Integration of Cooling into Mine Water Heat Pump Systems F1.1

European Research Fund for Coal and Steel
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LoCAL Project: Low Carbon Afterlife:

Sustainable Use of Flooded Coal Mine Voids as a Thermal Energy Source - a Baseline Activity for Minimising Post-Closure Environmental Risks

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Integration of Cooling into Mine Water Heat Pump Systems F1.1

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Contents

Foreword

This report forms part of the output from the LoCAL (*Low Carbon AfterLife*) project, funded by the European Commission Research Fund for Coal and Steel, grant number RFCR-CT-2014-00001.

The fundamental objective of LoCAL is to provide a number of technical, economic and management tools, aimed at overcoming barriers to the uptake of mine water in abandoned flooded coal mines as a source for heating and cooling (passively, or via the use of heat pumps). The project is divided into five Work Packages (WP) and a number of Tasks.

WP	Task		UoG	Alkane	NTU	UoO	HUNOSA	GIG	Armada
1	1.1	A new tool for heat transfer modelling in flooded mine workings							
	1.2	Quantifying important mixing processes at the system scale							
	1.3	Demonstration of new tools on a system in development							
2	2.1	Preventative strategies for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters							
	2.2	Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment systems.							
3	3.1	Technical, legal and management STEEP/ cost-benefit analysis of various types of decentralised heat pump system, versus centralised plant room system							
	3.2	Pathways to market							
	3.3	Models for incorporating cooling into a delivery system							
	3.4	Ownership, management and financial models							
	3.5	Toolbox assuring multiplication of the project results							
4	4.1	Pilot implementation at Markham site (UK)							
	4.2	Pilot implementation at pilot site in Asturias (ES)							
	4.3	Pilot implementation at pilot site in Bytom (PL)							
5	5.1	Project management							
	5.2	Reporting							
	5.3	Dissemination							

UoG = University of Glasgow (UK), Alkane = Alkane Energy Ltd. (UK), NTU = Nottingham Trent University (UK), a subcontractor to Alkane; UoO = University of Oviedo (Spain), GIG = Central Mining Institute (Poland). Black boxes indicate Task Manager, grey indicate Task Participant.

The LoCAL Project "*Low Carbon AfterLife - Sustainable Use of Flooded Coal Mine Voids as a Thermal Energy Source - a Baseline Activity for Minimising Post-Closure Environmental Risks*" aims at providing bespoke tools for investigating flow and heat transfer in flooded mine workings. New tools for quantifying and modelling heat transfer in networks of flooded mine workings are under development Another aim of the LoCAL project is to overcome the hydrochemical barriers to effective heat transfer from raw and treated mine waters. Ochre clogging is a well-known phenomenon which affects many mine water heating and cooling systems. The LoCAL project not only covers technical and engineering issues, but also provides economic and management models for efficient energy extraction and distribution. Technical, legal, managerial and cost-benefit analyses of various types of decentralised and centralised heat pump systems are being carried out. Project activities are being simultaneously undertaken in mining areas of the UK by research organizations in partnership with industrial enterprises (University of Glasgow in partnership with Alkane Energy Ltd.), Spain (University of Oviedo, with HUNOSA as the industrial partner) as well as in Poland (Central Mining Institute, in partnership with Armada Development).

Installation of a closed-loop "Energy Blade" heat exchanger at mine water treatment lagoon, Caphouse, Yorkshire (UK). Photo by Mr Alan Chalkley (National Coal Mining Museum of England)

This report describes the results of Task 3.3 of LoCAL – "Models for incorporating cooling into a delivery system".

1. Introduction

1.1 Objective

The objective of this Report is to fulfil the requirements of Task 3.3 of LoCAL Work Package 3. It will consider:

- Firstly, the various configurations by which cooling provision can be integrated into mine water-sourced geothermal heating systems, both passively (without the use of heat pumps, but merely by natural temperature gradients) and actively (using heat pumps).
- Secondly, to provide three case studies, illustrating, in more detail, how cooling has been integrated, in practice into mine water geothermal systems. The three chosen case studies are:
  - Barredo Shaft, Mieres, Asturias, northern Spain (one of the LoCAL pilot sites)
  - Springhill community heating / cooling schemes, Nova Scotia, Canada
  - The Heerlen mine water district heating and cooling system, Netherlands.

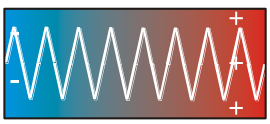
Criteria for decision making will be elucidated and the economic implications of the various configurations discussed. While the feasibility and economic viability of each solution will strongly depend on individual buildings and climatic conditions, three relatively straightforward spreadsheet models, incorporating both heat transfer and costings, have been developed. This report should be read in conjunction with the use of these models:

- **Model 1.** *LoCAL 3.3.1_Active heating or cooling tool.xlsm*. This model simulates the incorporation of cooling into active (heat pump-driven) systems. The model simulates both heating-dominated or cooling-dominated systems.
- **Model 2.** *LoCAL 3.3.2_Passive cooling tool.xlsm*. This tool simulates both straightforward passive cooling performed by mine water, and the incorporation of an element of passive cooling into an active cooling / heating system.
- **Model 3.** *LoCAL 3.3.3_Discrete heating and cooling arrays.xlsm*. This model simulates the use of "chillers" and heat pumps performing heating simultaneously in a system.

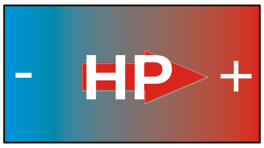
In many of the diagrams in this report, and in the models described above, the mine water flow through heat exchangers is depicted (potentially misleadingly) as a fixed quantity. In reality, of course, these models and diagrams are merely snapshots; the mine water flow can be regulated, either via the speed of the downhole submersible pump(s) or by valve controls, such that mine water flows are increased at times of high heating or cooling demand (which may be reflected in changes in temperature in secondary heat transfer circuits). This is, indeed, the case in systems such as that at FAEN, Mieres (Section 6.4).

1.2 Symbols

The diagrams shown in this report tend to be schematic for reasons of clarity and simplicity. Most valves, pressure / buffer tanks, filters and some circulation pumps are omitted. The following symbols tend to be used.



= heat exchanger (+or red = warm side; - or blue = cold side)



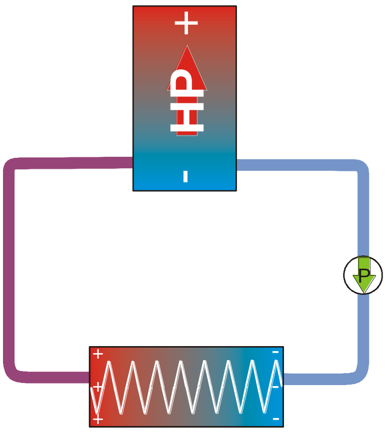
= heat pump (+or red = warm / condenser side; - or blue = cold / evaporator side)

= 3-way switching valve

= circulation pump

= submersible pump

= orange arrows typically indicate mine water flows



= a loop of pale mauve/blue typically indicates a closed loop of heat transfer fluid

1.3 Definitions

The *approach temperature* of a heat exchanger (HEX) is usually defined as the difference between the exit temperature of the process fluid and the entry temperature of the service fluid. For example, if a heat transfer fluid is cooled from 21°C to 17°C by a mine water at 14°C, the approach temperature is (17°C-14°C) = 3°C.

The coefficient of performance (COP_H) of a heat pump in heating mode is defined by:

$$\mathrm{COP_H} = \frac{\text{Heating effect } (\mathrm{kW_{th}})}{\text{Electrical energy input } (\mathrm{kW_e})} = \frac{\mathrm{H}}{\mathrm{E}} = \frac{\text{Heat supplied to building } (\mathrm{kW_{th}})}{\text{Electrical energy input } (\mathrm{kW_e})}$$

The coefficient of performance (COP_C) of a heat pump (or "chiller") in cooling mode is defined by:

$$\mathrm{COP_C} = \frac{\text{Cooling effect (kW}_{\text{th}})}{\text{Electrical energy input (kW}_{\text{e}})} = \frac{\mathrm{C}}{\mathrm{E}} = \frac{\text{Heat removed from building (kW}_{\text{th}})}{\text{Electrical energy input (kW}_{\text{e}})}$$

The effective coefficient of performance ($\mathrm{COP_{eff}}$) of a heat pump or ground coupled heating and cooling system, which is performing both heating and cooling simultaneously can be defined as:

$$\mathrm{COP_{eff}} = \frac{\text{Heating plus cooling effect (kW}_{\text{th}})}{\text{Electrical energy input (kW}_{\text{e}})} = \frac{\mathrm{H+C}}{\mathrm{E}} = \frac{\text{Heat supplied to+heat removed from building (kW}_{\text{th}})}{\text{Electrical energy input to system (kW}_{\text{e}})}$$

2. Passive Cooling

2.1 Passive Cooling of Living and Working Areas

The concept of passive cooling implies the removal of waste heat from a building or industrial process without the use of mechanical chillers or heat pumps. The concept is elaborated by Banks (2012).

In the context of air conditioning or space cooling of living or working spaces, one typically targets a temperature of around 20°C. Thus, passive "air conditioning" cannot be accomplished with a geothermal source (in this case, mine water) cooler than 20°C. In reality, of course, a significant temperature gradient must be established between the heat removal fluid and the building air to effect efficient heat transfer, so the upper threshold of mine water temperature will be much lower than this.

Conventional active (heat pump-driving) building cooling systems often operate with a flow temperature of c. 6 or 7°C and a return of c. 12°C. However, it is now possible to design cooling systems that operate with a flow temperature of 12°C or more. Indeed, chilled beams are now available with water inlet temperature of 13-17°C (and indeed, such relatively high temperatures are now recommended in order to prevent condensation on the beams). In order to achieve satisfactory cooling, however, with such relatively low temperature differentials between building and heat transfer fluid, one needs to:

- Install highly efficient heat exchangers (extractors) within the building, often with large surface area or air throughflow. These include chilled structural elements (chilled panels, beams etc.) and efficient fan coils.
- Pump larger quantities of the ground-coupled fluid (if ΔT is low, Q must be increased to maintain cooling effect).

  Heat removed (kW) = $Q_{fl} \times \Delta T \times \rho_{fl} c_{fl}$ (2.1)

  where Q_{fl} is the flow rate of a fluid (m^3 s^{-1})
  ΔT is the temperature change of the fluid across a heat exchanger (K)
  ρ_{fl} is the fluid density (kg m^{-3})
  c_{fl} is the fluid's specific heat capacity (kJ kg^{-1} K^{-1})
  $\rho_{fl} c_{fl}$ is the fluid's volumetric heat capacity (kJ m^{-3} K^{-1}), which, in the case of water, is around 4200 kJ m^{-3} K^{-1}.

Both of these factors typically lead to increased capital costs (larger heat exchange areas, more wells and larger pumps) and increased pumping costs. Energy expenditure (E) by pumping (kW) is given by:

$$E = (Q_{fl} \times \Delta h \times \rho_{fl} \times g) / \eta \qquad (2.2)$$

Where Δh is the sum of all elevation and frictional head losses, g is acceleration due to gravity (9.81 m s^{-2}) and η is pump efficiency (60% is 0.6).

However, the main attraction of passive cooling schemes is the low running cost, represented by the saving in electricity used to power the compressor of a heat pump.

On balance, therefore, passive cooling typically leads to an increase in CAPEX and a saving in OPEX. The relative magnitudes of the savings will depend strongly on local factors (including the depth of the mine water level: if deep, increased mine water pumping costs may be significant – see Equation 2.2).

A typical passive cooling scheme may appear as follows (in schematic, with indicative temperatures only).

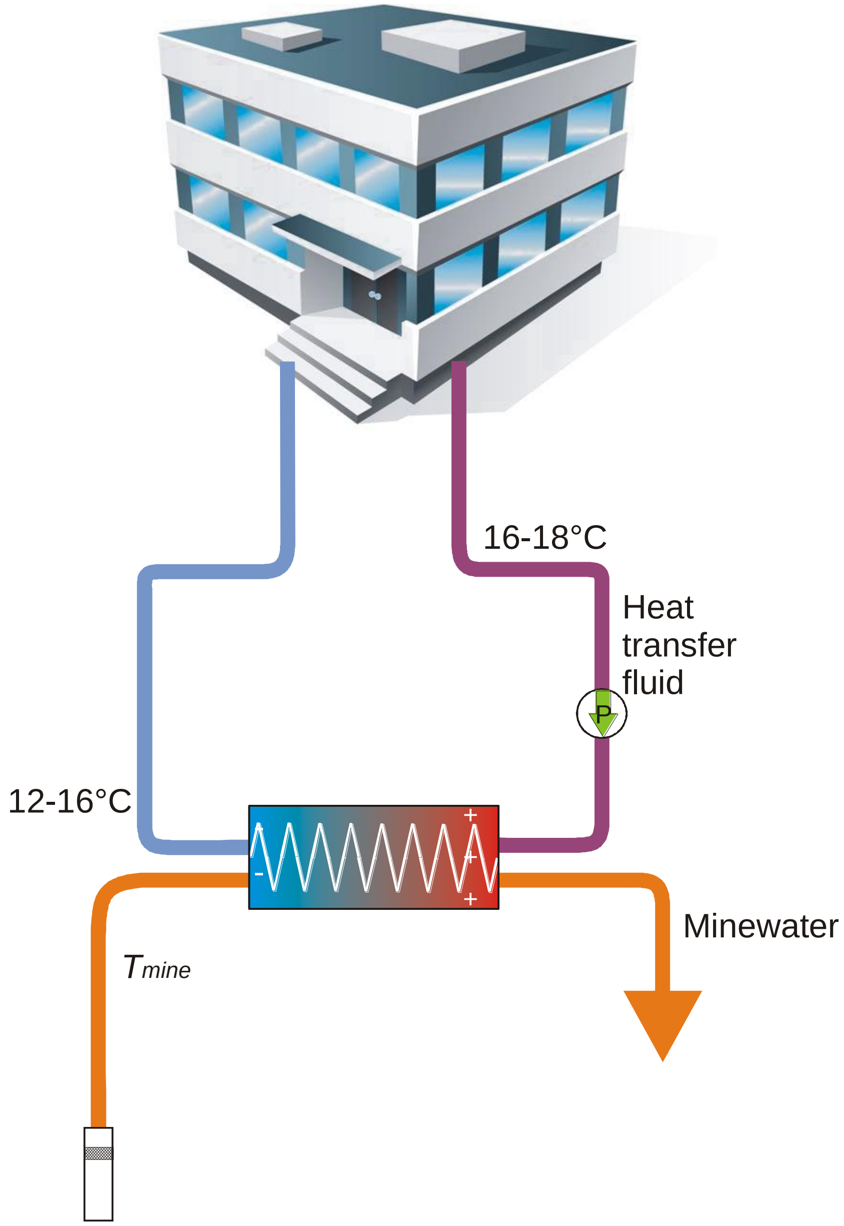


Figure 2.1. Schematic of typical passive mine water cooling system

The Excel Workbook ***LoCAL 3.3.2_Passive cooling tool.xlsm*** allows this configuration to be investigated.

As heat exchangers have a finite approach temperature (which will be related to cost: it may be as low as 1°C in exceptional cases, but may be no lower than 2°C), we can conclude that:

Passive cooling of working and living spaces is typically feasible when the mine water temperature is ≤ 12°C. The lower the temperature, the more attractive it is. In practice, this limits the application of passive cooling to northern / central Europe and Scandinavia (Figure 2.2).

