D3.7 Strategies for connecting the heat generation system with high electrical performance PVTs integrated to a heat pump

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Summary

The present deliverable was prepared in the context of Task 3.4 "Engineering, installation strategies and prototyping for thermal storage system integration with novel PVT configuration". Specifically, D3.7 focuses on the installation strategies for the heat generation system composed of high electrical performance unglazed liquid-based photovoltaic-thermal (PVT) collectors integrated with a heat pump (HP). This PVT-HP generation system produces thermal energy that is used in the MiniStor system and the building; while the electricity produced by the PVT collectors is used in the HP of the PVT-HP system, the MiniStor system as well as in the building.
The installation strategies include the general integration and location strategies, the strategies for installing the PVT solar field using the new developed unglazed PVT collector, the strategies for installing the heat pump selected for the PVT-HP system, safety considerations and PVT-HP base control installation strategy. These strategies are based on the design process performed for the solar PVT-HP system, as well as feedback from the implementation performed in the corresponding demonstration site of Santiago de Compostela (USC).

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Abbreviations and acronyms

AC	Alternating current
DC	Direct current
DHW	Domestic hot water
ESS	Electrical storage system
FPC	Flat plate collector
GND	Ground
HP	Heat Pump
HTF	Heat transfer fluid
HX	Heat exchanger
MPP	Maximum Power Point
PLC	Programmable logic controller
PCM	Phase-change material
PV	Photovoltaic
PVT	Photovoltaic-thermal
RES	Renewable energy sources
SOC	State Of Charge
STC	Standard testing conditions
TCM	Thermochemical material

1 Introduction

MiniStor[1] is a project funded by the European Union's Horizon 2020 research and innovation programme, focused on the design and production of an innovative compact integrated thermal and electrical storage system to implement sustainable energy storage for heating, cooling and electricity, adaptable to existing systems in residential buildings. The MiniStor thermal energy storage system is based on a thermochemical material reaction, in combination with PCM (phase-change materials) heat storage, and in parallel it has an electrical storage system (ESS) based on conventional batteries. The MiniStor system can use as input different Renewable Energy Sources (RES), such as hybrid Photovoltaic Thermal (PVT) collectors.

Hybrid solar collectors, also known as photovoltaic-thermal (PVT) collectors, combine, in a single collector, the ability to convert solar radiation to both electricity and thermal energy. According to the PVT collector type and the weather conditions of the location, this technology may be used for diverse applications, such as pool heating, domestic hot water production, and heat production at low temperatures for space heating and/or for industrial processes.

The MiniStor Project includes one pre demo site, located in Thessaloniki (Greece) and 4 demonstration facilities in Kimmeria (Greece), Sopron (Hungary), Cork (Ireland) and Santiago de Compostela (Spain). This deliverable was prepared in the context of Task 3.4: "Engineering, installation strategies and prototyping for thermal storage system integration with novel PVT configuration", in which a new high electrical performance PVT collector was developed, and a new PVT-HP system was designed.

The deliverable is focused on the installation strategies for the PVT-HP system, that integrated a PVT solar field with a high efficiency heat pump (HP) to produce electrical and thermal energy to be used in the MiniStor system and the building, that was installed in the Spanish demonstration site.

The installation strategies include first the general integration and location strategies which can be applied to the generic location, the strategies for installing the PVT solar field using the new developed PVT collector model, the strategies for installing the heat pump selected for the PVT-HP system, safety considerations and PVT-HP base control installation strategy. These strategies are based on the design process performed for the solar PVT-HP system, as well as the feedback from the implementation performed in the corresponding demonstration (Santiago de Compostela - USC).

The specific details about the implementations in the related demo site will be presented in D6.4 related to the Installation and commissioning report for all the MiniStor demo sites, prepared in the context of WP6.

2 Overview of MiniStor system

The MiniStor system for the Santiago de Compostela-USC demo site, explores a variant of the main configuration, that includes the following components depicted in Figure 1: a) a PVT-HP generation system (Hitachi heat pump, yellow rectangle), b) a TCM reactor containing ammoniated $CaCl_2$ salts, c) an ammonia refrigeration cycle with a storage tank, d) an internal small heat pump custom-made (Heat Pump, green rectangle) and e) phase

[1] *Minimal Size Thermal and Electrical Energy Storage System for In-Situ Residential Installation*

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change materials (Hot and Cold PCM) vessels through which the connection of MiniStor with the building is realized.

The PVT-HP generation system consists of a PVT solar field, coupled in parallel with a high efficiency air-to-water heat pump (Heat Pump Hitachi) through a small inertia or buffer tank. The solar field preheats the heat transfer fluid (HTF), while this heating process is completed using the vapor compression air-to-water HP. The thermal energy produced by the PVT-HP system increases efficiency in achieving the TCM reactor charging process, while the electricity produced through the PVT solar field, can be stored in an electrical storage system (ESS).

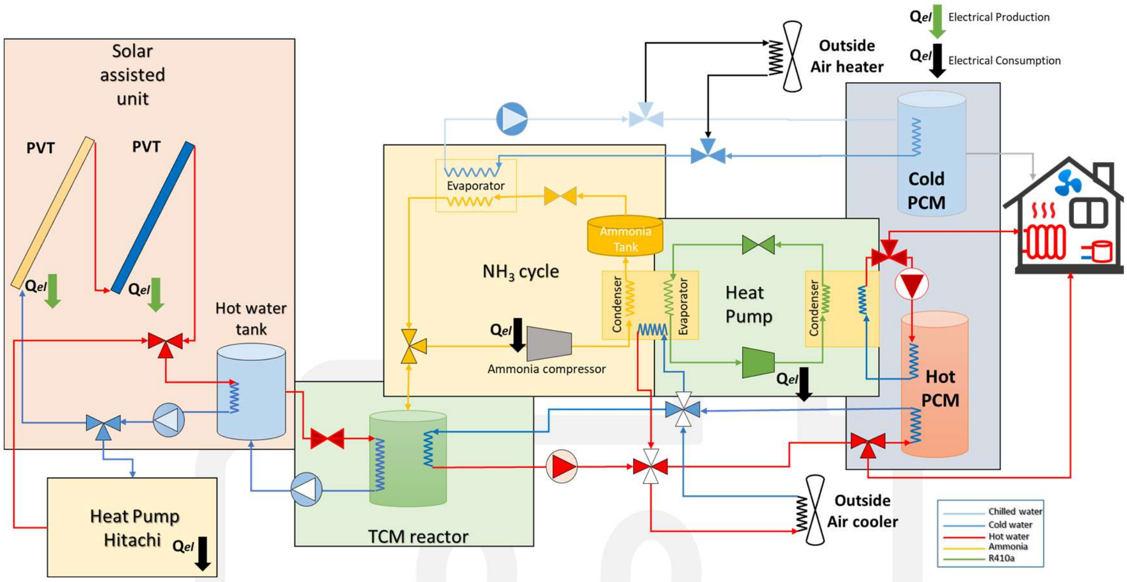


Figure 1. Overview of MiniStor system activated with a PVT-HP generation system for use in the demo site Santiago de Compostela

The operating principle of the TCM unit is based on reversible reactions using calcium chloride and ammonia that start at a given temperature during the charging phase. Thanks to the heat produced by the PVT-HP generation system the temperature can be reached faster, providing heat into the MiniStor system. This stored thermal energy is used later to meet the thermal heating demand in the home or building. The bespoke heat pump after theNH3 cycle is used to generate additional heat during the charging phase. Besides, the ammonia condensation incorporates a cooling effect that can be used during the summer to attend to the thermal cooling demand in the building or home and which is stored in the cold PCM. The overall MiniStor system description and details about how the system works were presented in D3.1-Initial dimensioning of the system according to general use typologies.

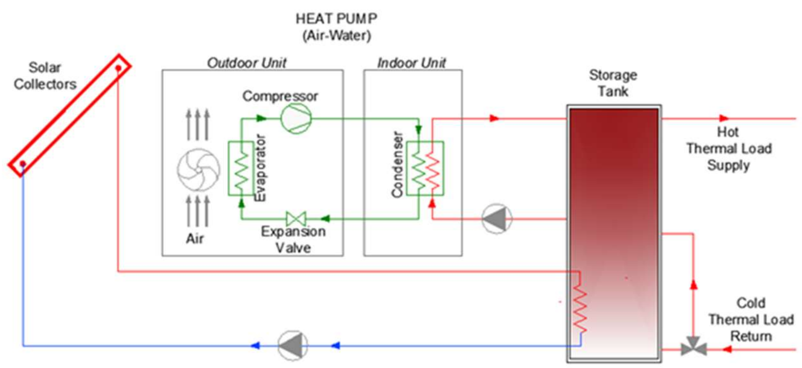
3 PVT-HP system concept and general integration strategies

This section summarizes the general integration strategies between PVT solar field and heat pumps for adoption in different sites where the MiniStor system is implemented. It also describes the concept of the PVT-HP system designed in the context of the MiniStor project. Finally, the general location strategies of the PVT-HP system together with the MiniStor system are presented.

