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TRI-HP PROJECT | Trigeneration systems based on heat pumps with natural refrigerants and multiple renewable sources

# Economic assessment of TRI-HP solutions

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Version 2.0

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# CONTENTS

# Executive Summary

The TRI-HP H2020 project is aiming to develop trigeneration integrated solutions that combine heating, cooling and electricity generation, based on heat pumps with natural refrigerants and using multiple renewable heat sources. One of the economic goals is to reduce the installation cost of the complete system by 10 % to 15 %. In this deliverable, a first economic assessment of the systems under development is presented, that is, the solar ice-slurry system and the dual source/sink system. The costs have been derived for the cases of Spain and Switzerland.

On the one hand, the cost of the elements which are not under development in the project have been derived using recognized references, such as commercial information, quotation requests to well-known manufacturers, or other relevant references. On the other hand, the costs of the new developments of the project have been derived for each of the heat pump systems. In order to gather those data, the experimental research carried out until the date, as well as a prospective for future improvements for each of the new developments, have been taken into account.

The main hardware developments of the project are based on the new design of three heat exchangers: i) tri-partite gas cooler; ii) dual source heat exchanger and iii) supercoolers. The tri-partite gas cooler is expected to cost around 308 €/kW, where kW refers to the nominal heating power of the heat pumps. The dual source/sink heat exchanger cost is assumed to be around 490 €/kW using the first design. An improved design of the dual source/sink heat exchanger is expected to reduce cost by 30 % due to an improvement of the heat transfer coefficient. Regarding the supercoolers, state-of-the-art flat plate heat exchangers will be used with the added cost of surface treatments. Icephobic coatings are assumed to increase cost by 3 €/kW to 4 €/kW, while Nickel treatment is expected to cost around ten times more compared to the icephobic coatings.

All these additional costs of the heat exchangers are in line with the previsions at the initial stage of the project and will be compensated by far by the cost reductions that they will imply, not only on the operational level by increasing efficiency, but also on the installation cost. The dual source/sink heat exchanger is expected to reduce the borehole length by 50 % and the supercooler heat exchanger will eliminate all the heat exchangers on the ice storage. These are expected to reduce the installation cost of the systems by 10 % to 15 %.

## LIST OF ACRONYMS

| | |
|---|---|
| **AEMS** | Advanced Energy Management System |
| **DSH** | Desuperheater |
| **DSHX** | Dual Source Heat Exchanger |
| **DHW** | Domestic Hot Water |
| **nZEB** | Near Zero Energy Buildings |
| **PV** | Photovoltaic |
| **SH** | Space Heating |
| **TES** | Thermal Energy Storage |
| **TRT** | Thermal Response Test |
| **VC** | Vitrovac |
| **VGHX** | Vertical Ground Heat Exchanger |
| **VZ** | Vitrobraze |
| **VP** | Vitroperm |

# 1 Introduction

The objective of this deliverable is to set a first economic assessment of the TRI-HP systems. For that purpose, firstly the economic assessment of the components of the systems in which no new developments are made within the project, is done based on commercial information. An economic assessment of the heat pumps without new developments has also been made. Secondly, for the components newly developed in the project, a first economic assessment is carried out, based on the experimental research carried out until the date, and when possible a prospective for improvement in the future.

In the project, two principal systems are being developed:

- Solar ice-slurry system
  - With R290 heat pump
  - With R744 heat pump
- Dual-source system
  - With R290 heat pump

The costs of the solar ice-slurry system have been derived for the case of Switzerland, and the costs of the dual-source for the case of Spain.

For the state-of-the art components, a cost structure for each of the items is derived, based on characteristic properties, such as capacity, area, etc. based on commercial information. In that way, the obtained equations can be implemented in the System Simulation Framework carried out in Task 1.3[1], so that the investment cost can be calculated for systems of different size.

Figure 1.1 shows the dual-source system with the state-of-the-art components marked in yellow, which are:

- PV panels and battery.
- Geothermal boreholes.
- Thermal installation (water tanks and auxiliary equipment).

The heat pump that will be integrated in the dual-source system, marked in pink, has a new development which is under development in the project, the Dual Source Heat Exchanger (DSHX).

Figure 1.2 shows the ice-slurry system with the state-of-the-art components marked in yellow, which are:

- PV panels and battery.
- Solar thermal collectors.
- Ice-slurry storage.
- Thermal installation (water tanks and other).

The heat pumps that will be integrated in the ice-slurry system, marked in pink, have new developments which are under development in the project:

- Supercooler (both heat pumps).
- Tri-partite gas cooler (R744 heat pump).

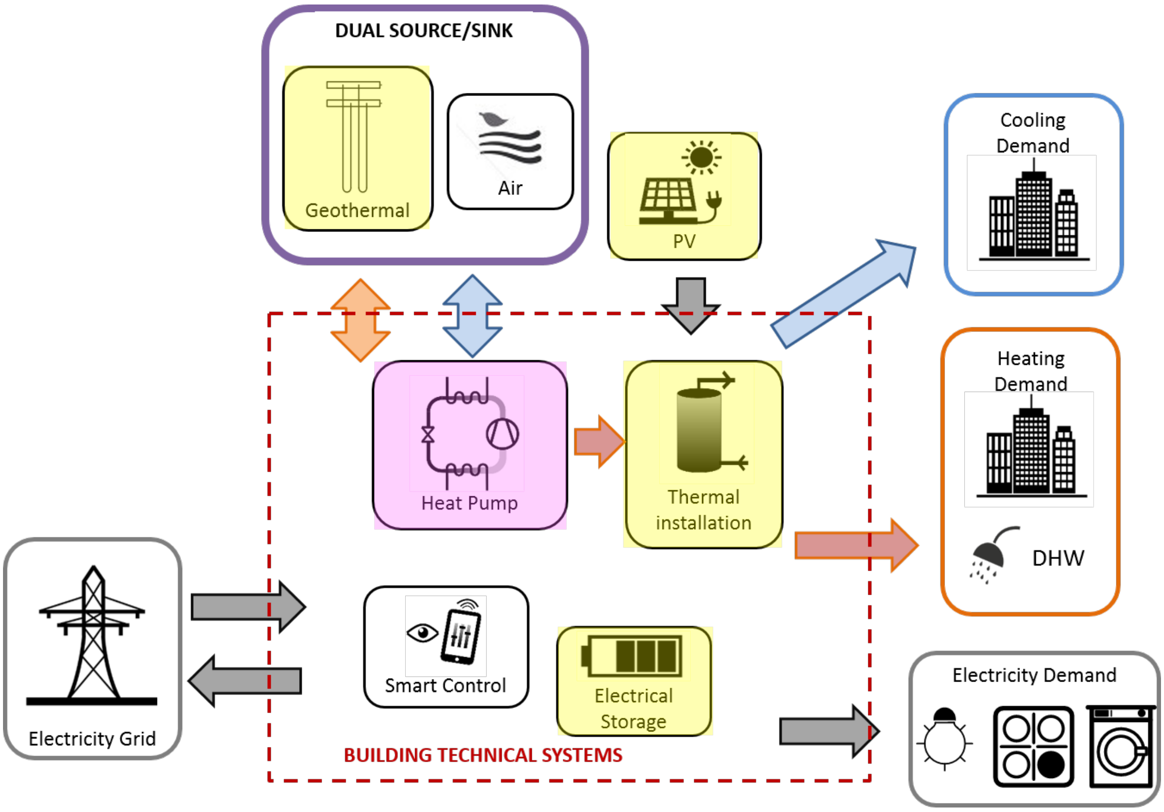


**Figure 1.1:** Dual-source heat pump system. State-of-the-art components marked in yellow.

Finally, for both systems an Advanced Energy Management System (AEMS) will be developed. A summary of the cost is provided in Table 1.1. An estimation of the cost for the AEMS has been done considering a local installation where the energy management software is installed in an application called EnergyBox. The annual cost of access to external data such as meteorological data and cost data is also included. Finally, the cost of an SCADA is included in case it is necessary (it might not be necessary if that is already included in the building).

**Table 1.1:** Estimated cost of the AEMS.

| AEMS product | Cost |
|---|---|
| AEMS backend<br>- Including thermal and electric energy management<br>- Residential system including Heatpumps, PV panels, battery, thermal and electrical demand<br>- Small cabinet hosting the EnergyBox (industrial PC with AEMS) | 725 € |
| Energy Prices and weather forecasts external provider services** | 78 € |
| Upgraded EnergyBox including more resources for the SCADA | 725 € |
| SCADA included (1 500 signals) | 2 610 € |
| **Total*** | **4 138** € |
| * These prices don't include the installation costs, training and documentation. Internet connectivity is assumed.<br>** This service must be yearly updated and so the price is valid for a period of one year. | |

[1]Task 1.3 System Simulation framework.

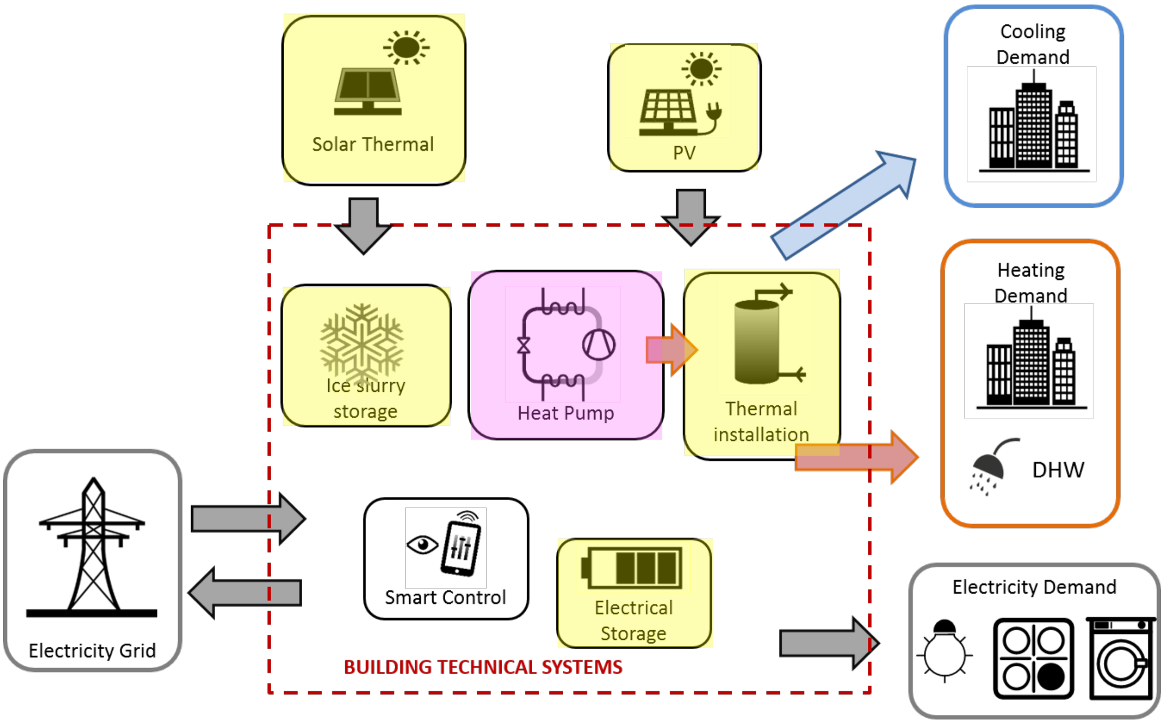


**Figure 1.2:** Ice-slurry heat pump system. State-of-the-art components marked in yellow.

# 2 Cost assessment of state-of-the-art components

## 2.1 Cost assessment of heat pumps

The cost of state-of-the-art heat pumps as components of the different TRI-HP systems have been gathered for the cases of Spain and Switzerland. All the heat pumps developed in TRI-HP project will include new innovations that will affect the cost. Therefore, reference heat pumps are defined for a base comparison in terms of investment cost. This information will be included in the System Simulation Framework which will be used during the project (firstly developed in Task 1.3[1]). A range of capacities has been considered for gathering the economic data of the units and equations that relate the cost to the capacity of the unit have been derived.

