Photovoltaic and Thermal for Europe

D5.1 Report on selected application scenarios and simulation models

Work Package: WP 5 PVT4EU system integration technologies, including heat pumps and absorption chillers

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Date: 2025/03/20

This project has been granted by the Clean Energy Transition Partnership Programme (project ID. CETP-2022-00403). The work is supported by national funds through, Sweden: Swedish Energy Agency (P2023-00884); Denmark: Innovation Fund Denmark (3112-00010B); and Portugal: FCT- Fundação para a Ciência e a Tecnologia, I.P. (CETP/0004/2022)

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Document history

Revision	Date	Status
V1.0	07 March 2025	Initial draft for external review
V1.1	20 March 2025	Modified draft after review
V2.0	20 March 2015	Final draft

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Executive Summary

Six different promising applications for the PVT panels manufactured by SOLARUS, (PVT-MG) and SolarPeak (PVT-SP) have been selected for detailed theoretical investigations:

- PVT-MG industrial systems with connection to return/condensate lines
- PVT-MG industrial systems with absorption chillers
- PVT-MG for single and multi family houses in Southern Europe
- PVT-SP/heat pump systems for multi family houses
- PVT-SP/swimming pool systems
- PVT-SP fields for low temperature district heating systems.

This report describes the boundary conditions and simulation models for each application.

The results of the calculations with the simulation models will be described in the report D5.2 “Report on system performance of the selected PVT applications (V1)”, which will be ready by July 2025.

1. Applications and boundary conditions

Besides the technological development, prototyping and testing of innovative PVT collectors, the PVT4EU project also aims to study the application of those collectors in the building and industry sectors. To do so, TRNSYS simulation studies will be carried out for a set of the most relevant applications for the PVT collectors manufactured by SOLARUS (PVT-MG) and SolarPeak (PVT-SP).

The following six applications have been selected based on evaluation by all partners in the project:

- PVT-MG industrial systems with connection to return/condensate lines
- PVT-MG industrial systems with absorption chillers
- PVT-MG for single and multi family houses in Southern Europe
- PVT-SP/heat pump systems for multi family houses
- PVT-SP/swimming pool systems
- PVT-SP fields for low temperature district heating systems.

The applications, the boundary conditions and preliminar simulation models for each application are described in the following sections.

1.1. PVT-MG industrial systems with connection to return/condensate lines

The industry sector accounts for a considerable share of the energy consumption in the European Union (EU), having been responsible for 25,1% of the final energy consumption in the EU [1] (and 34% worldwide [2]) in 2022. Figure 1.1.1 presents the final energy demand by industrial sector in the EU. The industrial sectors with higher energy consumption are the chemical and petrochemical industry (20,0%), the non-metallic minerals industry (14,5%), the paper, pulp and printing industry (13,5%), the food, beverages and tobacco industry (12,2%) and the iron and steel sector (10,2%) [1].

Detailed statistics of heat consumption in the EU industrial sector are unavailable, however, estimates based on survey methods combined with bottom-up models concluded that the share of heat in the final energy demand of the EU industries was 71% in 2012, 84% of which corresponds to process heat [3]. Figure 1.1.2 presents the final energy demand for process heat and the respective share by temperature levels for different industrial sectors in the EU . It can be seen that the Food, Beverages and Tobacco sector presented the higest share of heat demand at temperatures up to 100ºC and the third largest share of heat demand at temperatures up to 200ºC. Moreover, the share of heat in the final energy consumption of this sector was estimated to be 62% [4].

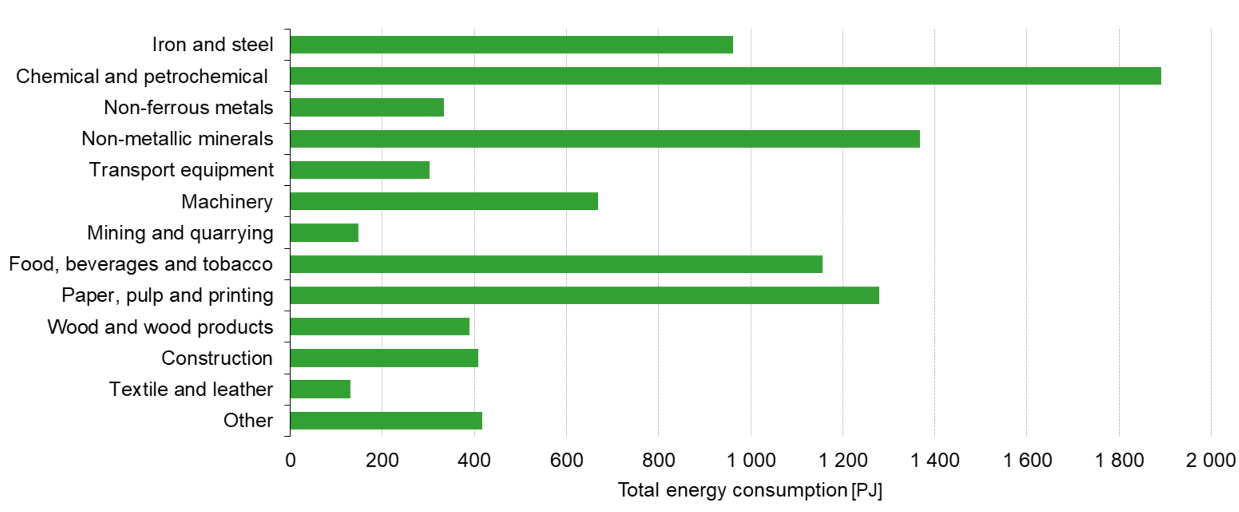


Figure 1.1.1 Total final energy consumption by industrial sector in the EU in 2022 [1]

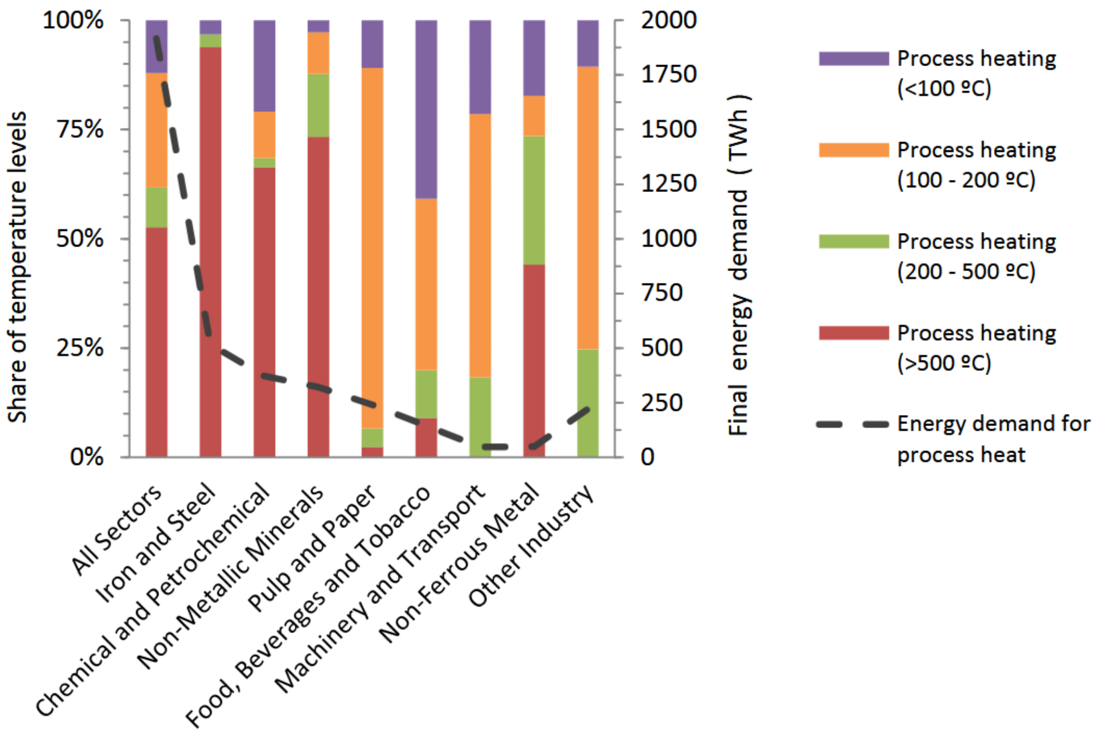


Figure 1.1.2 Final energy demand for process heat and share of temperature levels by industrial sector for EU in 2012 [4]

The use of solar energy to supply process heat can be achieved through several integration concepts, being the choice of the integration concept dependent on the particular industrial facility, the integration level (at the energy supply or process level) and the application being targeted [5].

Taking into consideration all of the above and considering the target operating temperatures of the collectors being developed under the PVT4EU project (up to 140ºC for the Solarus collector), the application of the PVT4EU collectors to the Food, Beverages and Tobacco sector has a high potential that should be further analyzed. Therefore, the Food, Beverages and Tobacco sector has been selected as the focus for the study of the integration of the Solarus PVT collector in industrial systems.

Steam is one of the prefered heat transfer fluids traditionally used in the industry sector due to its high energy density (allowing for heat distribution networks with smaller piping diameters) and high heat transfer rates (allowing for operation at constant temperature due to condensation) [5]. Therefore, for this case study, the integration of solar heat at the energy supply level in the steam generation system was targeted.

1.1.1. System design

Conceptually, the integration of solar heat, at supply level, in an industrial facility using steam as heat transfer fluid can occur at three points: steam generation; boiler feedwater; make-up water [5]. Considering that the PVT4EU sollutions, namelly the PVT-MG collector, are designed to operate in the low to medium-low temperatures (maximum target operation temperature of 140ºC) the focus of this analysis will lie in the pre-heating of boiler feedwater, figure 1.1.3 and/or make-up water, figure 1.1.4.

It is worthwile to notice that these two integration concepts are similar to another supply level integration concept applicable in facilities where the heat is distributed by a liquid heat transfer fluid (e.g. pressurized water, thermal oil), namely the pre-heating of the return line, figure 1.1.5.

Figure 1.1.6 presents a functional block diagram for a PVT system supplying thermal energy for the pre-heating of boiler feedwater and electrical energy to the industrial plant. The PVT collectors will provide electricity to the general electrical load of the plant and thermal energy to a buffer storage tank. The solar energy stored in the buffer tank will be used to pre-heat the feedwater and/or make-up water entering into the boiler, reducing the fuel consumption of the boiler. The heat demand of the industrial processes will be satisfied by the steam produced by the boiler.

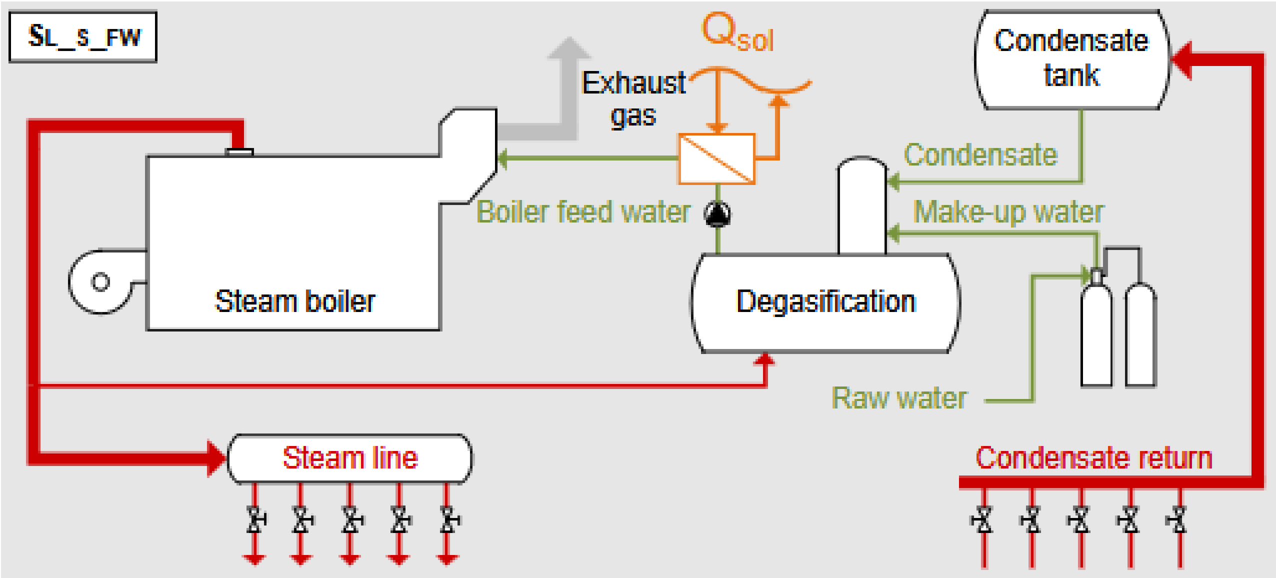


Figure 1.1.3 General integration concept for solar pre-heating of boiler feedwater [5]

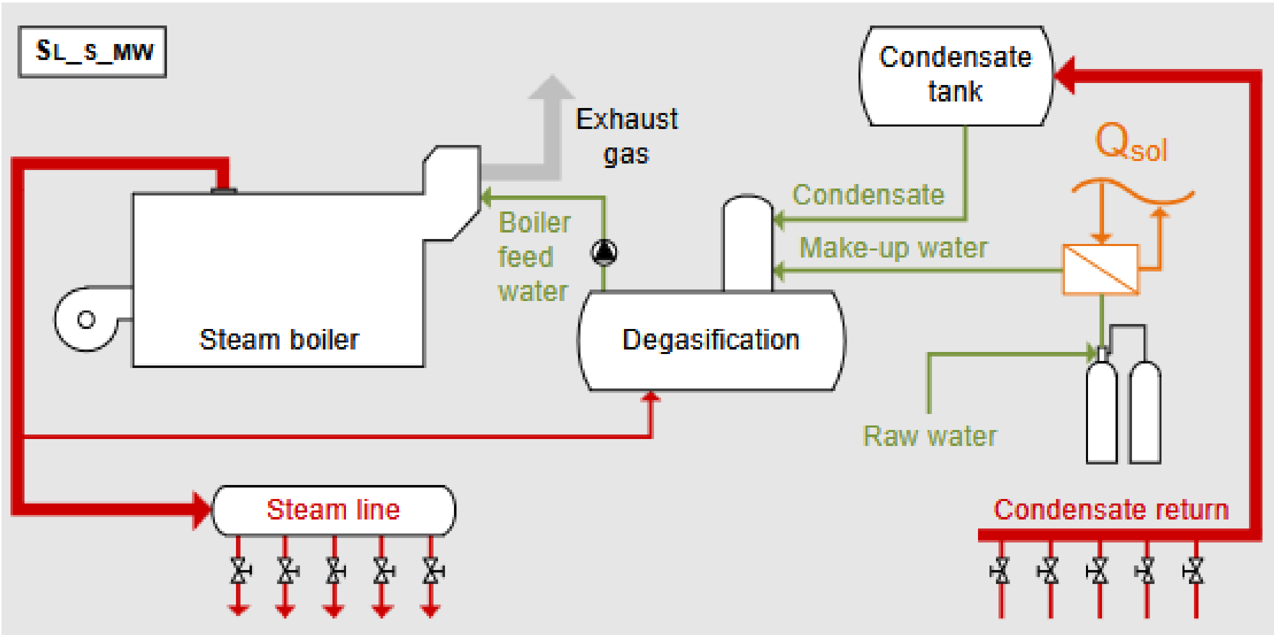


Figure 1.1.4 General integration concept for solar pre-heating of make-up water [5]

The PVT collectors will be grouped in several paralel batteries of collectors connected in series and the number of collectors in series and of paralel batteries will be defined from a techno-economic optimization. Likewise, the size of the buffer storage will be set from a techno-economic optimization.