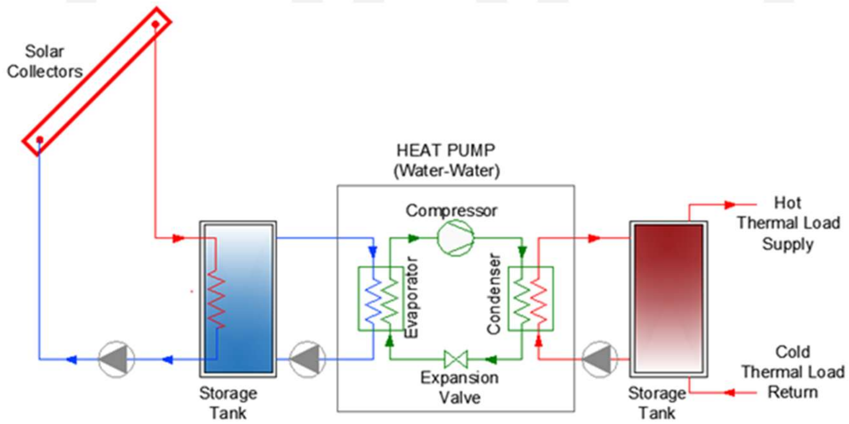
3.1 General integration strategies for PVT-HP systems

The integration of heat pumps with solar systems is a topic widely analysed in different studies, usually referenced as Solar Assisted Heat Pumps (SAHP) [1–3]. According to previous studies, there are two main alternatives for thermal integration of solar thermal technologies: PVT solar collectors and heat pumps. They are known as direct and indirect expansion integration options.

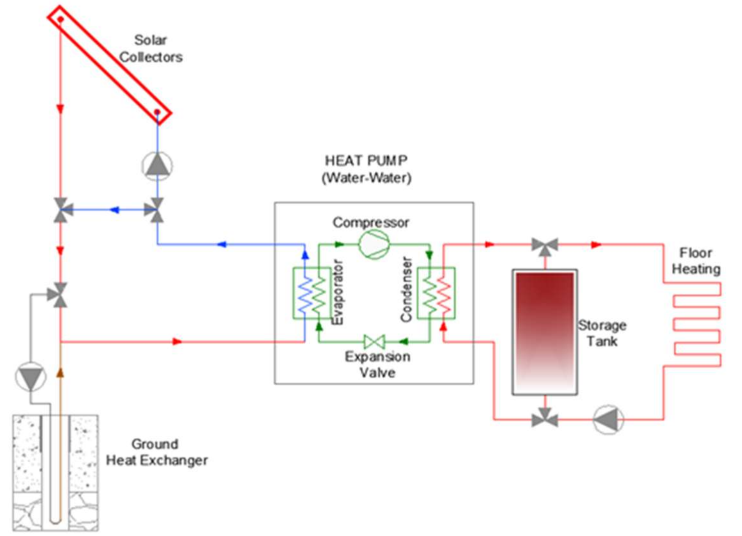
The direct expansion integration option consists on using a field of PVT collectors as the evaporator in a HP [3,4]. In this configuration, the PVT collectors operate as evaporators within the HP's thermodynamic cycle, so they must be designed in line with their overall internal heat pump components. This can deliver notable efficiencies in heat production at low temperatures (T < 50 °C) [1,5]; however, the market penetration of this type of systems has been limited, as standalone technologies (PVT collectors and vapor compression HPs) currently offer more cost competitive pricing.



(a) Parallel configuration [6–8]



(b) Serial configuration [7,9]



(c) Dual source configuration [3]

Figure 2: Indirect integration strategies between PVT collectors and heat pumps

The indirect expansion integration option, by contrast, is better suited for commercial heat pump models (air-to-water and water-to-water), thus it takes the benefit from the latest advancements in HP technologies without requiring special modifications in the materials used for manufacturing PVT collectors. This integration option can be conducted using three base configurations: a) parallel configuration, b) serial (one-source) configuration, and (c) dual-source serial configuration; Figure 2 presents the corresponding basic diagrams.

The parallel configuration (Figure 2.a), is primarily used with air-to-water heat pumps. In this case, the HP thermodynamic cycle uses air as a source on the evaporator side, while the heat provided by the HP and the PVT solar field are integrated in parallel through a water tank. The parallel configuration can adopt multiple variants for connecting the solar thermal circuit on the demand side, such us to pre-heat cold water before entering to a hot water tank, or to use different thermal storage tanks according to the required temperature level on the demand side.

The series configuration (Figure 2.b), is mainly used with water-to-water heat pumps. In this case, the solar thermal PVT loop is integrated with the secondary water circuit on the HP's evaporator side, using an intermediate storage tank. This tank allows decouple the flow rates of the two hydraulic circuits (PVT circuit and secondary water HP's evaporator circuit). The heat produced by the HP is delivered to the load through the secondary water HP's condenser circuit.

The dual-source configuration (Figure 2.c), is another option to perform the integration. It consists of a series configuration that utilizes two energy sources (ground and solar) in the secondary water circuit on the HP's evaporator side. This configuration is suitable for locations with harsher winters, were lower ambient temperatures limit the operation of air-to-water HP. Another advantage of this option is that the solar field helps regenerate the ground source during the summer season. Its main disadvantage is the higher complexity and investment costs compared to the parallel configuration.

In the context of the MiniStor project, the parallel configuration was selected for the implementation in the Santiago de Compostela demonstration site, considering the local weather conditions, the possibility of integrating a HP suitable for producing temperatures up to 70 °C in the PVT-HP system, as well as the global investment cost required. More details in this regard are presented in D3.6: "Design of a heat generation system with high electrical performance PVTs integrated with a heat pump".

3.2 PVT-HP system concept designed for the MiniStor project

This section summarizes the PVT-HP heat generation system concept, designed and presented in detail in deliverable, D3.6: "Design of a heat generation system with high electrical performance PVTs integrated with a heat pump", prepared in the context of Task 3.4. The system consists in a PVT solar field, that uses high electrical performance unglazed hybrid PVT collectors, integrated with a mechanical vapour compression heat pump (HP), using a small inertia/buffer tank. Figure 3 shows the simplified scheme of the PVT-HP Generation system; more detailed piping drawing is presented in Annex I.

The PVT solar field is integrated by liquid-based unglazed PVT collectors that use a high electrical performance PV laminate, with an electrical efficiency close to 20%. The PV laminate is made of monocrystalline silicon-PERC cells, connected through shingled technology. These PVT prototypes were developed in the context of T3.4 and presented in detail in D3.6.

The Heat Pump is a mechanical vapour compression type driven by electricity. The model selected is air-to-water type, commercially available, in which the evaporator uses the air as a source. In accordance with the requirements of the MiniStor system, this HP can produce heat at 65 °C, to guarantee the activation of the thermochemical (TCM) reactor in the range of 55 °C to 65 °C.

The integration of the PVT solar field and the air source HP is performed in a parallel configuration using an inertia tank. This configuration allows that both sources (air and solar) produce thermal energy to activate the TCM reactor in the MiniStor system. The inertia tank also allows decoupling of the flows of the different hydraulic circuits in the production side and the load/demand side and help to control the temperature in these hydraulic circuits.

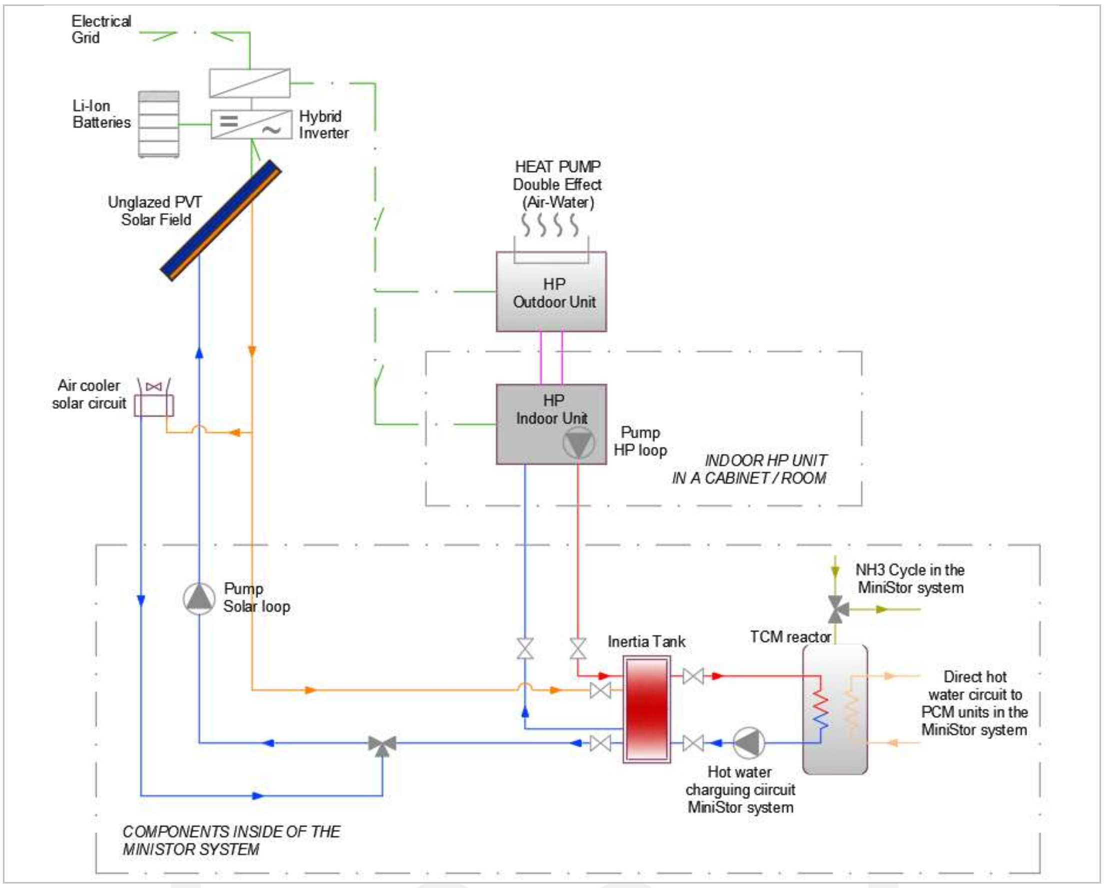


Figure 3: HP-PVT system concept

The electricity produced by the PVT solar field is primarily used to power the heat pump (HP) and the internal components of the MiniStor system. During periods of excess production, particularly in the summer, the surplus electricity is allocated to meet the building's energy needs. To achieve this, the system incorporates an electrical storage system (ESS) consisting of high-voltage lithium-ion batteries and a hybrid inverter. Detailed information about the design and installation strategies are presented in D3.8 and D3.9 respectively.