Where the mine water temperature is 8°C or less, passive cooling becomes a very attractive strategy. This is typically only the case in Scandinavia, however.

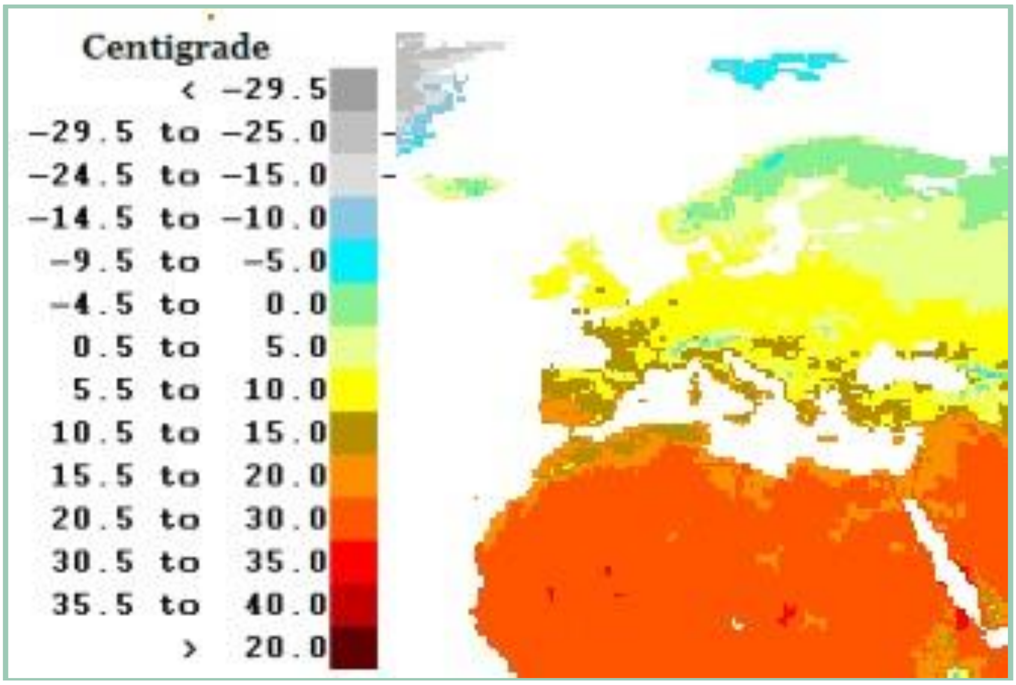


Figure 2.2. Map of annual average European air temperature (ground temperatures may be slightly higher). Modified after http://www.eldoradocountyweather.com/climate/world-maps/world-annual-temps-map.html

2.2 Passive Cooling of Industrial Processes

The above only applies to space cooling of living and working areas, where the target temperature is around 20°C. If the object of cooling is a higher temperature industrial process or condenser, passive cooling by mine water becomes more widely appropriate in a range of climatic zones.

Cooling of chilled areas (refrigerated stores, ice rinks etc.) cannot realistically be achieved by passive cooling techniques.

3. Active Cooling

The use of a heat pump (chiller) allows space cooling (or industrial cooling) to be achieved by creating enhanced temperature gradients between the building and the heat transfer fluid and between the heat transfer fluid and the mine water. This typically saves on CAPEX, but increases OPEX (due to the primary energy required to run the heat pump compressor). An exception to this general rule is when mine water levels are particularly deep and there may be an economic advantage (in terms of OPEX) to be had by minimising the quantities of pumped water (and thus the energy expense of pumping).

3.1 Cooling Only

The simplest form of active cooling, using mine water, is shown in Figure 3.1. In all the subsequent cases, it is assumed that the mine water is of insufficiently good quality to circulate directly through the heat pump's condenser, and thus that a prophylactic heat exchanger and intermediate loop of heat transfer fluid are applied.

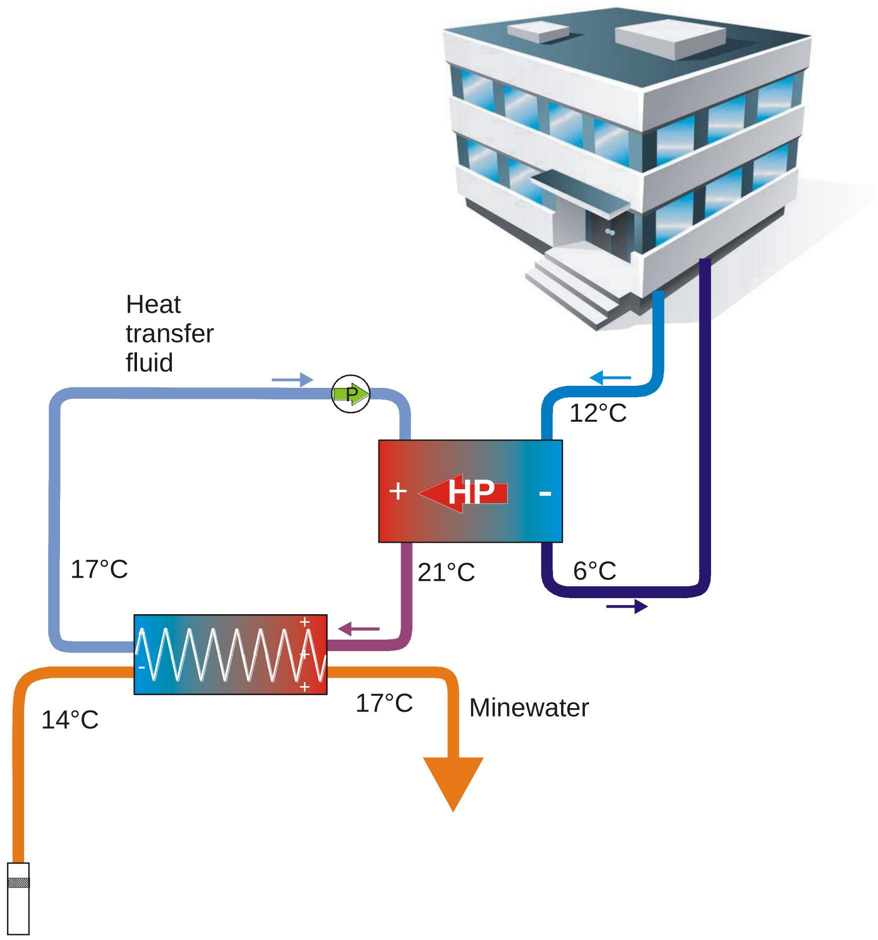


Figure 3.1. Highly schematic diagram of simple cooling of a conventional 6°/12°C air conditioning circuit using a heat pump and mine water as a sink.

In this case, the coefficient of performance in cooling mode (COP_C) of the heat pump is defined as

$$COP_C = \frac{\text{Cooling effect (kW}_{th})}{\text{Electrical energy input (kW}_{e})} = \frac{C}{E} = \frac{\text{Heat removed from building (kW}_{th})}{\text{Electrical energy input (kW}_{e})}$$

For an efficient heat pump:

Waste heat rejected to mine water = M = C + E = C + (C / COP_C) = C (1 + 1/COP_C)

The COP_C depends on:

- The temperature of the heat transfer fluid entering the condenser (which will be strongly related to the mine water temperature)
- The temperature of the chilled fluid leaving the evaporator
- Also, the temperature differentials across the condenser and evaporator / flow rates through the evaporator and condenser.

Figure 3.2 gives a rough idea of the dependence of the COP_C of a typical heat pump on these temperatures (these will be, to some extent, model specific).

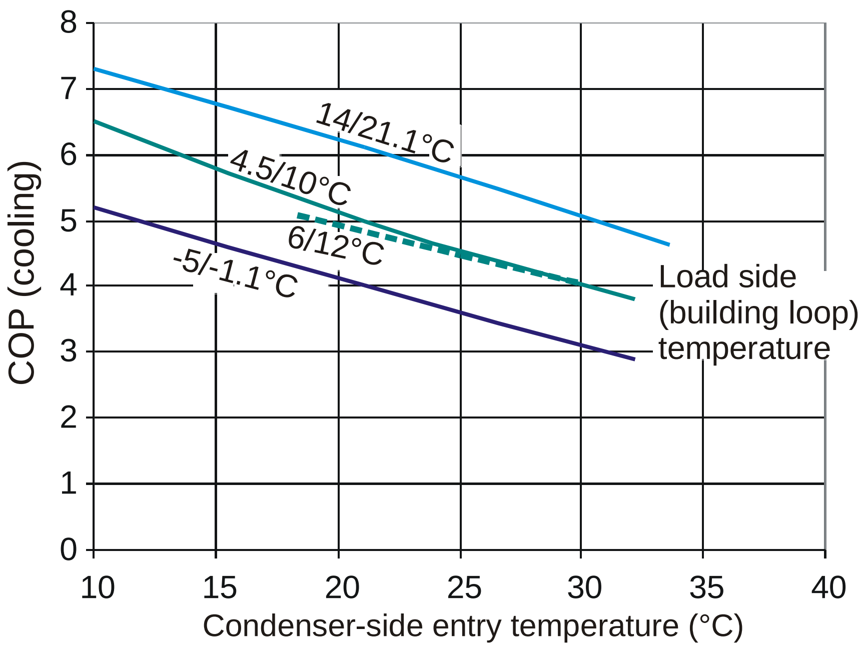


Figure 3.2. Dependence of COP_C on condenser and evaporator temperatures, based on two typical commercial heat pumps (modified after Banks, 2012). These curves will be model-dependent.

3.2 Reversible Systems for Seasonal Heating and Cooling

Where a building has well-defined seasonal heating and cooling requirements – i.e. heating only in winter, cooling only in summer – a reversible heat pump can be used.

In the winter, the condenser delivers heat to the building heating circuit and the evaporator is coupled to the mine water (usually via an intermediate heat transfer fluid circuit and a prophylactic heat exchanger).

In the summer, the evaporator is connected to the building cooling circuit while the condenser sheds heat to the mine water (usually via an intermediate heat transfer fluid circuit and a prophylactic heat exchanger). This can be achieved via:

- A true reversible heat pump, where the direction of refrigerant circulation is altered via a reversing valve, such that the condenser becomes the evaporator and vice versa.
- Adding valves to the intermediate heat transfer circuit and the building circuits (Figure 3.3), such that
    - (a) either the intermediate heat transfer circuit (winter) or the building cooling circuit (summer) can be coupled to the evaporator, or
    - (b) either the intermediate heat transfer circuit (summer) or the building heating circuit (winter) can be coupled to the condenser.
- In practice, this is usually most readily achieved by using two heat exchangers (one for heating and one for cooling) – see Figures 3.4 (bottom) and 3.5 (bottom) – see also Figures 6.10 to 6.13. The advantage of this is that the heating, cooling and primary water circuits are all kept hydraulically separate.

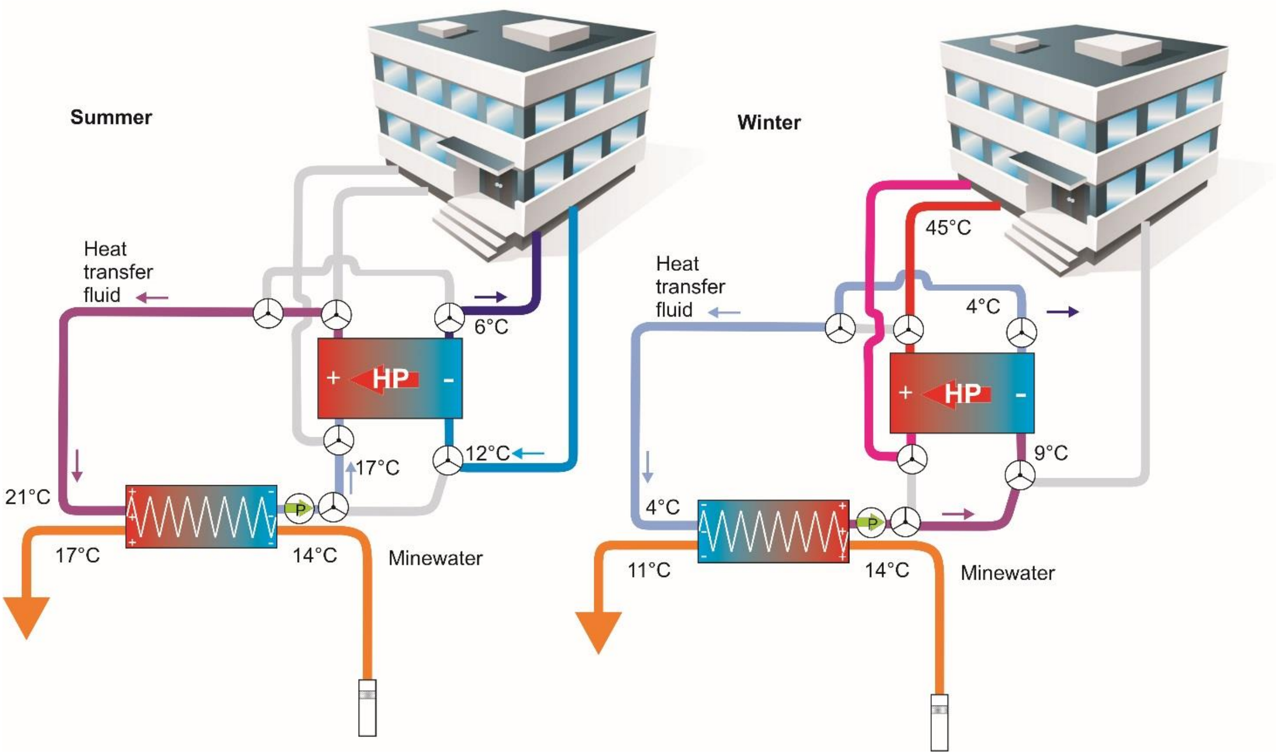


Figure 3.3. Schematic diagram of reversible heating and cooling achieved by altering flow in the building and intermediate heat transfer circuits. In this case, the fluid in all of the circuits should be compatible and similar.

3.3 Cooling with Simultaneous Subsidiary Heating (and vice versa)

If the building has a heating load, which is consistently smaller than the cooling load, it can be satisfied by coupling the evaporator to the building's cooling circuit and the condenser to the building's heating circuit *and* thereafter to the mine water heat exchanger (Figure 3.4). Similarly, if the cooling load is consistently less than the heating load, the evaporator side would be coupled to the building circuit and to the mine water heat exchanger (Figure 3.5).

If a small amount of higher temperature heat is required (e.g. for a modest high temperature heating circuit or for domestic hot water), it could be taken from a two-stage heat pump, or from a desuperheater (a modest, non-condensing heat exchanger mounted between the refrigerant compressor and the main condenser).