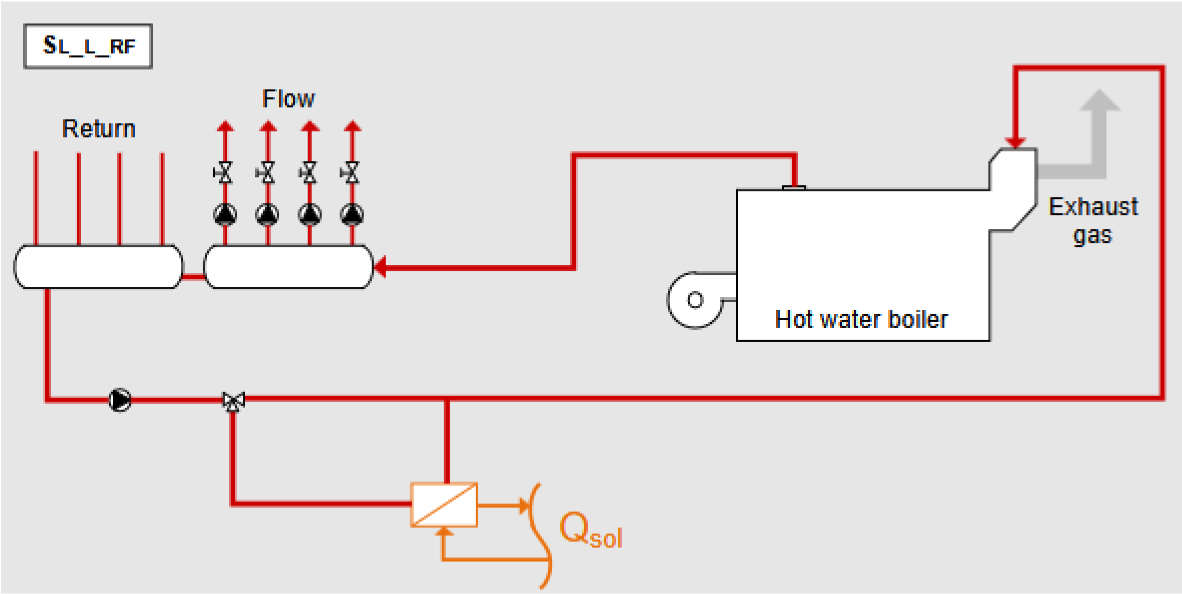


Figure 1.1.5 General integration concept for solar pre-heating of return lines [5]

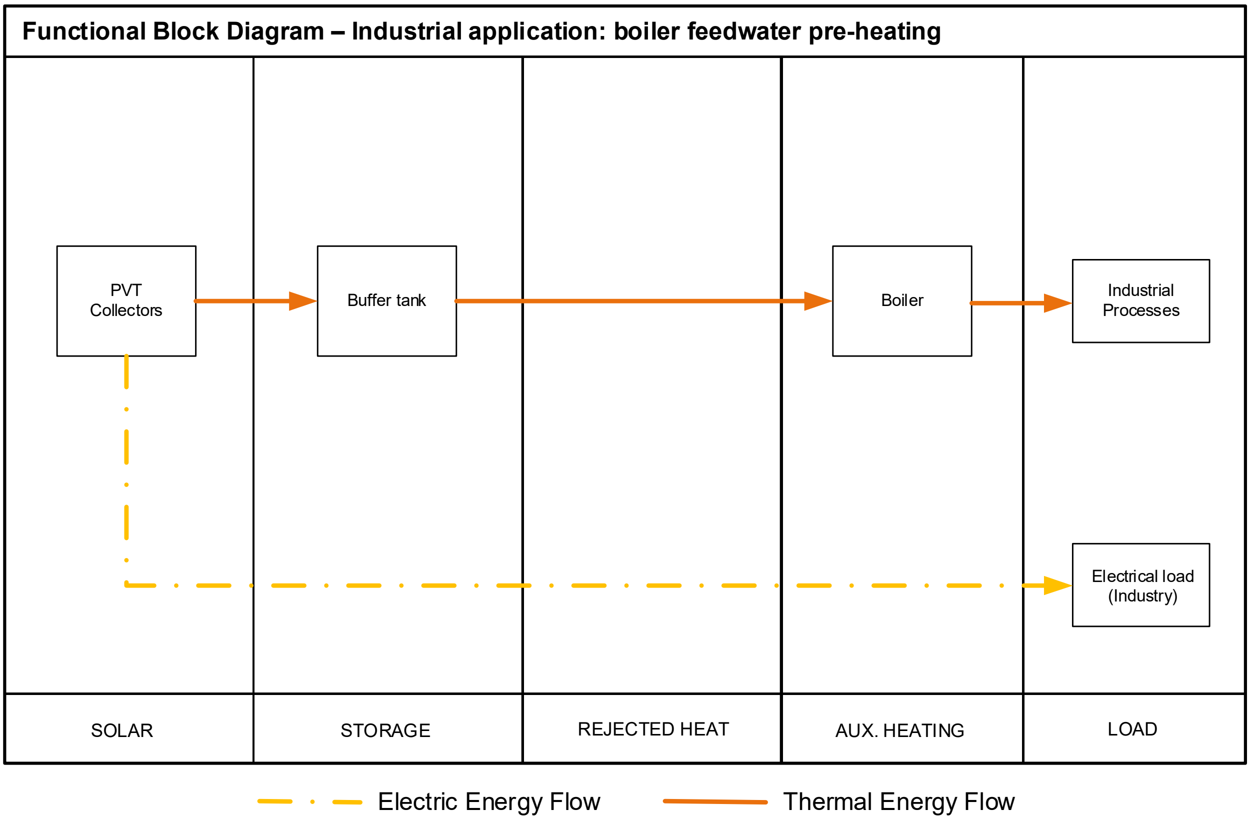


Figure 1.1.6 Functional block diagram of a PVT system applied to boiler feedwater pre-heating

A canned food production plant located in Portugal was selected as target for this case study.

This facility uses natural gas boilers to produce superheated steam for process heating in several processes such as thawing, cooking, cleaning and sterilization. Part of the steam used in those processes is recovered as condensate and gathered in a condensates tank. Make-up water is added to the condensates tank to cover for water mass losses in purges and in processes using open-steam lines.

Considering the configuration of the existing installation, the heat generated by the PVT collectors will be used to heat the condensate tank, pre-heating the condensate and make-up water mixture before it is pumped to the boiler's economizer.

1.1.2. Boundary conditions

At the moment of issuance of the report, a non-disclosure agreement is being established between the company and LNEG in order to allow access to real operation data for a full year, including profiles for:

i. Steam mass flow rate at the boiler's outlet;
ii. Water mass flow rate at the boiler's inlet;
iii. Make-up water mass flow rate;
iv. Temperature and pressure of the streams identified in i., ii. and iii.;
v. Electric energy consumption at the plant;
vi. Specific and total costs associated with consumption of electric energy and natural gas at the plant.

This data, together with meteorological data for the location of the plant will be used as boundary conditions for the case study.

1.1.3. Simulation model

A TRNSYS model was developed to simulate this system using the component models (types) identified in Table 1.1.1, see figure 1.1.7.

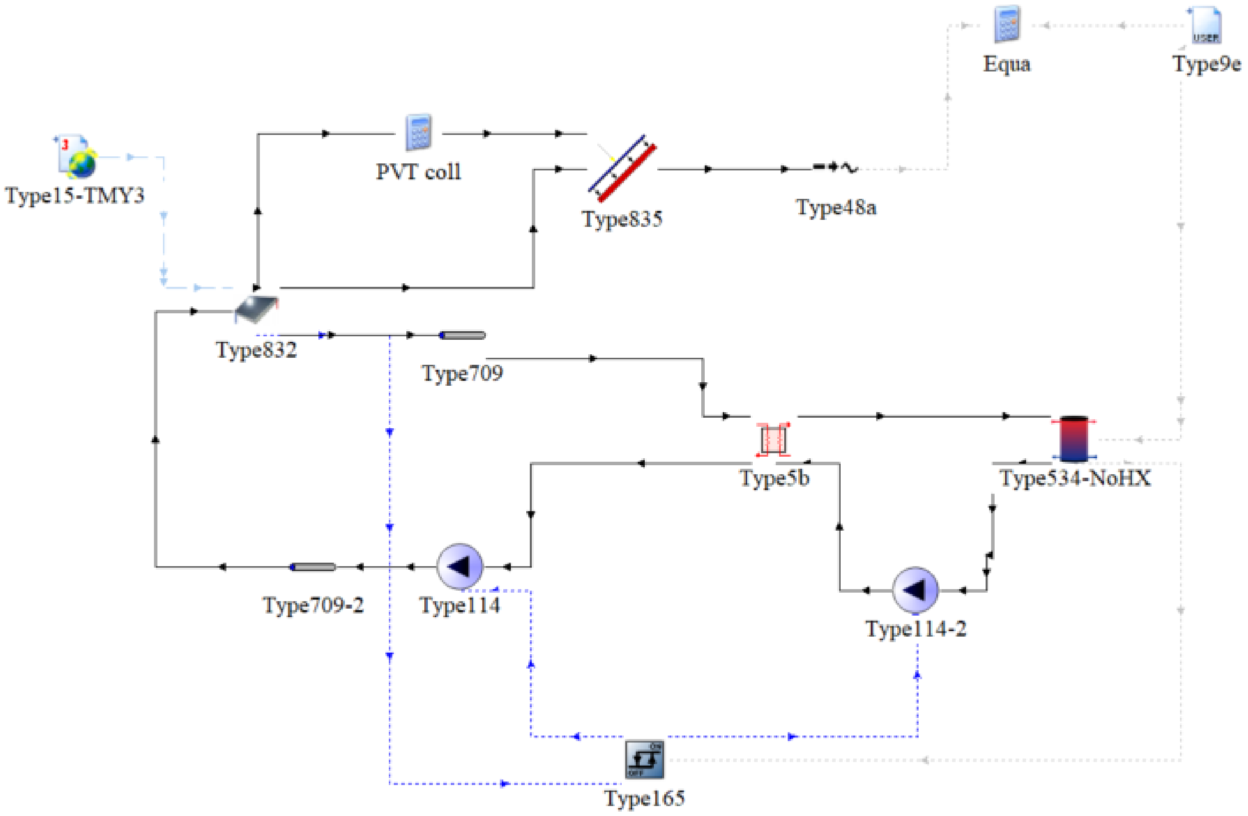


Figure 1.1.7 TRNSYS model for simulation of boiler feedwater preheating system using PVT collectors

Table 1.1.1 *Component models used in the TRNSYS model of the boiler feedwater preheating system using PVT collectors*

Component	Type	Component	Type
Meteorological data	15	Pumps	114
PVT collector field	832 and 835	Piping	709
Inverter	48a	Controller	165
Thermal energy storage	534	Load profiles	9e
Heat exchanger	5b	Equations	Equa

It should be noted the PVT collector field is modelled using two types. Type 832 models the thermal performance of a PVT collector according to the model used in the ISO 9806 quasi-dynamic testing method as described in [6]. Type 835 models the electric performance of a PVT collector considering the efficiency of PV cells thermally coupled to a solar thermal absorber as described in [7]. Experimental performance coefficients derived for the PVT-MG during experimental testing activities will be used in both types. Some parameters of the 835 can be set to typical PV cell values. Alternatively, they can be optimised according to experimental test results using existing algorithms in the TRNSYS software (TRNOPT).

1.2. PVT-MG industrial systems with absorption chillers

Process cooling represented 4% of the final energy demand of the industry sector in the EU in 2015, half of which corresponds to cooling demand at temperatures below 0ºC [8]. Amongst all industrial sectors, the food and beverage sector had the highest demand for process cooling, representing 10% of the final energy consumption in that sector in the EU in 2015 [4].

Cooling demand in the industrial sector is usually associated with cooling of equipment, process tanks, storages (e.g. freezers and cold storages), raw materials and products. Different technologies can be used for cooling applications in the industrial sector, such as electrically driven compression chillers (the most common in industries), cooling towers (direct or indirect contact), dry coolers and thermally driven sorption chillers [5].

Commercially available thermally driven sorption chillers are classified as absorption or adsorption chillers, depending on the physical process used to produce cooling. Absorption chillers require heat supplied at higher temperatures than adsorption chillers, but also present higher Coefficient of Performance [9, 10]. Both single effect absorption chillers and adsorption chillers can be operated with heated water at temperatures below 100ºC, typically providing cooling at temperatures down to 7ºC, with ammonia-water absorption chillers being able to provide cold below 0ºC [10].

In this case study, the use of PVT systems to provide low temperature heat (<100ºC) for absorption chillers and electricity to an industrial plant from the Food, Beverages and Tobacco sector will be assessed.

1.2.1. System design

Conceptualy the heat generated by a PVT system can be used to drive an absorption or adsorption chiller. In a generic solar cooling system based on PVTs, heat from the solar field is used to drive the thermally driven chiller or, in case the available heat exceeds the chillers' requirement, used for heating purposes, see figure 1.2.1. If available, other heat sources, such as waste heat or geothermal heat, can be used both to supply heating demand or to drive the chiller, complementing the heat supplied by the solar field. Conventional chillers can be used as back-up systems to supply the part of the cooling demand not covered by the thermally driven chiller. Finnally, the electricity generated by the PVT collectors can be used to drive the conventional chillers or to supply the electricity demand.

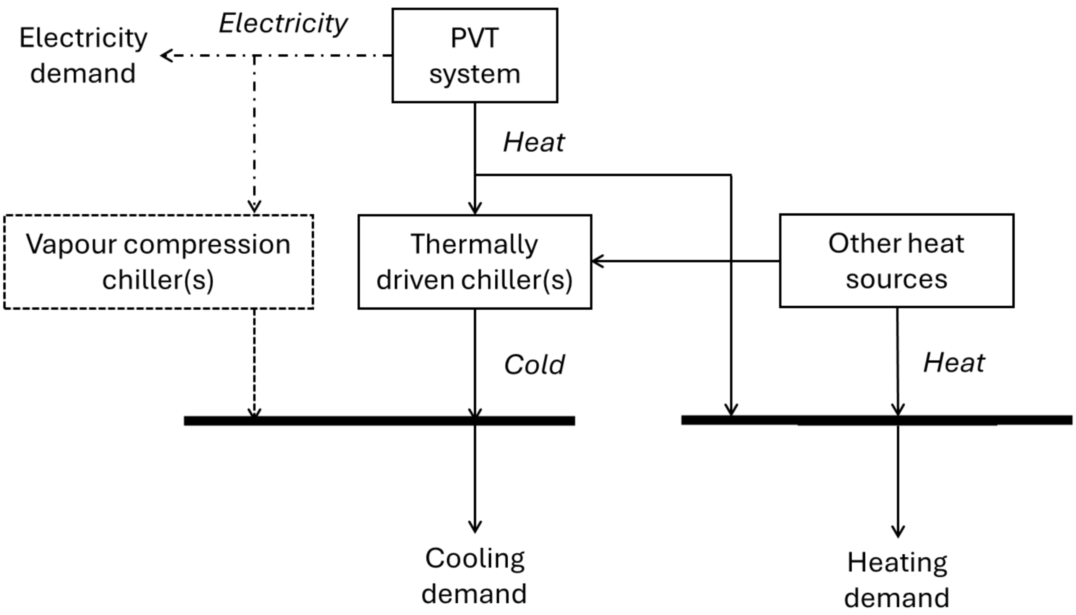


Figure 1.2.1 Basic layout of a generic solar cooling system (adapted from [11])

Figure 1.2.2 presents a functional block diagram for a PVT system supplying electrical energy to cover part of the load of the industrial plant and thermal energy to drive an absorption chiller producing cold for an industrial process. The low temperature waste heat from the chiller will need to be rejected, using cooling towers or, if the temperatures are compatible, to pre-heat make-up water for the boiler circuit.