The thermal energy produced by the PVT-HP system is utilized either to activate the thermochemical reactor (TCM) within the MiniStor system or to supply heat directly to the PCM units to meet the thermal building demand. The low-temperature production coming mainly from the PVT solar field is used to minimize thermal losses in the MiniStor system, as the equipment will be housed in an outdoor container. To prevent overheating in the solar loop, especially during summer, an air cooler is integrated into the solar thermal circuit.

3.3 General strategies for positioning the PVT-HP system

The location of the PVT-HP system depends on the space available in the building or home to install the solar field and the HP, as well as the location of the MiniStor system itself and safety requirements. In general, the PVT-HP location should consider the following general recommendations:

- The MiniStor system is housed in a machinery room and utilizes ammonia as the refrigerant in its internal thermodynamic circuit, so for safety reasons, the suitable location for the system is outdoors.

- The PVT solar field as well as the HP should be located as close as possible to the MiniStor system, to minimize thermal losses from the thermal generation equipment to the inertia tank, which is installed inside the MiniStor container.
- The PVT solar field can be also located on the building roof or in a garden area, depending on the PVT solar field size and the space available. It is strongly recommended to use south orientation for the PVT collectors (for the north hemisphere) and slopes close to the latitude to increase the production temperature and better profitability from the thermal energy produced.
- The HP uses a refrigerant in its internal thermodynamic cycle, so the safety restrictions associated with the refrigerant, as well as the manufacturer's specifications, must be reviewed. The location of the components (mono block or bi-block) can be done according to Table 1.

Table 1: PVT-HP location strategies

Case	MiniStor system location strategies	PVT solar field location strategies	HP location strategies
(a) Individual dwelling	Outdoors in an individual home, in a garden area	Outdoors in an open area if there is available space Outdoors on the roof	HP monobloc type: outdoors close to MiniStor system HP bi-block type: indoors unit close to MiniStor system, outdoors unit, close to indoor unit, maximum distance indicated by manufacturer
(b) Multifamily building	Outdoors in an open area		

Table 1 summarizes in a simplified way the location strategies that can be adopted for the general components indicated above; MiniStor System, PVT solar field and HP heat pump, broken down into two general cases: (a) individual dwelling and (b) multi-family building.

In the case (a), individual dwelling, the MiniStor system can be installed particularly in houses with enough space available in the garden area. The location for the PVT solar field can be in the garden area or on the roof of the house, trying to maximize the PVT solar field surface and to reduce the distance to the HP and the MiniStor System.

In case (b), Multifamily buildings, the location adopted for the MiniStor system can be installed in the garden area or in the building roof depending on the space available and the roof conditions. Similarly to the previous case the PVT solar field can be installed in the garden area or in the building roof. In this case, it is especially important to maximize the PVT solar surface to get more relevant solar thermal fractions.

The HP integrated into the PVT-HP system can be either a monoblock or a bi-block type. The monoblock type should be installed outdoors, positioned near to the MiniStor system and the inertia tank. The bi-block type consists of an internal unit and an external unit. The internal unit must be installed indoors, close to MiniStor system, in a separate cabinet or room, while the external unit must be installed outdoors, following the distance specifications provided by the manufacturer.

4 PVT solar field connection strategies

4.1 Layout definition, structures and canalizations

After defining the PVT solar field location according to the location strategies presented in section 3.3, it is necessary to conduct a detailed design to define the specific solar field layout, considering the canalizations, support structures and complementary elements.

For the PVT-HP system to be connected to the MiniStor system, the PVT layout was arranged in two groups of PVT collectors. The purpose is to gain a first temperature increment in the Heat Transfer Fluid (HTF) through one PVT collector group and a second temperature increment through the other PVT collector group. Thanks to this configuration it will be possible to increase the overall temperature production in the PVT solar field and improve the corresponding solar thermal fraction.

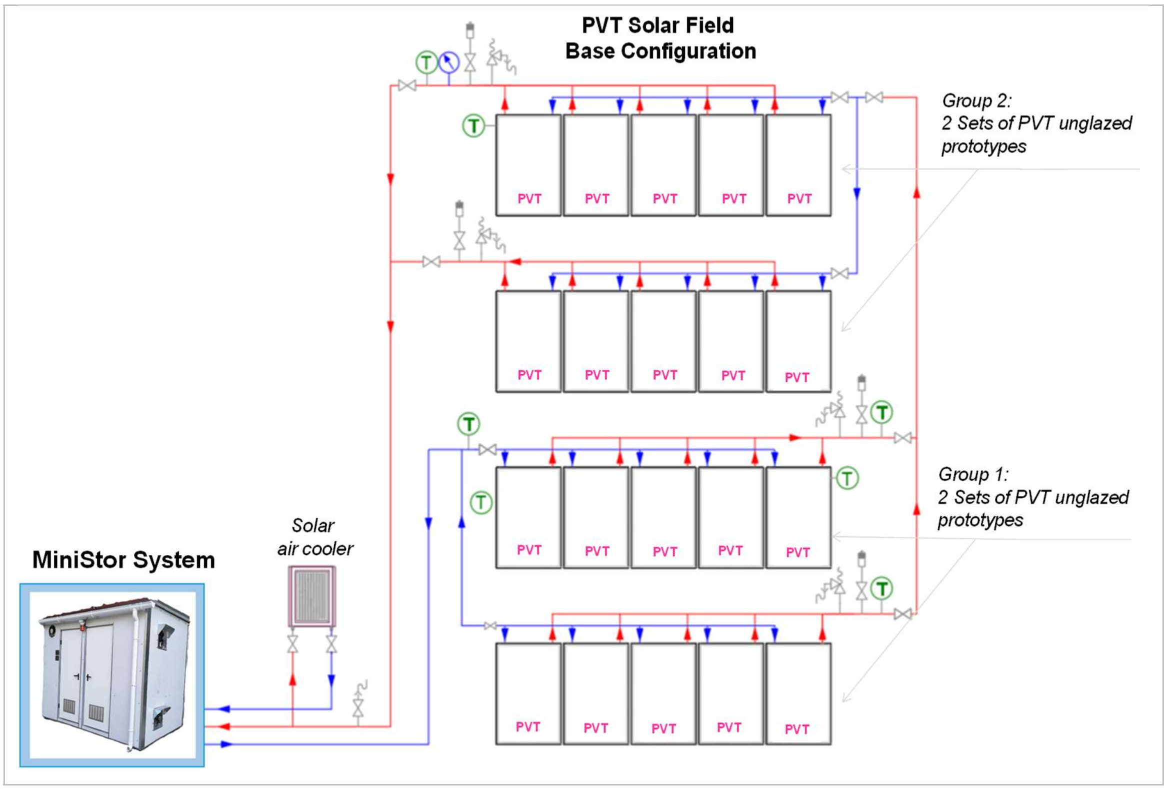


Figure 4: PVT solar field – base layout defined for the MiniStor project

Figure 4 illustrates the specific layout designed for the implementation in the Santiago de Compostela- USC demonstration site in the context of the MiniStor Project. There are two groups, each with 10 PVT collectors, for a total of 20 PVT collectors. Each group of 10 PVT collectors is distributed into two sets of 5, although all PVT collectors within each group are connected in parallel to each other.

In this hydraulic configuration, the HTF is pumped from the inertia tank, pre-installed inside the MiniStor system container, to the solar field. Upon reaching the solar field, the HTF enters the "Group 1" of PVT collectors, where the initial heating occurs. It then flows into "Group 2" of PVT collectors for further heating. Finally, the HTF returns to the inertia tank, located within the MiniStor system container. The solar hydraulic circuit also includes a solar air cooler (as Figure 4 shows), which is activated in case of overheating.

Before installing the PVT collectors, the corresponding supporting structures must be installed. Given the lightweight design and compact size (< 2 m^2) of the developed PVT prototypes, various commercially available structures designed for PV panels are suitable for these PVT collectors. Table 2 summarizes the main technical characteristics of two types of structures, manufactured by Sunfer Energy, which have been defined and selected for installing the unglazed PVT collectors developed for the MiniStor project's PVT-HP system.

Table 2: Structures models defined for the PVT collectors.

	Type	Reference and model	Main technical characteristics
1.	Structure for flat/ smooth zone. PVT collectors installed in single row	Model 10.V manufactured by Sunfer Energy 	- Closed triangle inclined support - Profiles made of aluminium and screws made of stainless steel - Vertical unglazed PVT collector arrangement in a single row. - Valid for collector/modules thicknesses of 30 to 45 mm. - Standard inclination 15° and 30°. - Suitable for collector/modules' size up to 1800 x 1150 mm (2.07 m^2) - Kits available from 1 to 6 collectors/modules. - Requires installation of counterweights, anchoring screws not included.
2.	Structure for flat / smooth ground zone, PVT collectors installed in double wow	Model 38.V manufactured by Sunfer Energy 	- Elevated structure to be installed on the ground zones. - Pillars and beams made of hot-dip galvanized steel; profiles made of aluminum and screws made of stainless steel. - Vertical PVT collector arrangement in a double row. - Valid for collector/modules thicknesses of 28 to 40 mm. - Standard inclination 20°. - Suitable for collector/modules' size up to 2279 x 1150 mm (2.62 m^2) - Modular system from 8 to 20 collectors/modules. - Requires anchoring to the concrete. Anchoring screws not included.

The primary advantage of Type 1 Structure is that there are several commercial structures that can be used to install the PVT collectors, and the necessary counterweights are usually available as standard products, resulting in a lower cost for the overall structure. However, the final layout with the type of structure requires a larger area to install the PVT solar field. On the other hand, Type 2 structure is less commonly found in the market, but reduces the space required to locate the PVT solar field, although it comes with higher costs due to both structures and civil works.