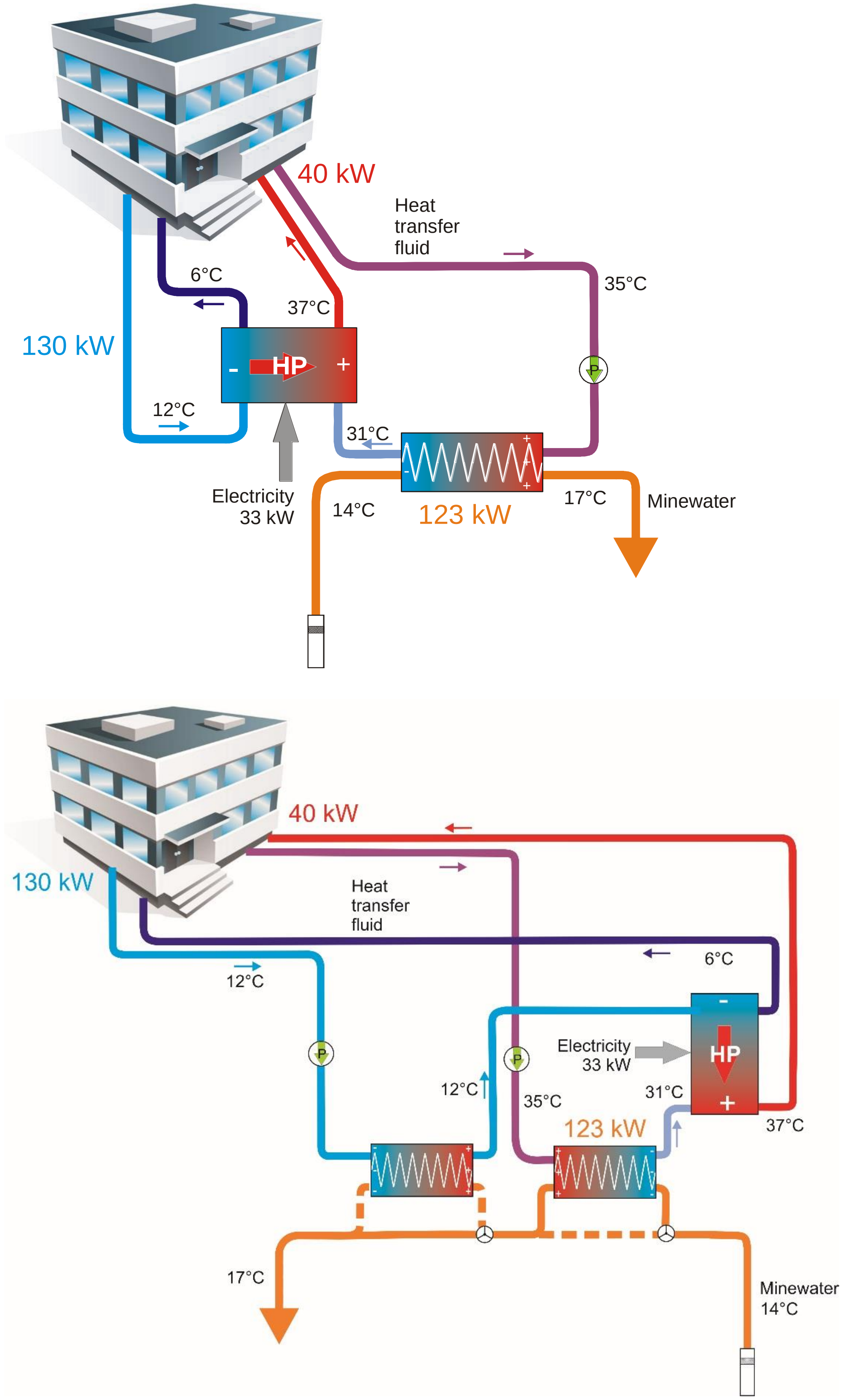
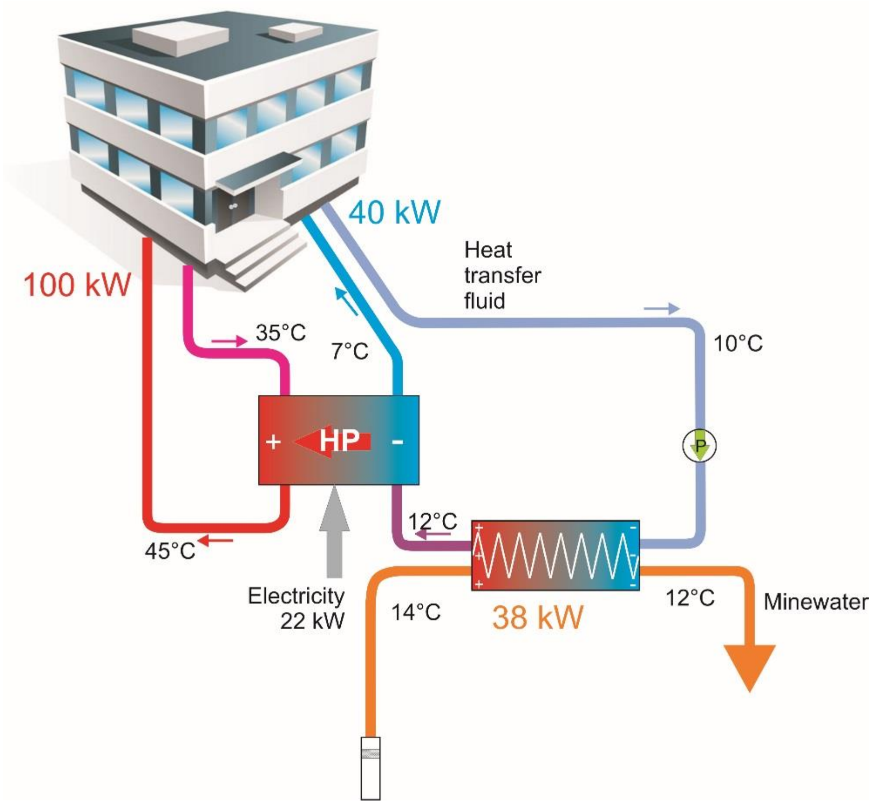


Figure 3.4 (top). A schematic example of a mine water heat pump performing cooling, with a subsidiary heating load from the condenser. Here the COP_C = 130/33 = c. 3.9, while the effective COP ([heating effect + cooling effect] / electricity) is 170/33 = 5.1. **(bottom)** Topologically, the same circuit, but employing two heat exchangers to facilitate switching between heating-dominant and cooling-dominant modes. Dashed orange = inactive minewater circuit.



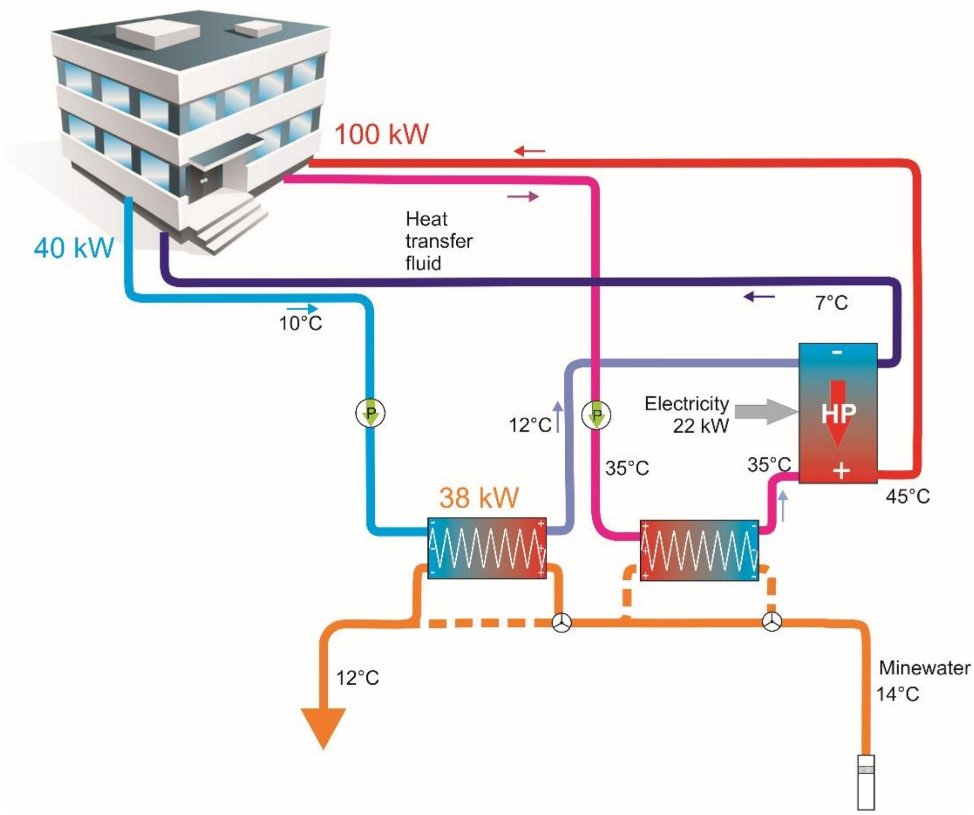


Figure 3.5 (top). A schematic example of a mine water heat pump performing heating, with a subsidiary cooling load from the evaporator. Here the COP_H = 100/22 = c. 4.5, while the effective COP ([heating effect + cooling effect] / electricity) is 140/22 = 6.3. **(bottom)** Topologically, the same circuit, but employing two heat exchangers to facilitate switching between heating-dominant and cooling-dominant modes. Dashed orange = inactive minewater circuit.

The Excel Workbook ***LoCAL 3.3.1_Active heating or cooling tool.xlsm*** allows these configurations to be investigated.

If heating and cooling loads fluctuate throughout the year, with heating-dominated loads in winter and cooling-dominated loads in summer, an arrangement with two heat exchangers is often favourable, with the mine water being directed through one or the other (Figures 3.4 (bottom) and 3.5 (bottom) – see also Figures 6.10 to 6.13. The advantage of this is that the heating, cooling and primary water circuits are all kept hydraulically separate.

3.4 Incorporation of Passive Cooling into a Cooling-Dominated Systems

In a situation where a cooling load dominates and where active cooling is necessary, it is still possible to incorporate an element of passive cooling into the system, provided that the mine water temperature is cooler than the return from the building. In this case, an initial heat exchanger HEX1 (typically with a high heat transfer coefficient, due to the low temperature gradient), rejects heat from the building cooling circuit directly to the mine water. This means that the capacity of heat pump necessary can be reduced. Heat from the condenser side of the heat pump can then be rejected via a second heat exchanger HEX2 (which may be much smaller than HEX1, due to the higher temperature gradients and the need to maintain a high temperature on the heating circuit).

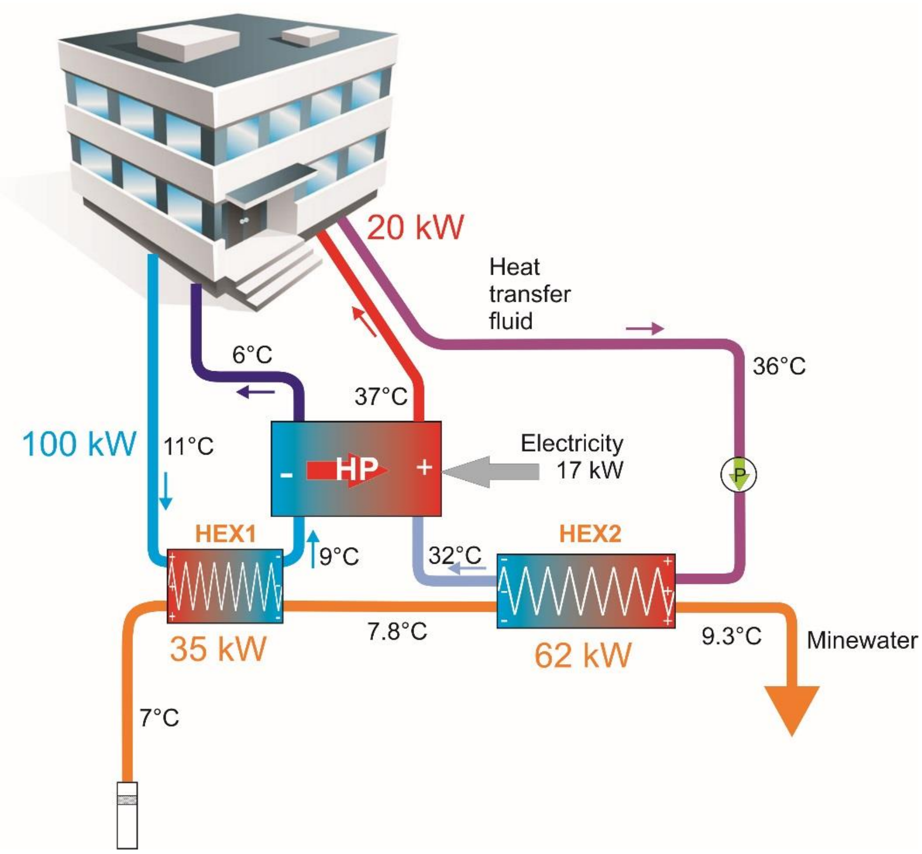


Figure 3.6. A schematic example of a mine water heat pump performing cooling, with a subsidiary passive cooling heat exchanger (HEX1) in addition to the "active cooling" heat exchanger (HEX2). Here, the effective COP ([heating effect + cooling effect] / electricity) is 120/17 = 7.1.

The Excel Workbook ***LoCAL 3.3.2_Passive cooling tool.xlsm*** allows this configuration to be investigated.

3.5 Dedicated and Reversible Heat Pumps for Simultaneous Heating and Cooling

In cases where heating and cooling loads are relatively large and stable over time, it can be an attractive solution to have an array of heat pumps dedicated to providing space heating and a second array of heat pumps dedicated to cooling.

For hydraulic reasons, it will be attractive to "plumb" the heat pumps within each array in parallel, such that each parallel circuit only sees one hydraulic resistance within the heat pump array (a condenser or evaporator) and not several in series.

It may be attractive to place the cooling array directly "after" the heating array, in series, such that the heat pumps performing cooling ("chillers") take advantage of the cooler transfer fluid leaving the evaporator of the heat pumps performing heating, or *vice versa* (Figure 3.7). This, of course, leads to two hydraulic resistances in series: a negative factor from the point of view of hydraulics. Additionally, although the "chillers" operate more efficiently, it means they "dump" less heat into the heat transfer fluid (which could have been used by the heat pumps performing heating on the next "pass".

An alternative arrangement would be to plumb all the heat pumps "in parallel" so that they all "see" the same entry fluid temperature (Figure 3.8).

Heat pumps can be brought "on" or taken "off" line in response to fluctuating heating and cooling demands, although if demands fluctuate heavily there is a risk that heat pump capacity may be unused for large portions of the year (arguably, a waste of capital investment).

Additional flexibility can be introduced into such an arrangement by assigning some of the heat pumps to be reversible, providing heating at some times of the year / day and cooling at other times (Figure 3.7). Reversibility may be most easily achieved by installing "warm" and "cold" heat exchangers, allowing either the cooling / evaporator circuit or the heating / condenser circuit of the "reversible" heat pumps to be coupled to the main heat transfer fluid circuit - similar to the arrangement in Figure 3.4 (bottom) or 3.5 (bottom), and similar to that employed in the hospital plant room at the Mieres system (Chapter 6). The advantage of this is that the heating, cooling and primary heat transfer circuits are all kept hydraulically separate.

Which arrangement is optimal will depend heavily on hydraulics and the performance of the specific heat pump in question. The Excel Workbook ***LoCAL 3.3.3_Discrete heating and cooling arrays.xlsm*** allows various configurations to be investigated.