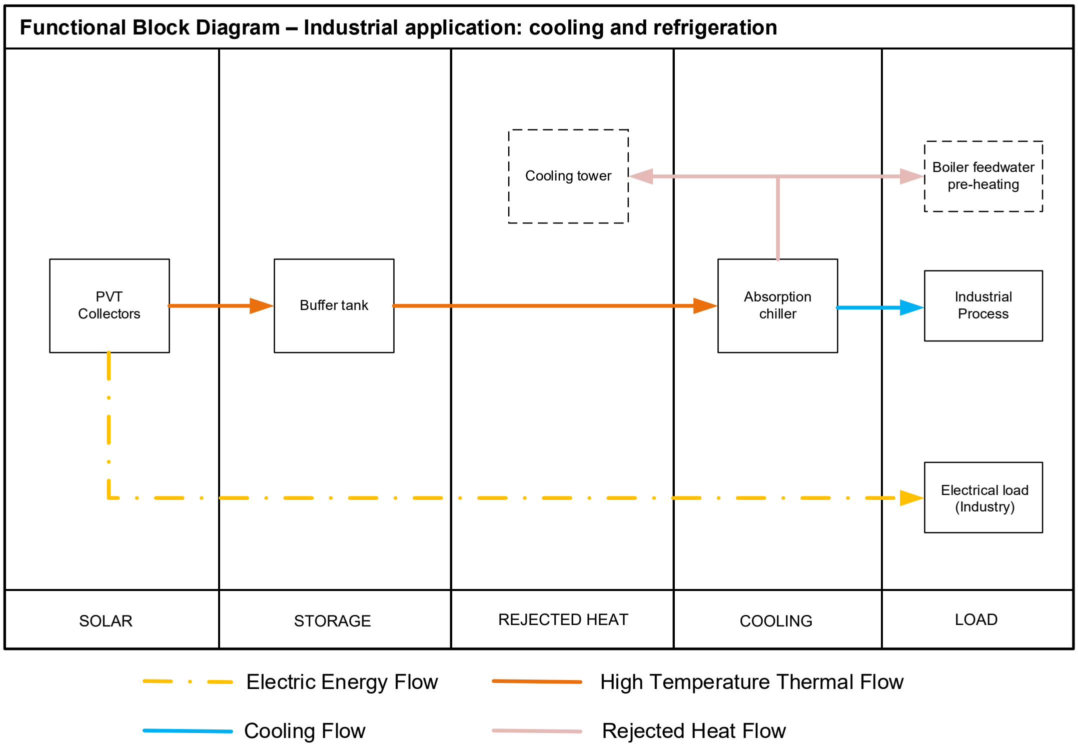


Figure 1.2.2 Functional block diagram of a solar cooling system driven by PVT collectors for industrial process cooling

A canned food production plant located in Portugal was selected as target for this case study. This facility uses cooling towers to cool the food cans after the sterilization process occurring within autoclaves. Currently the time required to reduce the temperature of the cans is a limiting factor in the production line. Therefore, the possibility of using chilled water to achieve a faster cooling of the cans is of interest.

Considering the configuration of the existing installation, heat generated by the PVT system will be used to drive an absorption chiller that will produce chilled water to cool the cans. The electricity generated by the PVTs will be used to partially cover the electricity demand of the production plant.

1.2.2. Boundary conditions

At the moment of issuance of the report, a non-disclosure agreement is being established between the company and LNEG in order to allow access to real operation data for a full year, including profiles for:

i. Cooling circuit mass flow rate:

ii. Boiler's make-up water mass flow rate;

iii. Inlet and outlet temperatures of the cooling circuit;

iv. Boiler's make-up water temperature;

v. Electric energy consumption at the plant;

vi. Specific and total costs associated with consumption of electric energy at the plant.

This data, together with meteorological data for the location of the plant will be used as boundary conditions for the case study.

1.2.3. Simulation model

A TRNSYS model was developed to simulate this system, figure 1.2.3 using the component models (types) identified in table 1.2.1.

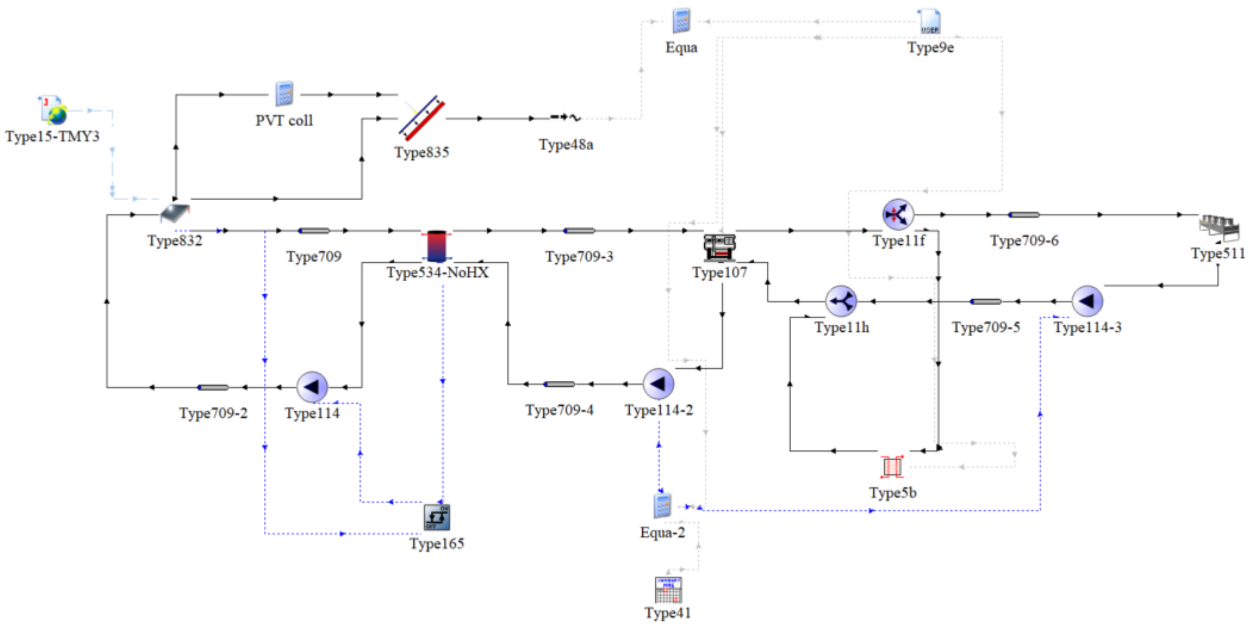


Figure 1.2.3 TRNSYS model for simulation of a solar cooling system driven by PVT collectors

for industrial process cooling

Table 1.2.1 *Component models used in the TRNSYS model of the PVT driven solar cooling system*

Component	Type	Component	Type
Meteorological data	15	Piping	709
PVT collector field	832 and 835	Heat exchanger	5b
Inverter	48a	Controller	165
Absorption chiller	107	Scheduling profiles	41
Dry cooler	511	Load profiles	9e
Thermal energy storage	534	Flow diverter	11f
Equations	Equa	Flow mixer	11h
Pumps	114		

1.3. PVT-MG for single and multi-family houses in Southern Europe

The residential sector was responsible for 26,9% of the final energy consumption in the EU in 2022, with space heating being responsible for a share of 63,4% of the used energy, followed by domestic hot water production with a share of 14,8% (space cooling represents a share of only 0,6%). These shares will vary from country to country, depending on several factors namely the climate. For example, in the Iberian Peninsula, the share for space heating is much lower (39,4% in Spain and 32,3% in Portugal) while the share for water heating is higher (19,1% in Spain and 16,2% in Portugal) [12].

Data collected in 2020 suggested that in Portugal, 81,6% of households used space heating. A large majority (64,8%) used radiative or convective electric heaters, while only 20,3% used heat pumps. Nearly half of the households used heaters fueled by biomass (24,2% used fireplaces with heat recovery system, 15,0% used fireplaces without heat recovery and 9,3% used biomass stoves) and 16,6% used biomass or gas boilers. In terms of energy, space heating is mainly provided by biomass (81,2%) and electricity (7,6%) [13].

A majority of Portuguese households heated water for domestic use with gas heaters (67,3%), boilers (16,7%), electric water heaters (16,7%), solar thermal collectors (8,0%) and heat pumps

(0,8%). In terms of energy, water heating is mainly provided by gas (75,5%) and solar thermal (9,5%) [13].

In this case study, the use of PVT systems to provide low temperature heat (~65 ºC) for the preparation of domestic hot water in both single and multi-family buildings in Portugal will be assessed.

1.3.1. System design

There are several alternatives for the integration of solar heat in the domestic hot water heating (DHW) system in residential buildings, depending on several factors such as the type of system (direct or indirect, thermosyphon, forced circulation, etc.), it's integration in the building (decentralized vs centralized) or the back-up system. For the purpose of this study, four different configurations will be studied:

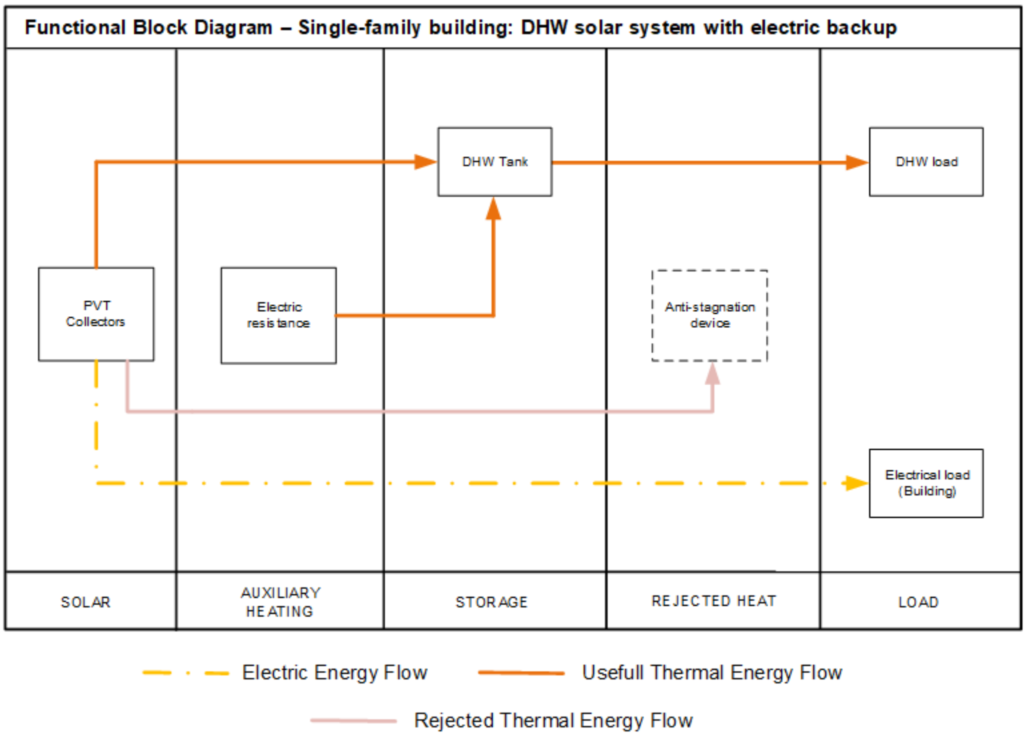
i. Single-family building with solar DHW system with back-up from an electric resistance;

ii. Single-family building with solar DHW system with back-up from an heat pump;

iii. Multi-family building with solar DHW system with back-up from an electric resistance and distributed storage;

iv. Multi-family building with solar DHW system with back-up from an heat pump and centralized storage.

Figure 1.3.1 presents the proposed functional block diagrams for the integration of heat provided by PVT systems in the domestic hot water preparation system in single-family houses. The heat collected in the PVT collectors is transferred to a tank where it is used to heat the potable water that is used to supply the DHW load. Whenever the PVT field is unable to provide the required heat, a back-up system is applied. Two different back-up systems are considered, resistive heating using an electric resistance or a heat pump. In order to avoid reaching stagnation temperatures in the collectors, during periods of low DHW use and high irradiance (e.g. the summer holidays), anti-stagnation device may be used to reject heat. All electricity generated by the PVT collectors will be provided to the supply of the building's electrical load.



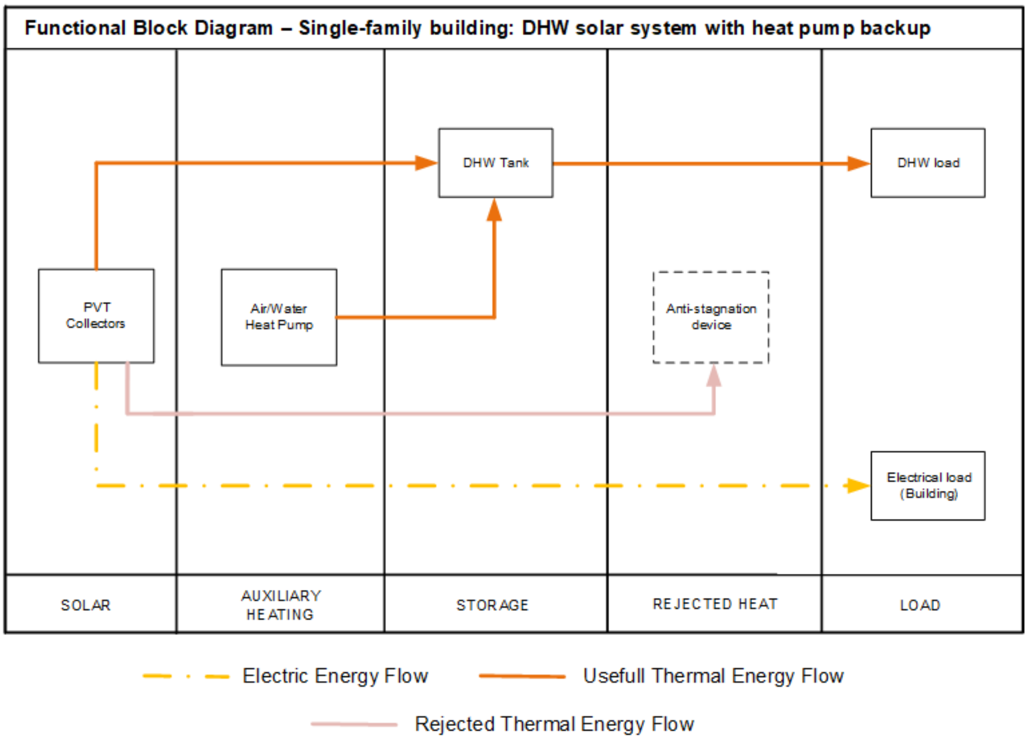


Figure 1.3.1 Functional block diagrams of domestic hot water solar systems using PVTs in

single family buildings

Figure 1.3.2 presents the proposed functional block diagram for the integration of heat provided by PVT systems in the domestic hot water preparation system of a multi-family building using decentralized storage. Conceptually the system is similar to the one presented above for single-family buildings using electric resistances as back-up, with the PVT collectors distributing heat across the DHW tanks installed in the different fractions of the building.