The final placement of the PVT solar field layout must be verified during the installation process, considering several factors such as: the condition of the area where the PVT collectors will be placed, the path or routes for the hydraulic, electrical, and communication pipelines, and any potential intersections with other existing pipelines.

4.2 Connection of Individual PVT collector

The PVT collector used in the PVT-HP system field is a prototype developed in the context of Task 3.4, with the respective results presented in D3.6: "Design of the heat generation system with high electrical performance PVTs integrated to a heat pump". The corresponding development process considered the selection of new high electrical performance of PV laminate, the absorber re-design, the manufacture of PVT prototypes and the testing procedure in ENDEF facilities following the European Norm EN ISO-9806:2014[2]. This PVT developed prototype is unglazed type, with a high electrical performance PV laminate; Table 3 summarizes its main general characteristics, more technical details are included in the above-mentioned deliverable.

Table 3: Main characteristics of PVT prototype developed for the PVT-HP system.

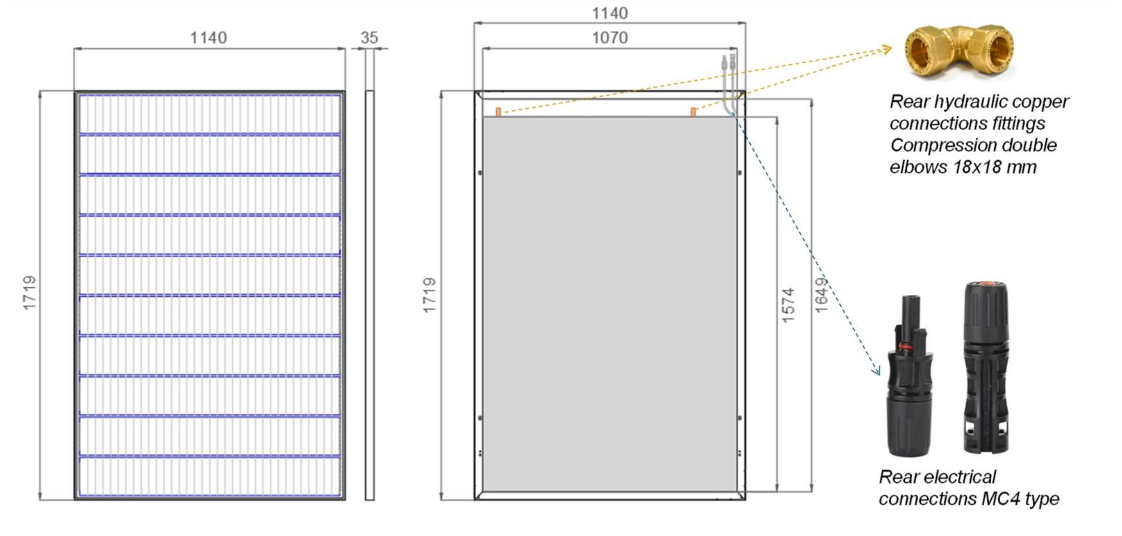
Description	Unit	Value
Gross area	[m^2]	1.96
Absorber area	[m^2]	1.65
Electrical power MPP (1)	[W]	390
Electrical efficiency STC(2)	[%]	19.9%
PV cells Type	[-]	*Silicon, monocrystalline, PERC*
Cells connection type	[-]	*Shingled connection*
Absorber type	[-]	Sheet & tubes
Material absorber	[-]	Aluminium/copper
Frontal glass type	[-]	Tempered 3.2 mm, anti-reflective
Rear insulation	[-]	Yes
Closing back-sheet	[-]	Aluminum
Fluid content	[l]	0.47
Maximal pressure	[bar]	6
Total weight	[kg]	32.17
Electrical connections	[-]	MC4 connectors, solar cable 4 mm^2
Hydraulic connections	[-]	2 x 15 mm fittings (upper side)

(1) Standard Testing Conditions, (2) Maximum Power Point

The individual connection of a PVT collector involves both hydraulic and electrical connections. The hydraulic connection must be made using the two upper fittings (2x15 mm) positioned on the rear side of the PVT collector. The hydraulic connection between PVTs collectors is performed using two copper double elbows 18x18 mm, as illustrated in Figure 5.

The electrical connection must be conducted by using the two electrical connectors, MC4, 4mm^2, located on the rear-upper side of the PVT collector, as shown in Figure 5. These MC4 connectors are connected to an internal electrical box installed in the PVT collector. The electrical connection between individual collectors will be completed using copper tubes and solar cables, which must be suitable for 1000 V DC and outdoor installations.

[2] *This standard was prepared by the European Committee for Standardization (CEN), Technical Committee CEN / TC 312 - Thermal solar systems and their components, in collaboration with Technical Committee ISO / TC 180, Solar Energy.*



(a) Frontal view (b) back view (c) Hydraulic and electrical connections

Figure 5: PVT prototype details

4.3 Hydraulic connection for an array of PVT collectors

This section outlines the installation strategy defined for connecting a PVT collector bench, which may consist of a set of unglazed PVT collectors. Figure 6, illustrates a PVT bench with five PVT collectors connected in parallel to each other; however, the number of PVT collectors can range from two to six units, according to the specific conditions of the site.

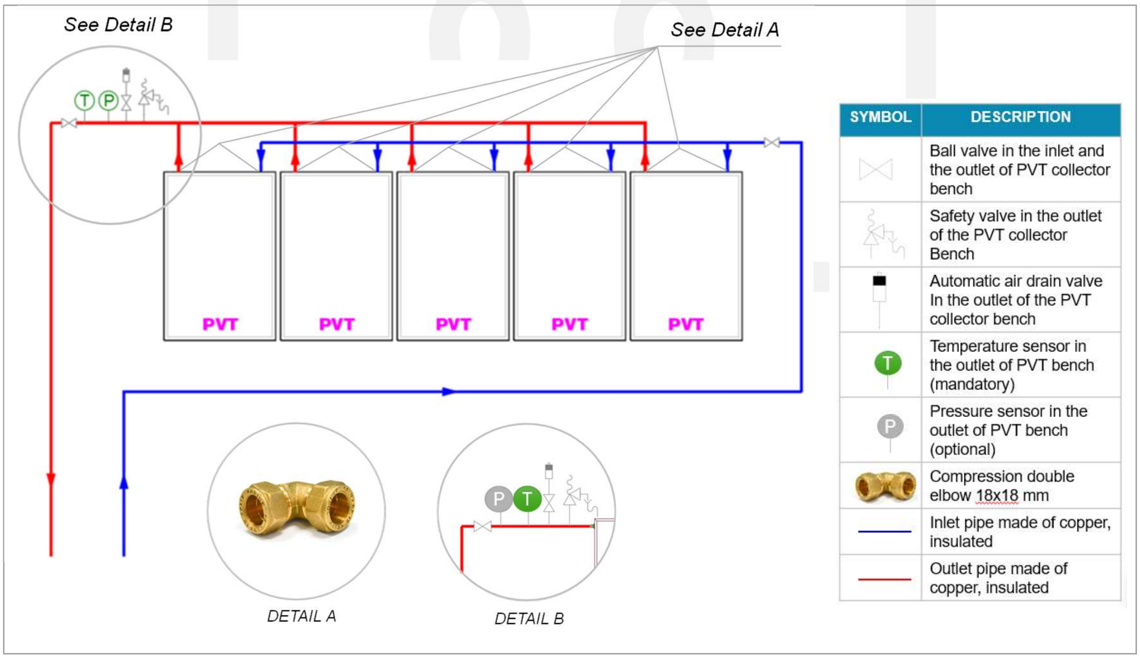


Figure 6: Hydraulic connection for a typical PVT bench

The connection between the PVT collectors is performed by joining their upper fittings 2x15 mm, using two compression double elbows shown in the "Detail A" in Figure 6. Thanks to these fittings the inlet and outlet flows can be collected in the rear top side of the PVT bench, that helps to optimize the hydraulic pipes disposition, as Figure 7 shows, and reduce the overall connection time.

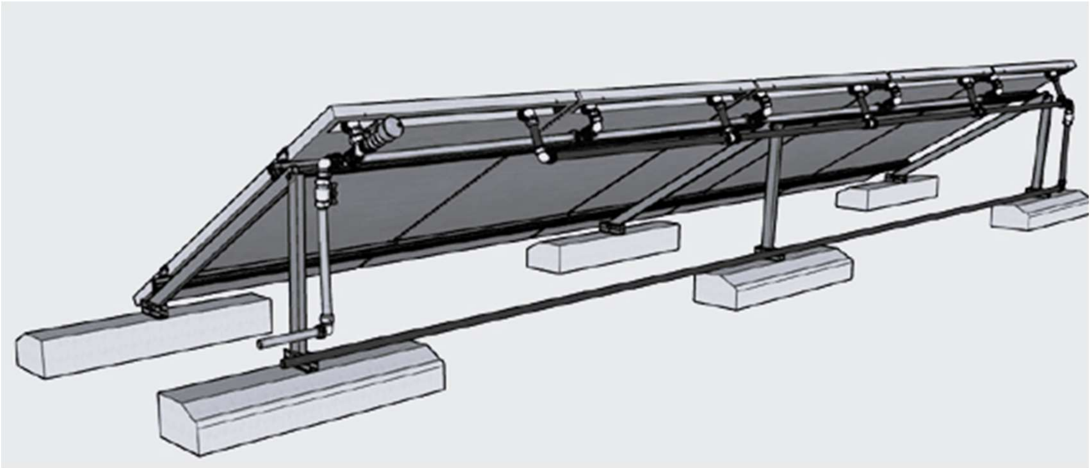


Figure 7: Indicative route for the hydraulic pipes in a PVT bench
Source: ENDEF

Each PVT collector bench must include a ball valve at both the inlet and the outlet to facilitate closing and opening operations in the hydraulic circuits for maintenance purposes. Besides, a set of valves and safety components must be installed at the outlet and the highest point of the PVT collector's bench. These components include a safety valve, an automatic air drain valve, a temperature sensor, and, optionally, a pressure sensor (see 'Detail B' in Figure 6).