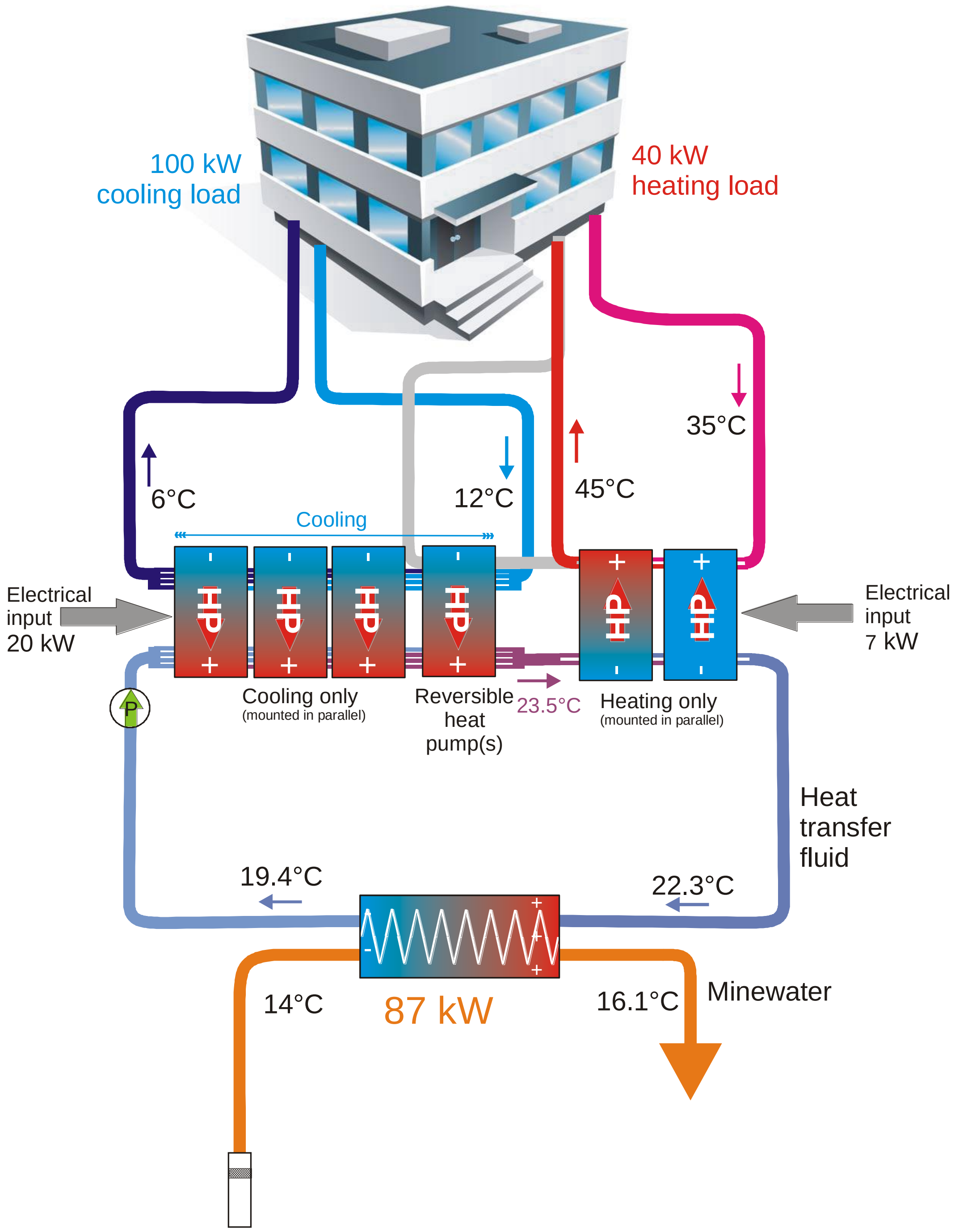


Figure 3.7. A schematic example of a mine water heat pump performing cooling and heating, with the chillers placed before the heating heat pumps on the heat transfer fluid circuit. The grey circuit shows (highly schematically – for a real example, see Chapter 6 on the Mieres hospital plant room, where two heat exchangers allow either the condenser/heating circuit or the evaporator/cooling circuit to be coupled to the primary heat transfer circuit: Figs. 6.10-6.13) one of the chillers being able to be reversed in case of excess heat demand. Here, the effective COP ([heating effect + cooling effect] / electricity) is 140/27 = 5.2. The mine water flow in this case is 10 L/s.

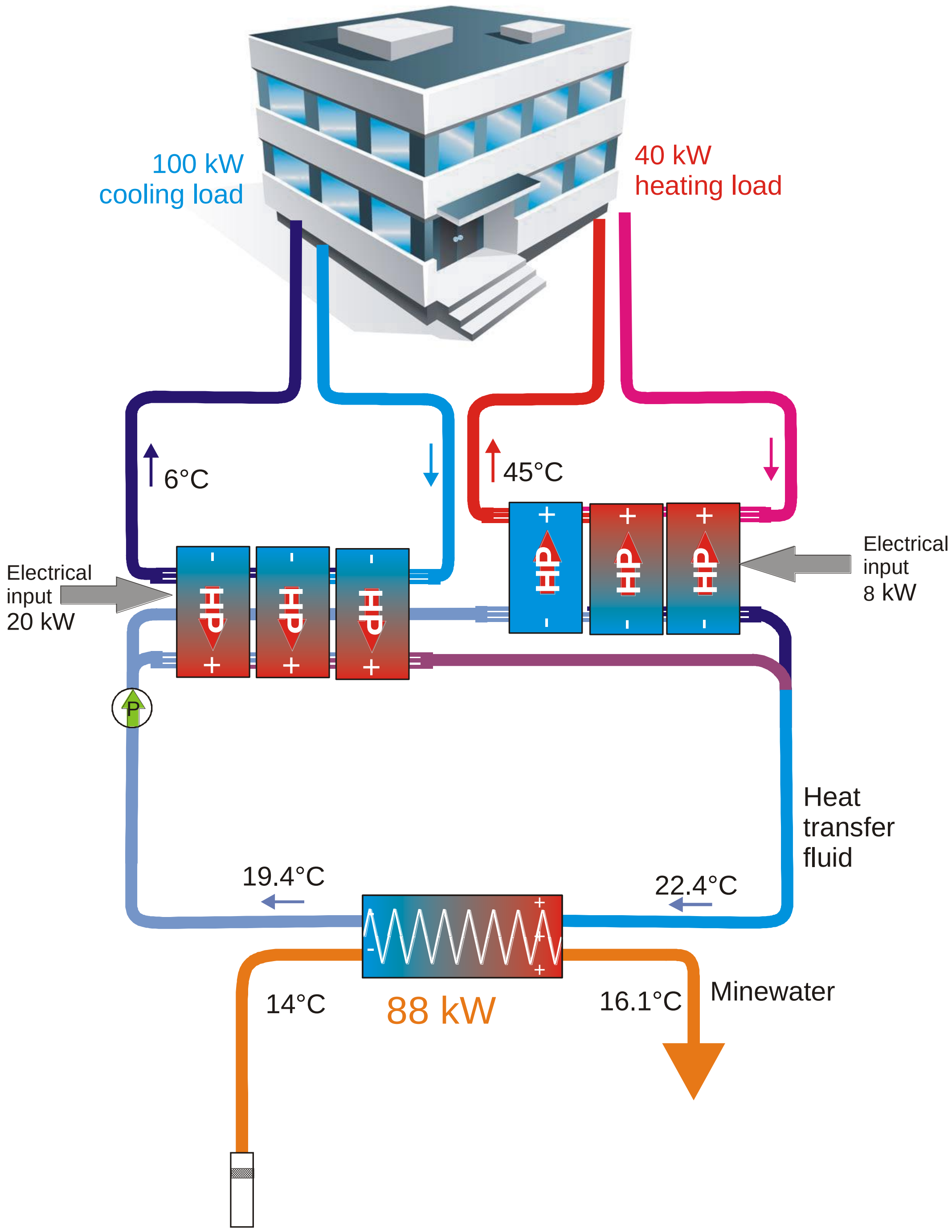


Figure 3.8. A schematic example of a mine water heat pump performing cooling and heating, with dedicated parallel arrays of cooling and heating heat pumps. Here, the effective COP ([heating effect + cooling effect] / electricity) is 140/28 = 5.1, slightly lower than the example in Figure 3.7. This arrangement is likely to be more hydraulically efficient, however, and result in energy savings in circulation pumping. The mine water flow in this case is 10 L/s.

4. Cooling Delivery

4.1 District Cooling Networks (DCN)

Cooling can be provided to multiple consumers via a district cooling network (DCN). This is done, for example, in the Swedish capital city of Stockholm (Banks, 2012), via insulated flow (containing cool water) and return pipes. A DCN is conceptually similar to a district heat network (DHN), with the important distinction that, where the ambient mine water temperature is relatively low, it may be possible to provide some component of passive cooling (at least at certain times of the year, when demand is modest), without the use of heat pumps.

Figure 4.1. Installation of district cooling network in central Stockholm. *(Photo by David Banks)*

Task 3.1 of LoCAL has examined the benefits and disadvantages of centralised and decentralised district heating systems[1] for delivery of heat from mine water:

(a) Delivering heat as a hot fluid (at space heating temperature) from a centralised heat pump plant room (*centralised)*, versus:

[1] Here, the terms "district heating" and "district cooling" are used rather loosely to simply describe the provision of heating or cooling from one or more heat sources or sinks, to a network of targets (buildings, properties, industries) at some distance from these sources or sinks.

(b) Distributing the mine water, or a heat transfer fluid thermally coupled to the mine water, at or near the ambient mine water temperature, to individual businesses or households, who then use their own heat pumps to extract heat from the low temperature fluid (*decentralised*).

In brief, many of the same advantages and disadvantages apply to the provision of district cooling.

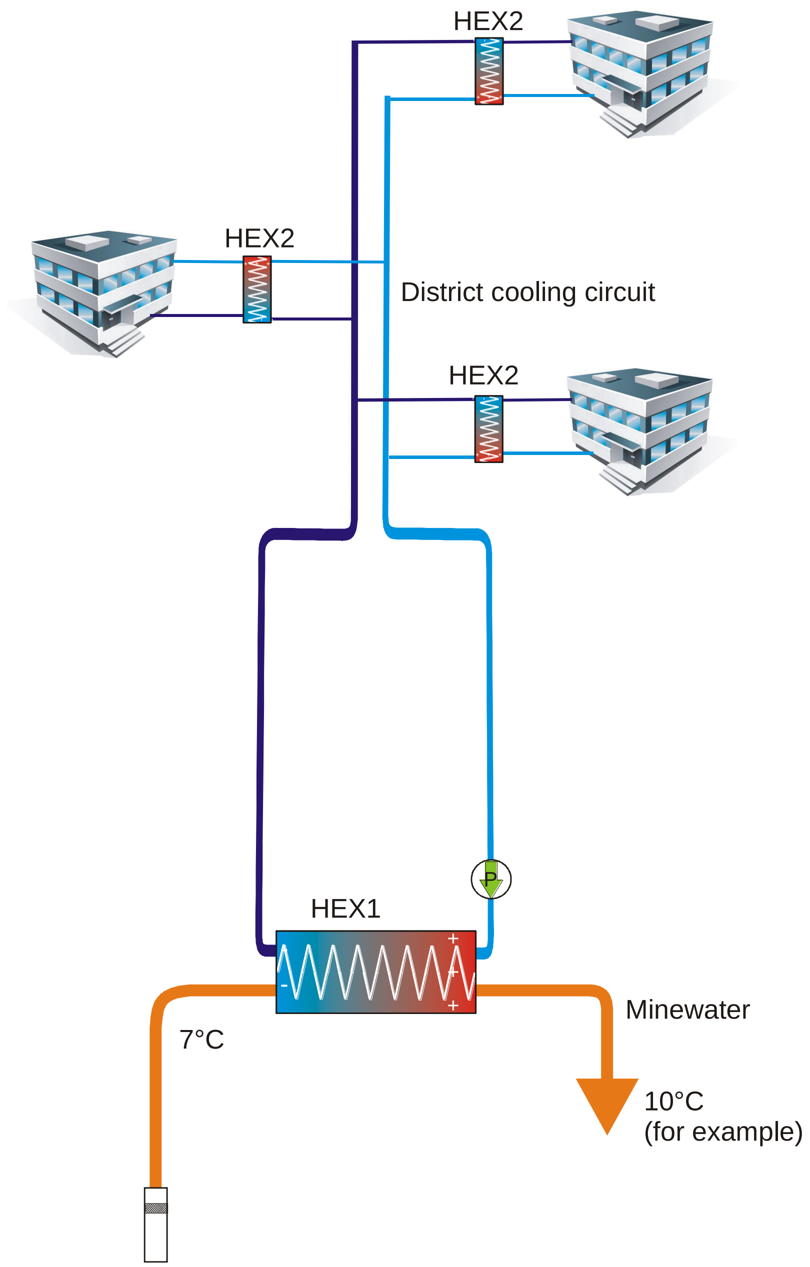


Figure 4.2. District cooling system where the mine water is cool enough to permit passive cooling (at least at certain times of the year). Temperatures are indicative examples only. HEX1 is a primary prophylactic heat exchanger. If the mine water is of benign enough quality, it could arguably be circulated directly in the district cooling network. HEX2 are secondary heat exchangers, which serve to hydraulically separate each property from the network. Arguably, these are not strictly necessary, and each additional heat exchanger will add a temperature increment to the circulation temperature and render the cooling less effective. However, HEX2 allows different heat transfer fluid types in the common and private portions of the network, and also provides a clear boundary (from the point of view of liability and maintenance).

4.2 Centralised District Cooling Networks (DCN)

In such networks, one (or several) plant rooms employ large chillers to chill water in a district cooling network, the waste heat being transferred to the mine water flux.

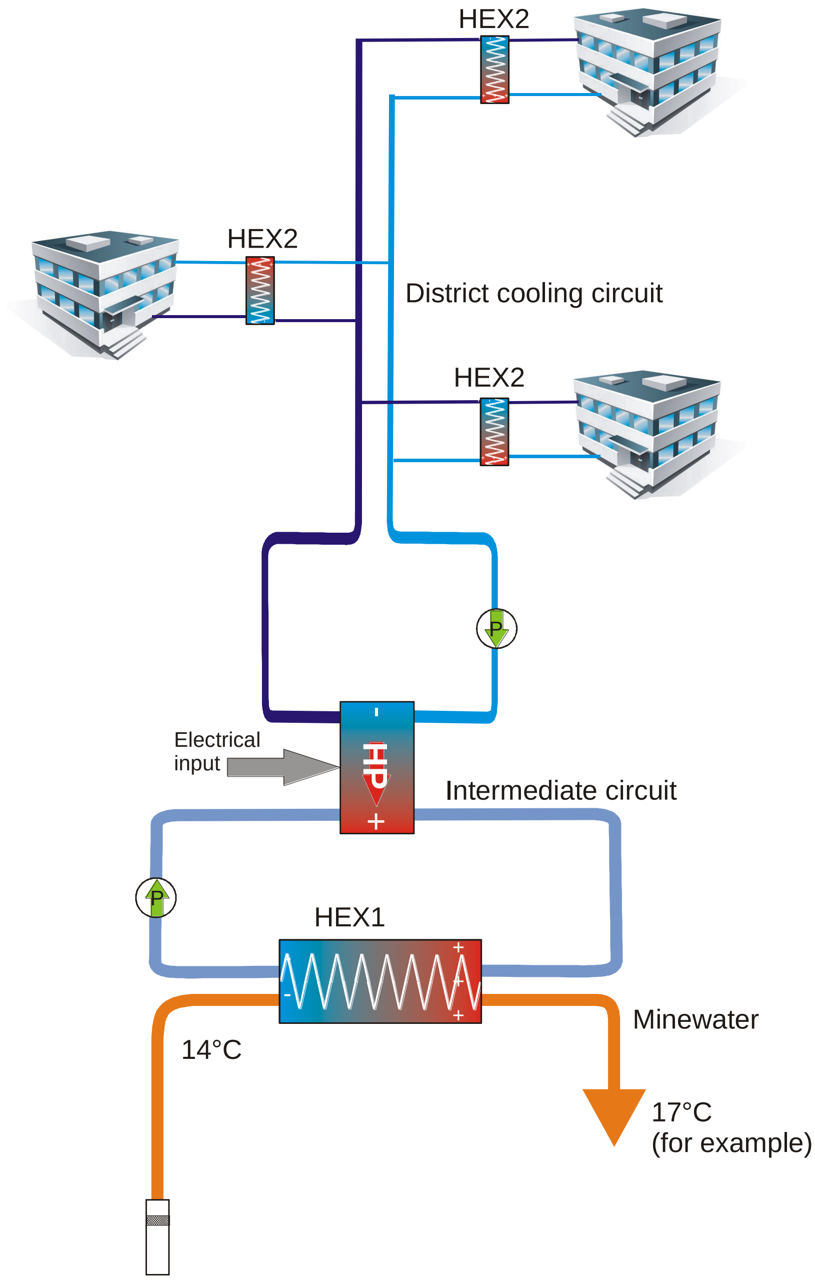


Figure 4.3. A centralised district cooling system. Temperatures are indicative examples only. HEX1 is a primary prophylactic heat exchanger. If the mine water is of benign enough quality, it could arguably be circulated directly through the condenser of the heat pump. HEX2 are secondary heat exchangers, which serve to hydraulically separate each consumer from the network.