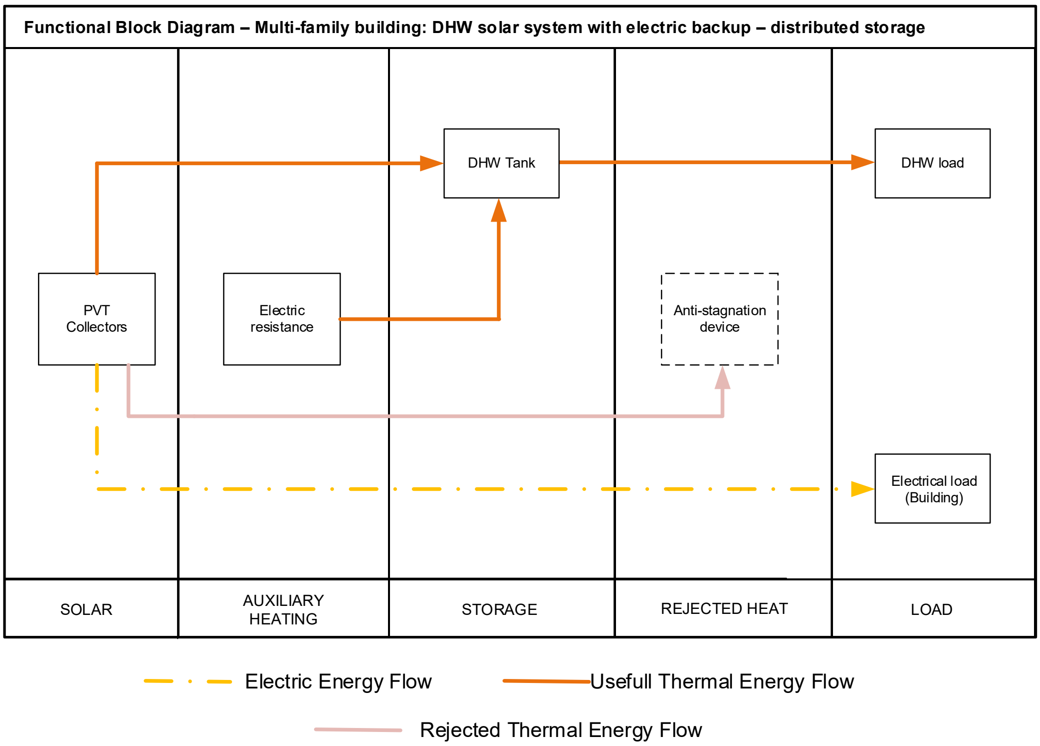


Figure 1.3.2 Functional block diagram of domestic hot water solar systems using PVTs in multi- family buildings using distributed storage

Figure 1.3.3 presents the proposed functional block diagram for the integration of heat provided by PVT systems in the domestic hot water preparation system of a multi-family building using centralized storage.

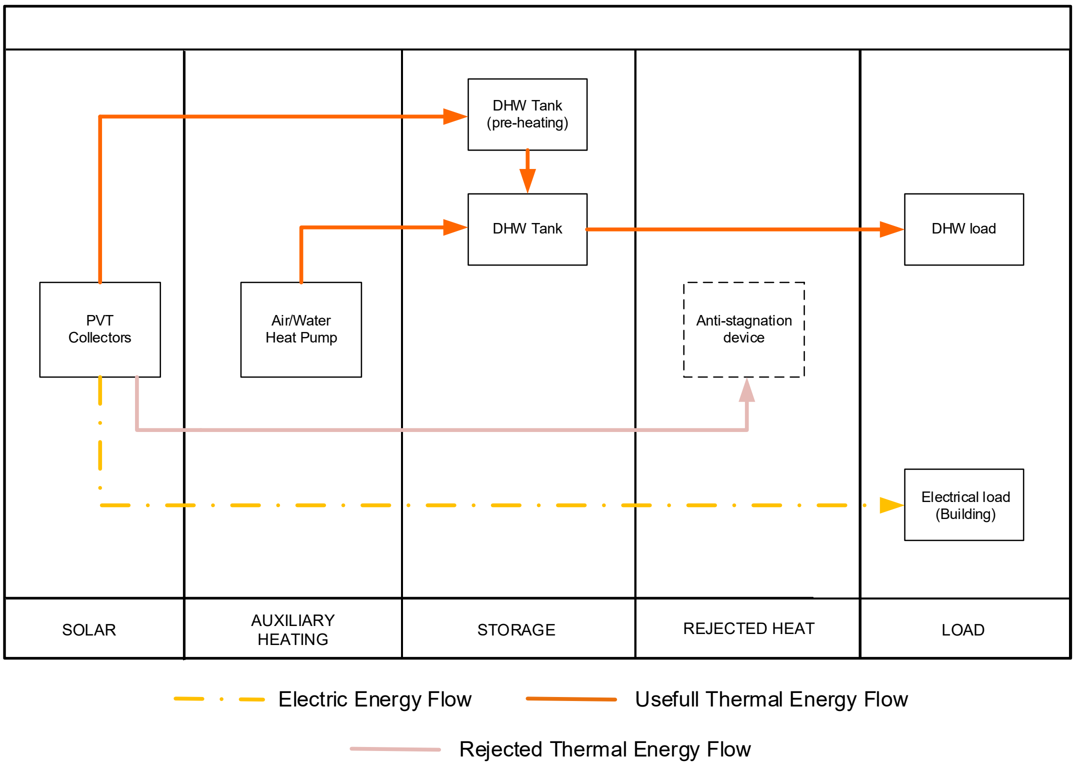


Figure 1.3.3 Functional block diagram of domestic hot water solar systems using PVTs in multi- family buildings using centralized storage

In this case, the heat generated by the PVT collectors is used to prepare domestic hot water in a first tank. This water passes through a second tank where it can be further heated by an air-water heat pump before being provided to supply the domestic hot water demand of the households of the building. Similar to the previous system designs, in order to avoid reaching stagnation temperatures in the collectors, during periods of low DHW use and high irradiance (e.g. the summer holidays), anti-stagnation device may be used to reject heat. All electricity generated by the PVT collectors will be supplied to the supply of the building's electrical load.

1.3.2. Boundary conditions

Both the single- and multi-family buildings analyzed in these case studies are located in Lisbon, Portugal, for which a typical meteorological year, derived using Meteonorm 8, will be considered.

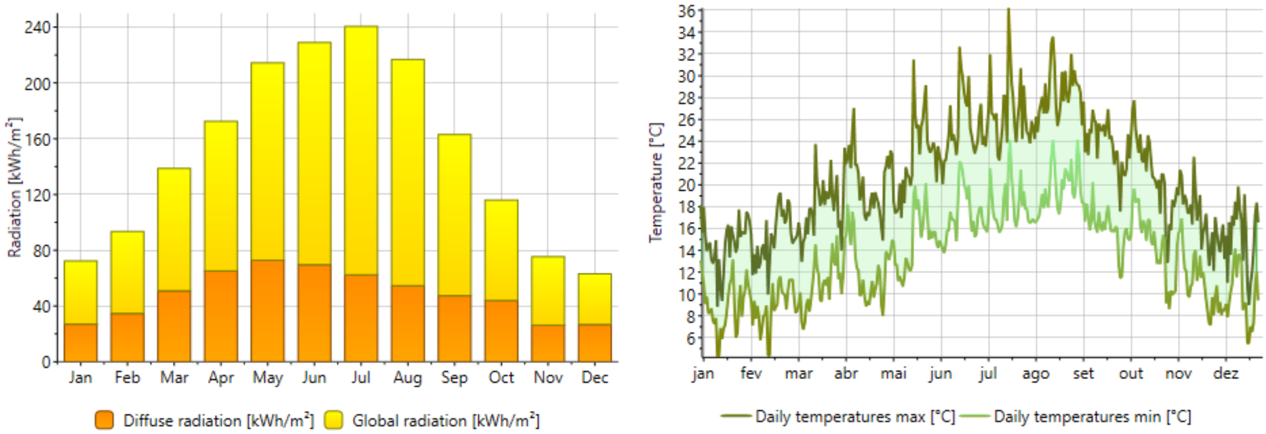


Figure 1.3.4 Typical meteorological year for Lisbon, Portugal: Irradiation (left); Maximum and minimum daily temperatures (right)

The average household is considered of having a size of 2,4 persons (average household size in 2021 in the Lisbon region [14]). The number of households in multi-family buildings was determined considering available information for the number of households per type of building in the Lisbon Metropolitan Region [15], being set at 8.

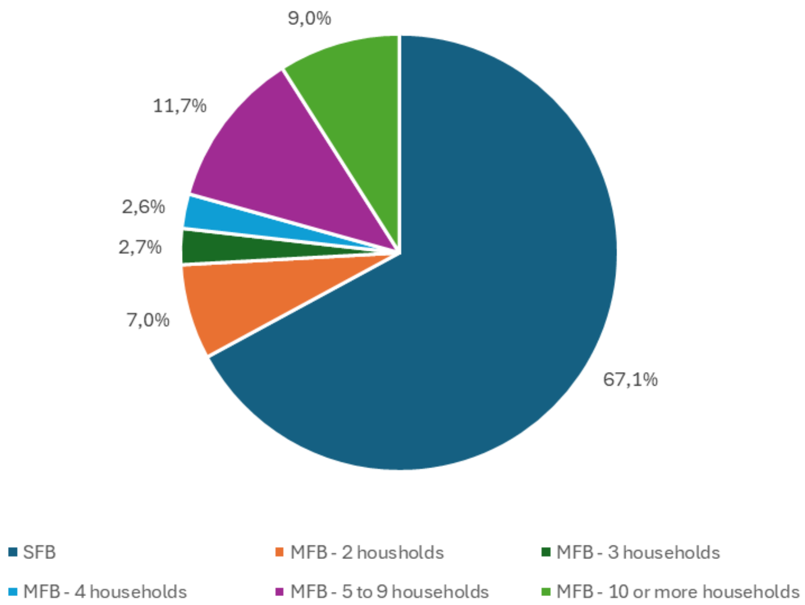


Figure 1.3.5 Number of households per type of building in the Lisbon Metropolitan Region

The electricity demand for each household will be constructed from standard profiles for low voltage consumers with installed power capacity below 13,8 kVA with annual consumption less than 7 140 kWh provided by E-Redes [16]. This class of consumers corresponds mostly to residential consumers.

The daily domestic hot water demand for each household will be constructed from the conditions and profile of DHW consumption per inhabitant established in the Portuguese Building Energy Certification System [17]. Average daily consumption patterns will be established from water consumption profiles for Portugal [18], assuming the domestic water consumption pattern follows a similar pattern as the total water consumption.

Annual electricity and water demand profiles will be developed using the information from electricity and DHW demand referred above using stochastic load profiles tools such as DHWcalc [19].

1.3.3. Simulation model

Four different models were implemented in TRNSYS to represent the four cases under study:

i. Case 1 (SFB-E) - Single-family building with solar DHW system with back-up from an electric resistance;

ii. Case 2 (SFB-HP) - Single-family building with solar DHW system with back-up from an heat pump;

iii. Case 3 (MFB-D) - Multi-family building with solar DHW system with back-up from an electric resistance and distributed storage;

iv. Case 4 (MFB-C) - Multi-family building with solar DHW system with back-up from an heat pump and centralized storage.

1.3.3.1. Case 1

A TRNSYS model was developed to simulate a solar DHW system for a single family building with an electric resistance as back-up (Figure 1.3.6) using the component models (types) identified in Table 1.3.1.

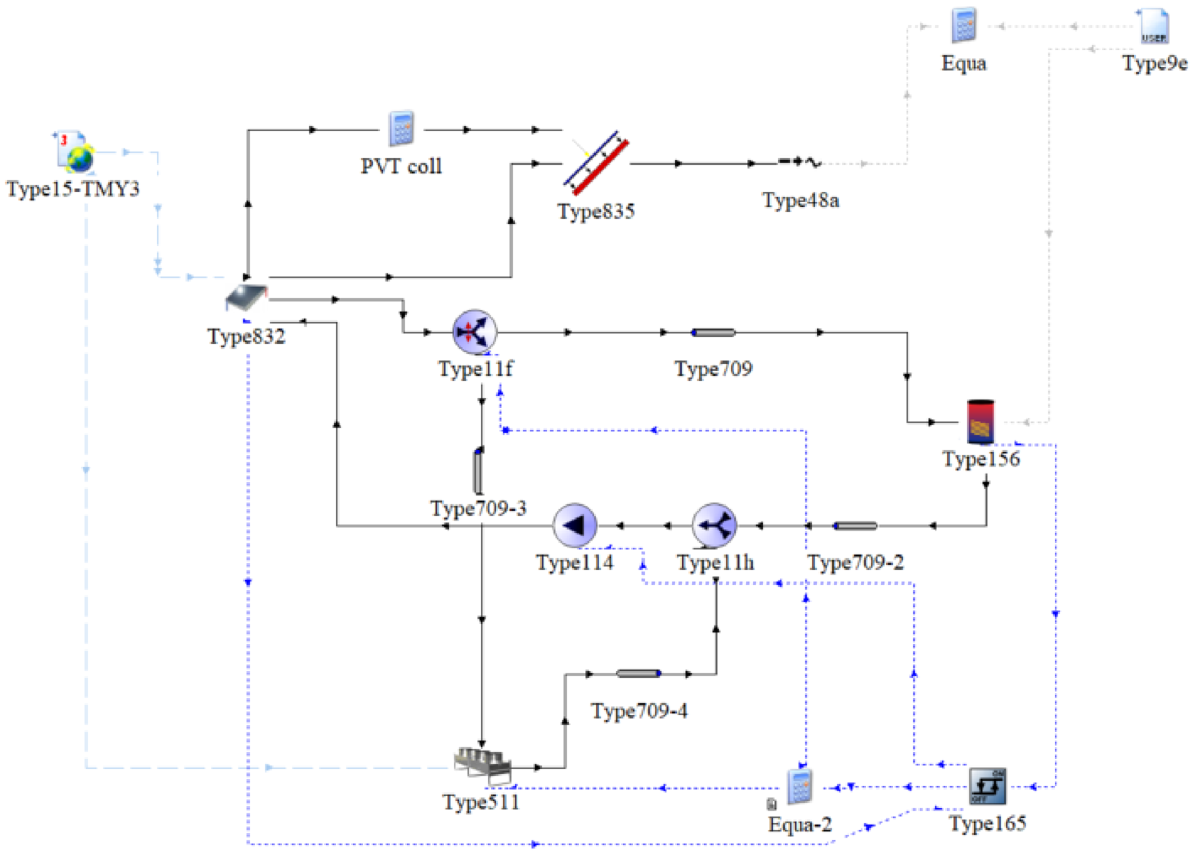


Figure 1.3.6 TRNSYS model for simulation of a single-family solar DHW system driven by PVT collectors and an electric back-up system

Table 1.3.1 *Component models used in the TRNSYS model of a single-family solar DHW system with electric back-up*

Component	Type	Component	Type
Meteorological data	15	Piping	709
PVT collector field	832 and 835	Flow diverter	Type 11f
Inverter	48a	Flow mixer	Type 11h
Dry cooler	511	Controller	165
Thermal energy storage	156	Load profiles	9e
Pumps	114	Equations	Equa

1.3.3.2. Case 2

A TRNSYS model was developed to simulate a solar DHW system for a single family building with an air-to-water heat-pump as back-up, see figure 1.3.7, using the component models (types) identified in Table 1.3.2.