### 2.1.1 Cost of heat pumps in Spain

The analysis is oriented to a heat pump as close as possible to the newly developed dual-source heat pump. Different heat pump models had been previously analyzed (see D5.1[2]), and based on their characteristics and the availability of those units' cost, the selected commercial heat pumps to be taken as a reference are the ecoGEO from Ecoforest[3], with a range of 10 kW to 100 kW capacity. Two unit types are included to cover this capacity range, the ecoGEO Compact (capacity ranges of 1-9 kW / 3-12 kW / 5-22 kW), and the ecoGEO High Power (capacity ranges of 12-40 kW / 15-70 kW / 25-100 kW).

The selected heat pump model has the following technical characteristics:

- Brine-water heat pump.
- Refrigerant: R410A.
- Compressor with inverter.
- Reversible cycle.
- Including brine and demands circulation pumps.
- Independent generation of heating/cooling and Domestic Hot Water (DHW).
- DHW production up to 70 °C without electrical support.

This is the closest commercially available heat pump compared to the unit which is going to be developed in TRI-HP project (R290-dual heat pump, see D5.2[4]), except from the fact that it uses R410A as a refrigerant. The manufacturer provides the option of installing an additional air evaporator/condenser, in order to have a hybrid system (aerothermal/geothermal), in which air or brine could be used as a source/sink. The approach in the TRI-HP dual-source heat pump is to have this double source/sink in a unique component, the dual-source heat exchanger (see D4.2[5]).

The selected commercial heat pumps' cycle is reversible, and the compressor works with inverter in order to adapt to the demand, such as in the R290-dual heat pump. The commercial heat pump includes the brine and demands (space conditioning and DHW) circulation pumps. In the case of the R290-dual heat pump, the first prototype developed includes the brine circulation pump, but not the demands circulation pumps. Finally, the commercial heat pump provides independent generation of heating/cooling and DHW, by making use of a Desuperheater (DSH),

[1]Task 1.3 System Simulation framework.
[2]D5.1 Detailed (Modelica) model of heat pumps for design purposes.
[3]www.ecoforest.com
[4]D5.2 Design of R290-dual heat pump and Bill of Materials.
[5]D4.2 Design of dual-source Heat Exchanger.

with the possibility to produce hot water until 70 °C. The R290-dual heat pump will also provide heating/cooling + DHW, and its target is to reach 70 °C.

The cost of the selected commercial heat pumps has been taken from a Price List Catalogue from 2019 (Spain). The base unit for the cost calculation is the installed capacity (heating capacity referred to maximum capacity at nominal conditions B0W35). Figure 2.1 shows the cost of the heat pump for different capacities, and the derived equation. The unit cost varies between around 10 000 € to 25 000 € (range of 10 kW to 100 kW).

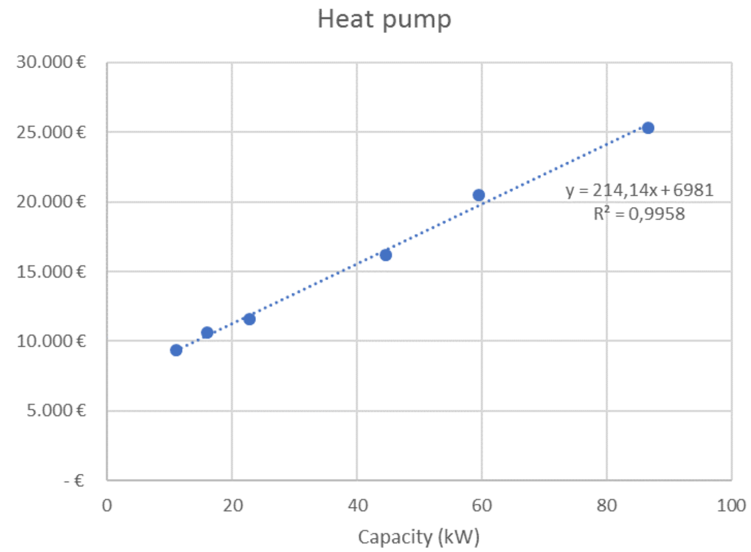


**Figure 2.1:** Cost of the heat pump base reference for the case of Spain.

The linear regression cost of the heat pump in Spain is:

$$\text{Cost of HP (ES)} = 6981\,€ + 214\,€/\text{kW (validity range 10 kW to 100 kW)} \tag{2.1}$$

### 2.1.2 Cost of heat pumps in Switzerland

The analysis of costs for heat pumps in Switzerland orientates on the assumed heat demand of the reference building for a multi-family house in Switzerland. Heat pumps of different companies in the range of 5 kW to 50 kW are considered. For making the costs better comparable to the European market the price is given in €, assuming an exchange rate of 1.1 CHF/€.

The costs are taken from Swiss price lists for heat pumps[6]. For the costs of brine-water heat pumps the following products are considered:

- Oertli SIN (R410A)
- alterra SWC (R410A)
- alterra pro SWP (R407C)

[6] Data provided from HEIM.

All of the heat pumps considered are heat pumps with fixed compressor speed. Data for brine-water heat pumps with inverter-controlled compressor speed were not available. Comparing prices of inverter-controlled and fixed compressor speed heat pumps for the case of air-water heat pumps shows that the inverter controlled heat pumps (orange dots) are not more expensive (Figure 2.2).

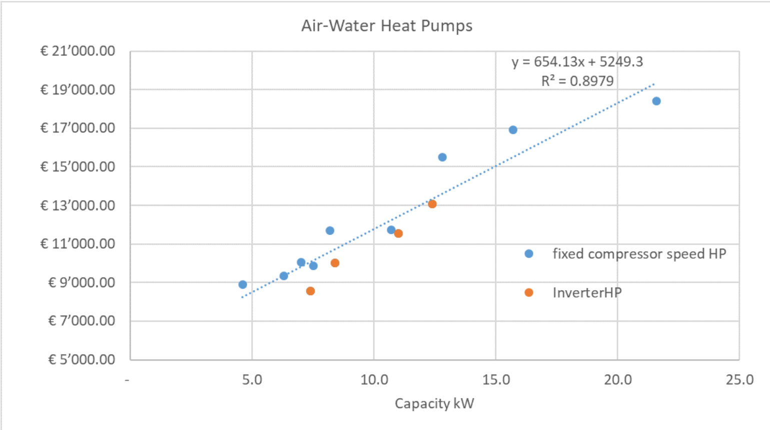


**Figure 2.2:** Cost of air-water heat pumps in Switzerland. The orange dots indicate the costs for an inverter controlled air-water heat pump in different capacities.

The costs of the selected commercial brine water heat pumps are shown in Figure 2.3. The unit costs varies between 10 000 € to 25 000 € in the range of 10 kW to 50 kW.

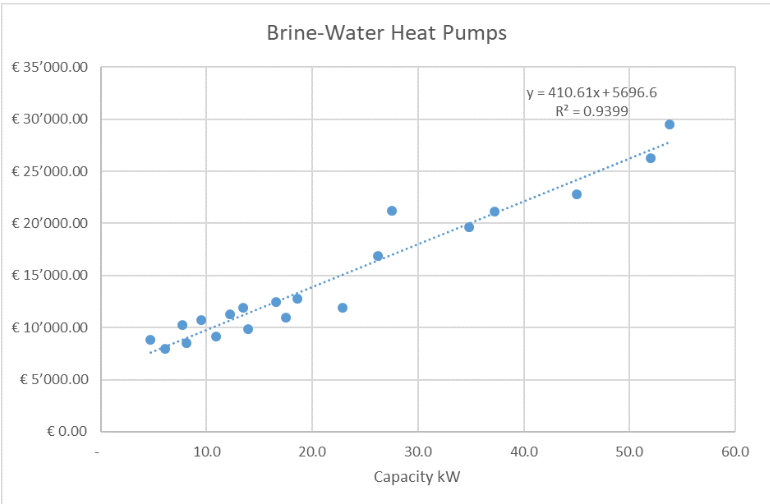


**Figure 2.3:** Cost of brine-water heat pumps in Switzerland.

The linear regression cost of a brine water heat pump in Switzerland is:

$$\text{Cost of HP (CH)} = 5696\,€ + 410\,€/\text{kW (validity range 10 kW to 50 kW)} \quad (2.2)$$

Costs for air-water heat pumps are disregarded here as brine-water heat pumps are more relevant for the project.

## 2.2 Cost assessment of geothermal boreholes

The geothermal installation is an important part of the dual-source heat pump system developed in TRI-HP. The possibility to use energy from the air or from the ground to operate, or to use them as a sink, allows a reduction of the cost of the geothermal installation, based on the reduction of the boreholes length. The cost of the geothermal boreholes is usually a major part of the investment cost of a geothermal heating/cooling system. Cost will be evaluated in Spain but also in Switzerland since the dual source system could be potentially installed in central Europe and comparisons in those climates with the solar-ice slurry system would be possible.

