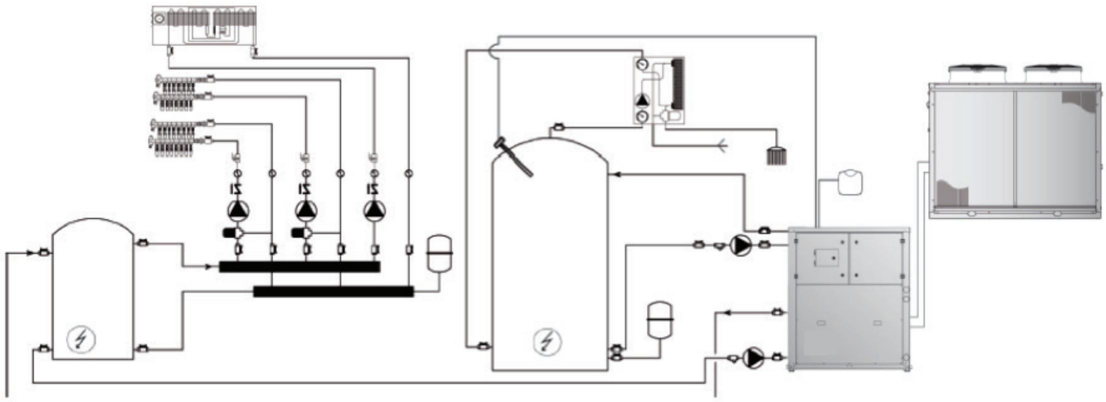


Figure 47. Air-to-water heat pumps with external and internal units for space heating, air conditioning and domestic hot water with two thermal storages (one for domestic hot water and one for and one for air conditioning system) and integration of electric heaters, one for each storage. Reprinted from Product Guide of WZT Heat Pump (p. 38), by HIdROS, 2018

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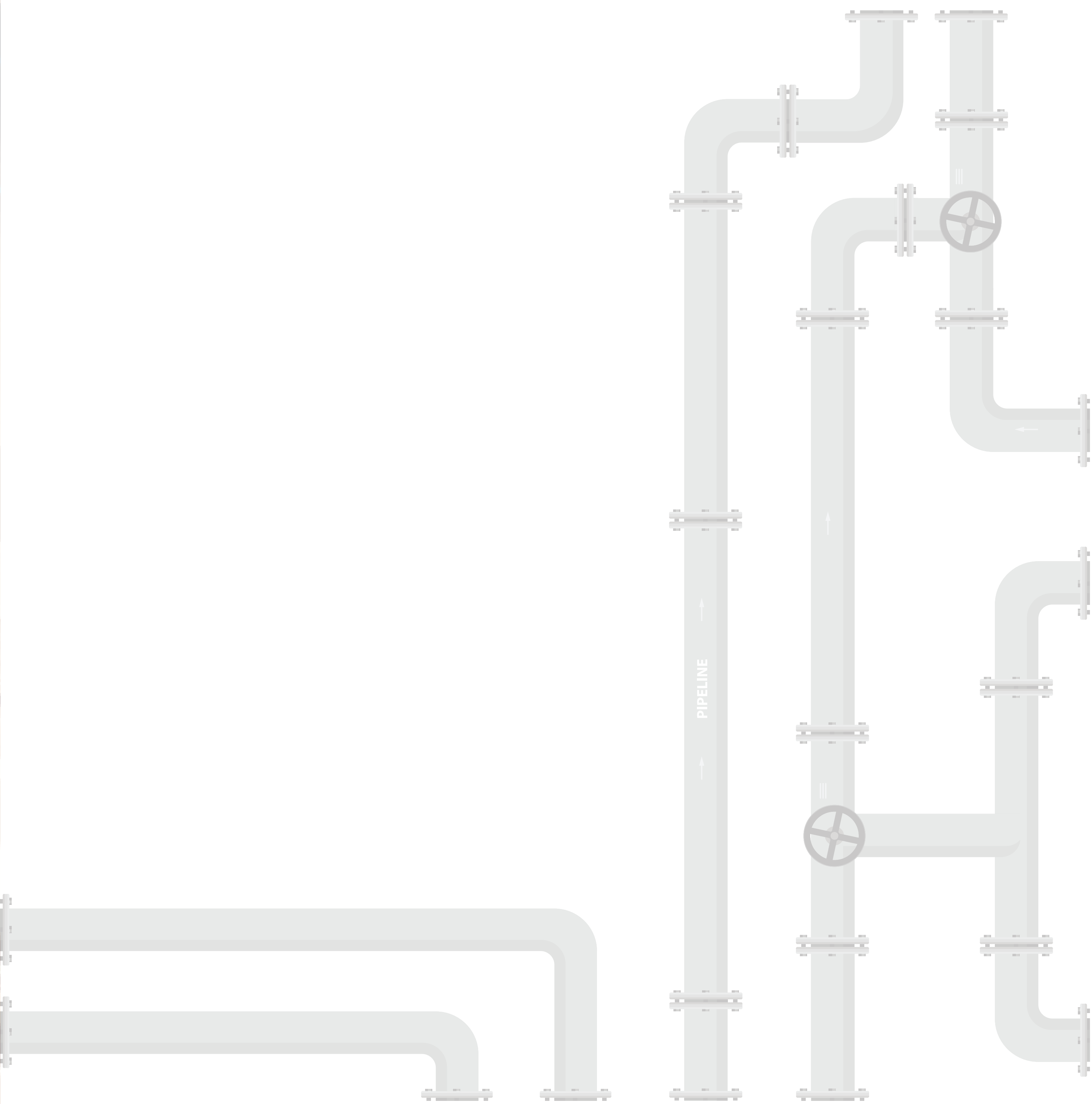
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