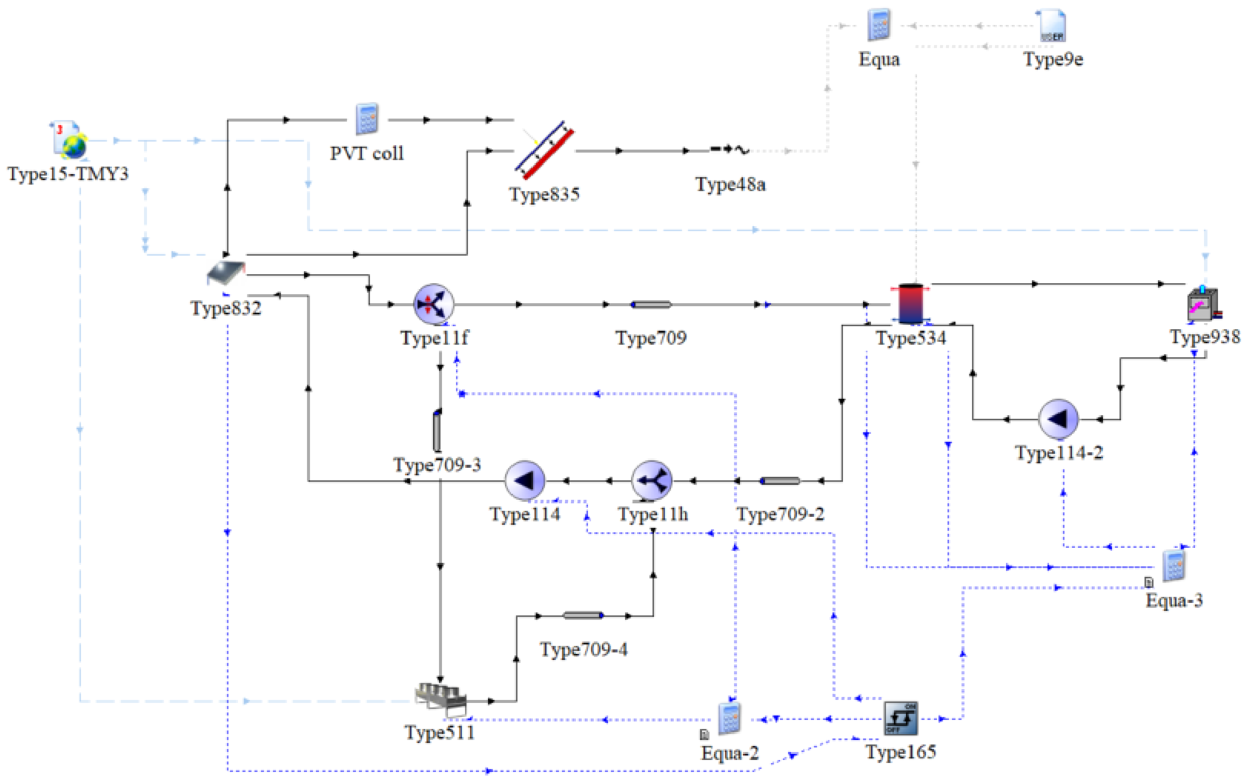


Figure 1.3.7 TRNSYS model for simulation of a single-family solar DHW system driven by PVT collectors and an air-to-water heat pump back-up system

Table 1.3.2 *Component models used in the TRNSYS model of a single-family solar DHW system with electric back-up*

Component	Type	Component	Type
Meteorological data	15	Piping	709
PVT collector field	832 and 835	Flow diverter	Type 11f
Inverter	48a	Flow mixer	Type 11h
Dry cooler	511	Controller	165
Thermal energy storage	534	Load profiles	9e

Pumps	114	Air-water heat pump	938
Equations	Equa		

1.3.3.3. Case 3

A TRNSYS model was developed to simulate a solar DHW system for a multi-family building with distributed storages with electric resistance back-ups (Figure 1.3.8) using the component models identified in Table 1.3.3.

Table 1.3.3 *Component models used in the TRNSYS model of a single-family solar DHW system with electric back-up*

Component	Type	Component	Type
Meteorological data	15	Piping	709
PVT collector field	832 and 835	Flow diverter	Type 11f
Inverter	48a	Flow mixer	Type 11h
Thermal energy storage	156	Controller	165
Pumps	114	Load profiles	9e
Equations	Equa		

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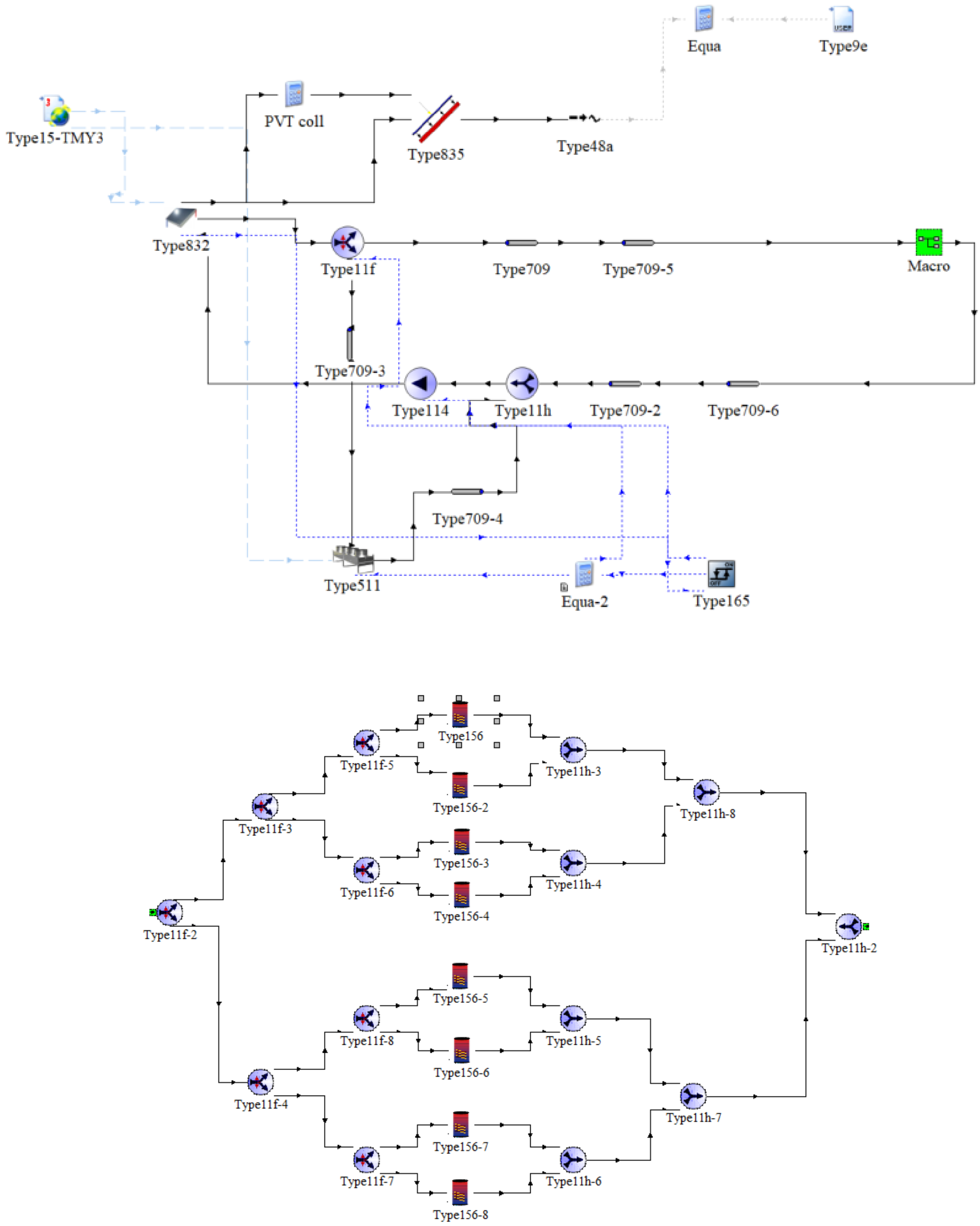

Figure 1.3.8 TRNSYS model for simulation of a multi-family solar DHW system driven by PVT collectors and distributed storages with electric resistance back-up (top) and exploded view of

the distribution network macro (bottom)

1.3.3.4. Case 4

A TRNSYS model was developed to simulate a solar DHW system for a multi-family building with centralized storage with a heat pump as back-up (Figure 1.3.9)) using the component models identified in Table 1.3.4.

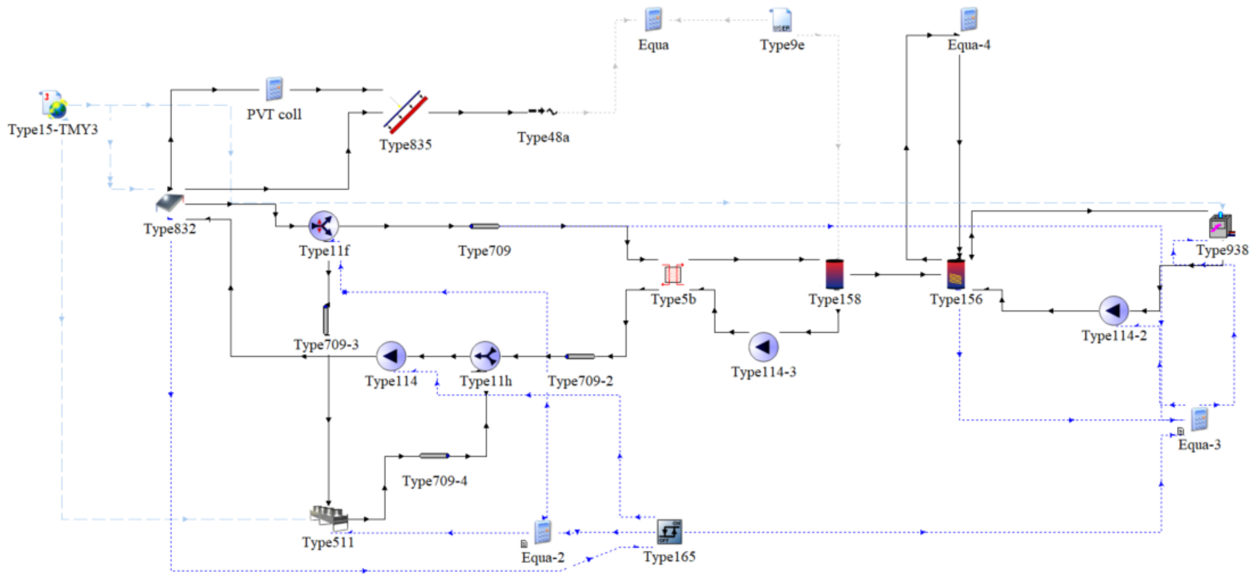

Figure 1.3.9 TRNSYS model for simulation of a multi-family solar DHW system driven by PVT collectors centralized storage with a heat pump as back-up.

Table 1.3.4 *Component models used in the TRNSYS model of a single-family solar DHW system with electric back-up*

Component	Type	Component	Type
Meteorological data	15	Piping	709
PVT collector field	832 and 835	Flow diverter	Type 11f
Inverter	48a	Flow mixer	Type 11h
Dry cooler	511	Controller	165
Thermal energy storage	158 and 156	Load profiles	9e
Pumps	114	Air-water heat pump	938
Equations	Equa		

Co-funded by the European Union

1.4. PVT-SP/heat pump systems for multi family house

A system for supplying space heating and domestic hot water for a multifamily house is designed with PVT collectors, water-water heat pump and bore hole heat storage as the main components. The bore hole will supply stable and not too low temperatured brine for the source for the heat pump. The PVT collectors will recharge the bore hole and also supply the heat pump directly when the solar collector fluid temperatures are favorable.

Many heat pump systems based on bore holes have been used in Sweden for many years. Therefore a lot of knowledge and experience on such systems have been gained in Sweden. Section 1.4.1 gives an overview of the Swedish experience on the technology.

1.4.1. Technology background – bore holes

Sweden has more than 30 years of experience from geothermal energy utilization, almost entirely based on shallow geothermal energy. The market for shallow geothermal systems and in particular GSHP systems with vertical boreholes in hard rock peaked around 2009 and has since levelled out. All in all, the potential for ground source heat pump (GSHP) systems throughout Sweden, using the ground (rock or soil) or groundwater as heat sources, is very good, [20].

Figure 1.4.1 shows the split of renewable energy production from heat pumps on a country level. France is the country that produces the most renewable energy, followed by Sweden, Germany and Italy, [21].

Most of the Swedish shallow geothermal energy systems are vertical boreholes in hard rock, serving as heat source for heat pumps to single-family houses. There are around two million single-family houses in Sweden, and approximately 20-25% of these houses are today heated with a GSHP, [22].

The Swedish geology with mainly crystalline bedrock, abundant groundwater and a climate with a large temperature difference between summer and winter, are all favorable factors for GSHPs and BTES.