Different ways of extracting heat from the ground exist, based on the different temperatures and underground depth, and on the technology used, based on different kinds of heat exchangers (vertical, horizontal, foundations). The geothermal installation of TRI-HP dual-source system uses shallow geothermal resources, which comprise the shallow subsurface (normally less than 250 m) and the groundwater. Figure 2.4 shows the most common ground-coupling methods in shallow geothermal systems. The type of geothermal system considered for TRI-HP dual-source system is the closed-vertical loops system, with single U-tube heat exchanger, as shown in Figure 2.5. In geothermal vertical loops, higher depths normally mean higher drilling costs; therefore, in some cases it is preferable to make a higher number of boreholes, allowing to shorten each boreholes length. In TRI-HP dual source system, each borehole's length is considered to be 150 m (around 5-6 kW per borehole), and the pipes are of 40 mm diameter and made of PEX-A (cross-linked polyethylene). The heat transfer fluid shall resist temperatures near 0 °C and be a non-toxic and biodegradable substance. Normally, aqueous solutions of propylene glycol or ethylene glycol are used.

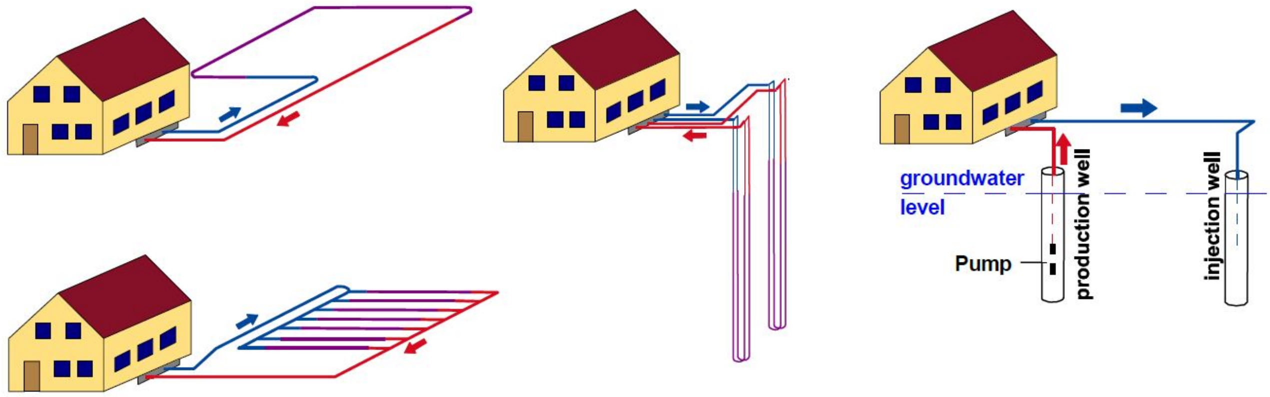


**Figure 2.4:** Schematic diagram of the most common ground-coupling methods (from left): horizontal loops, BHE (vertical loops), and groundwater wells. [1]

### 2.2.1 Cost of geothermal boreholes in Spain

For the economic assessment of the geothermal boreholes, quotations from a geothermal installer and a real project cost breakdown data have been taken into account.

Initially, the building which has been used for the demands calculation in Task 1.1 (see D1.1 [3]) has been taken as a reference. In the real building aerothermal heat pumps are installed, therefore there is no project cost breakdown for a geothermal installation. Based on the building yearly and peak demands, a quotation for a hypothetical system with geothermal heat pumps has been inquired to a recognized installer in the north of Spain, which is

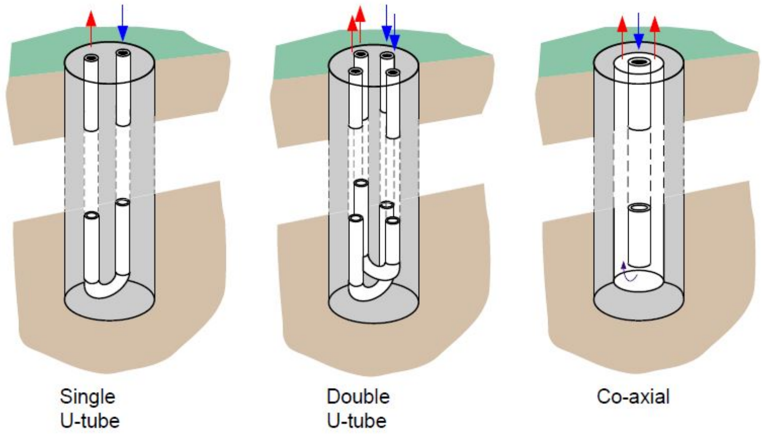


**Figure 2.5:** Schematic diagram of the most common ground-coupling methods (from left): horizontal loops, BHE (vertical loops), and groundwater wells. [2]

specialized in geothermal installations. Another quotation has been inquired to the same installer for the hypothetical case in which a part of the demand would be covered by aerothermal energy and the rest with geothermal energy, to see the effect this would have on reduction of geothermal borehole length and cost. Finally, in order to have data for a bigger installed capacity, a real cost breakdown for a geothermal installation in a big multi-family building in the same location (Bilbao) has been used.

The quotations and real project cost breakdown include the total cost of drilling and installing the boreholes until the machinery room, and also include the Thermal Response Test (TRT) and commissioning. Circulation pump is not included in the specific cost. The base unit for the cost calculation is the lineal meter of geothermal boreholes. Figure 2.6 shows the cost of the geothermal boreholes for the three different considered cases, and the derived equation.

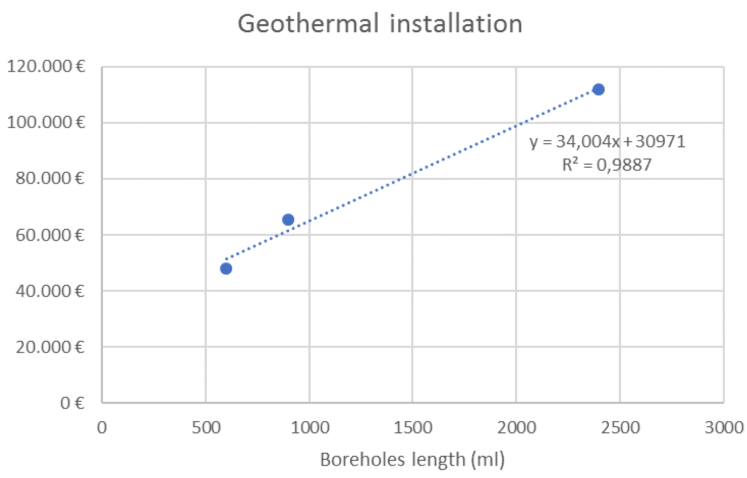


**Figure 2.6:** Cost of the geothermal boreholes for the case of Spain.

The linear regression cost of the Vertical Ground Heat Exchanger (VGHX) considering installation and commissioning in Spain is:

$$\text{Cost of VGHX (ES)=30 970 €+ 34 €/m} \tag{2.3}$$

where m is the lineal depth meter of the borehole. The derived costs for the geothermal boreholes shown in Eq. 2.3 correspond to a specific location, in this case Bilbao, in the north of Spain. It shall be noted that usually the cost of geothermal boreholes is highly dependent on the drilling methods used, that will depend on the soil characteristics, which will vary for different locations.

Drilling cost for closed vertical circuits with good rate of penetration (> 100 m/day), can vary between 20 €/m to 40 €/m, depending on the soil conditions and other factors. Consolidated terrains include limestone, sandstones or shale. Unconsolidated terrains can be formed of sand, gravel, mud or boulders.

$$\text{Cost of drilling (ES)=20 €/m to 40 €/m} \tag{2.4}$$

For large projects (> 30 kW), the first step will be to drill a pilot borehole, which will make possible the realization of the TRT and the determination of the lithology, rate of penetration, aquifers, need for auxiliary casing, etc. This will make possible the planning of the drilling operations and the final cost assessment.

In the specific case under study (location: Bilbao), it is recommended to execute the perforations using the rotopercussion technique with pneumatic hammer drill, technique especially suitable for terrains which are stable and consolidated. This method consists of introducing high pressure compressed air through the drill rods until the jackhammer provided with cut tools which, through percussion and rotation movements, cut the ground. The air comes out of the drill hole cooling it and evacuating the debris through the gap between the rod and the wall of the hole. The fluid to be used is a mixture of water and propylene glycol at 30 % (maximum recommended by the heat pump manufacturer).

#### 2.2.2 Cost of geothermal boreholes in Switzerland

For borehole lengths in a range of 1000 m to 2000 m the costs in Switzerland are 80 €/m to 90 €/m including installation work, costs for heat transfer fluid and connections to the technical room. The cost data are gathered from 14 offers[7]. For rocky underground like compact limestone or granite the costs of drilling increase the price.

$$\text{Cost of drilling with installation (CH)=80 €/m to 90 €/m (validity range 1000 m to 2000 m)} \tag{2.5}$$

### 2.3 Cost of thermal storage tanks

The cost of the tanks has been derived separately, in order to be able to provide versatility and adapt to different possible layouts in the specific cases to be cost assessed during the project.

[7] Data provided by HSLU Lucerne University of Applied Sciences and Arts.

### 2.3.1 Cost of thermal storage tanks in Spain

For both the space conditioning tank and the DHW tank, the characteristics of the tanks installed in the reference building for the calculation of demands [3] have been taken into account. As a reference for the characteristics of the tanks, the installed tanks have the following characteristics:

- Space conditioning tanks. Buffer tank, brand VALINOX or similar, model INR-PLUS 1000, in carbon steel, to work at a continuous temperature of 80 °C, with S / 97/23 / CEE certificate. Capacity 1000 l, insulation of 100 mm polyurethane and removable polypropylene lining and covers upper and lower rigid. Vertical placement. It will have a lateral manhole. Including 1500 mm × 1500 mm × 150 mm civil works bench, freight, auxiliary means for its location, cathodic protection, valve safety, placement and workmanship. Fully installed and functioning.
- DHW tanks. Accumulation tank of DHW, brand VALINOX or similar, model TS-PLUS 750, in AISI 316 l stainless steel, to work at a continuous temperature of 80 °C, with S / 97/23 / CEE certificate. Capacity 750 l / 1000 l (two DHW tanks installed), 100 mm polyurethane insulation and lining removable polypropylene and rigid top and bottom covers. Vertical placement. It will have a lateral manhole. Including 1500 mm × 1500 mm × 150 mm civil works bench, freight, auxiliary means for its location, cathodic protection, safety valve, placement and workforce. Fully installed and operational.

Based on those characteristics, the most similar tanks have been selected and their costs derived, in this case from a Price List Catalogue of Valinox[8]. Figure 2.7 shows the cost of the tanks for Space conditioning and Figure 2.8 shows the cost of the tanks for DHW, with their corresponding equations.