Additionally, the PVT collector prototype features a central rear-upper point for installing a specific temperature sensor for control purposes. This sensor must be installed on the last bench of PVT collectors and connected to the solar controller, which is included in the MiniStor System, to activate the circulation pump in the solar circuit.

4.4 Electrical connection of a string of PVT collectors

The unglazed PVT collectors, developed for the PVT-HP system, produce electricity in direct current (DC), which comes from groups of PVT collectors arranged in strings and connected in a series configuration, as Figure 8 shows. The number of collectors per string is determined based on the inverter's specifications and limitations, including the maximum DC power input per string, the minimum required start-up voltage, the MPP voltage range, and the inverter's short-circuit capacity. The DC electrical wiring must use appropriate cables designed for outdoor use, with a rated voltage of 1 kV, halogen-free insulation, and compliant with H1Z2Z2-K type standards. These must adhere to the EN50618 standard as well as local regulations and requirements.

Inverters typically support two or more strings, so their technical specifications should be thoroughly reviewed before choosing the appropriate model for installation. For the MiniStor project, a hybrid inverter was selected to connect compatible high-voltage lithium-ion batteries. Figure 8 highlights the base models utilized in the implementation, specifically the Gen24 inverters manufactured by Fronius International GmbH.

After the hybrid inverter converts the DC into AC electricity, the AC is sent to the main electrical panel of the home or building for self-consumption. The connection between the hybrid inverter and the Li-ion batteries is made at high voltage. Any excess electricity generated is either stored in the Li-ion batteries or fed into the external grid, depending on local regulations. Further details on this process can be found in D3.9, which covers the installation strategies for the ESS.

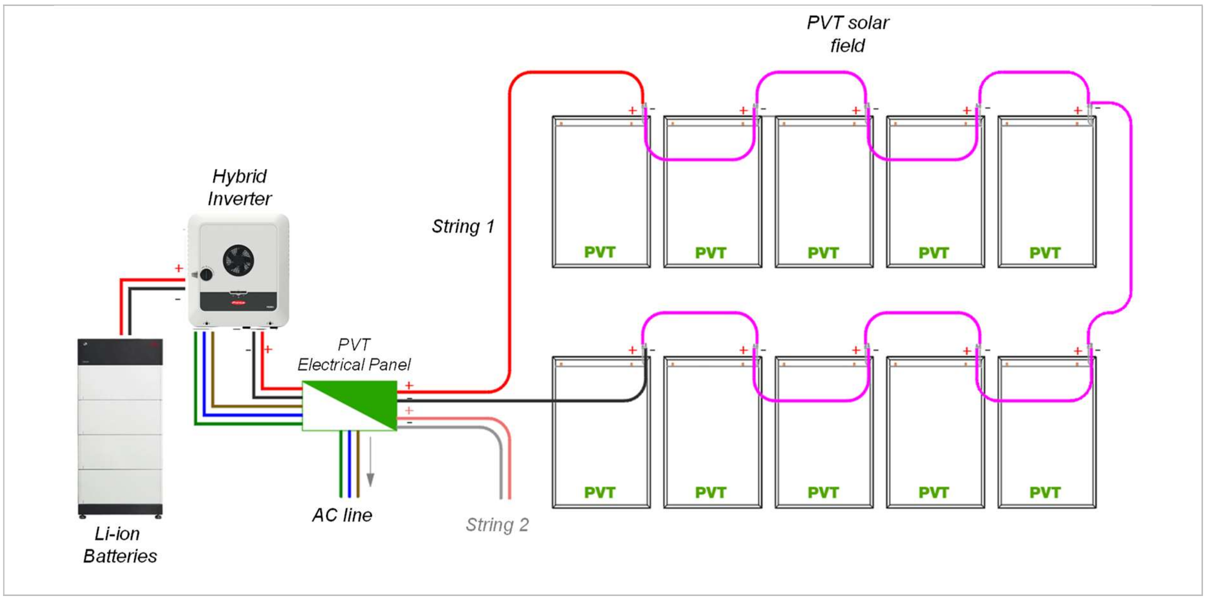


Figure 8: Electrical connection wiring in the PVT electrical production subsystem

5 HP connection strategies

This section outlines the connection strategies and main installation procedures for the HP integrated in the PVT-HP generation system defined and designed in the MiniStor project context. This includes the general description of the HP type selected for the PVT-HP system, the specific safety considerations for the HP location, as well as the installation connection requirements and considerations regarding the hydraulic, electrical and refrigerant circuits.

5.1 HP selected and the main components

As stated in section 3.2 the heat pump (HP) selected for the PVT-HP system, implemented in the MiniStor project is a vapor compression HP, double stage, air-to-water type. The specific model selected has the capacity to produce hot water in the range required by the MiniStor project (55 to 65 °C). Besides, the double stage allows to produce heat up to 80 °C, if the project requires this temperature level for specific testing purposes.

This HP model needs to activate only the first compression stage to produce hot water up to 60 °C. The second compression stage is activated for higher production temperatures. Table 4 summarizes the main technical characteristics of the HP selected and further details are included in D3.6: "Design of the heat generation system with high electrical performance PVTs integrated to a heat pump".

Table 4: Main characteristics of HP selected for the PVT-HP system.

Description	Unit	Value
Manufacturer / Model	[-]	Hitachi / Yutaki S80 4
Heat-Pump type	[-]	Air-to-Water, biblock
Heating capacity (min / nominal / max)	[kW]	4.30 / 11.00 / 15.20
Power consumption (nominal)	[kW]	2.20
COP (nominal)	[-]	5.0
Outside temperature range	[°C]	-25 to 35
Production temperature range Heating / DHW	[°C]	20 to 80 / 30 to 75
Compressor type (outdoor unit)	[-]	Scroll DC Inverter, R410A
Compressor type (indoor unit)	[-]	Scroll DC Inverter, R134a

Factory refrigerant charge in the outdoor unit/indoor unit	[kg]	3.3 /1.9
Air mass flow rate	[m^3/h]	4,800
Water mass flow rate (min / nominal / max)	[m^3/h]	1.00 /1.26 / 2.80
Weight outdoor unit / indoor unit	[kg]	103 /127

In terms of the installation process, the selected HP is a bi-block type and includes the following main components: i) a block or outdoor unit with the compressor of the first compression stage, ii) a block or indoor unit that houses the compressor of the second compression stage, iii) a wired remote control for wall installation, with the possibility of Modbus integration and iv) the Modbus adapter or compatible Gateway, which allows the integration of the relevant variables of the heat pump into a common platform of the MiniStor project. Figure 10 shows each of these main components.

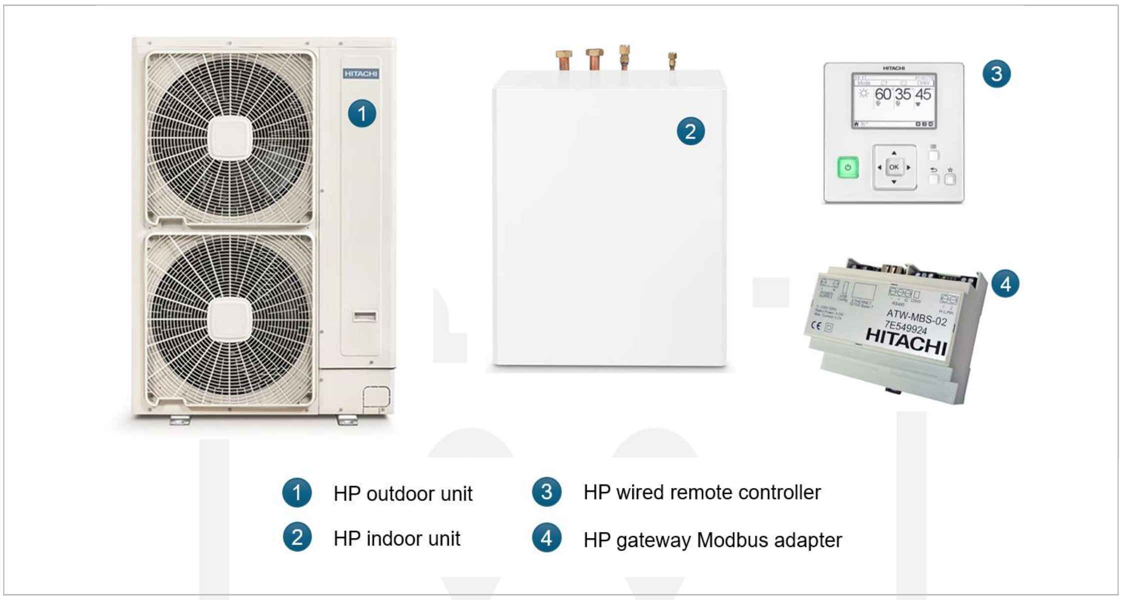


Figure 9: HP main components to be installed

5.2 Specific safety location considerations

The location of the heat pump must consider safety requirements to ensure that possible refrigerant leaks will not bring concentration levels in closed rooms to exceed the maximum values allowed. These refrigerant concentration limits (RCL) depend on the type of refrigerant used in the heat pump and are regulated by European and local norms.

This issue is particularly important in bi-block heat pumps, since the indoor units must be installed in rooms of adequate size and ventilation. The RCL according to EN378-1, depending on the type of refrigerant, are summarized in Furthermore, given the flammability of the refrigerant, appropriate safety measures must be implemented.