Advantages of centralised provision of district cooling

1. Business advantage. A provider is able to supply a "complete product" – i.e. chilled fluid which can immediately be used to effect cooling in consumers' properties, which is likely to represent a high value business model.

2. The operator retains a much greater degree of control and management of the entire system. The ownership structure is also simpler.
3. Larger chillers (heat pumps) can be used in a centralised plant room. Such large-scale heat pumps typically operate somewhat more efficiently than many small heat pumps and will be more attractive in terms of capital cost per installed kW.

4.3 Decentralised District Cooling Networks (DCN)

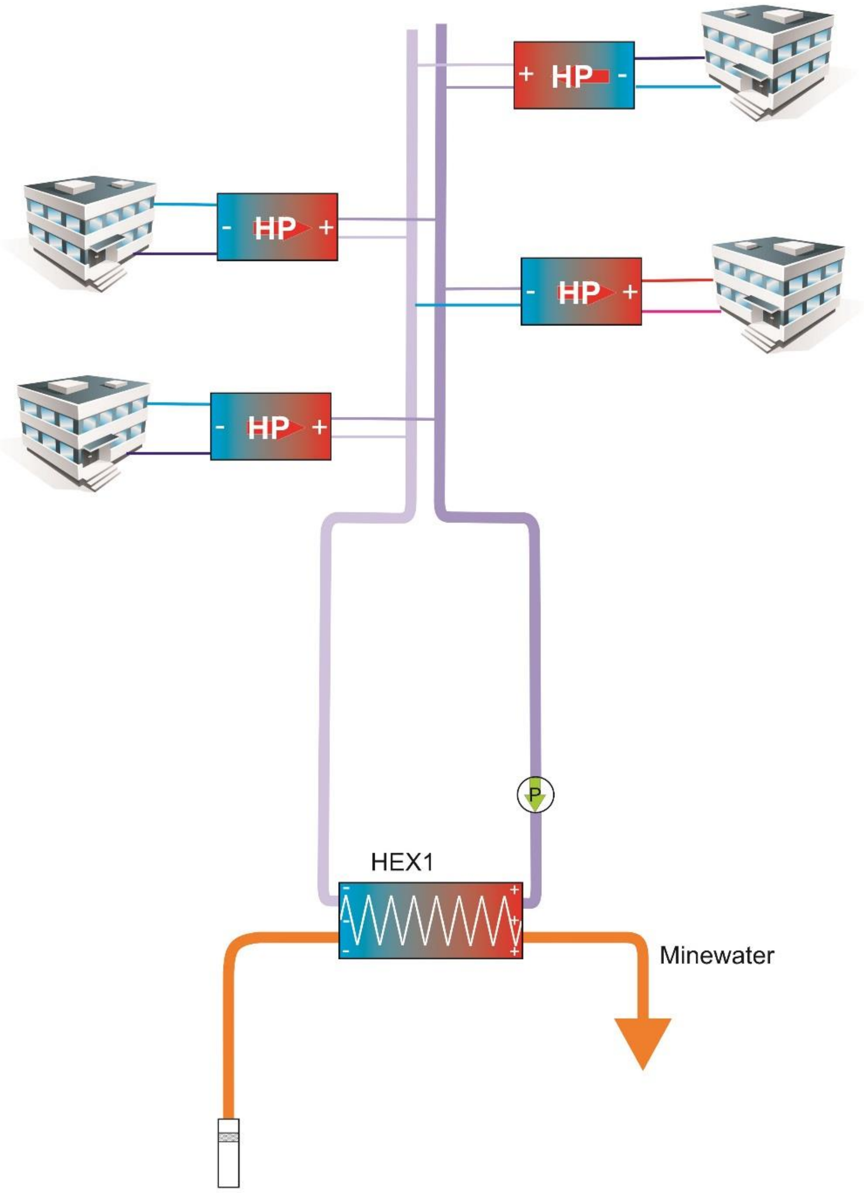


Figure 4.4. A decentralised district cooling / heating system. HEX1 is a primary prophylactic heat exchanger. Note that one consumer is using its heat pump to perform space heating.

In such networks, a heat transfer fluid, thermally coupled to the minewater (or, conceivably, the mine water itself, if of sufficiently benign quality) is circulated to consumers at ambient temperature. Each consumer utilises a heat pump and/or heat exchanger to dump its waste heat to the return flow.

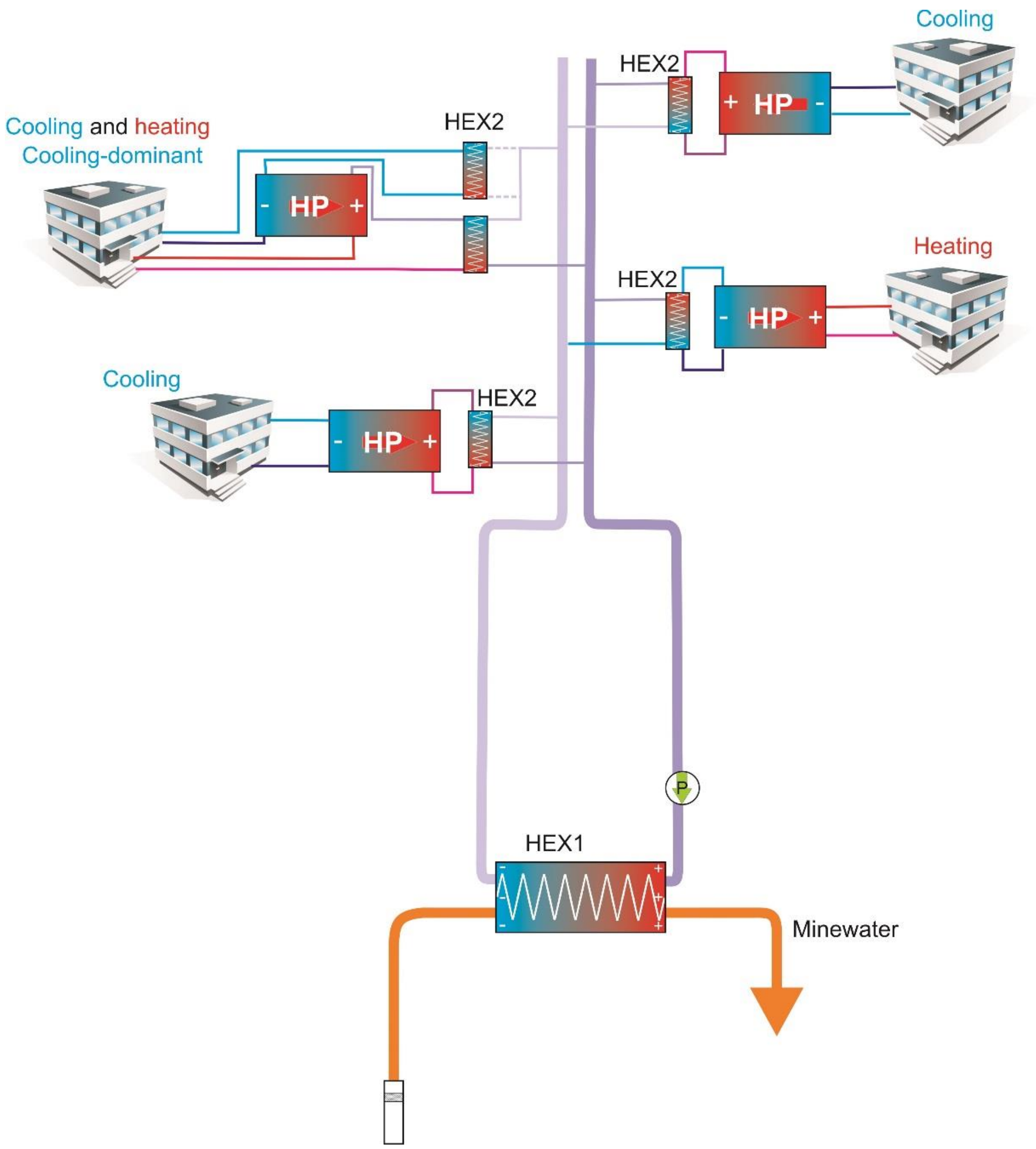


Figure 4.5. A decentralised district cooling / heating system, where secondary heat exchangers separate the consumers' heat pumps from the district heating/cooling network. HEX1 is a primary prophylactic heat exchanger. HEX2 are the secondary heat exchangers. Note that one consumer is using its heat pump to perform space heating, two to perform space cooling. One consumer has a system employing double heat exchangers, enabling simultaneous or reversible cooling and heating.

In Figure 4.5, each consumer's heat pump exchanges heat with the main district circuit via a secondary heat exchanger (HEX2). This system, while arguably less thermally efficient than Figure 4.4, more readily allows reversible heating and cooling and also forms a natural "legal" boundary between the consumers' facilities and the district heating / cooling loop.

Advantages of decentralised provision of district cooling

1. The fact that the mine water (or heat transfer fluid coupled to the mine water) is distributed at ambient subsurface temperature means that the temperature differential between the fluid and the ground in which the distribution pipe is buried is low. This means that losses of heat / "coolth" are kept to a minimum and also potentially saves on insulation costs. If the fluid is pre-chilled at a centralised heat pump station, the

distribution main would have to be well-insulated to prevent heat leakage from the ground into the chilled pipe.

2. The arrangement arguably allows the consumer greater flexibility to control the temperature of the cooling arrangement in each individual property. A consumer could theoretically extract heat for space heating from network – both heating and cooling could be achieved from the same network. This would often be achieved by a 2-heat exchanger arrangement, of the type indicated in Figures 3.4 (bottom) and 3.5 (bottom), such that either the hot / condenser side of the heat pump (when cooling dominates) or the cold / evaporator side of the heat pump (when heating dominates) can be coupled to the main heat transfer fluid network – see Figures 6.10 to 6.13.

4.4 District Heating and District Cooling from Minewater

Using the basic principles discussed in Chapter 3, it should be possible to see that there are several configurations for servicing a district heat network and a district cooling network from a single mine water flux.

The DHN might have its own flow and return pipe systems, and the DCN also its own flow and return pipes. Alternatively, it may be possible for the DCN and DHN to share a single combined return pipe, as has been the case at Heerlen in the Netherlands.

4.5 Multiple geothermal doublets

A final scenario for supplying multiple users with heating and or cooling from a single mine is *not* to use district heating or cooling networks, but rather to install separate well doublets (abstraction / injection) at each individual commercial user's premises. This is the type of system that has evolved at Springhill, Nova Scotia, Canada (Chapter 7) and which has been operated with success.

The main **advantages** of installing individual well doublets are:

- Each business or user retains control and management of the entire system (this may, of course, not be an advantage if the user is inexperienced at managing mine water or heat pumps).
- The large costs of laying DHN or DCN pipes are avoided (costs of £600 to £1500 per metre are regarded as typical for urban settings in the UK – Al-Habeibeh, 2016, *pers. comm.*), as are the heat losses / gains over long pipe distances.

The main **disadvantages** of installing individual well doublets are:

- It may not be possible to achieve adequate separation within the doublet, if drilling is restricted to single commercial premises.
- Nearby geothermal doublets may interfere with each other both hydraulically and thermally and some form of overall resource management or licensing would then be desirable.
- Individual operators may not be able to provide the necessary skills base required to effectively understand, monitor and maintain a complex system such as a minewater thermal doublet.

5. Ground Configurations

5.1 Depth of Production

In cases where coal or metals have been mined at several different levels in the ground, the mine water in the deepest workings *may* be substantially warmer than that in the shallower workings. Thus, it may make sense (depending on the capital costs of deep drilling) to source the mine water that is to be used for space heating from these deepest horizons. The thermally spent (cooler) water could then be reinjected to the shallowest horizons, provided that this offers a long enough flow pathway between the abstraction and reinjection boreholes or shafts.

Similarly, if the mine water is to be used for cooling, it may be attractive to abstract water from the shallower levels of the mine and reinject it at depth.

Other factors will, of course, come into play. It is important to remember that mine water chemistry can vary significantly with depth:

- Deep minewater may be saline and reducing (corrosive).
- Shallow minewater may be fresher but also more oxidising (more difficult to retain iron and manganese in solution).

It should be noted that, if deep mine water is both saline and warm, the less dense, fresher, shallow cool water will tend to remain "floating" above it in the mine system.

If, however, deep warm water is not more saline than the shallow cool water, there may be a tendency for convective overturn in the mine system (whether this will actually happen will depend also on the geometry and aperture openings in the mine system). This potential for convective overturn should be kept in mind if considering a system where shallow, low salinity cool water is being abstracted from a mine, used for space cooling (rejection of waste heat) and the "thermally spent" warm mine water water is being reinjected to a deeper, more saline level in the mine (or *vice versa*)

5.2 Seasonal considerations

If the heating and cooling demands are strongly seasonal and if the mine system enjoys some degree of lateral or vertical compartmentalisation, it may be attractive to consider some form of mined aquifer thermal energy storage (MATES). Consider the scenario in Figure 5.1. The mine comprises a deep section containing warm water, which is penetrated by a deep borehole, and a shallow section, containing cooler water, also penetrated by a borehole. The mine sections are hydraulically connected via a drift. Although the two boreholes are relatively close at the surface, the subsurface pathway connecting them is rather long and tortuous.