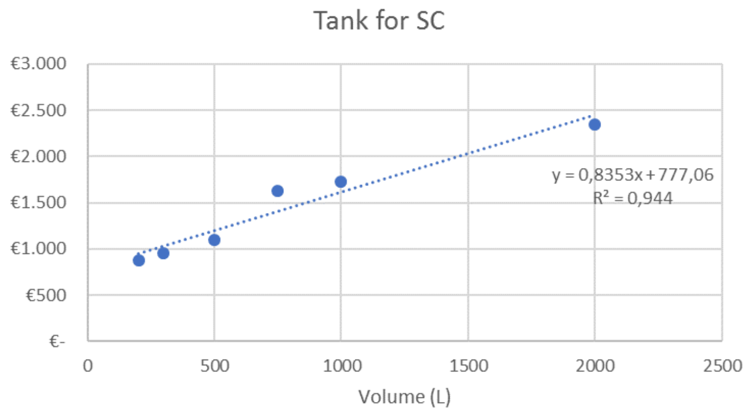


**Figure 2.7:** Cost of the tanks for space conditioning for the case of Spain.

The cost of the thermal energy storages TES for space conditioning (SC) and DHW in Spain as a function of the volume in liter are:

$$\text{Cost TES for SC (ES)} = 777\,€ + 0{,}8353\,€/\text{l (validity range 200 l to 2000 l)} \quad (2.6)$$

$$\text{Cost TES for DHW (ES)} = 506\,€ + 2.95\,€/\text{l (validity range 200 l to 5000 l)} \quad (2.7)$$

[8] http://www.depositosvalinox.com/

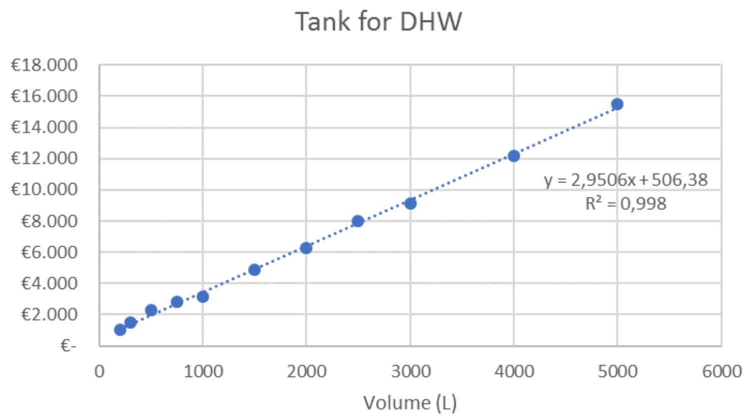


**Figure 2.8:** Cost of the tanks for DHW for the case of Spain.

### 2.3.2 Cost of thermal storage tanks in Switzerland

For estimating the costs storage tanks for domestic hot water with a volume up to 2000 l and space heating buffer storage tanks with a volume up to 1000 l are considered. Tanks made of stainless steel are much more expensive than those made of steel. In the following we consider stainless steel tanks for domestic hot water (see Figure 2.9) for hygienic reasons and steel tanks for space heating (see Figure 2.10). If a freshwater module is used for heating up the domestic hot water, it would be possible to use a steel tank for domestic hot water as well.

For the costs for the storage tanks prices from the following tanks are used for getting the range of costs for Switzerland:

- Meier Tobler SFW1, simple coil (stainless steel)
- Meier Tobler SFW2, double coil (stainless steel)
- CTA AG CHBI (stainless steel)
- Hoval Combival (stainless steel)
- Hoval (steel)
- CTA AG CHHS (steel)

The costs for a storage tank for domestic hot water range between 8000 € and 16 000 € for capacities between 1000 l and 2000 l. The steel tanks for space heating are much less expensive. The price ranges from 800 € and 1800 € for capacities between 2000 l and 1000 l.

The cost of the thermal energy storages TES for space heating (SH) and DHW in Switzerland as a function of the volume in liter are:

$$\text{Cost TES for SH (CH)} = 606\,€ + 1.103\,€/l \text{ (validity range 200 l to 2000 l steel)} \tag{2.8}$$

$$\text{Cost TES for DHW (CH)} = 1970\,€ + 5.596\,€/l \text{ (validity range 200 l to 1000 l stainless steel)} \tag{2.9}$$

$$\text{Cost TES for DHW (CH)} = -1818\,€ + 9.248\,€/l \text{ (validity range 1000 l to 2000 l stainless steel)} \tag{2.10}$$

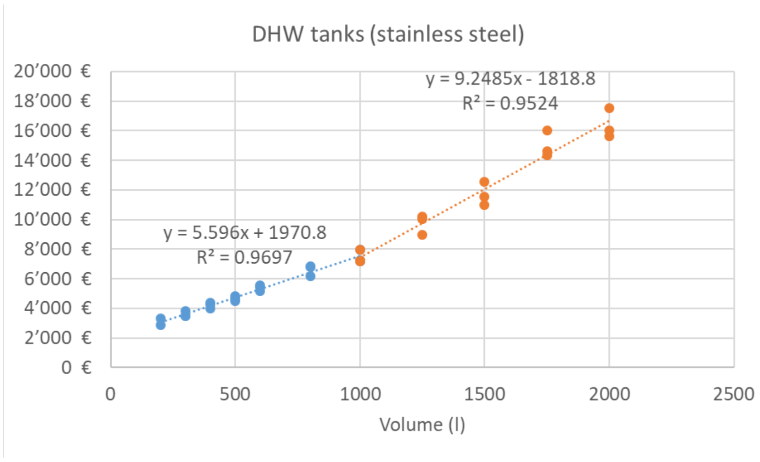


**Figure 2.9:** Cost of DHW Storage (stainless steel) in Switzerland with a linear curve fitting for tanks with a volume below and above 1000 l.

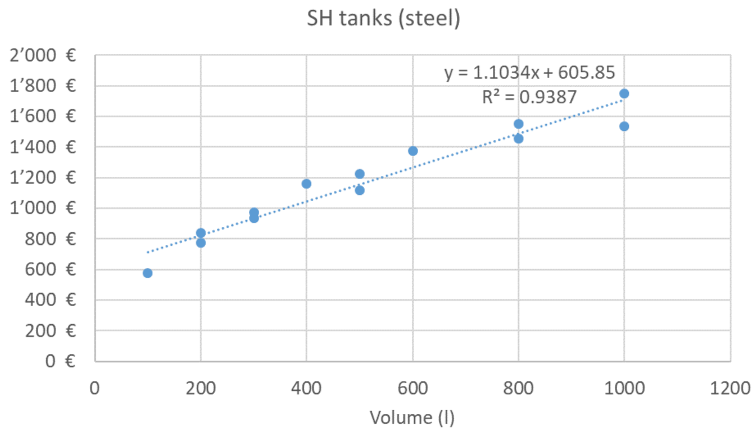


**Figure 2.10:** Cost of SH Storage (steel) in Switzerland.

## 2.4 Cost assessment of thermal installation

The thermal installation for the TRI-HP cost calculation is considered to be everything in the machinery room, except from the heat pump and storage tanks. Heat pump and thermal storages are considered separately. The machinery room in a building includes the following items:

- Heating/Cooling and DHW generation machines (heat pumps, boilers, etc.)
- Space conditioning water tanks
- DHW water tanks
- Circulation pumps
- Expansion vessels
- Heat exchangers
- Piping
- Valves
- Filters

- Sensors
- Etc.

For the TRI-HP case, the thermal installation costs are derived separately. It is difficult to derive equations for thermal installations that would be applicable to every case, as the layouts are going to be variable in each building installation project, and so the cost will be case-to-case dependant. However, our goal is to compare a state-of-the-art system with the systems developed in TRI-HP and the thermal installation part is expected to be the same.

### 2.4.1 Cost of thermal installation in Spain

The first reference taken for the thermal installation cost calculation has been the real cost breakdown of the building taken as a reference for the case of Spain (See D1.1 [3]). In that building, located in Bilbao, the installation consists of two aerothermal heat pumps of around 45 kW. Assuming the installation would be exactly the same with geothermal heat pumps (inside the machinery room), and that we can calculate the cost of the heat pumps and the geothermal boreholes in a separate way, the cost of the thermal installation can be taken as a reference. A simplified layout of the thermal installation of the building is shown in Figure 2.11 (note that the real installation includes two heat pumps).

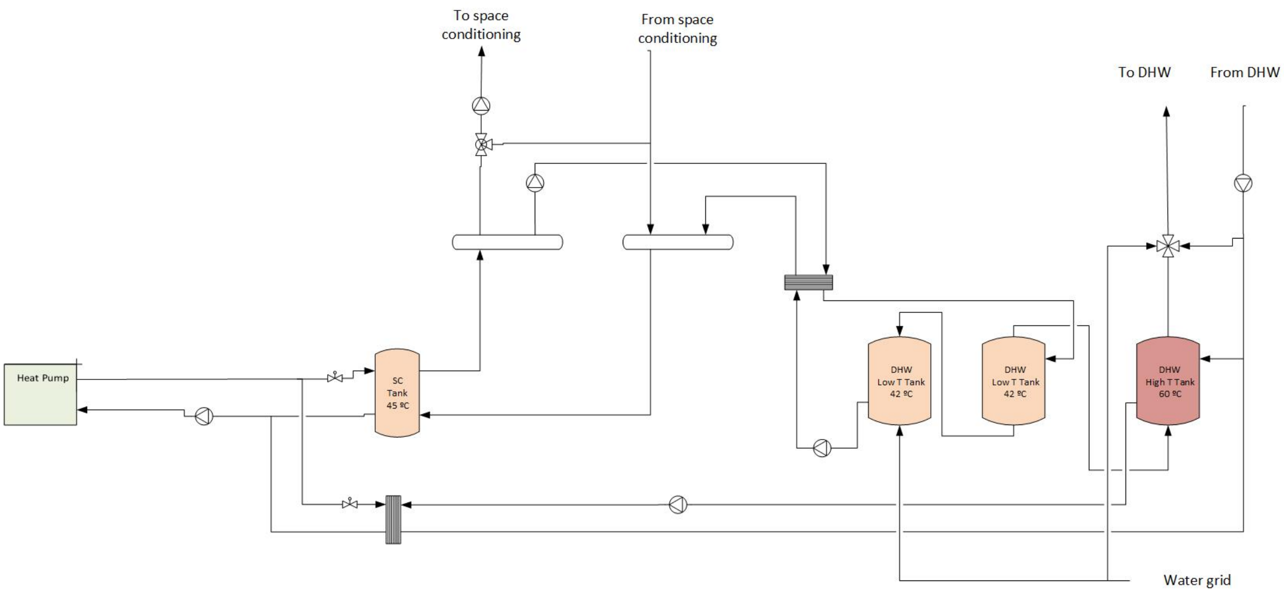


**Figure 2.11:** Simplified layout of the machinery room taken as a reference for the cost calculation.

$$\text{Cost of hydraulic system (ES)= -6379 €+ 300 €/kW (validity range 95 kW to 150 kW)} \tag{2.11}$$

In order to complete the cost analysis, another real project cost breakdown has been taken into account. In this case, a real cost breakdown for a geothermal installation in a big multi-family building in the same location (Bilbao) has been used. This building has 72 dwellings, and the thermal system comprises a geothermal heat pump for covering the base demand (150 kW nominal capacity at B0W35 according to EN 14511 [4]) and an auxiliary natural gas condensing boiler (120 kW). As the cost breakdown is separated for both systems, only the part corresponding to the heat pump installation has been taken into account.