Table 5. Furthermore, given the flammability of the refrigerant, appropriate safety measures must be implemented.

Table 5: Maximum concentration allowed in closed room for some refrigerants.

Refrigerant		*Refrigerant concentration limits [kg/m^3]*
R290	Propane	0.008
R600a	Isobutane	0.0096
R717	Ammonia	0.00035
R718	Water	-

R744	CO2	0.1000
R32	Difluormetane	0.061
R410a	-	0.440
R134a	1.1.1.2 Tetrafluoretane	0.250

In the specific case of the indoor unit of the HP selected for the PVT-HP system, the minimum size of the room must be 7.6 m^3, as indicated by the manufacturer in the corresponding installation and operation manual. In case of installing the indoor unit in a smaller room, additional safety measures must be implemented, such as natural or forced ventilation, refrigerant detectors, and other measures required by the applicable norms and regulations.

5.3 HP connection strategy and installation requirements

As indicated in Section 5.1, the heat pump selected for the PVT-HP system in the MiniStor project is a mechanical vapor compression type with a bi-block configuration, consisting of an indoor unit and an outdoor unit. This type of heat pump requires the installation of three types of circuits: the refrigerant circuit, the hydraulic circuit, and the electrical circuits. Figure 10 illustrates the basic connection scheme for the HP, which is also included in the general hydraulic scheme for the PVT-HP system presented in Annex I.

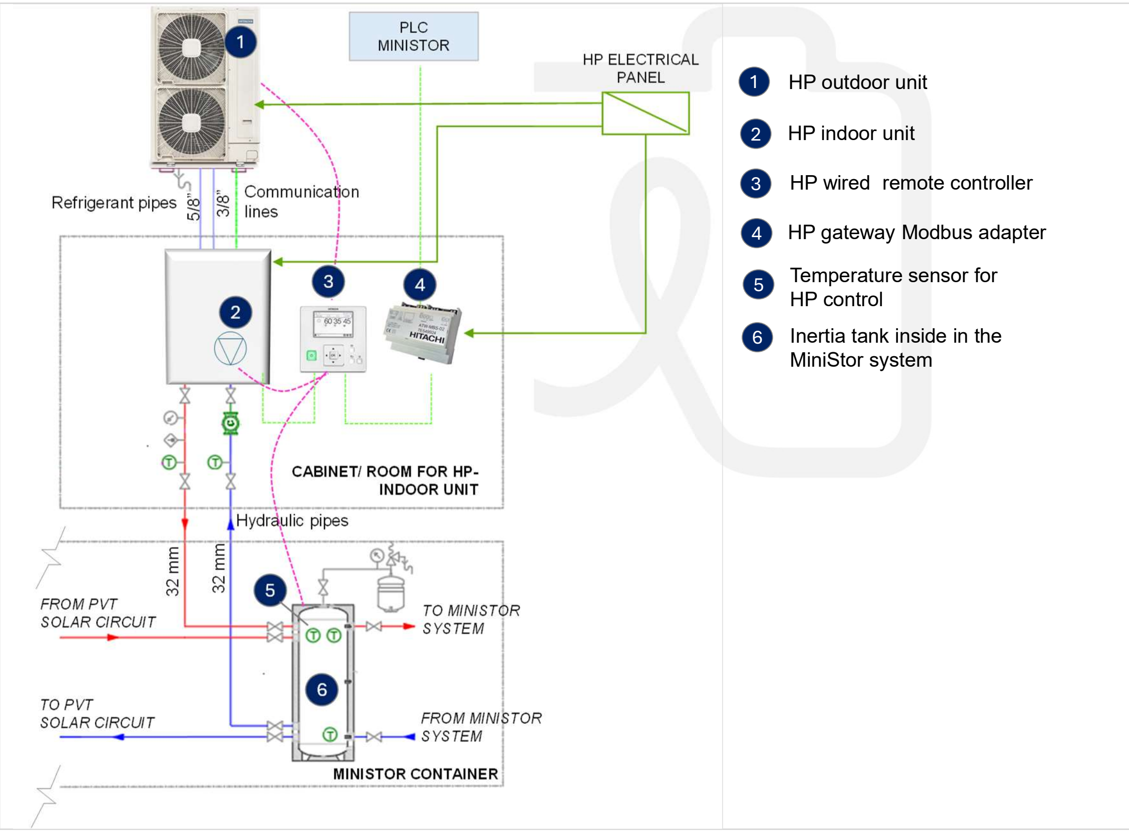


Figure 10: Base connection scheme for the HP
Source: Based on Hitachi manuals and design prepared for MiniStor implementation

The refrigerant circuit connects the indoor and outdoor units using suitable copper pipes and the refrigerant specified by the HP's manufacturer. The hydraulic circuit corresponds to the secondary water circuit on the HP condenser side, running between the indoor unit and the inertia tank, where the parallel integration between the PVT and HP hydraulic circuits is performed. The electrical circuits supply power to the indoor and outdoor units, as well as the control elements, from a low-voltage electrical panel, typically dedicated to the HP.

All circuits (refrigerant, hydraulic, and electrical) must be installed by qualified personnel, following the manufacturer's instructions and complying with local standards and regulations. Once the installation process is complete, the heat pump (HP) must be commissioned in coordination with the manufacturer's local technical service. Table 6 summarizes the general recommendations that should typically be considered during the installation process for each circuit category

Table 6: General recommendations for the installation and connection of HP circuits

Circuit		Main recommendations for the installation
1.	Refrigerant Circuit	- Position the indoor and outdoor units while respecting the minimum and maximum distances allowed by the manufacturer. - Use pipe with the diameters and materials specified by the HP manufacturer (5/8" and 3/8" in the MiniStor Project). These pipes are usually made of insulated copper, specifically designed for the conduction of refrigerant fluids. - Verify the circuit's tightness using nitrogen gas at the pressure specified by the manufacturer, in coordination with their technical service. - Perform the final refrigerant charge in the circuit, applying the pressure specified by the manufacturer and in coordination with their technical service. - Consider any other additional requirements specified in the local regulations.
2.	Hydraulic circuit	- Use pipes made of suitable materials and dimensions, in accordance with the operating conditions allowed by the heat pump. For the HP selected for the MiniStor implementation, the conditions are a pressure range of 1.0 to 1.8 bar, a maximum pressure of 3.0 bar, a maximum temperature of 80 °C, and a flow rate ranging from 1 to 2.8 m^3/h. - Include a buffer tank in the circuit with the minimum volume specified by the HP manufacturer (40 L for the HP selected for the MiniStor project). - Position the indoor unit and the inertia tank while ensuring the distance between them does not exceed the maximum allowed and maintain pressure losses within the operating range of the circulation pump incorporated in the HP indoor unit. - Use flexible joints to connect hydraulic pipes, to mitigate the impact of vibrations. - Install the necessary safety elements (see Section 6), insulate all pipes and accessories to minimize heat loss, and comply with local regulations. - Perform tightness tests on the circuit following the HP manufacturer's specifications, including valve opening, drain opening, filling pressure, and test duration. - Perform the final filling of the circuit with a heat transfer fluid (usually water)3, ensuring that it meets the quality regulations for pH, $CaCO_3$ levels, electrical conductivity, ammonia content, Sulphur, etc.
3	Electrical circuits	- Use an exclusive electrical sub-board to power the HP components, including the outdoor unit, the indoor unit (if present), and the control and communication elements. - Assign an exclusive electrical circuit to each component; this means a circuit for the outdoor unit, a circuit for the indoor unit, and a circuit for the controller and communication elements. - The cables for each circuit must be considered the maximum current specified by the manufacturer for each component.

[3] *The specific implementation in the MiniStor Project required 332.5 l of Heat Transfer Fluid, of which 185.7 l are inside the MiniStor system container and 146.8 l are outside the container. The indoor volume corresponds to the inertia tank (57l), the TCM and piping (102 l) and the PCM units and piping (26.7 l). The outdoor volume corresponds to the solar circuit (112.2 l) and the heat pump circuit (34.6 l).*

		- The total voltage drop from the building's general electrical low-voltage board must be below 10%. This limit will be adjusted according to local regulations and standards. - Each electrical circuit must be equipped with all necessary protection (see Section 6). - The indoor and outdoor units must be connected using shielded communication cables of the minimum gauge specified by the HP manufacturer, typically 0.75 mm².

For the HP installed at the Santiago de Compostela-USC demonstration site, the horizontal and vertical distances between the indoor and outdoor units is within the range allowed by the manufacturer (horizontal: 5 to 75 m, vertical <20 m); therefore, no additional refrigerant charge is required. Regarding the hydraulic circuit, the operating pressure is 1.5 bar, which aligns with the operating pressure of the MiniStor system and falls within the HP's allowable operating range (1 to 1.8 bar). For the electrical circuits, considering the maximum electrical power of the indoor and outdoor units, the cables will have minimum gauges of 4×2.5 + GND mm², respectively, as specified by the manufacturer. Furthermore, in compliance with local regulations, these cables will be halogen-free and feature reduced opacity. Besides, communication shielded cables between the indoor and outdoor unit must be installed with a minimum gauge of 2x0.75 mm².