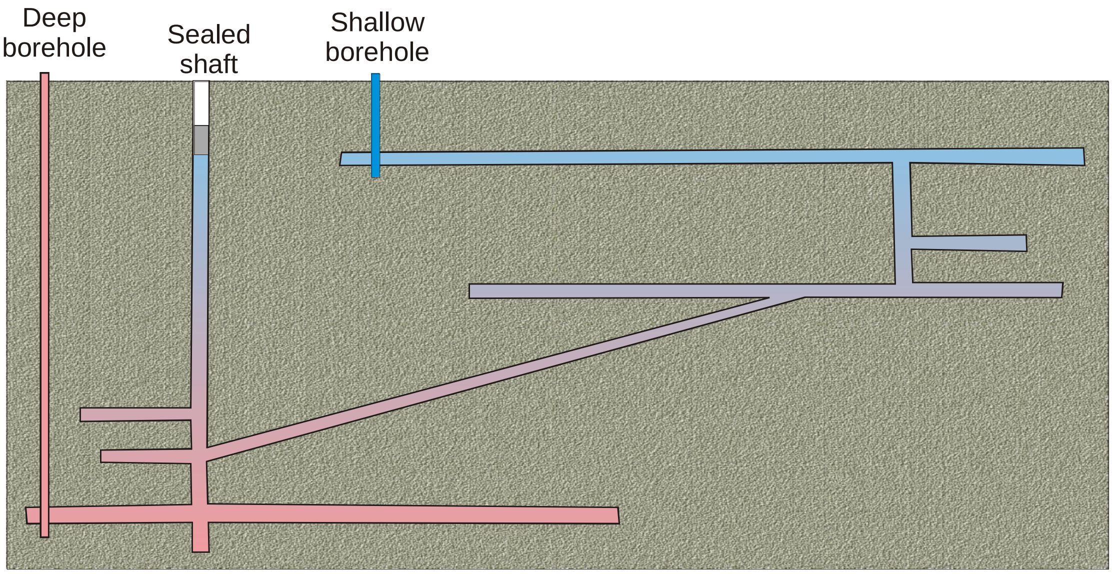


Figure 5.1. Schematic section of a mine system containing a shallow and deep portion, connected by a drift. The pink shading indicates somewhat warmer mine water, the blue shading, somewhat cooler water.

We could assume that, in winter (Figure 5.2), the deep borehole is pumped and the warm groundwater therefrom is passed through a heat exchanger / heat pump system to deliver space heating. The cold, thermally spent groundwater is reinjected into the shallow portion of the mine system, thus potentially accumulating a larger volume of cold water in the shallower portions of the mine (depending on natural groundwater throughflow characteristics).

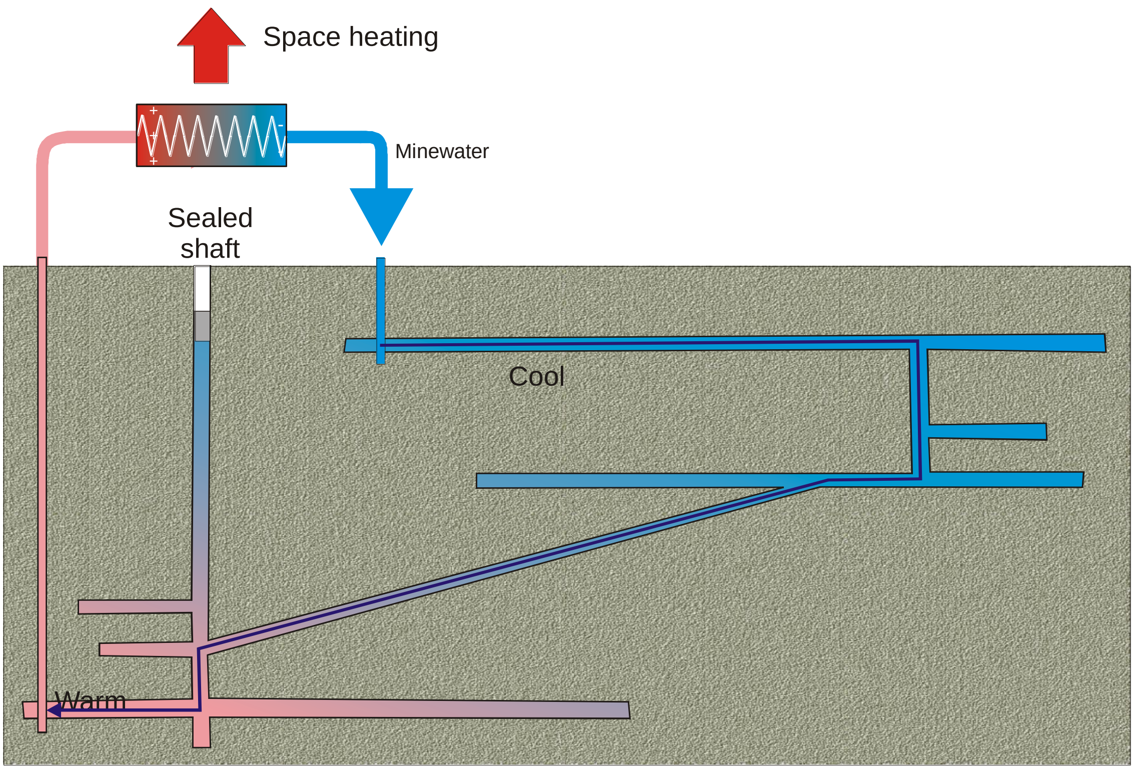


Figure 5.2. Schematic section of a mine system with deep workings being pumped to provide space heating in winter. The deep blue arrow shows the subsurface flow pathway between the reinjection and abstraction boreholes.

Of course, one needs to ascertain whether reinjected cold water risks circulating through the mine water system to emerge in the abstraction well. Ideally, a long and tortuous flow pathway will allow the recirculating water to gain heat from the rocks in the walls of the mine. Several models are available to aid this evaluation (Loredo et al. 2016). The risk of convective overturn should also be considered (see above).

In the summer, this shallow enhanced "reservoir" of cold water could be drawn upon to provide space cooling. In this scenario, the shallow well is pumped, and the warm water, with its load of waste heat from space cooling, is reinjected to the deep borehole to supplement the deep warm mine water resource. The success of this concept will, of course, depend on the temperatures of the thermally "spent" water from the space heating and cooling, relative to the ambient mine temperatures, and the natural groundwater throughflow characteristics.

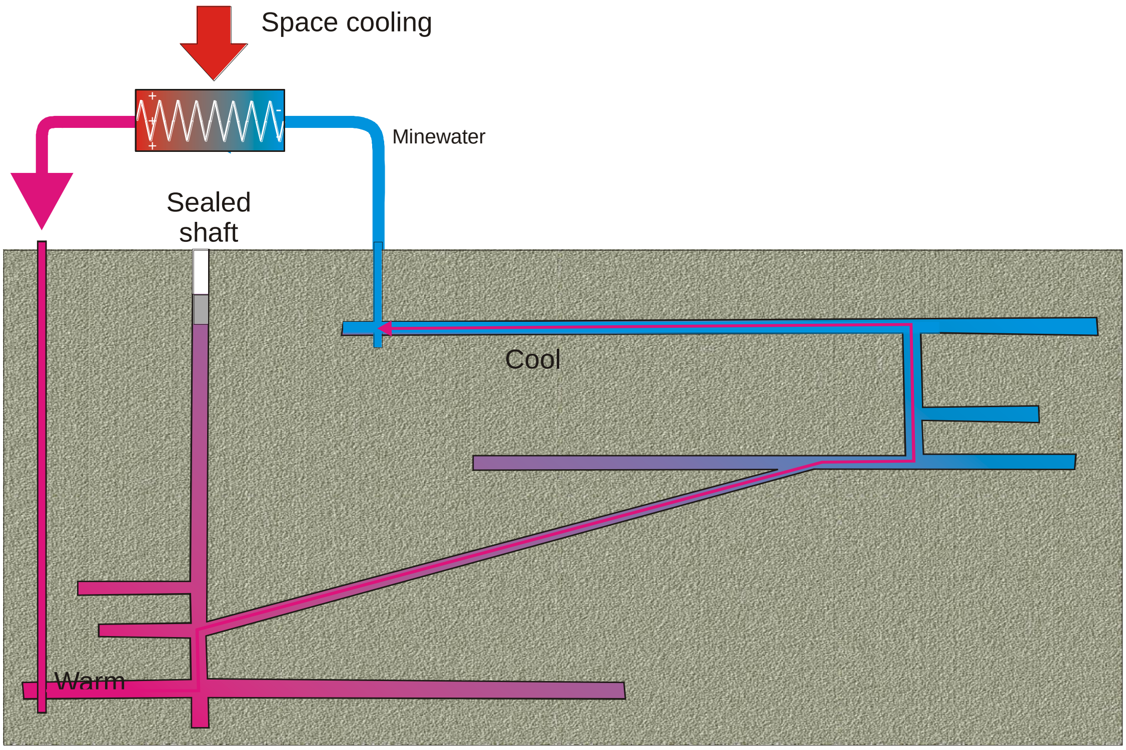


Figure 4.7. Schematic section of a mine system with shallow workings being pumped to provide space cooling in summer. The magenta arrow shows the subsurface flow pathway between the reinjection and abstraction boreholes.

Effectively, with such a scheme, one is cyclically recharging and then depleting "cool" and "warm" portions of the mine. For this to function, natural groundwater throughflow must be relatively low, else the stored heat and "coolth" risks being advected away. The risk of convective overturn should also be considered (see above).

The "polarity" can be changed from "abstraction" to "reinjection" in one of two ways:

1. By installing a submersible pump on a rising main together with one (or more), typically narrower diameter, recharge mains in the same well or shaft. The well or shaft must be of sufficient diameter to allow this. The recharge main(s) often have a lower diameter to act as a hydraulic throttle, preventing negative pressures (suction) from developing on the recharge line.

2. By using the same rising main for pumping and recharge. To do this, either:

   - The pump needs to be able to tolerate some degree of backspin or backflow. It has even been shown that backspin on a pump can be used to generate modest quantities of electricity, thus recovering some of the pumping costs (Misstear et al. 2017). However, some pumps do not tolerate backspin and turbines/impellers would need to be "locked" during backflow / recharge.

   - There can be some kind of valve arrangement that opens a recharge vent located above the submersible pump, when the well is operating in reinjection mode. This type of valve is produced, for example, by Cla-Val (2016), Melotte (2016) and by Hoek Engineering (2016)

6. Case Study 1: Mieres

This chapter is strongly based on information and diagrams kindly provided by Adrian Peña Fernandez of the public-sector company Grupo HUNOSA (http://www.hunosa.es), who are owned by the public holding company SEPI and who are responsible for mine water management in the coal mines of Asturias, northern Spain, and who operate the mine water thermal energy scheme at Barredo shaft.

6.1 The Barredo coal mine shaft

The Barredo shaft (*Pozo Barredo*) is located on the outskirts of the town of Mieres del Camino, in Asturias, northern Spain, at grid reference 43°14'33.94"N 5°46'29.36"W (Loredo et al. 2017).

Mieres del Camino lies in a clearly-defined N-S valley, with the *Rio Caudal* river flowing north to join the *Rio Nalón*, which flows into the Atlantic at *San Juan de la Arena*. At Mieres del Camino, the river level is around 209 m asl, and the Barredo shaft top is some 10-11 m above the river level at +220 m asl.

The shaft is 362 m deep (to c. -142 m asl) and is regionally connected underground to the

- Figaredo mine (43°12'34.51"N 5°46'6.19"W), (San Inocencio and San Vicente shafts)

And possibly with some degree of interconnection with

- San José (43°12'30.68"N 5°44'16.73"W),
- Santa Barbara (43°12'49.67"N 5°43'6.03"W) and

The Barredo shaft was opened in 1926 and ceased working coal in around 1993. It worked from five main levels. The rocks hosting the coal are Carboniferous sequences of sandstones, siltstones and shales. The shaft is still pumped for purposes of regional mine water management (and this pumping is also supported by intermittent pumping at Figaredo and San José).

Barredo shaft is pumped by four submersible pumps at 95 m, 100 m, 105 m and 200 m depth. The water is maintained between 50 and 70 m below the surface and a water level of around +169 m asl is regarded as typical. The typical yield is cited by HUNOSA as 8300 m^3/d (96 L/s). The water is relatively iron poor and, despite a relatively high mineralisation, is regarded as being of good quality – it is therefore discharged (following heat exchange) directly to the *Rio Caudal*. The pumped water typically has a temperature of some 23°C.

The mine system is described in papers by Loredo et al. (2011), Ordóñez et al. (2012), Jardón et al. (2013) and Díez & Díaz-Aguado (2014).

The water pumped from Barredo shaft is used to supply thermal energy to three customers:

- The new Álvarez Buylla Hospital, around 1.9 km south of the Barredo shaft
- The University's Edificio de Investigación, around 150 m WNW of the shaft
- The enterprise FAEN (Fundación Asturiana de la Energía), only some 50 m ENE of the shaft. The FAEN system will not be described in detail here, as it is relatively modest, providing only some 100 kW thermal energy.

Figure 6.1. Google Earth image showing location of Barredo shaft (northernmost yellow pin) and the University building and Hospital that are consumers of thermal energy from the mine. For scale, the Hospital is around 1.9 km south of the shaft.

6.2 The University thermal energy system

After the mine water has been pumped up from Barredo shaft, it is split into two main streams (Fig. 6.14):

- one stream feeds the pipe heat exchangers, which transfer heat to/from the secondary heat transfer circuit supplying the hospital (see below and Figs. 6.15-6.17)
- the other stream of mine water is circulated to the plant room of the University building, some 150 m WNW of the shaft.

In the plant room of the University building, the mine water passes through plate heat exchangers, which exchange heat with secondary heat transfer fluid passing through the heat pump evaporator (heating mode) or condenser (cooling mode) – see Figure 3.5 (bottom) and Figure 6.5. The plate heat exchanger specifications are:

- Evaporator plate exchanger: Sedical UFP-102/71 LM. Nominal 536 kW.
- Condenser plate exchanger: Sedical UFP-102/55 L. Nominal 725 kW.

Although the iron content of the mine water is relatively low, there have been some issues with clogging of the plate heat exchangers with iron hydroxide precipitate, resulting in a decline in capacity (Loredo et al. 2017). The heat exchangers were successfully cleaned and returned to service following disassembly and washing. This experience leads HUNOSA to suggest that plate heat exchangers are more prone to clogging than pipe / shell-and-tube exchangers (although kW for kW are likely to be significantly smaller and cheaper).

The system utilises two Trane RTWB 210 heat pumps – each with a nominal heating capacity of 353 kW heating and 256 kW cooling. The system is capable of supply heating only, cooling only or both simultaneously. However, during operation, the system has hitherto almost exclusively provided heating (Figures 6.2-6.4).