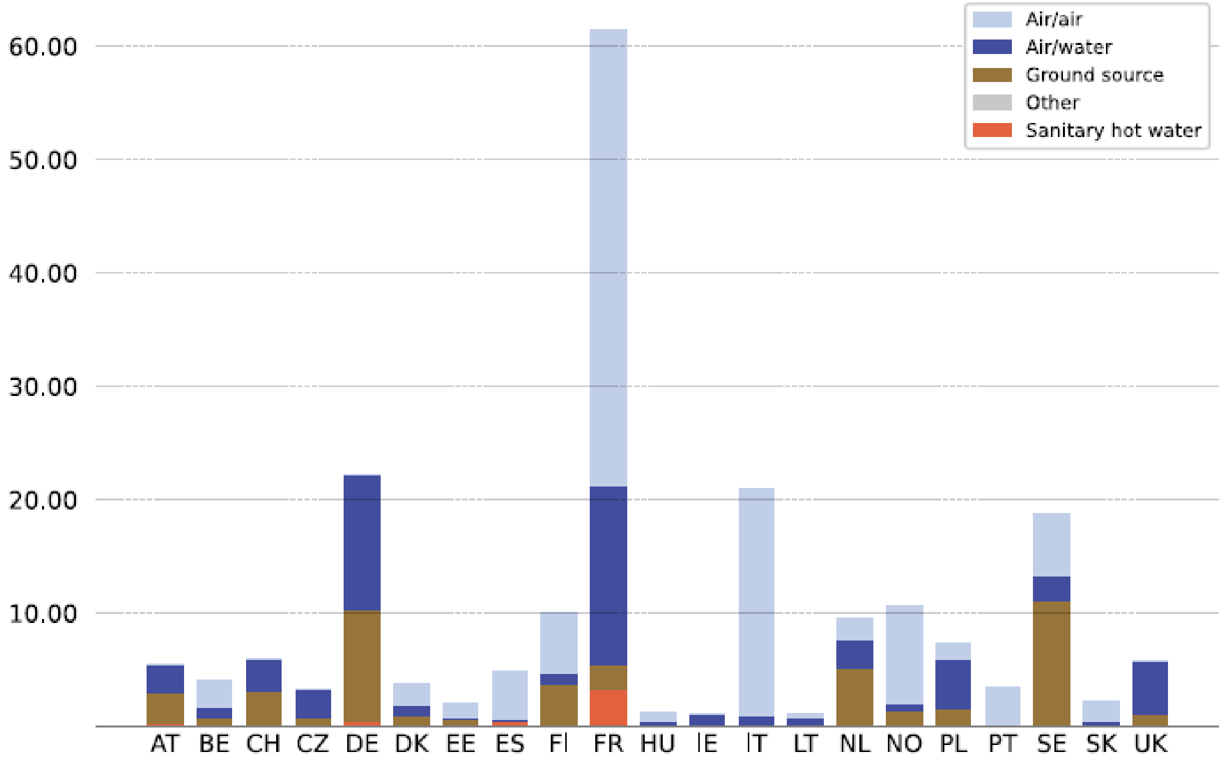

Figure 1.4.1 Renewable thermal energy provided per country, by type, 2022 (in TWh); "H-" indicates primary heating function. (Source: EHPA)

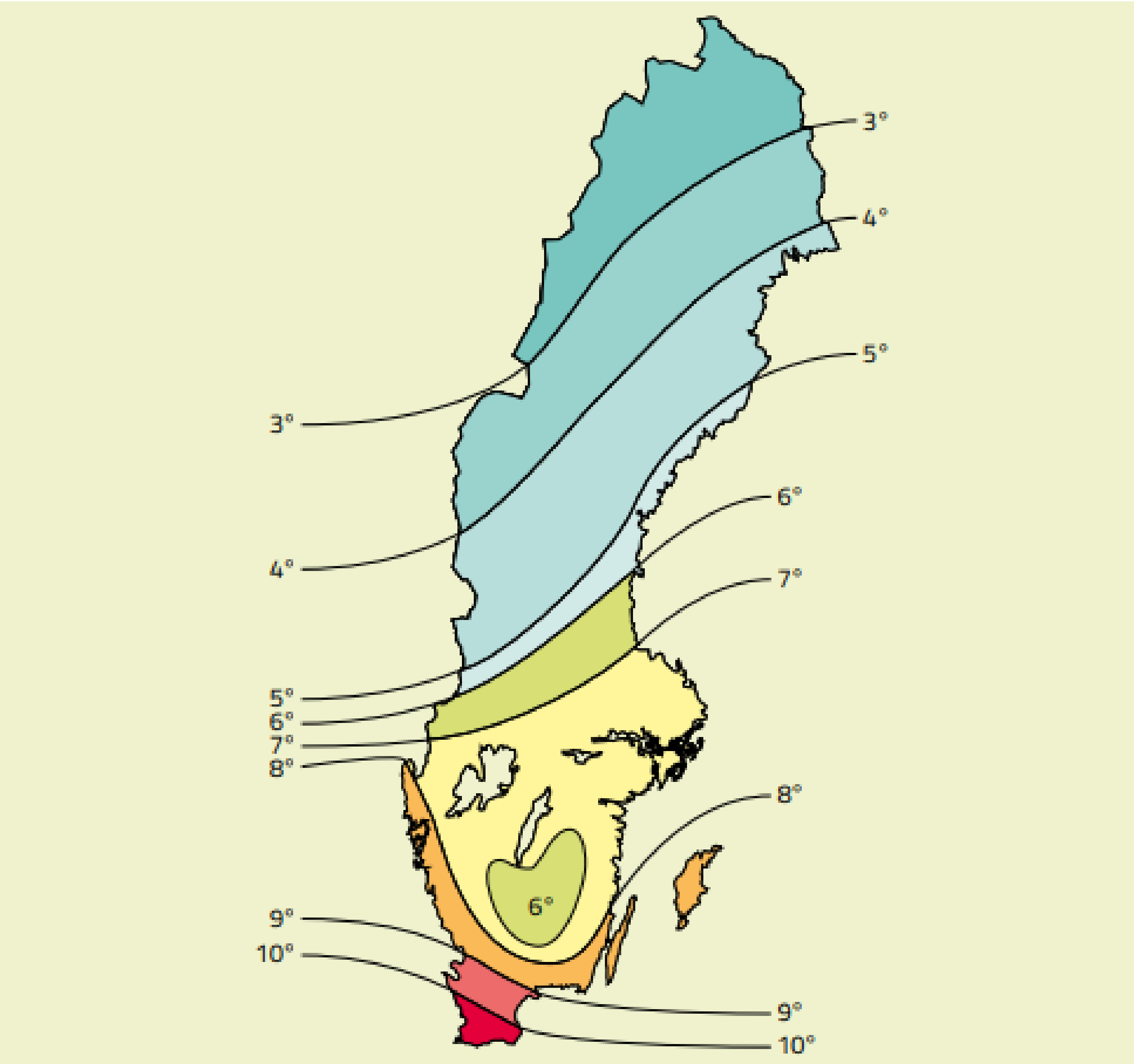

Figure 1.4.2 The temperature at a depth of 100 m reflects the average ambient air temperature except in the north where snow insulates during the winter. (Source: Geological survey of Sweden)

The southern half of Sweden has a temperate continental climate, while the northern half has a more continental type of climate. The temperature varies considerably from north to south, especially during the winter. Average high temperatures in summer are 21^{0}C in the south and 20^{0}C in the north, while average low temperatures in winter are -3^{0}C in the south and -14 ^{0}C in the north. This is clearly reflected in the underground temperature, see figure 1.4.2. **The climate difference is the obvious reason why the frequency of vertical GSHP systems is much lower in the northern part of the country.** However, this does not affect the potential

of using BTES for seasonal storage of heat and cold. On the contrary, these systems are even more suitable in the more continental type of climate.
There are at least 500 000 GSHP and BTES installations in Sweden so far, of which approximately 400 000 are vertical boreholes in hard rock. Most of these systems are installed in single-family houses with one or occasionally two boreholes. In later years there has been an increase in the market also for larger systems, [20].

SGU's National Drill Core collection consists of more than 3 million meters of drill core from more than 18 000 boreholes from all over Sweden.

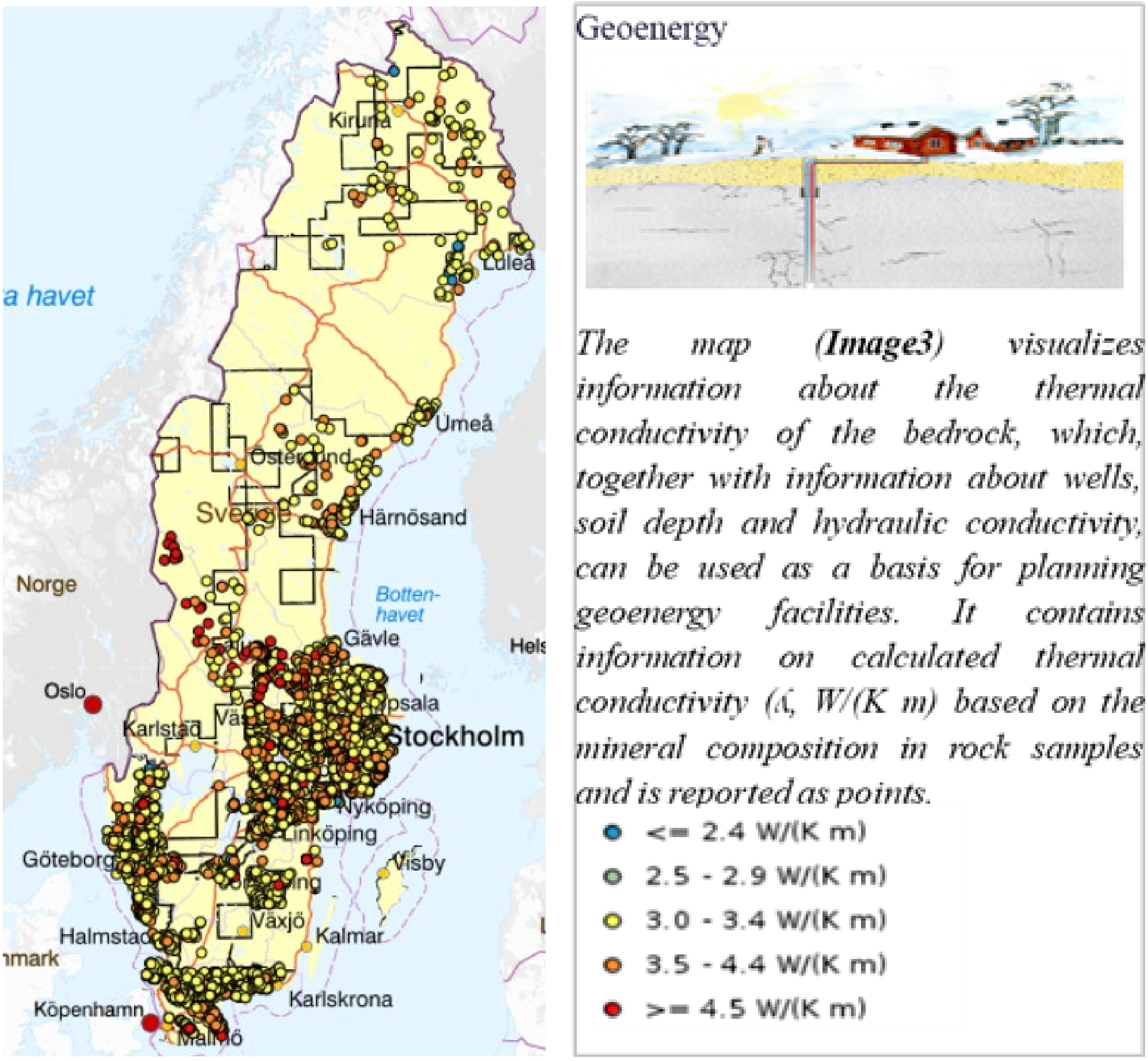

Figure 1.4.3 (Source: Geological survey of Sweden)

In Sweden, certain cities have become notable for their extensive use of boreholes and ground source heat pumps (GSHPs) due to their favorable geological conditions, proactive energy policies, and strong emphasis on sustainable practices. Thermal conductivity for rocks in different parts of Sweden appear from figure 1.4.3. Here are some cities with the highest number of existing boreholes and GSHP systems:

Stockholm

Overview: As the capital city, Stockholm has been a pioneer in adopting sustainable energy technologies, including GSHPs. In Stockholm, more than one third of all single-family houses not connected to district heating have a ground source heat pump, [23].

Existing Infrastructure: Extensive use of boreholes and GSHPs in both residential and commercial buildings. Many districts, including Södermalm, Östermalm, and Kungsholmen, have widespread adoption of GSHPs.

Notable Projects: The city's sustainable energy initiatives and urban planning often include GSHPs as a key component.

Gothenburg

Overview: As Sweden’s second-largest city, Gothenburg has a strong focus on green energy solutions. Gothenburg has a high concentration of GSHPs and boreholes, particularly in residential areas. Gothenburg's focus on reducing carbon emissions and improving energy efficiency has made GSHPs a common heating solution.

Existing Infrastructure: Significant deployment of GSHPs, especially in new residential developments and public buildings.

Notable Projects: Projects in areas like Hisingen and large residential complexes have integrated GSHP systems. Topographic maps of Stockholm and Gothenburg appear from figure 1.4.4.

In comparison with big cities above, the map of Skellefteå (located in the northern part of Sweden) in figure 1.4.5 shows the low density of energy wells.

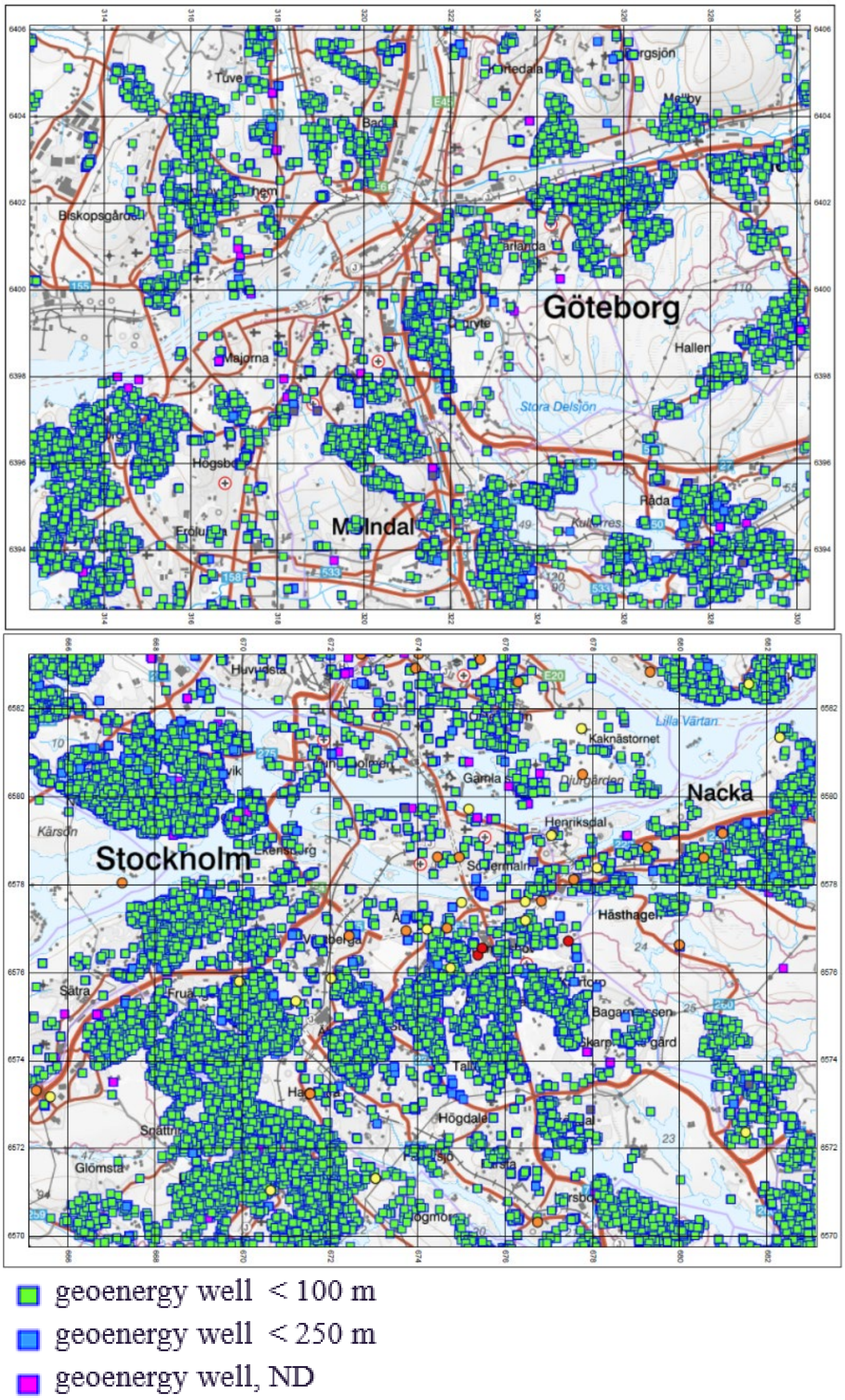

Figure 1.4.4 The topographic maps of Stockholm and Gothenburg regions indicate located geo-energy wells of different depths. (Source: Geological survey of Sweden)