Taking both cost breakdowns, the obtained cost for the hydraulic system is shown in Figure 2.12. The base unit is the installed capacity in kW.

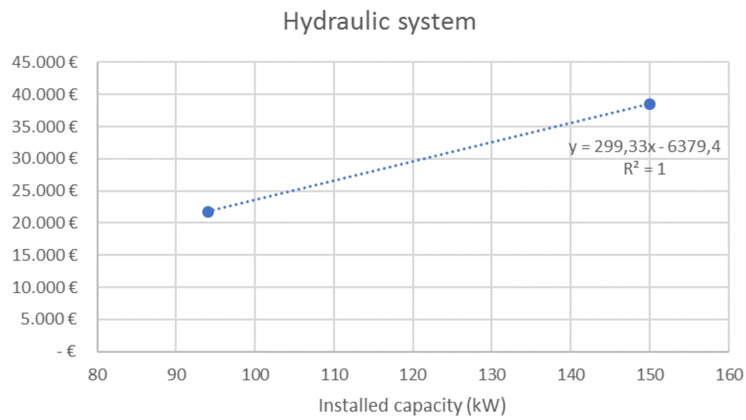


**Figure 2.12:** Cost of the hydraulic system (everything in the machinery room except from the HP and the tanks) for the case of Spain.

### 2.4.2 Cost of thermal installation in Switzerland

For estimating the cost of the hydraulic system in Switzerland, a set of data provided by different installers has been taken into account. The data have been obtained for different cases (brine-water heat pumps and air-water heat pumps), and in each of the cases, for different installed capacities (20 kW to 150 kW in brine-water heat pumps and 10 kW to 60 kW in air-water heat pumps). The total cost is included in the equation, but the cost breakdown corresponds to the following items:

- Installation cost heat source
  - Hydraulic material (piping, valves, pumps, glycol filling, etc.)
  - Insulation
  - Labor
  - Piping refrigerant (including material and labor)
- Installation cost heat sink
  - Hydraulic material (piping, valves, pumps,water filling, etc.)
  - Insulation
  - Labor
- Electrical installation

Taking into account the cost breakdowns, the obtained cost for the hydraulic system is shown in Figure 2.13. The base unit is the installed capacity in kW.

$$\text{Cost of hydraulic system (ES)= 22360 €+ 176 €/kW (validity range 20 kW to 150 kW)} \quad (2.12)$$

$$\text{Cost of hydraulic system (ES)= 21693 €+ 139 €/kW (validity range 10 kW to 60 kW)} \quad (2.13)$$

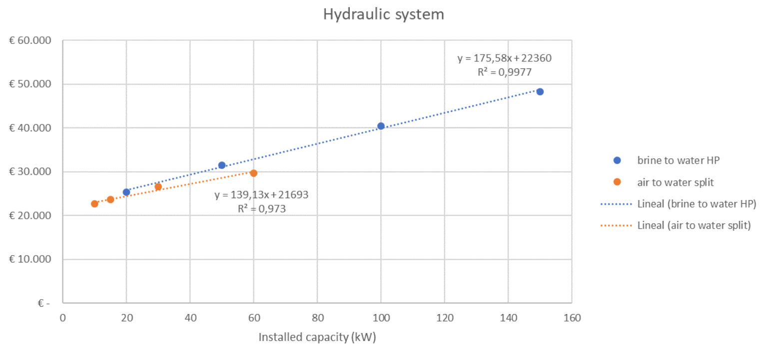


**Figure 2.13:** Cost of the hydraulic system (everything in the machinery room except from the HP and the tanks) for the case of Switzerland.

## 2.5 Cost assessment of PV panels and battery

PV systems can be stand-alone systems or grid-connected systems. In the standalone systems the electricity generation is matching the energy demand. Due to the difference in the solar energy generation and the energy demands from the connected loads, storage systems (batteries) are normally used.

In both TRI-HP systems (dual-source system and ice-slurry system), PV panels with batteries will be used, and the system will be connected to the grid in order to make possible to import/export electrical energy. This approach is the one usually taken in most of the Near Zero Energy Buildings (nZEB), in which PV technology is used for self-consumption and exporting to the grid. The target is to reach a high renewable self-supply of 80 %. The electricity self-consumption is dedicated to the general electric loads of the building (lighting and appliances), and to the heating/cooling and DHW production, when coupled to a heat pump.

Solar PV panels' cost are decreasing with an expectation to continue to drop, which is a big advantage for the inclusion of this renewable source in new and existing buildings. Moreover, operating and maintenance cost for PV panels is considered to be very low. The main limitation when it comes to building installation can be the space limitation. Enough surface for PV panels installation is not always available, therefore in some cases this can affect the sizing of the system and the solar self-consumption ratio. Another limitation they have is the low efficiency, even tough it is increasing with the new generation cells.

Existing PV technologies include crystalline silicon cells, which account for the vast majority of the produced PV panels; III-V compound semiconductor PV cells, and thin film cells. Among crystalline silicon technologies we can find:

- Monocrystalline or single crystal silicon cells (sc-Si), with conversion efficiencies between 16 % and 25 % (26.7 % record lab cell efficiency [5]), and normally higher investment costs.
- Multicrystalline silicon cells (mc-Si), with typical conversion efficiencies between 14 % and 18 % (22.3 % record lab cell efficiency [5]), but less expensive to produce.

The majority of the installed PV panels are monocrystalline silicon cells (66 % monocrystalline vs. 29 % multicrystalline production share in 2019 [5]), with an increasing trend over the last years. The price of both kind of panels is getting closer recently, and both kind of installations may have comparable costs nowadays. This Si-wafer based PV technology have has been taken as the basis for TRI-HP PV panels cost calculation.

### 2.5.1 Cost of PV installation in Spain

For the PV panels cost calculation, up-to-date market reference costs have been taken into account. By analyzing various size installations and corresponding cost references a linear relation was observed between peak power and specific cost. The values that define that line are the following references:

- For smaller systems (reference 5 $kW_p$ installed), a cost of 1200 €/$kW_p$ is considered.
- For larger systems (reference 100 $kW_p$ installed), a cost of 800 €/$kW_p$ is considered.

Those references account for the overall system installation cost (including all the relevant elements such as inverters, but excluding additional storage, i.e. batteries-), based on market average prices for various size installations.

These specific costs are represented in Figure 2.14. The direct cost per installed peak capacity ($kW_p$) has been derived, considering the aforementioned references in the range from 5 $kW_p$ to 100 $kW_p$.

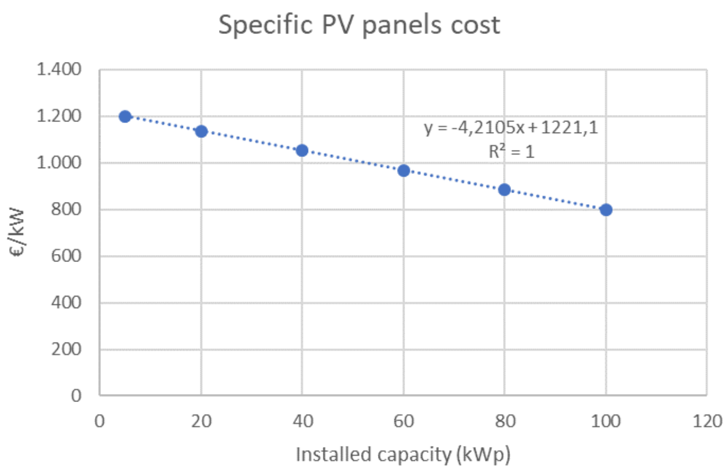


**Figure 2.14:** Specific cost of the PV panels for the case of Spain.

$$\text{Specific Cost of installed PV system in €/kW}_p\text{ (ES)}= 1221.1 - 4.21\,\text{kW}_p \text{ (validity range 5 kW}_p\text{ to 100 kW}_p\text{)} \quad (2.14)$$

In the case of the batteries, a fixed specific cost is considered.

$$\text{Cost of battery (ES)}= 600\ \text{€/kWh} \quad (2.15)$$

This reference corresponds to the average market value for the expected capacity range according to the project specifications. Regarding battery characteristics, a standard 2-hour system (energy-to-power ratio = 2) has been considered, which is a typical setup for domestic applications that adjusts to the generation capacity and enables maximizing the renewable self-consumption fraction. The exact final cost may be slightly different, depending on the case-specific particularities and corresponding system sizing.

### 2.5.2 Cost of PV installation in Switzerland

The costs for PV installation and batteries in Switzerland have been calculated in external studies that evaluated a huge number of offers in a wide range of installed power (PV) or capacity (battery). In case of PV installation we refer to [6]. For installed power up to 150 kWp the costs are shown in Figure 2.15.

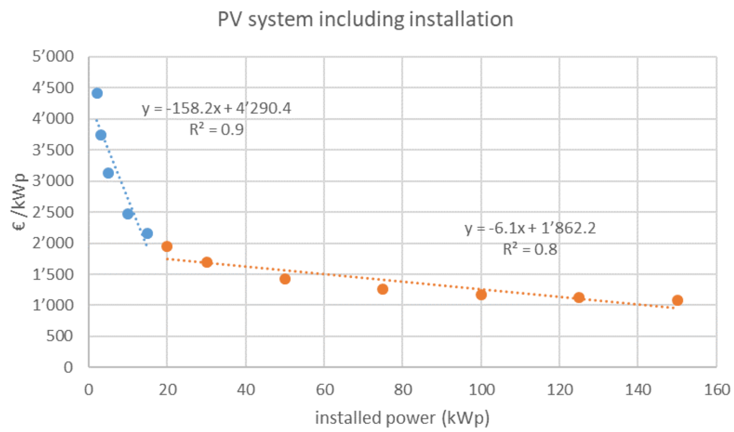


**Figure 2.15:** Specific cost of the PV panels for the case of Switzerland.

$$\text{Cost of installed small PV system in €/kW}_p\text{ (CH)= }4290 - 158\,\text{kW}_p\text{ (validity range }5\,\text{kW}_p\text{ to }20\,\text{kW}_p) \quad (2.16)$$

$$\text{Cost of installed large PV system in €/kW}_p\text{ (CH)= }1862 - 6\,\text{kW}_p\text{ (validity range }20\,\text{kW}_p\text{ to }150\,\text{kW}_p) \quad (2.17)$$

For households (battery capacity between 2 kWh and 16 kWh) the prices for battery systems range from 1000 €/kWh to 2000 €/kWh for the hardware (lower costs for higher capacity). These data are from a market analysis for Switzerland presented by Alpiq[9].