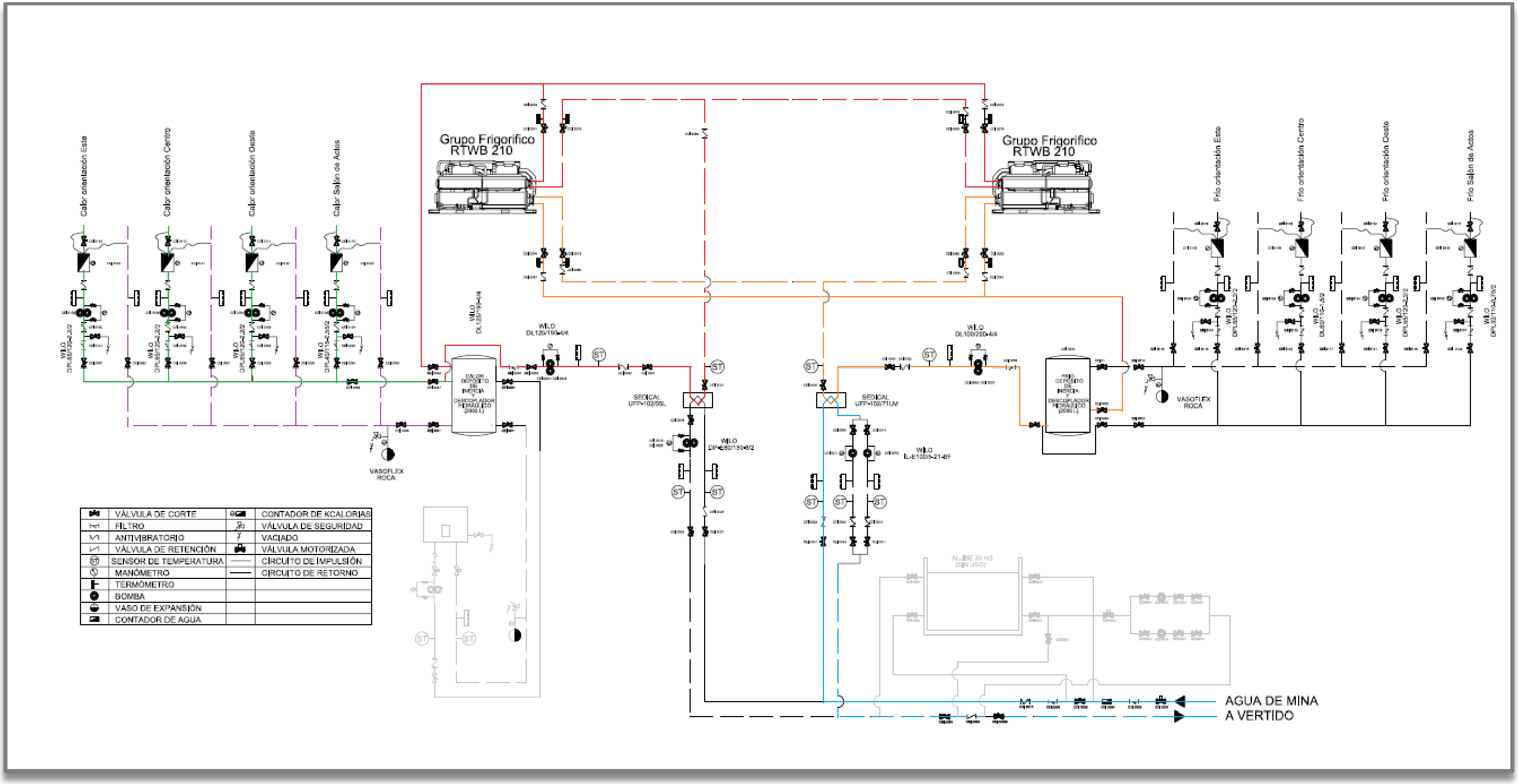


Figure 6.2. The University heat pump system in heating mode. Blue line: mine water, orange = evaporator circuit, red = condenser circuit, green = heating flow, purple = heating return.

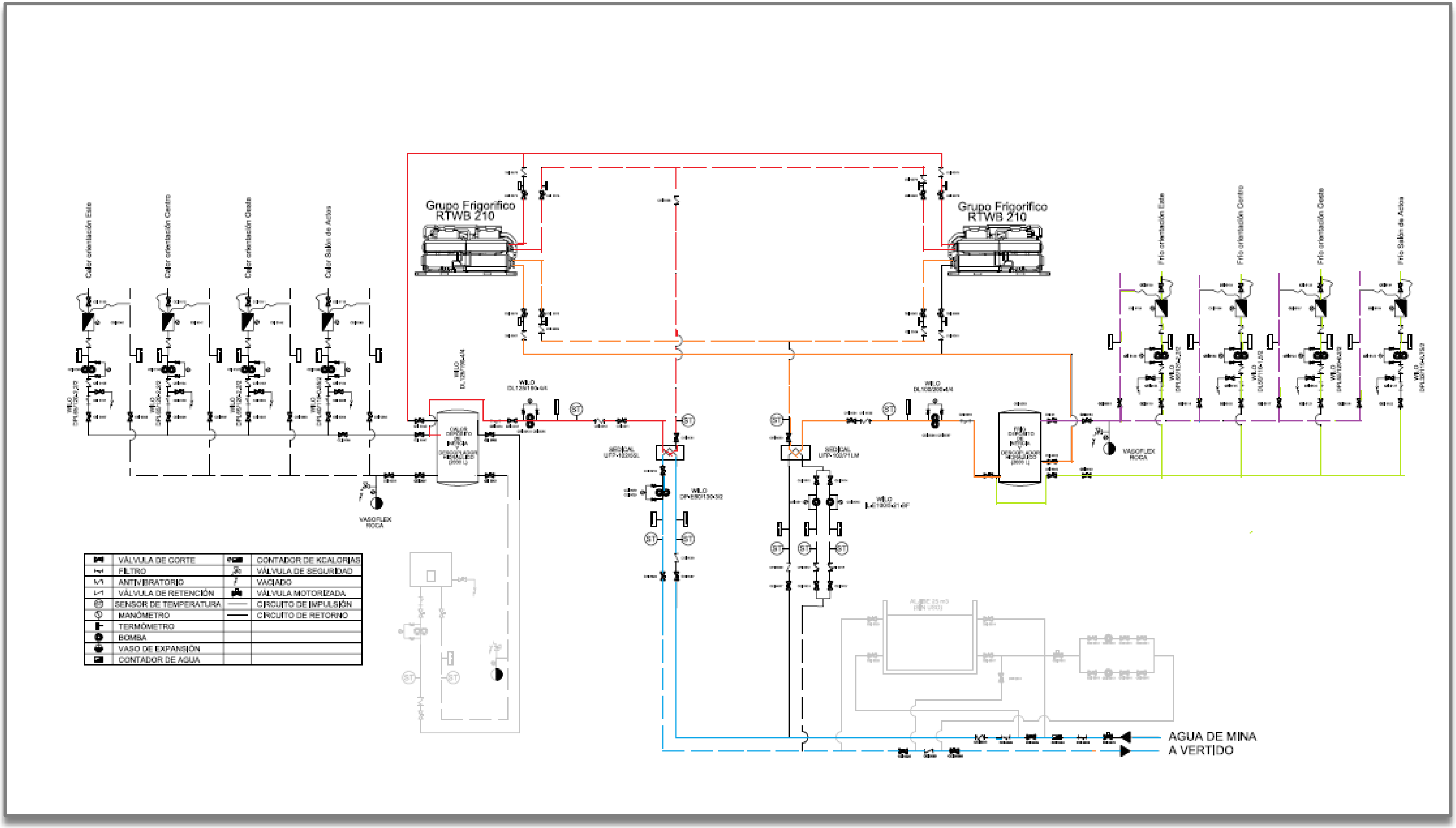


Figure 6.3. The University heat pump system in cooling mode. Blue line: mine water, orange = evaporator circuit, red = condenser circuit, green = cooling flow, purple = cooling return.

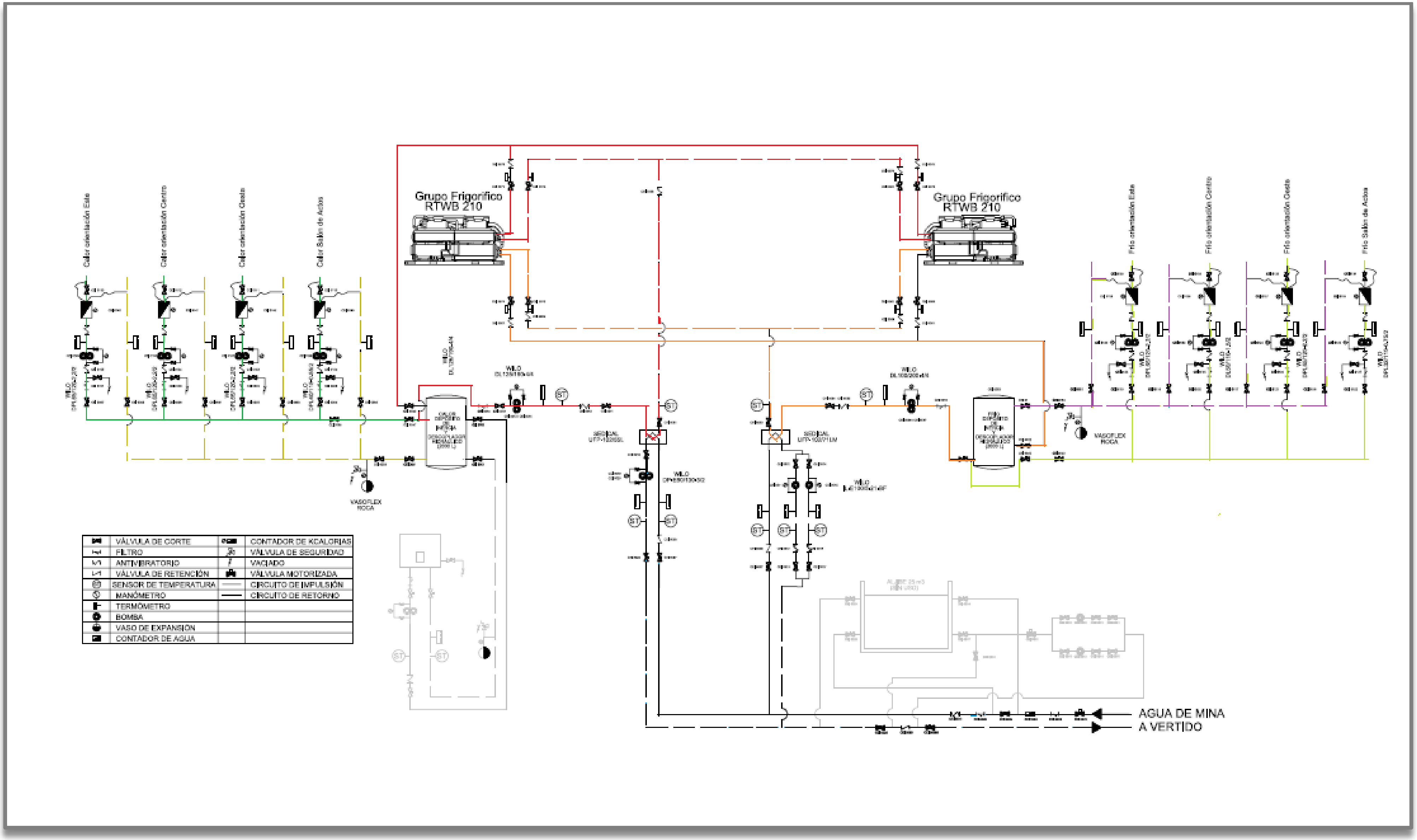


Figure 6.4. The University heat pump system in heating/cooling mode. Blue line: mine water, orange = evaporator circuit, red = condenser circuit, lime green = cooling flow, purple = cooling return, green = heating flow, yellow = heating return.

Figure 6.5. Mine water to secondary circuit plate heat exchangers. Mieres university building. Photo by © David Banks

Figure 6.6. Trane heat pump. Mieres university building. Photo by © David Banks

6.3 The Hospital thermal energy system

The hospital "stream" of pumped mine water passes through an array of three shell and tube heat exchanger units within the headworks building of Barredo shaft. Individual units of the heat exchanger array can be isolated and taken out of service for maintenance while the remainder maintain the heat exchange capacity. The heat exchanger specifications are as follows:

- Gradient exchange between 25°C and 32.8°C in the primary circuit and between 34°C and 28.2°C in the secondary circuit (in summer).
- Gradient exchange between 23°C and 13.9°C in the primary circuit and between 12°C and 19°C in the secondary circuit (in winter).
- Water flow 400,000 L/h (111 L/s) in primary circuit and 520,000 L/h (144 L/s) in secondary circuit. Speed of water flow: 1.13 m/s in primary circuit and 1.30 m/s in secondary circuit.
- Maximum pressure loss of 1.1 bar in primary circuit and 0.7 bar in secondary circuit.
- Design pressure: 6 bar. Minimum diameter 18 mm. Heat exchange area of 498 m²
- Minimum total nominal performance 3500 kW.
- The exchanger has a pressure cleaning system.

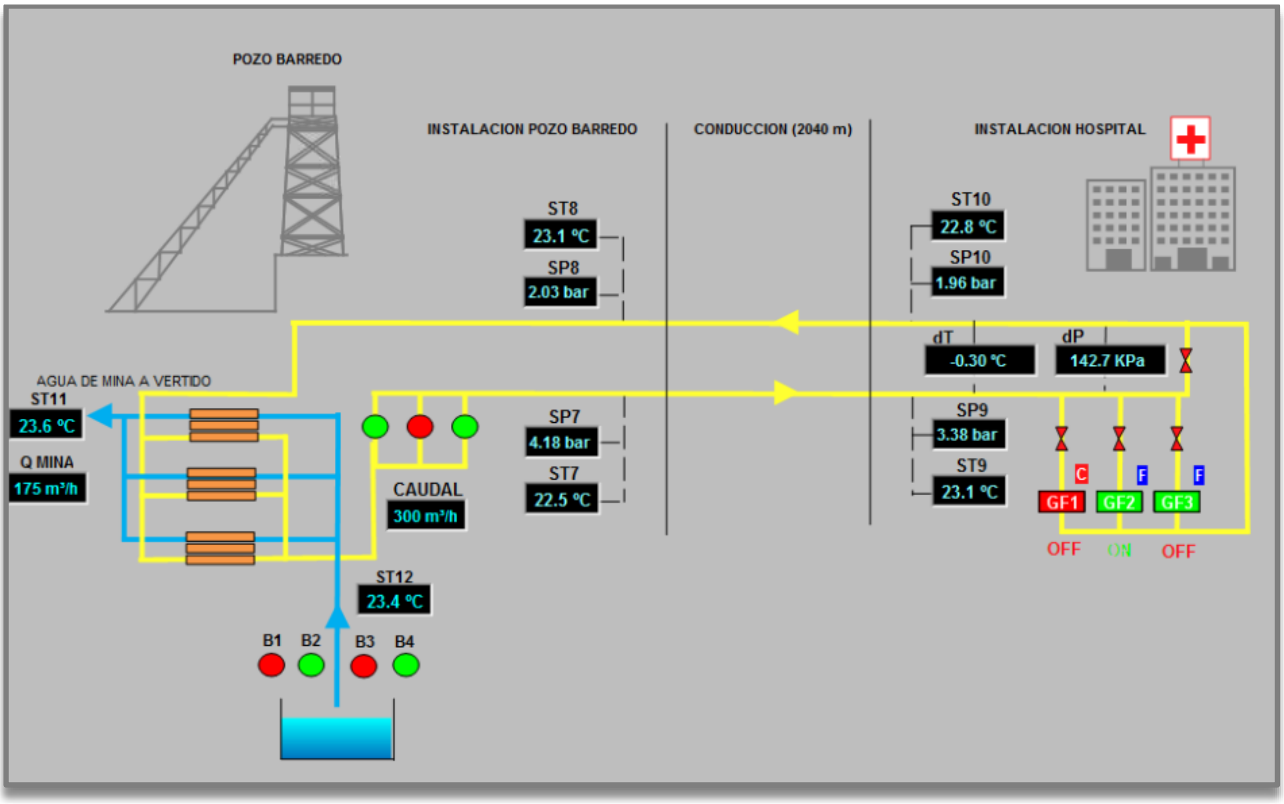


Figure 6.7. Digital monitoring snapshot of Barredo hospital system (blue = mine water, yellow = secondary heat transfer circuit to hospital, B1-B4 = submersible pumps in shaft, GF1-GF3 = heat pumps, C = *calor [*heat*]*; F = *frio [*cooling*]*)

The shell and tube heat exchangers are not reported to have suffered any significant problems with iron clogging. They transfer heat to a long secondary heat transfer circuit connecting the Barredo shaft to the plant room in the basement of the Hospital, some 2 km to the south. The plant room at the hospital contains three heat pumps:

- 1 x Carrier 30XWH-652 water-water chiller (GF2), used for heating only, cooling only or both heating *and* cooling, of nominal power 652 kW
- 2 x Carrier 30XWH-1152 water-water chillers (GF1 and GF3), used for either heating *or* cooling, of nominal power 1152 kW each.