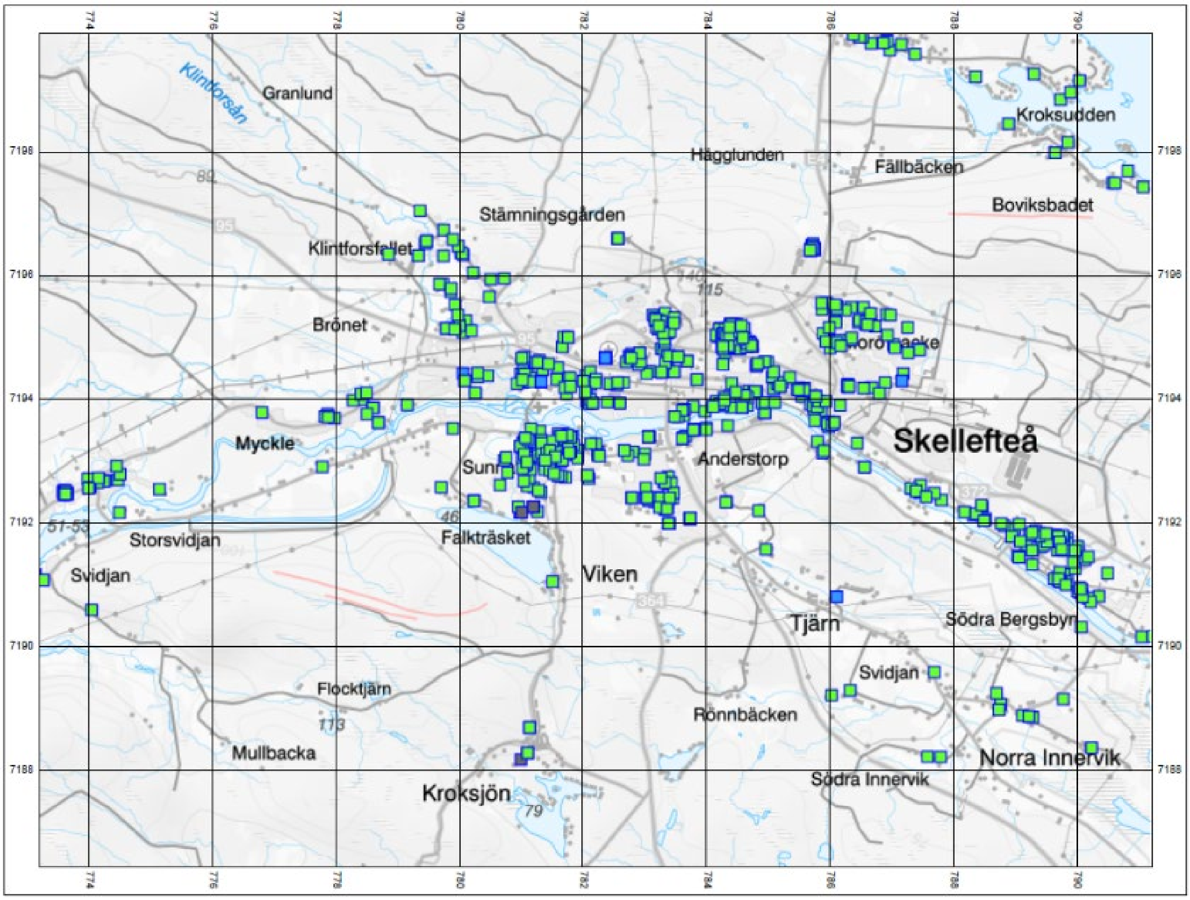

Figure 1.4.5 The topographic maps of Skellefteå indicate located geo-energy wells of different depths. (Source: Geological survey of Sweden

Based on the Swedish conditions mentioned in this section, two locations for the calculations have been selected: Stockholm and Gothenburg.

For Denmark and Portugal, the weather conditions do not vary as much as it is the case in Sweden. Consequently, the calculations for Denmark and Portugal are limited to one location for each country, that is Copenhagen and Lisbon.

1.4.2. System design

The systems are designed with a DHW tank for the hot water demand and a buffer tank for the space heating demand, SH tank, on the load side, SH load. A water-water heat pump is the primary source of heat for the demands. On the source side of the heat pump, it can draw energy either from the borehole or from the PVT collectors when the outlet temperature of the PVT collector exceeds that of the borehole. When the heat pump is inactive, the PVT collectors can replenish the borehole with flow towards them. The system simulation includes the electrical demand in the building. Figure 1.4.6 shows a functional block diagram of the system.

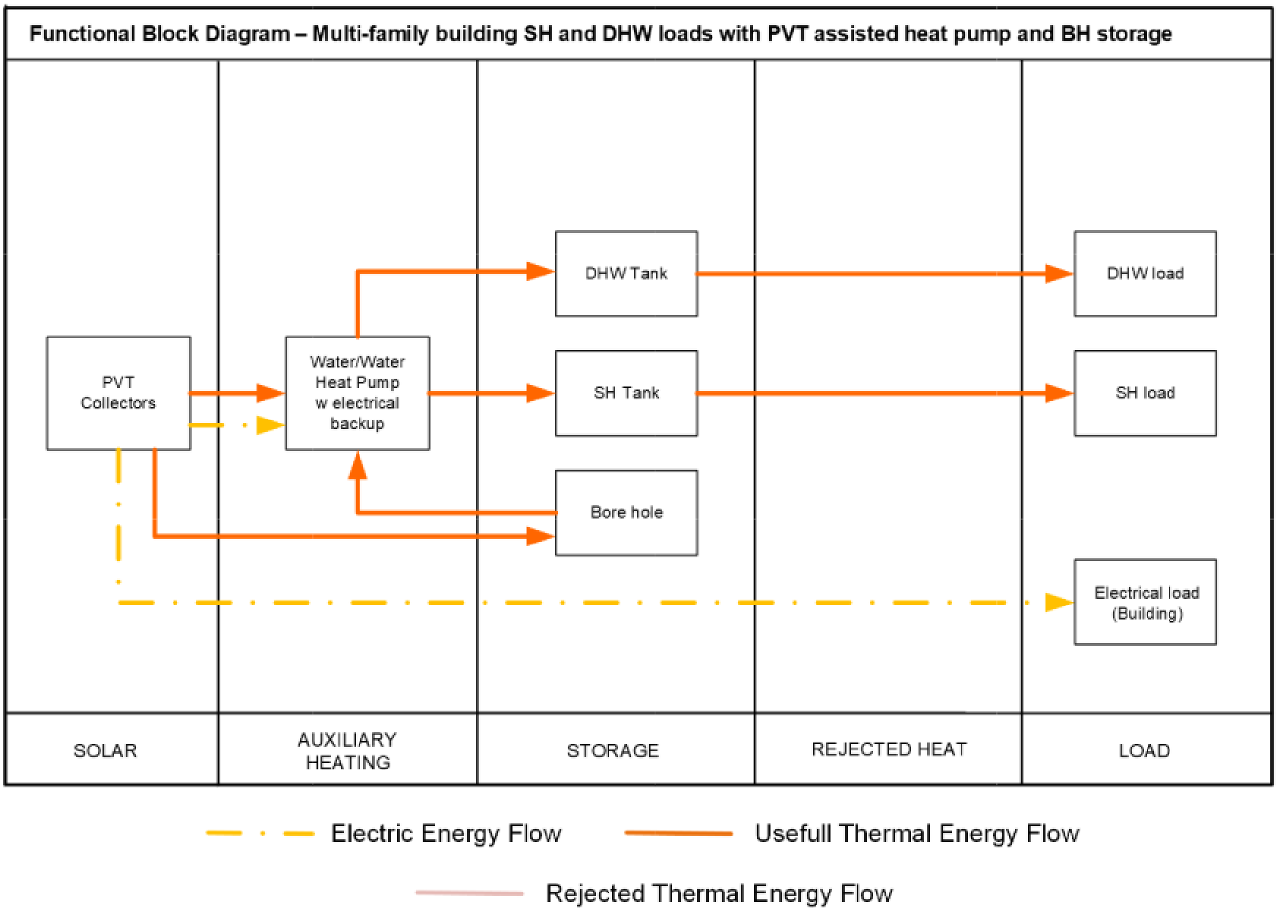

Figure 1.4.6 Functional block diagram of a PVT assisted heat pump system with bore hole storage for multi-family houses

1.4.3. Boundary conditions

The multifamily house is located in Copenhagen, Denmark, Stockholm, Sweden, Gothenburg, Sweden, or Lisbon, Portugal. The building block is five levels tall, with six apartments on each level. There are a total of 30 apartments with a size of 80 or 60 m².

The dimensions of the building are 40 m wide, 10 m deep, and 14 m tall. The walls, floor, and roof heat loss coefficients are according to the Danish building regulations BR18. The window area was set to 20% of the floor area. The overall U value of the building is 880 W/m^{2}K and a total thermal capacity of 1.8 GJ/K.

Each of the apartments is occupied by 1.5 persons on average.

1.4.4. Simulation model

The simulation model is created in TRNSYS. Figure 1.4.8 shows the schematic layout of the multifamily house PVT heat pump system with bore holes in TRNSYS.

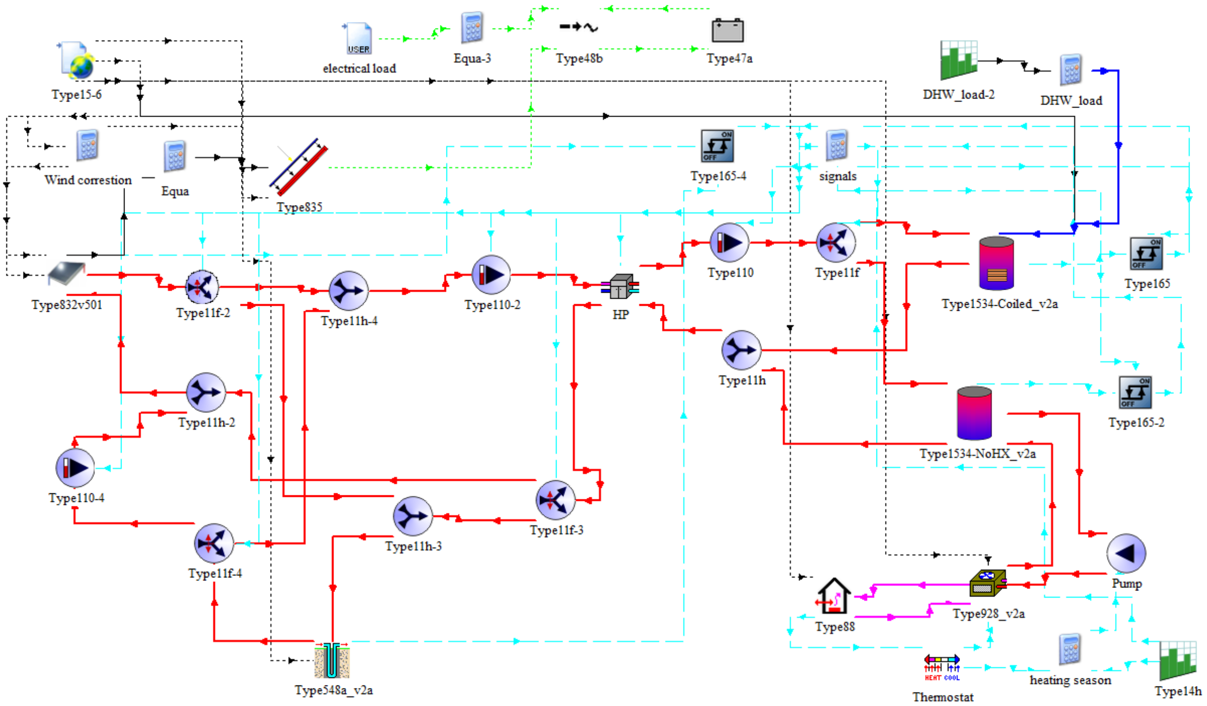

Figure 1.4.8 PVT heat pump and bore hole system in TRNSYS

The main components used for the model are presented in Table 1.4.1.

Table 1.4.1 TRNSYS types used for the calculations

Component	Type	Component	Type
PVT collector	832 and 835	Pump	110
Borehole	548	Flow diverter	11f
Heat pump (HP)	927	Tee piece	11h
DHW and buffer tanks	1534	Weater reader	15
Building component	88	Data reader	9
Heating unit	928	Inverter	48
Battery	47a	Controller	165

Thermostat	108	Forcing function	14

The combination of Type 835 and Type 832 was used to model the PVT panels.

The coefficients for the thermal part of the PVT panel used in the simulation study were obtained from the characterization of the PVT-SP-V1 collector, [24]. Parameter analysis for the characteristics of the PVT panel will also be carried out.

The parameters given in table 1.4.2 were used for the thermal part of the PVT collector:

Table 1.4.2 *Parameters for Type 832*

Parameter	Value
Area - Collector aperture area	1000 m^2
Eta0 - optical efficiency or effective tau-alpha	0.55
Kdiff - IAM for diffuse radiation	0.9
a1 - Linear heat loss coefficient	9.5 W/m^2K
a2 - Quadratic heat loss coefficient	0.14 W/m^2K^2
cwhl - Wind speed dependency of heat losses	8.5 J/m^3K
cIR - Infrared radiation dependency of collector	0.79
Ceff - Effective heat capacity	21.000 J/m^2K
cwF - Wind speed dependency of the zero heat loss efficiency	0.084 s/m
cp - Fluid specific heat	3.80 J/gK
Beta - Collector slope	25º

The DHW demand is simulated with a forcing function giving a load 3 times 2 hours per day starting at 6, 12, and 17. The DHW demand fror each apartment is 45 liters per day, corresponding to recent measurements of average domestic hot water consumption in Danish apartments [25]. The electricity demand is set to 2500 kWh per year with daily peaks at 8 and 20 and varied for each month, as shown in Figure 1.4.7.

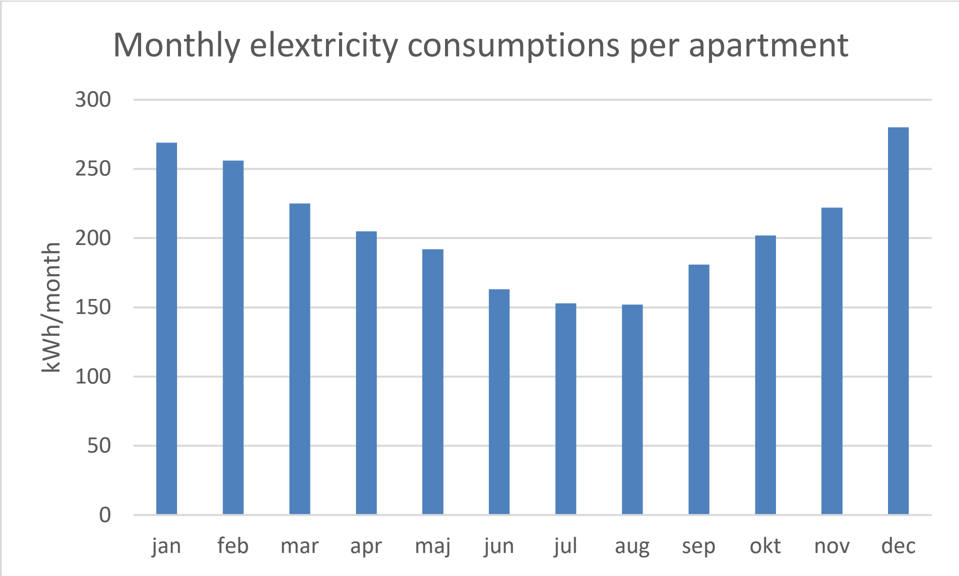

Figure 1.4.7 Monthly electricity consumption of each department

1.5. PVT-SP/swimming pool systems

This study will investigate the effect of heating a swimming pool with PVT panels. It will focus on the thermal performance of the PVT panels, the increase in water temperature in the swimming pool, and the electrical output of the PVT panels compared to the electrical output of a PV array with the same area.