## 2.6 Cost assessment of solar ice-slurry system

The solar ice-slurry system contains solar-thermal collectors in combination with an ice slurry storage. An ice releaser is also necessary for a robust continuous ice-slurry production.

### 2.6.1 Cost of solar ice-slurry in Switzerland

Typically an ice storage system is fed by solar-thermal energy from uncovered selective solar-thermal collectors. For the cost estimation we use cost data from previous SPF projects [7].

The specific costs for the solar-thermal plant with collectors from Energy Solaire is about 860 €/m$^2$ for collector fields of about 100 m$^2$ gross area, what is a common range in an ice storage system for a multi family building in Switzerland. The costs for the collectors themselves is about 515 €/m$^2$, for installation work, mounting and hydraulic installation in the cellar about 345 €/m$^2$.

[9] Cost data of batteries from a presentation of Roger Burkhart, Alpiq - Helion, Elektrosuisse-Tagung

$$\text{Cost for installed uncovered selective collectors (CH)} = 860\,€/m^2 \tag{2.18}$$

The costs for conventional ice storages include the heat exchangers for solar heat and heat pump as well as the tank itself with insulation. The maximum ice fraction is assumed to be 70 % of the tank volume. Ice-slurry tanks can be of more simple construction because they do not have to withstand the pressure of the ice formed inside the tank. Therefore, simple tanks like retention tanks can be used. Additionally, an ice-slurry tank does not need to have heat exchanger inside the tank. Using an external heat exchanger instead lowers the costs of the ice storage by about 50 %. The ice slurry store has to be of bigger volume for storing the same amount of latent heat, as the maximum ice fraction is only about 50 %. For the ice-slurry system developed for multi-family buildings in Switzerland an ice-slurry storage volume in the range of 30 $m^3$ to 50 $m^3$ is necessary, which corresponds to about 1 $m^3$ per MWh of space heating and DHW demands. This corresponds to a latent heat capacity of about 1385 kWh to 2309 kWh, and to a volume of a conventional ice-storage of about 21 $m^3$ to 36 $m^3$ storage volume. A comparison between the specific costs per €/kWh of latent heat for a conventional ice storage and two estimates of specific costs for ice slurry tanks are given in Table 2.1.
One option for the ice-slurry storage is using tanks that are on the market and usually used for storing oil. The price for the oil tanks is taken from an offer from ROTEX. Another option considered is using retention tanks. The price for the retention tank is taken from the catalogue from Ripalgo. Further options would be simple concrete constructions with a waterproof surface inside the tank, but those are not considered here. For the ice-slurry tanks the price for an insulation of a 20 mm Aeroflex insulation is added to the costs for the tank itself. This insulation is not for preventing heat losses or gains but only to prevent condensation at the tank surface. Costs for an ice releaser of about 200 € are added to the ice-slurry tank costs.

| ice-storage | specific costs ice-storage €/$kWh_{latent}$ |
|---|---|
| conventional ice-storage | 42.5 |
| ice-slurry storage oil-tank | 20.9 |
| ice-slurry storage retention tank | 11.8 |

**Table 2.1:** Comparison of specific costs of conventional ice storage and estimated costs for possible solutions for ice slurry storage tanks with a latent heat capacity of 1380 kWh (21 $m^3$ for conventional ice storage, 30 $m^3$ for ice-slurry storage).

The ice-slurry tanks are thought to be placed in a cellar room. If they have to be buried in the ground some more costs have to be added to the tank costs:

- costs for excavation about 50 €/$m^3$
- costs for pipes from tank to cellar: about 2700 €

The ice slurry will have no internal heat exchangers. Thus, the solar energy will be provided by conventional plate heat exchangers that are rather cheap. For a 10 kW heat exchanger we assume 300 € to 500 € in Switzerland.

While extracting the heat from the ice storage by the heat pump the water will be supercooled. For supercooling a special plate heat exchanger that is coated with a ice-phobic coating is necessary, the costs for this are estimated in section 3.2.

## 2.7 Comparison of standard components between Spain and Switzerland

### 2.7.1 Heat pumps

For obtaining the cost of heat pumps, brine-water heat pumps have been taken into account, when possible with inverter and working with non-natural refrigerants. The cost analysis in the case of Switzerland has revealed that there are not significant differences in cost whether the heat pump has an inverter or not. The difference of cost between Spain and Switzerland can be appreciated in Figure 2.16, being minimal at low capacities and reaching around 37 % for higher capacity units (50 kW).

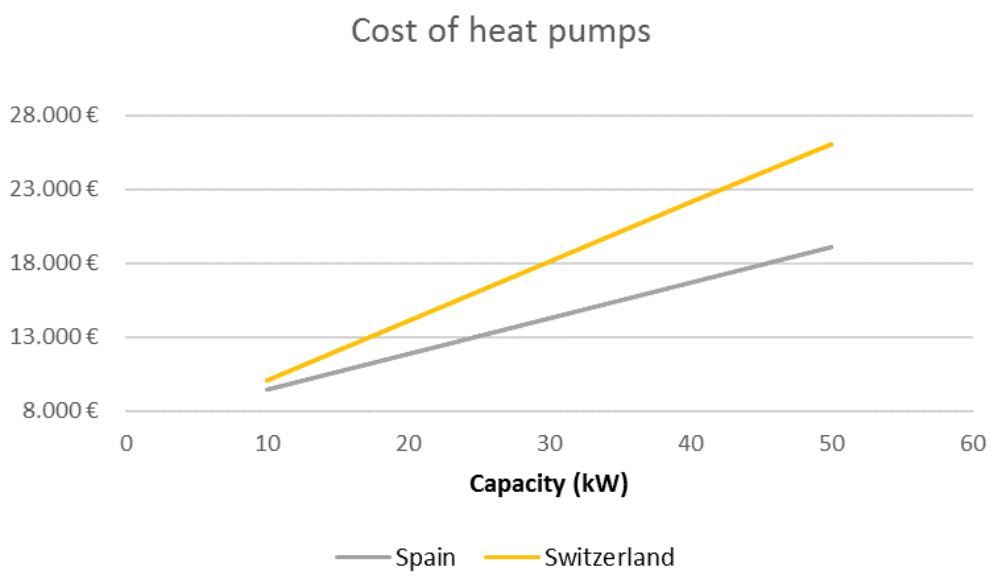


**Figure 2.16:** Cost of heat pumps. Spain and Switzerland.

### 2.7.2 Geothermal boreholes

Geothermal boreholes cost is derived based on the boreholes length, taking into account different real projects' cost breakdown. The cost includes installation and commissioning. As can be seen in Figure 2.17, a higher cost is expected in Switzerland, with an increase of between 20 % and 60 %, when compared to Spain, depending on the total boreholes length. It has to be taken into account that the cost of a geothermal installation can vary in a wide range, depending on the characteristics of the soil.

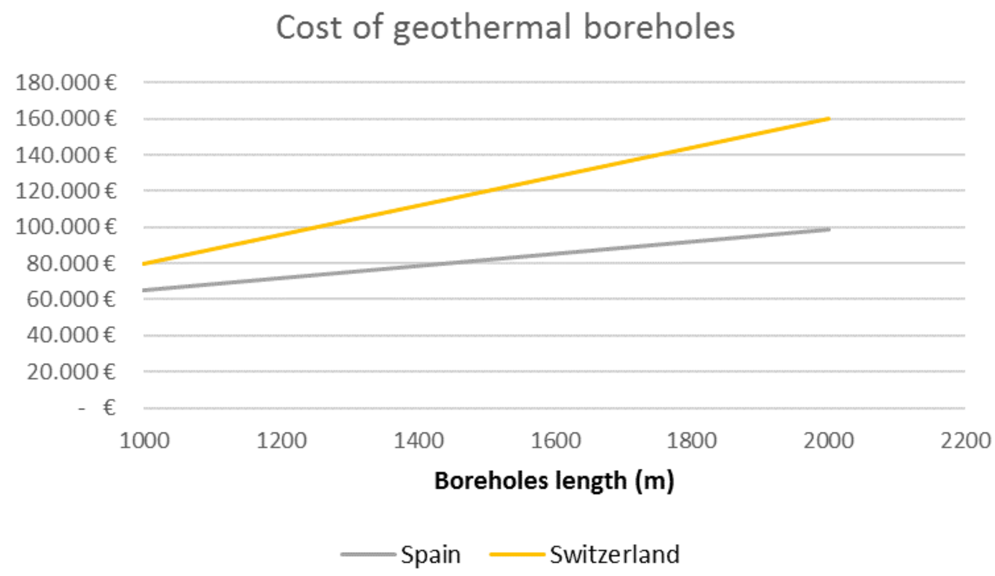


**Figure 2.17:** Cost of geothermal boreholes. Spain and Switzerland.

### 2.7.3 Thermal storage

The thermal storage costs have been derived separately for the space conditioning tanks and the DHW tanks. The derived cost for the space conditioning and DHW tanks is shown for both countries, in Figure 2.18 and Figure 2.19 respectively, referred to the tank volume. DHW tanks are made of stainless steel, and space conditioning tanks of carbon steel. As with the rest of the components, costs are significantly higher in Switzerland.