6 Main safety elements in the PVT-HP system

The PVT-HP system requires safety and protection elements for the hydraulic circuit as well as for the electrical connections. Following it is summarized the main protections and safety elements that must be included

6.1 Safety elements in the hydraulic circuits

Both the solar hydraulic circuit[4] as well as the HP hydraulic circuit must incorporate different protection elements as follows:

- For high pressure protection: the hydraulic circuits incorporate the following elements, that should be installed in accessible points for maintenance and operation purposes: (i) Expansion vessels to absorb the volume increment due to variations in the fluid temperature. The pressure at the air chamber in the expansion vessels must be set 0.5 bar below the filling circuit pressure[5] and following the manufacturer specifications and local standard.
  (ii) Safety valves which act when the circuit pressure exceeds the maximum allowed value (3 bar). There are preinstalled safety valves in the solar stations as well as inside the HP indoor unit; besides, a safety valve must be installed in each solar bench. (iii) Air-vent valves at the highest points of the circuits, which drain the air inside the circuit to avoid punctual overpressures due to the air.
- For overheating protection, the hydraulic solar circuit includes an air-cooler, which is activated when the solar field outlet temperature exceeds the design temperature of

[4] *The safety elements indicated for the solar hydraulic circuit are used in the two types of solar thermal installations implemented in the MiniStor project, and therefore their description is included in the related deliverables: D3.5 - Installation strategies of improved PVT electrical generation system, as well as the present deliverable D3.7.*

[5] *The filling circuit pressure can be estimated as the circuit operation pressure (1.5 bar) plus the static pressure in the expansion vessel.*

PVT collectors. The solar air cooler is activated through the solar controller to dissipate the excess of thermal energy to the outside environment, particularly during the summer season. Figure 11.a shows a solar cooler model used in the MiniStor implementations, suitable for outdoors installation; this equipment needs hydraulic connections according to the manufacturer's requirements, as well as electrical wiring at 230V, 50 Hz.

The solar air cooler selected must be anchored using metal profiles and incorporate anti-vibration elements such as silent blocks, as shown in Figure 11.b. For proper operation, it is recommended to maintain a minimum separation between the equipment and adjacent physical obstacles, as the Figure 11.c illustrates.

As an additional overheating protection measure, the MiniStor system incorporates a second air-cooler (fan coil) inside the MiniStor room, which is activated in case the inertia tank temperature excesses the desired maximum value.

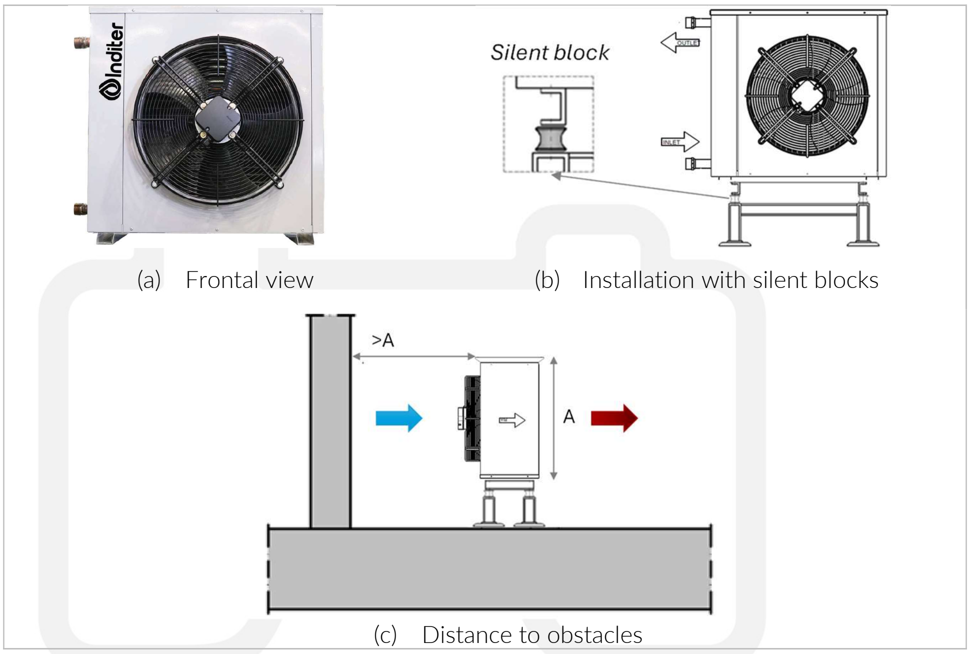


Figure 11: Solar air cooler for overheating protection.
Source: adapted from inditer.com

- For freezing protection, All-hydraulic circuits utilize a water-propylene glycol mixture as the heat transfer fluid (HTF), as it has a lower freezing point than water. To provide additional protection, the solar controller can activate the circulation pump when the ambient temperature falls below a minimum desired level. Additionally, the heat pump can be engaged to ensure the circuit temperature remains above the desired threshold.
- Additional alarms: the MiniStor system includes a PLC that communicates with the solar controller via the Modbus protocol to monitor key variables. Based on the data received, the PLC is programmed with additional safety alarms, such as one for high temperatures in the inertia tank and others for low and high pressure in the solar circuit.

6.2 Safety elements in electrical circuits

Regarding the electrical protection elements in the PVT-HP system, all DC and AC electrical circuits must incorporate the following protection types:

- Overload protections

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869821

- Short circuit protections
- Transient overvoltage
- Differential protections

These protections must be installed inside power board or panels, following the local regulations and standards. The PVT-HP system included electrical protections in three power boards: i) PVT power board, which collects the electricity generated by the PVT collectors, ii) HP power board, with the corresponding electrical protections for the HP (internal unit, external unit, and control elements), and iii) MiniStor board, which is pre-installed inside the MiniStor system container and include electrical protections for consumption elements in the solar thermal circuit (circulation pump, solar air-cooler, and control elements). Figure 12 illustrates a power panel used in a typical PV of PVT systems, available in the Spanish market. The final implementation must adopt the local regulation and requirements.

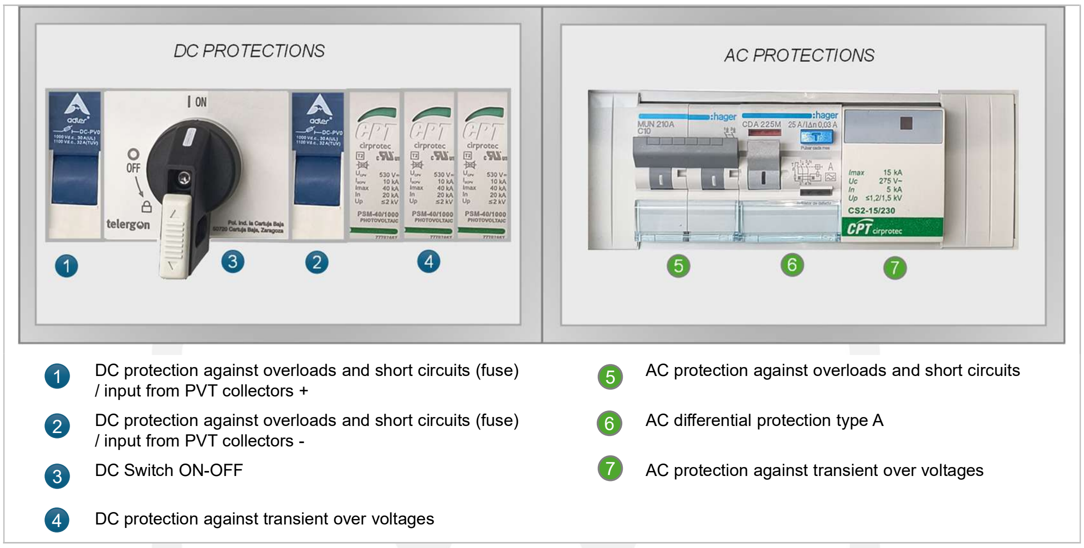


Figure 12: Electrical protections in the PVT electrical panel
Source: Adapted from Saltoki S.A

7 PVT-HP control elements installation and base control strategy

7.1 Control strategy for the PVT-HP thermal circuits system.

The control of the PVT-HP thermal circuits is managed by two local units: the solar thermal controller and the HP controller. The installation of these controllers must be carried out in accordance with their respective installation and operation manuals. This section describes how these controllers operate and outline the base control strategy defined for the thermal circuits in the PVT-HP system, which was implemented in the MiniStor project.

- Solar thermal circuit control

The solar thermal circuit is managed by a commercially available solar controller that is pre-programmed with various functionalities to ensure the optimal operation of the PVT solar thermal system. This solar controller is pre-installed inside the MiniStor container and communicates with the MiniStor system PLC via the Modbus protocol, enabling relevant variables to be read and integrated into the MiniStor monitoring system.

To activate the PVT solar thermal circuit, at least two temperature sensors are required: one installed at the outlet of the PVT solar bench and another at the bottom zone of the inertia tank. Using these sensors, the solar controller evaluates the temperature difference between the two points and activates the solar circulation pump when the outlet temperature of the solar system exceeds the temperature measured in the inertia tank.

The solar controller is also programmed with a dissipation functionality that activates the solar air cooler if the temperature in the PVT solar bench exceeds the desired limit for these collectors (85 °C). To achieve this, the solar controller first activates a relay output, which sends a signal to the corresponding contactor in the electrical circuit that powers the solar air cooler and a 3-way valve, dissipating excess heat into the environment.

In addition to the previous basic control functions, performed by the solar controller, to get an effective charging operation of the TCM in the MiniStor system, control strategy was parameterized with the set temperatures values presented in Table 7.

Table 7: Set temperatures used in the PVT control strategy

Operation	Description	Value [°C]
Charging TCM	Set temperature - Start - Stop	65[6] 65 55
Inertia Tank (Solar Circuit)	Set temperature Maximum temperature - Start - Stop	72 74 ΔT PVT -Tank > 5 ΔT PVT -Tank < 2
Solar air cooler (Solar Circuit)	Set temperature PVT - ΔT Valve (temperature difference valve open) - Start - Stop	76 2 79 76
Restriction (PVT)	Maximum temperature in PVT Conservative value adopted	< 85 < 77

- <u>HP thermal circuit control</u>,

The HP water thermal circuit is regulated by a wired remote control, which is provided together with the HP. This controller allows the visualization and regulation of relevant variables in both outdoor and indoor HP units, including the first and second compression stage, outdoor fans, as well as the secondary water circuit in the condenser side incorporated in the indoor unit.