1.5.1. System design

Integrating the PVT array to heat the swimming pool is relatively simple. A pipe loop connects the pool with the PVT collectors, and a simple differential controller decides when a pump is running. Figure 1.5.1 shows a functional block diagram of the system.

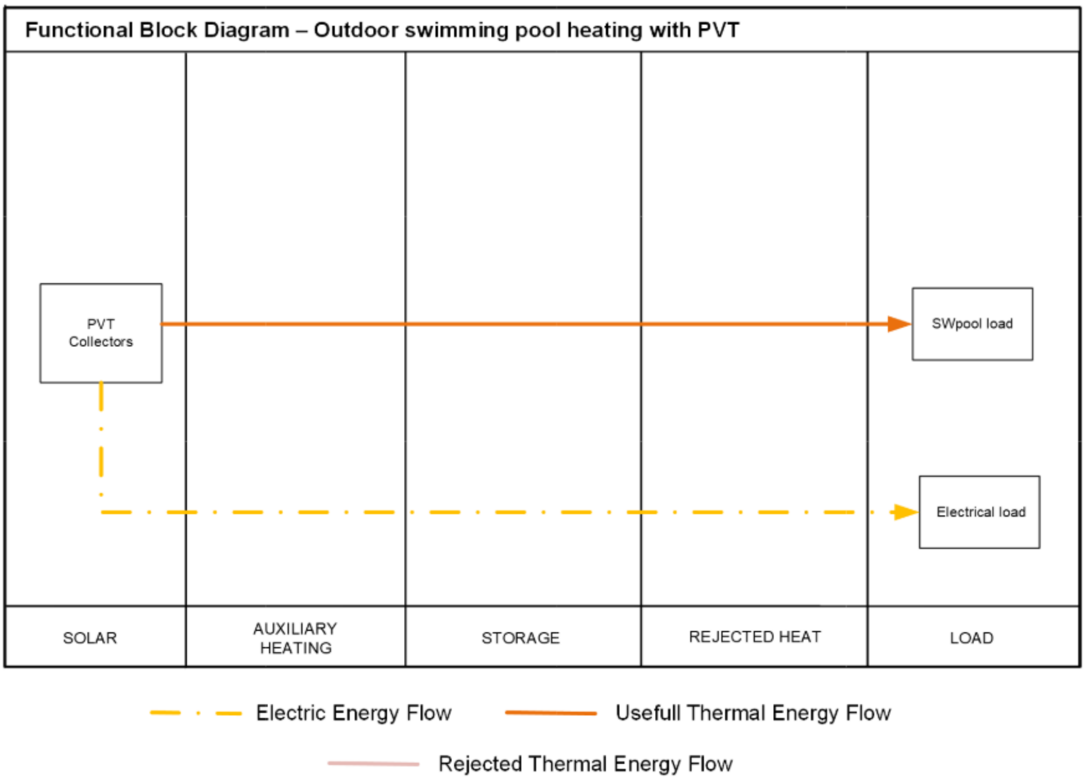

Figure 1.5.1 Functional block diagram of a PVT heated swimming pool system

1.5.2. Boundary conditions

The climate for Lisboa was used for the simulations. The pool was occupied from 8 to 18. The pool is outdoor.

1.5.3. Simulation model

The model was developed in TRNSYS. Type 344b was used for the outdoor swimming pool (see Figure 1.5.2), which represented an Olympic-sized pool.

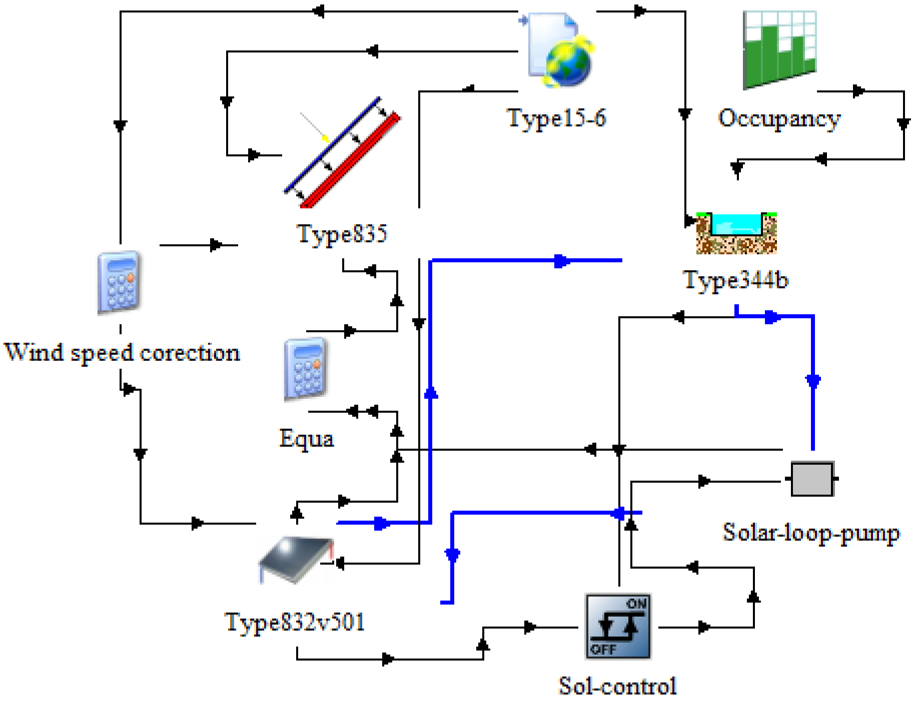

Figure 1.5.2 PVT heated swimming pool in TRNSYS

The combination of Type 835 and Type 832 was used for the PVT panels.

The parameters given in table 1.5.1 were used for the thermal part of the PVT collector:

Table 1.5.1 *Parameters for Type 832*

Parameter	Value
Area - Collector aperture area	1000 m^2
Eta0 - optical efficiency or effective tau-alpha	0.55
Kdiff - IAM for diffuse radiation	0.9
a1 - Linear heat loss coefficient	9.5 W/m^{2}K
a2 - Quadratic heat loss coefficient	0.14 W/m^{2}K^2
cwhl - Wind speed dependency of heat losses	8.5 J/m^{3}K
cIR - Infrared radiation dependency of collector	0.79
Ceff - Effective heat capacity	21.000 J/m^{2}K

cwF - Wind speed dependency of the zero heat loss efficiency	0.084 s/m
cp - Fluid specific heat	4.19 J/gK
Beta - Collector slope	25º

The parameters used for the swimming pool are given in Table 1.5.3.:

Table 1.5.3 *Parameters for swimming pool type 344b*

Parameter	Value
Pool surface area	1250 m²
Pool volume	2500 m³
Cover emissivity	0.6
Cover absorption coefficient	0.6
Cover thermal conductivity	0.25 W/mK
Cover thickness	0.005 m
Height of wind velocity measurement	5 m
Surroundings factor	4

1.6. PVT-SP in low-temperature district heating systems

1.6.1. System design

Solar energy plants in low-temperature district heating systems based on low-temperature PVT panels consisting of many rows of serial-connected PVT panels are considered. The rows are connected in parallel, and the number of panels in each row can vary up to about 20. The PVT panels are placed on the ground. Figure 1.6.1 shows a functional block diagram of the system.

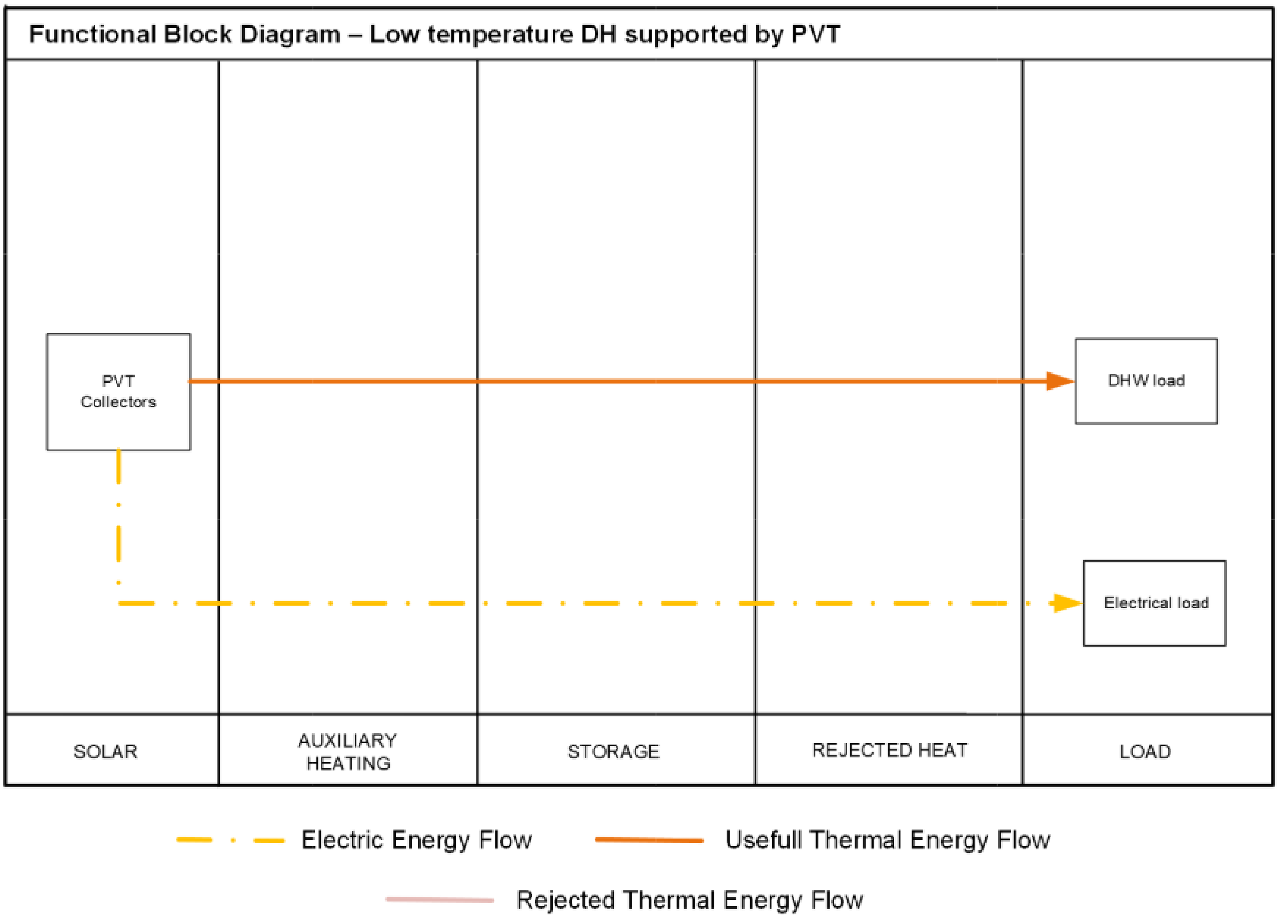

Figure 1.6.1 Functional block diagram of PVT panel field for low-temperature district heating

1.6.2. Boundary conditions

The thermal performance and the electricity production are calculated for different constant temperature levels of the panels during the year. Hourly weather data from typical DRYs (Design Reference Years) and the thermal and electrical efficiency equations for the PVT panels are used to calculate the performances hourly, monthly, and yearly. Shadows from a panel row in front of each panel row are included in the calculations [26]. It is assumed that the PVT panels' temperature is constant throughout the year. The yearly performances are thus calculated as a function of the PVT panel temperature.

1.6.3. Simulation model

A simulation model developed by DTU Construct is used for the calculations. A user-friendly program based on the model will be available on the website https://solperfield.streamlit.app/

For each time step of the year with a duration of 1 h, the heat and electricity production by the

PVT panels are calculated for each hour of the year by the following approximated equations:

Thermal performance:

Equation 1

$$\dot{Q} = \begin{bmatrix} \eta_{0,b} \cdot K_b(\theta) \cdot G_b + \eta_{0,b} \cdot K_d \cdot G_d - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2 \\ -a_3 \cdot u \cdot (T_m - T_a) + a_4(E_L - \sigma T_m^4) - a_6 \cdot u \cdot (G_b + G_d) - a_7 u(E_L - \sigma T_m^4) \end{bmatrix}$$ [27, 28, 29]

where the incidence angle modifier is determined by:

Equation 2

$K_b(\theta) = 1 - b_0 \left(\frac{1}{\cos\theta} - 1\right)$ or

Equation 3

$K_b(\theta) = 1 - tan^p(\theta/2)$

Electrical performance:

Equation 4

$P/A_G = G(b_D - b_1 \cdot \Theta_m - b_2 \cdot \Theta_a - b_3 \cdot G)$ [29]

The symbols used appear from table 1.6.1.

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Table 1.6.1 *Nomenclature*

Symbol	Meaning
$\dot{Q}$	Heat production, W/m²
$\eta_{0,b}$	Peak collector efficiency based on Gb, -
$K_b(\theta)$	IAM for direct solar irradiance, -
Θ	Incidence angle, °
G_b	Beam irradiance, W/m²
K_d	IAM for diffuse solar radiation, -
G_d	Diffuse irradiance, W/m²
a_1	Heat loss coefficient, W/(m²K)
T_m	Mean temperature of the heat transfer fluid, K
T_a	Ambient air temperature, K
a_2	Temperature dependence of heat loss coefficient, W/(m²K²)
a_3	Wind speed dependence of heat loss coefficient, J/(m³K)
u	Wind speed, m/s
a_4	Sky temperature dependence of the heat loss coefficient, -
E_L	Longwave irradiance, W/m²
σ	Stefan-Boltzmann constant, 5.6704×10^{-8} W / (m^{2}K^4)
a_6	Wind speed dependence of zero loss efficiency, s/m
b_0	Constant in IAM coefficient, -
p	Constant in IAM coefficient, -
P	Electricity production, W
A_G	Gross area of PVT panel, m²
G	Total solar irradiance on PVT panel ($G=G_b+G_d$), W/m²
b_D	Coefficient for the electric power output, -

b_1	Coefficient for the electric power output, 1/K
Θ_m	Mean temperature of the heat transfer fluid, °C
b_2	Coefficient for the electric power output, 1/K
Θ_a	Ambient air temperature, °C
b_3	Coefficient for the electric power output, m^2/W

2. Plan for presentation of calculated results

The monthly and yearly calculated performances of the different simulated systems will be presented in the report D5.2 *Report on system performance of the selected PVT applications*. The main results will be presented by means of tables, diagrams, and figures. For each application, the monthly and yearly electricity production, the monthly and yearly electricity bought from and sold to the grid are given, if relevant. Also, the monthly and annual thermal performance of the PVT panels are provided, if relevant.

Besides that, calculated temperatures in different parts of the system are shown using figures for typical operation conditions on different days during the year.

The presented results will provide an understanding of how the systems performs and their strengths and weeknesses and show the potential of each system.

Selected key performance indicators for each system will give opportunities to evaluate and compare the selected systems to similar systems.

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