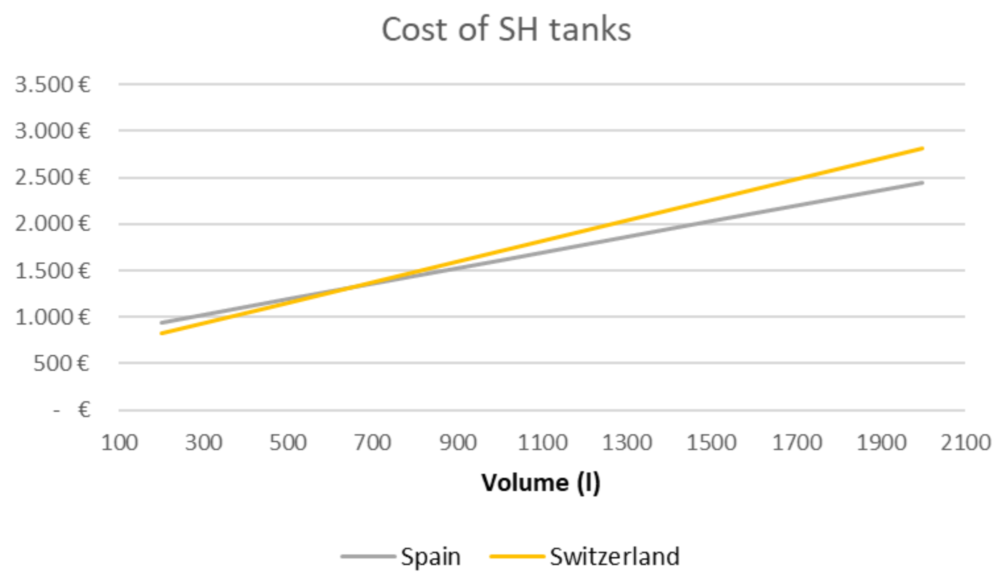


**Figure 2.18:** Cost of Space Heating (SH) tanks. Spain and Switzerland.

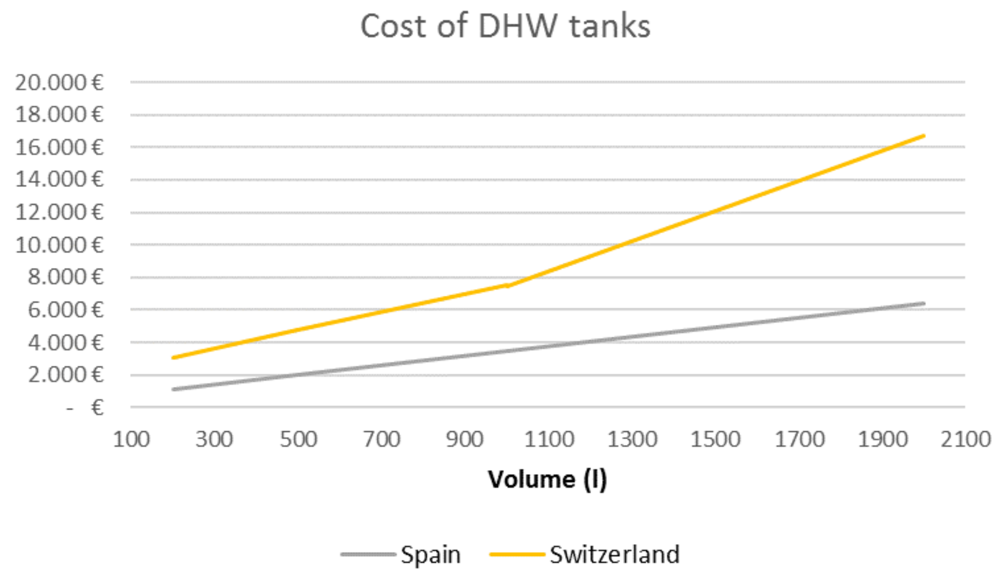


**Figure 2.19:** Cost of DHW tanks. Spain and Switzerland.

### 2.7.4 Thermal installation

The derived cost for the thermal installation including pipes, valves, pumps, insulation and the rest of components included in the machinery room (except heat pump and storage tanks). The thermal installation cost is shown for both countries in Figure 2.20, referred to the installed capacity.

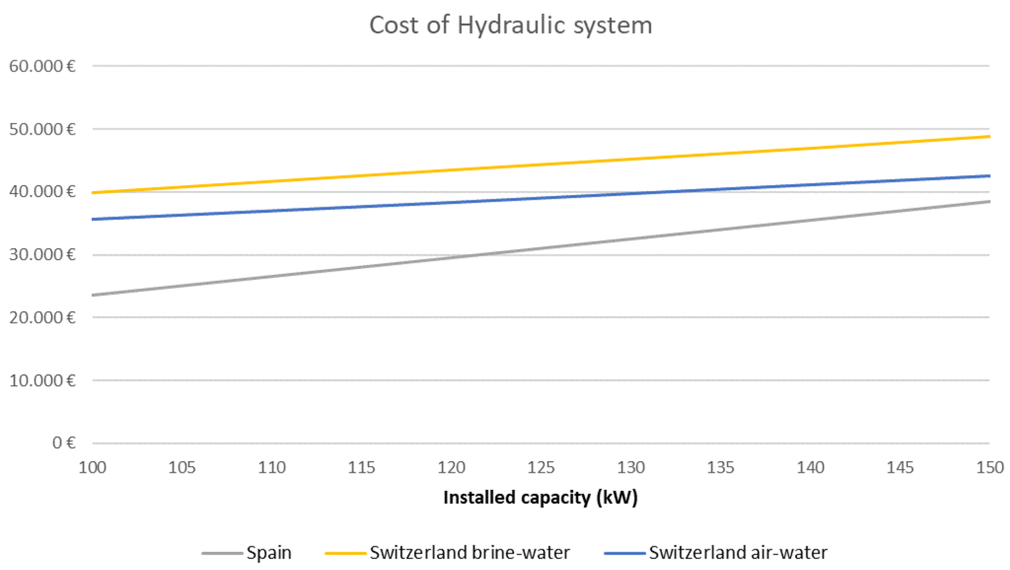


**Figure 2.20:** Cost of hydraulic system. Spain and Switzerland.

### 2.7.5 PV panels and battery

PV panels cost has been derived taking into account up-to-date market reference costs. In the case of Switzerland, the costs can be between 40-80 % higher when compared to Spain, as shown in Figure 2.21.

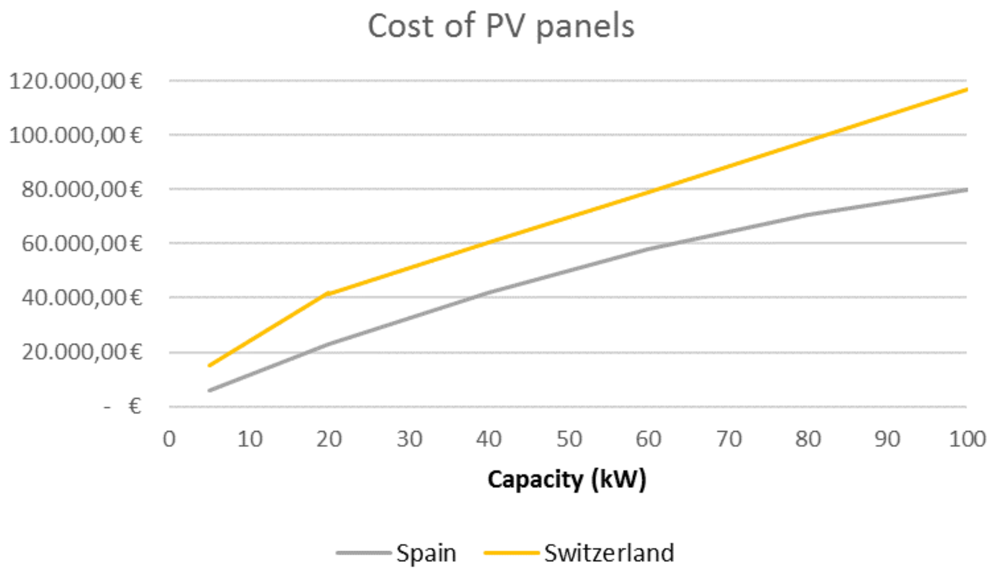


**Figure 2.21:** Cost of PV panels. Spain and Switzerland.

# 3 Cost assessment of new components

## 3.1 Cost assessment of tri-partite gas cooler

A tri-partite gas cooler is now made by combining standard brazed plate heat exchangers. In the future, combining all functionalities of a tri-partite gas cooler in a new plate design, the tri-partite gas cooler can be made of only one specially designed brazed plate heat exchanger (See D4.1[1]). The cost of this specially designed tri-partite gas cooler will be 5 – 10 % higher than a state-of-the-art gas cooler depending of production volume but that results in a more compact heat pump with less piping.

The cost of the tri-partite gas cooler which has been experimentally tested has been derived from Alfa Laval's CAS channel selection software, by getting the cost of the selected model (AXP14, see Figure 3.1) with different number of plates from the software, and then using the information in order to get the cost of the specific parts (preheater, space heating and reheater parts) taking into account the corresponding number of plates. The required areas for the preheater, space heating and reheater parts are 0.2 $m^2$, 1.15 $m^2$ and 0.49 $m^2$ respectively, and the total cost of the unit (net cost), calculated as previously explained, is 3085 €, leading to a specific cost of 1669 €/$m^2$, or 308 €/kW, when referred to nominal conditions[2] (see D1.1[3]). The number of plates in the space heating part (80) differs from the number of plates that were considered in D4.1 and D4.3[4]. This is due to the increase of number of plates in the final design, in order to reduce the pressure drop on the water side.

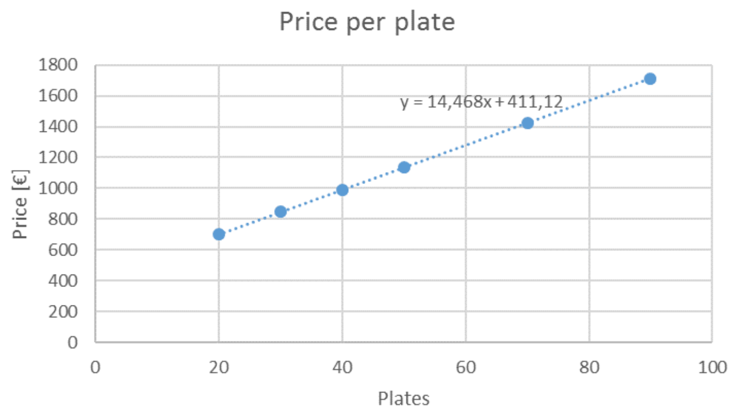


**Figure 3.1:** Cost per plate for Alfa Laval's AXP14 model.

NTNU has also derived the cost of a tri-partite gas cooler with a different geometry (helical counter-flow tube-in-tube heat exchangers), in order to establish a basis of comparison. NTNU has worked in the past with such kind of gas coolers [8], so they have asked for a quotation to a recognized manufacturer[5], taking into account the capacity and range of operation of the tri-partite gas cooler of TRI-HP in the design conditions. The required areas for the preheater, space heating and reheater parts are 0.17 $m^2$, 0.25 $m^2$ and 0.31 $m^2$ respectively, and the total cost of the unit is 2553 €, leading to a specific cost of 3497 €/$m^2$, or 255 €/kW, when referred to nominal conditions.