This HP controller also communicates with the MiniStor system PLC, via a Modbus gateway, which is also provided by the HP manufacturer. Like the solar thermal controller, relevant variables can be read via Modbus and integrated into the MiniStor monitoring system.

Through the HP controller, the setpoint temperature for hot water production is established, and the HP compressors as well the circulation pump in the water HP circuit are activated. The thermal energy produced by the HP is sent to the inertia tank only if the

[6] *For some demonstrative purposes, this temperature can be increased up to 70 °C in the context of the MiniStor project.*

temperature in the top zone in the inertia tank is lower than the set temperature point defined in the HP controller.

Besides, the set temperature and activation of the HP can be performed via Modbus through the PLC; in this regard a specific schedule is established for better profit from the solar thermal resource.

- Base control strategy for the PVT and HP thermal circuits

As the base control strategy, the activation of the PVT and thermal circuits is performed as follows:

(1) The solar thermal PVT system is activated in the morning, before noon, while the HP circuit remains deactivated. This way allows to pre-heat the thermal circuits, the inertia tank and the overall internal volume of the MiniStor system using only solar thermal energy.

(2) After 12 noon, the HP water circuit is activated, using as setpoint temperature the values required by the MiniStor system (above 44 °C). Thanks to this schedule, the COP of the HP is improved due to the higher ambient temperature.

(3) The HP is deactivated again after total or partial charging process of the TCM in the MiniStor system.

This base strategy is improved by applying different charging times depending on the season and in accordance with the simulations performed in the context of D3.1: “Initial dimensioning of the system according to general use typologies”. Additionally, in the context of WP5, the control can be optimized by varying the HP activation time, also considering the State of Charge (SOC) in the Electrical Storage System (ESS)

7.2 Control strategy for the PVT electrical system.

The control strategy for the electrical PVT production system is managed by the hybrid inverter, which serves as the smart component of the system. It is responsible for overseeing various operating modes, which primarily include:

(1) supplying electricity to the electrical receptors in the HP, MiniStor system and the building.

(2) charging the Electrical Storage System (ESS) with surplus electricity or, when permitted, using grid electricity during off-peak periods,

(3) discharging the ESS to meet electricity demand, or

(4) feeding surplus electricity back into the grid in accordance with the regulatory conditions at the demo site (e.g., compensation rates, net metering).

This equipment allows measuring electricity PVT production via sensors built into the inverter, as well as the electrical consumption of the demand subsystem through a bidirectional power meter (smart meter) that is compatible with the inverter. The demand subsystem includes consumption in the HP, in the MiniStor system and in the building.

These control strategies will be detailed in D3.9, which discusses the ESS installation strategies, as well as in WP5-related deliverables, which focus on the overall control subsystems, including Modbus integration components."

8 Conclusion

This Deliverable presents the installation strategies for the PVT-HP system, which integrates high electrical performance unglazed PVT collectors with a heat pump to provide energy to the MiniStor system and the building.

Various options exist for the thermal integration between the PVT collectors and heat pumps, such as direct expansion, indirect-parallel configuration and indirect-serial configuration. For the implementation carried out within the MiniStor Project at the Santiago de Compostela demonstration site, an indirect parallel integration was selected as the most suitable option for the local weather conditions.

A key consideration in the installation strategies is the optimal placement of the main subsystems and components, including the PVT subsystem, the heat pump (HP), and the MiniStor container, to minimize thermal losses, as well as, to fulfill the safety requirements for the HP and the MiniStor system.

The connection strategies for these subsystems were also addressed, considering the electrical, hydraulic, and refrigerant connection requirements for the PVT solar field, the HP, and their integration with the MiniStor system. This information is intended to serve as a general guide for the installation of PVT-HP systems used as energy generation solutions in MiniStor system implementations.

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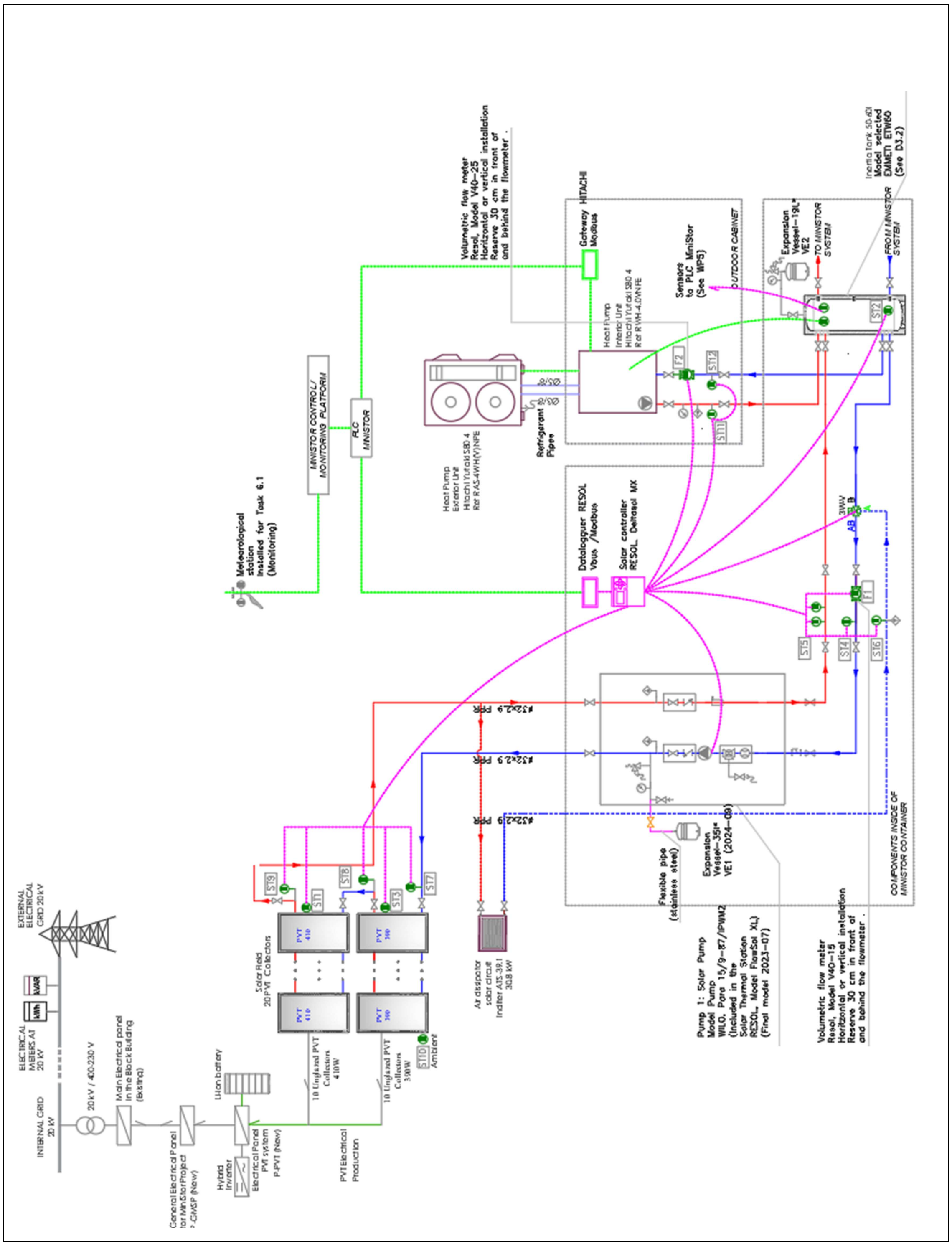
Annexes

Annex I – Detailed general piping scheme for the PVT-HP system designed for the MiniStor implementation



Annex II. Summary of installation and connection strategies applied Santiago de Compostela -USC demo site

This section summarized the installations and connection strategies performed in the Santiago de Compostela – USC demonstration site. Further details about the installation process and the implementation are presented in D6.4 "Installation and commissioning report".

Table 8: Summary of main installation strategies applied to the PVT-HP system in the MiniStor project.

Demo site	Main installation strategies applied to the PVT-FPC system
PVT solar field 	▪ Solar field location strategy: in outdoors in a garden area, close to MiniStor system to limit thermal losses ▪ Number of collector's bench in the solar field: PVT benches: 4 arrays with 5 unglazed PVT collectors each (PVT model 1.90 m2) ▪ Structures in closed triangle for flat zone in single rows, adapted to 20 °C slope. ▪ Hydraulic connection of PVT collectors using standard fittings and additional individual drain valves by PVT collector to reduce de air drain in the installation ▪ General Hydraulic circuit performed with insulated copper pipes. Thermal production sent into an inertia tank pre-installed inside the MiniStor system. ▪ Electrical connections of PVT collectors using the MC4 connectors incorporated in the PVT collectors. Electrical production is fed into a PVT power board.
Heat pump 	▪ HP selected, air-to-water, biblock type, with indoors and outdoors unit, with production temperature rate up to 80 °C. ▪ location strategy for the indoor unit: in a room close to MiniStor system to reduce the hydraulic circuit length and limit the thermal losses. ▪ Location strategy for the outdoor unit: close to internal unit, according to the manufacturer specifications, not needs additional refrigerant charge. ▪ Room for internal unit volume and natural ventilation in accordance with safety requirements. ▪ Hydraulic circuit performed in copper insulated, using all safety elements required. Thermal production sent into an inertia tank pre-installed inside the MiniStor system. ▪ Electrical circuit performed following the local standard and manufacturer specifications, with an exclusive electrical board panel.
Inertia tank for parallel integration	▪ Use of inertia tank, pre-installed inside the MiniStor System for parallel hydraulic integration between the PVT solar field and the HP. ▪ Inertia tank volume, 57 l, above the minimal value required by the HP manufacturer, and in agreement with D3.2 related to specifications for peripherical equipment.

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