[1] D4.1 Design of tri-partite gas cooler.
[2] Note that the heat exchanger has been designed for 10 kW DHW only, 8 kW for SH only and 10 kW for DHW + SH.
[3] D1.1 Energy demands for multi-family buildings in different climatic zones
[4] D4.3 Experimental results of a tri-partite gas cooler.
[5] Klimal – Frigomec. www.frigomec.com

### 3.2 Cost assessment of supercooler

The developed supercooler is going to be based on commercially available corrugated flat plate heat exchangers from Alfa Laval. The new developments specially applied to this component are the icephobic coatings (developed by DTI and ILAG) and the bulk materials (developed by UASKA).

Estimation of the coating price

A precise estimation is not possible as the coating systems will first be defined in the course of the project. Thus, as a start value, a model calculation for an existing DTI coating has been performed. Final costs of any other developed product may differ significantly in both directions. The cost assessment is focused on the total cost (Production + Application) of the coating.

- Volume of coating required per $m^2$
  For the model coating, a 5 µm thick layer is required. The solid content of the coating is about 15 %. Thus, 33 ml coating per 1 $m^2$ surface has to be applied. Due to loss by unused coating remainders, approximately 50 ml/$m^2$ are needed.
- Production cost of coating
  Realistic production cost for 1 l of liquid coating produced at industrial scale of around 500 kg is in the range of 50-60 €/l. This would result in a raw material price, without application costs, of about 2.5-3 €/$m^2$.

Total Cost

The application costs have a stronger influence than raw material costs. Dip coating the assembled heat exchangers is a realistic option for large quantities. If amounts such as 250 $m^2$ per day can be reached application costs are expected to be in the range of 15-20 €/$m^2$. With a required area of 2 $m^2$ in nominal conditions, the specific cost per kW would be 3-4 €/kW. Table 3.1 shows the technical requirements and the cost assessment for the DTI and ILAG coatings.

**Table 3.1:** Technical requirements needed for the icephobic coatings. Assumptions per $m^2$ of coating surface. Total cost include production and application.

| Manufacturer | Dry film thickness | volume use per $m^2$ | volume use with losses per $m^2$ | Scale up | Production costs (500 kg batch size) | Coating cost €/$m^2$ | Total cost €/$m^2$ | Total cost €/kW |
|---|---|---|---|---|---|---|---|---|
| DTI | 5 µm | 33 ml | 50 ml | easy | 50-60 €/l | 2.5-5 | 15-20 | 3-4 |
| ILAG | 20 µm | ~0.1 kg | 0.150 kg | easy | 50-60 €/kg | 7.5-9 | | |

Estimation of the bulk material price

Like the coatings, a precise estimation is not possible yet. The price estimation of the bulk materials vary with the heat exchanger design and the different prices of the bulk materials used. Furthermore, the heat transfer of the heat exchanger determines the area required to achieve the specified supercooling. The bulk materials Vitrovac (VC), Vitrobraze (VZ) and Vitroperm (VP) chosen in D3.3 are supplied by the manufacturer in the widths 50 mm and 100 mm. It should be noted that the manufacturer Vacuumschmelze only supplies to large customers and requires a minimum purchase quantity of 225 kg or 450 kg. Based on the thermal conductivity target of the bulk materials of 150 W/mK the bulk material needed for a 10 kW heat exchanger can be calculated. A counter flow plate heat exchanger is assumed with a wall thickness of 5 mm. The temperature difference at the entrance of the water is roughly 8 K and at the outlet 5 K, where the water is supercooled. Heat transfer coefficients on the water and refrigerant side are calculated using the VDI heat atlas [9]. A cost summary is presented in Table 3.2.

**Table 3.2:** Price estimation of bulk materials only.

| Bulk Material | Cost [€/kg] | Length [m/kg] | Required length m | Cost [€/m$^2$] | Cost [€/kW] | Material price [€] |
|---|---|---|---|---|---|---|
| VP 220 | 51.83 | 135 | 40 | 7.68 | 1-1.1 | 15.36 |
| VC 7600 | 76.23 | 125 | 40 | 12.20 | 1.6-1.7 | 24.40 |
| VZ 2133 | 88.62 | 31 | 20 | 28.59 | 3.8-4.1 | 57.18 |

On the basis of the bulk materials examined, it is determined that nickel contents are credited with a special role in supercooling. A further literature review shows the favourable properties of nickel, especially nickel coatings [10]. A nickel coating applied by a high phosphorous electroless nickel method creates an amorphous surface. Furthermore, the coating can be applied in existing heat exchangers where it uniformly follows the complex geometry, which means there is no deposition at edges. This also eliminates high development costs of customized a supercoolers for the amorphous band strip materials. The nickel layer covers defects in the base material with a smooth surface and also protects it from corrosion. This method is already widely used in industry, which makes it cost-effective and therefore perfectly suited for the bulk materials approach. Based on the required area of 2 m$^2$ the application cost for the high phosphorous nickel treatment are shown in Table 3.3. A cost estimation is based on an offer from a German provider of the nickel treatment for gasketed heat exchangers. Taking into account the assumption of production of 10000 yearly units, the cost of treating a 40 plates heat exchanger, suitable for the application of the project, is 350 €. This leads to a specific cost of 175 €/m$^2$, or 35 €/kW in nominal conditions.

**Table 3.3:** Price estimation of high phosphorous nickel coating. Total cost includes production and application.

| Bulk materials | Dry film thickness [µm] | volume use per [ml/m$^2$] | Scale up | Total cost [€/m$^2$] | Total cost [€/kW] |
|---|---|---|---|---|---|
| electroless Nickel | 10 | $\sim$ 55 | easy | 175 | 35 |

## 3.3 Cost assessment of dual-source heat exchanger

The initial design of the DSHX is presented in D4.2[6]. The particularity of this component is that it can exchange energy with air or brine from the ground, providing an evaporator or condenser (depending on the heat pump working mode) with both sources separately or combined. Therefore, it needs a special design in which the refrigerant is in contact with both the external air and the brine coming from the ground.

The manufactured DSHX consists of internal bare tubes and external finned tubes, and has been manufactured by a recognized manufacturer of refrigeration systems in Spain. The first unit has a relatively high investment cost when compared with an evaporator/condenser coil, which would be reduced if units were to be produced in series. It has to be taken into account that the first unit has been sized in order to be able to reach the capacities calculated in the design conditions of the heat pump, for all the possible cases (heating with air, heating with brine,

[6] D4.2 Design of dual-source heat exchanger.

cooling with air, cooling with brine), leaving aside the combined air-brine modes for the moment. Those combined modes will be evaluated once the unit has been experimentally tested in Task 4.6[7].

The specific cost of the DSHX in this stage of the project is 43.7 €/m², which would correspond to 490 €/kW.

TECNALIA plans to construct a second version of the DSHX, once the experimental results of the first manufactured unit have been completed. It is expected that the area of the second DSHX can be considerably reduced, based on the redesign of diameters, and also on the use of enhanced internal tubes. With the use of the enhanced tubes, an enhancement of the phase change heat transfer coefficient of around 200 % is expected, therefore reducing the required heat transfer surface, which leads to a more compact unit.

The cost of the enhanced internal tubes is going to be higher than the cost of bare tubes (expected increase of 25 %), but with the expected area reduction due to the improvements in heat transfer coefficient, the total cost is expected to decrease by around 35 %.

[7] Task 4.6 Testing and optimizing a dual-source heat exchanger.

# 4 Conclusions

A first economic assessment of the systems under development in TRI-HP project has been carried out, that is, the solar ice-slurry system and the dual source system. The costs have been derived for the cases of Spain and Switzerland. In the project, two principal systems are being developed:

- Solar ice-slurry system
  - With R290 heat pump
  - With R744 heat pump
- Dual-source system
  - With R290 heat pump

Taking into account the particularities in both systems, costs for the state-of-the-art components have been derived, taking into account recognized references, such as commercial information, quotation request to recognized manufacturers, or other relevant references. Also, the costs of the new developments of the project have been derived for each of the heat pump systems. In order to gather those data, the experimental research carried out until the date, as well as a prospective for future improvements for each of the new developments, have been taken into account.

State-of-the-art components correspond to:

- Heat pumps, as a base for comparison with the new developed heat pumps.
- PV panels and battery.
- Geothermal boreholes.
- Solar thermal collectors.
- Ice-slurry storage.
- Thermal installation (water tanks and auxiliary equipment).

For the state-of-the art components, a cost structure for each of the items has been derived, based on characteristic properties, such as capacity, area, etc. In that way, it will be possible to use the obtained equations for complete systems' investment cost calculation. Solar thermal collectors and ice-slurry systems have been only considered for the case of Switzerland. For the rest of the components, the differences in cost between Spain and Switzerland have been analyzed.

New developments of TRI-HP project include the following improvements for the heat pumps:

- Tri-partite gas cooler (R744 heat pump).
- Supercooler (both heat pumps).
- Dual source heat exchanger (DSHX).

The cost of the tri-partite gas cooler has been derived from the unit which has been experimentally tested in NTNU, by using Alfa Laval's selection software. The obtained specific cost is 308 €/kW, referred to the nominal conditions. NTNU has also obtained the cost of an equivalent version of the tri-partite gas cooler (same design conditions), but with a different geometry (tube-in-tube heat exchanger). This version of the tri-partite gas cooler has a specific cost of 255 €/kW.

For the cost assessment of the supercooler, the newly developed icephobic coatings and the bulk materials have been taken into account. The cost assessment of the coating is based on the production and application cost.

Total cost varies between 15-20 €/m$^2$ with the coatings considered by DTI and ILAG. Regarding the bulk materials, the cost of three of them has been assessed. A cost variation between 7.7 €/m$^2$ to 28.6 €/m$^2$ has been assumed. However, custom-made heat exchanger would be necessary increasing considerably the overall heat exchanger cost. Instead, a high phosphorous Nickel treatment can be used. The estimated cost is of around 145 €/m$^2$. Referring those cost to the heat pump power, a range of 3 €/kW to 4 €/kW for icephobic coatings and around 35 €/kW for the Nickel treatment are obtained.

Finally, the cost assessment of the DSHX has been done based on the first design of the component (see D4.2[1]), obtaining a specific cost of 490 €/kW. A future version of the DSHX including enhanced tubes is expected to lead to a decrease in cost of around 35%.

[1]D4.2 Design of dual-source heat exchanger

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TRI-HP PROJECT

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