The various modes of operation of the heat pumps are shown below:

Heat pumps GF1 and GF3 in cooling mode

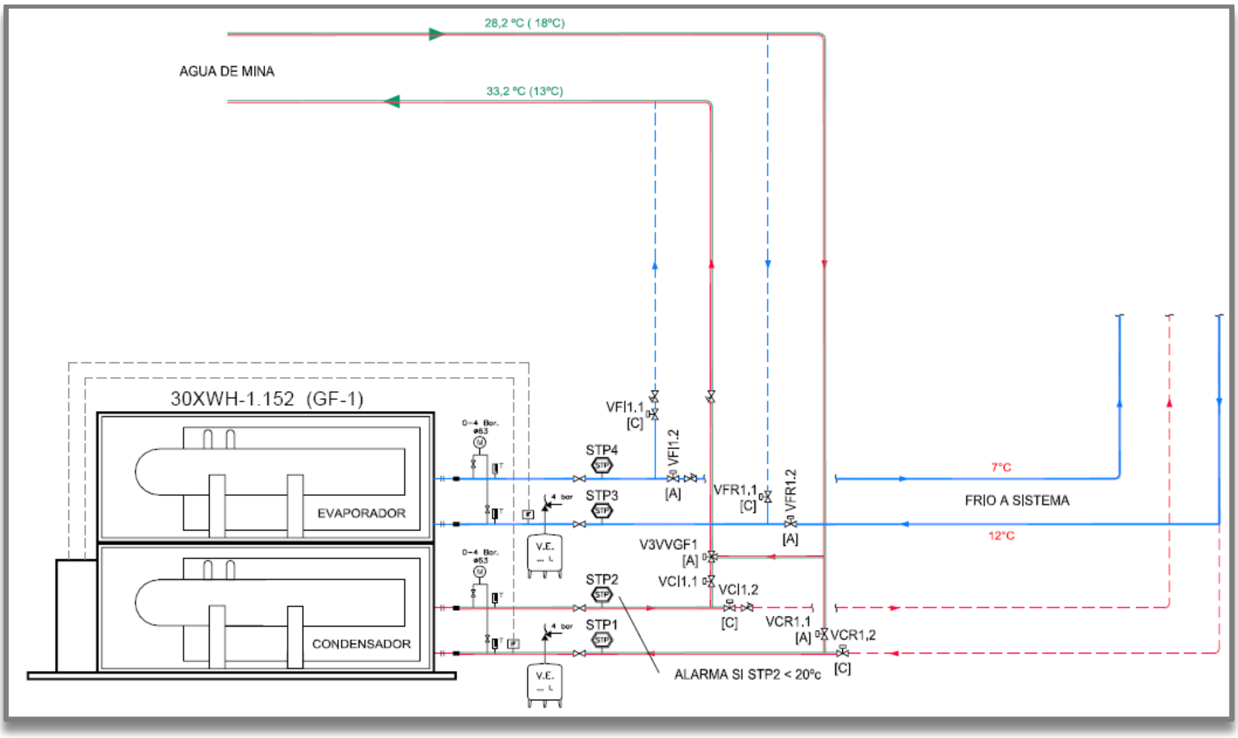


Figure 6.8. Heat pumps GF1 and GF3 in cooling mode. V.FI1.1 = closed; VFR1.1 = closed; VCR1.2 = closed; VCI 1.2 = closed. *Frio a Sistema* = building cooling circuit, *Agua de Mina* = secondary heat transfer circuit coupled to mine water.

Heat pumps GF1 and GF3 in heating mode

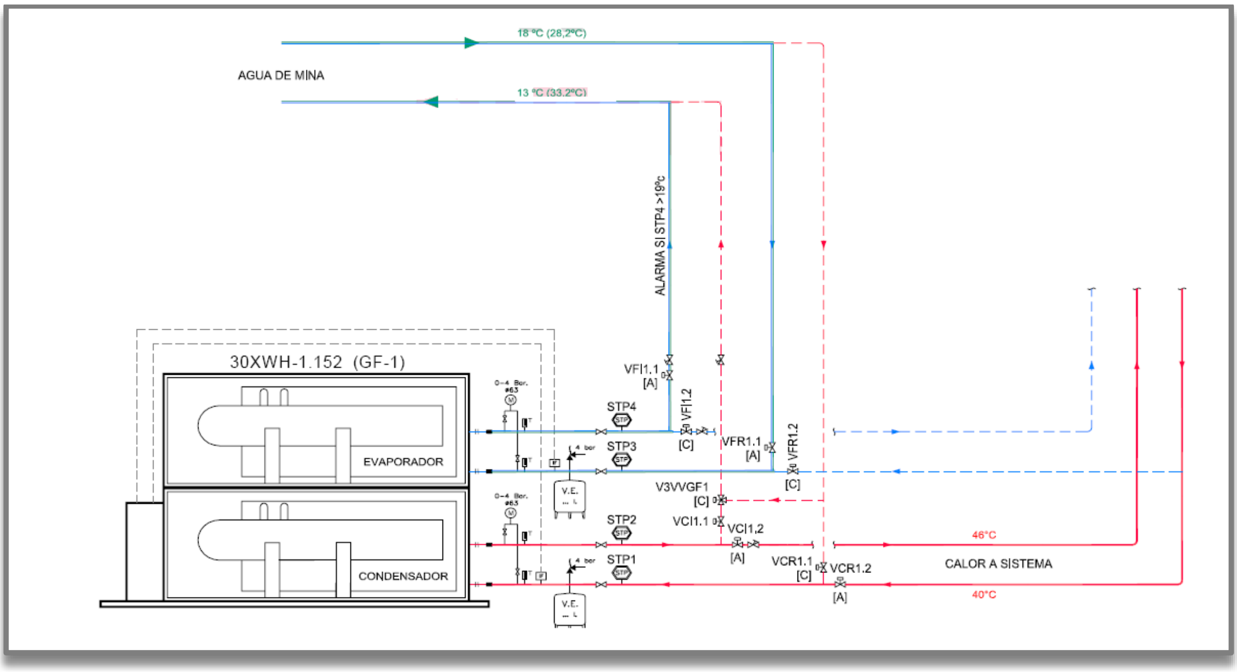


Figure 6.9. Heat pumps GF1 and GF3 in heating mode. V.FI1.2 = closed; VFR1.2 = closed; VCR1.1 = closed; VCI 1.1 = closed. *Calor a Sistema* = building heating circuit, *Agua de Mina* = secondary heat transfer circuit coupled to mine water.

Heat pump GF2 schematic

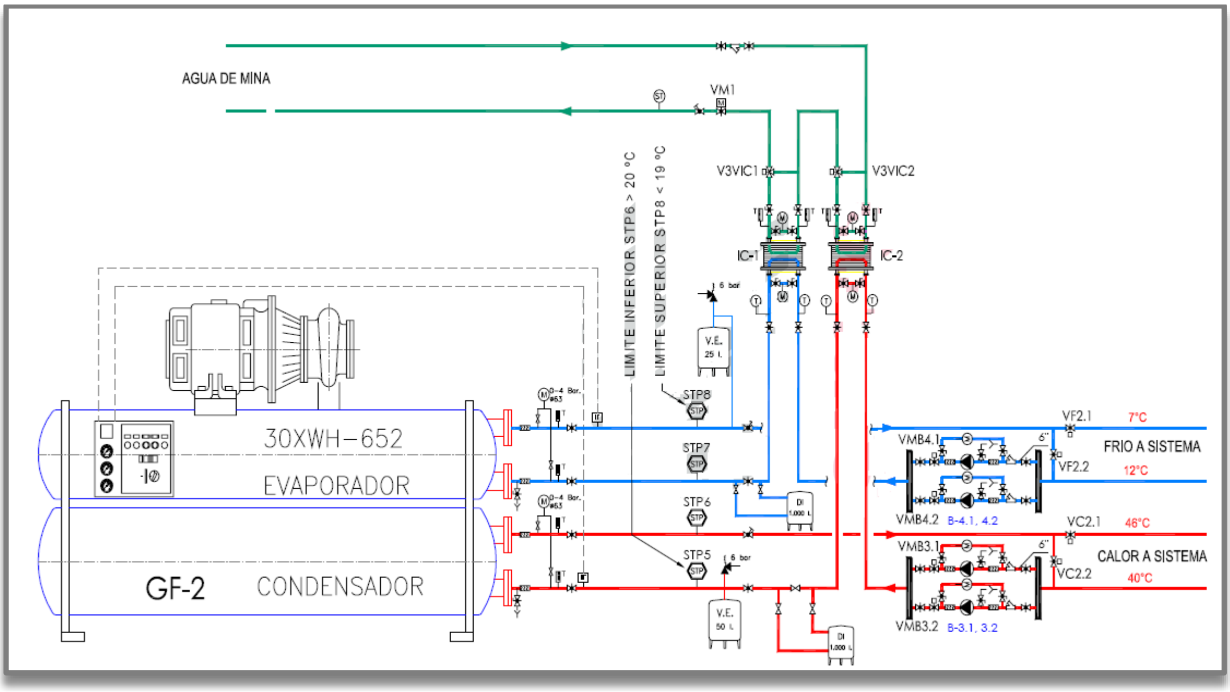


Figure 6.10. Heat pump GF2. This can operate in three modes: cooling only, heating only, both cooling and heating. The heating circuit operates at a flow/return temperature of c. 46/40°C, the cooling circuit at c. 7/12°C.

Heat pump GF2 in cooling mode

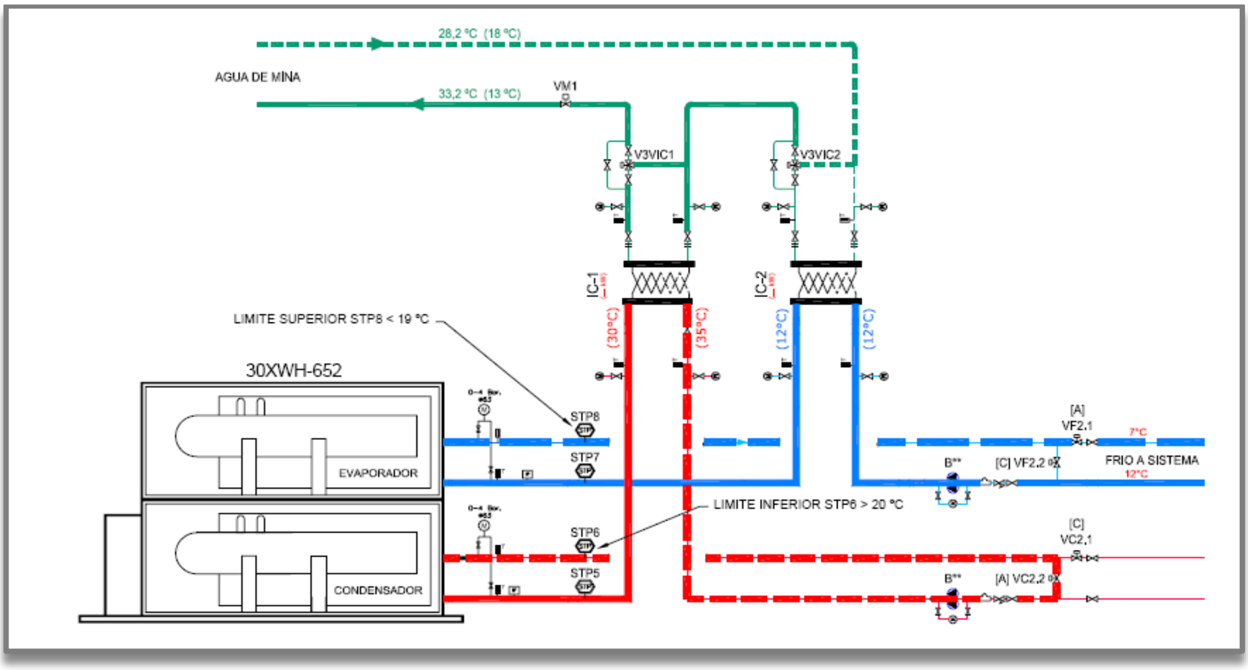


Figure 6.11. Heat pump GF2 in cooling mode. Essentially, the condenser of the heat pump is coupled to the secondary heat transfer circuit (and thence to the mine water) via a heat exchanger (IC-1).

Heat pump GF2 in heating mode

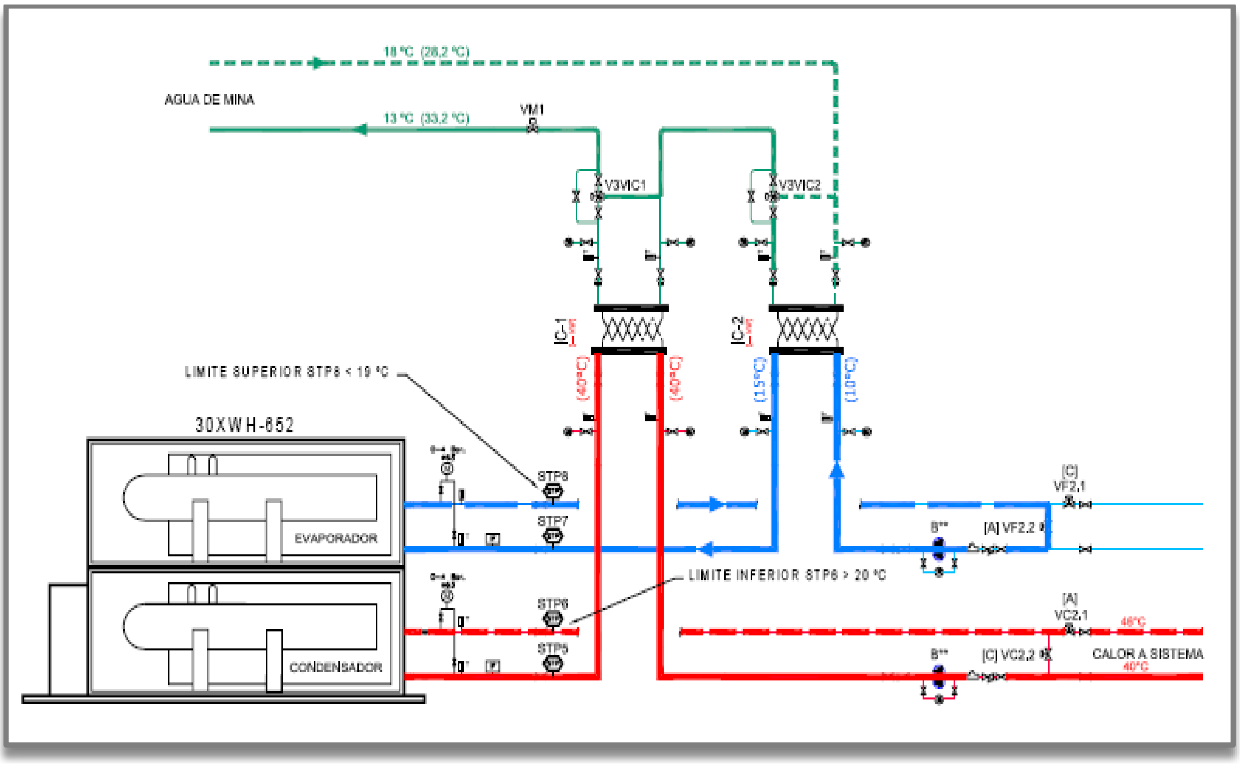


Figure 6.12. Heat pump GF2 in heating mode. The evaporator of the heat pump is coupled to the secondary heat transfer circuit (and thence to the mine water) via a heat exchanger (IC-2).

Heat pump GF2 in simultaneous heating and cooling mode

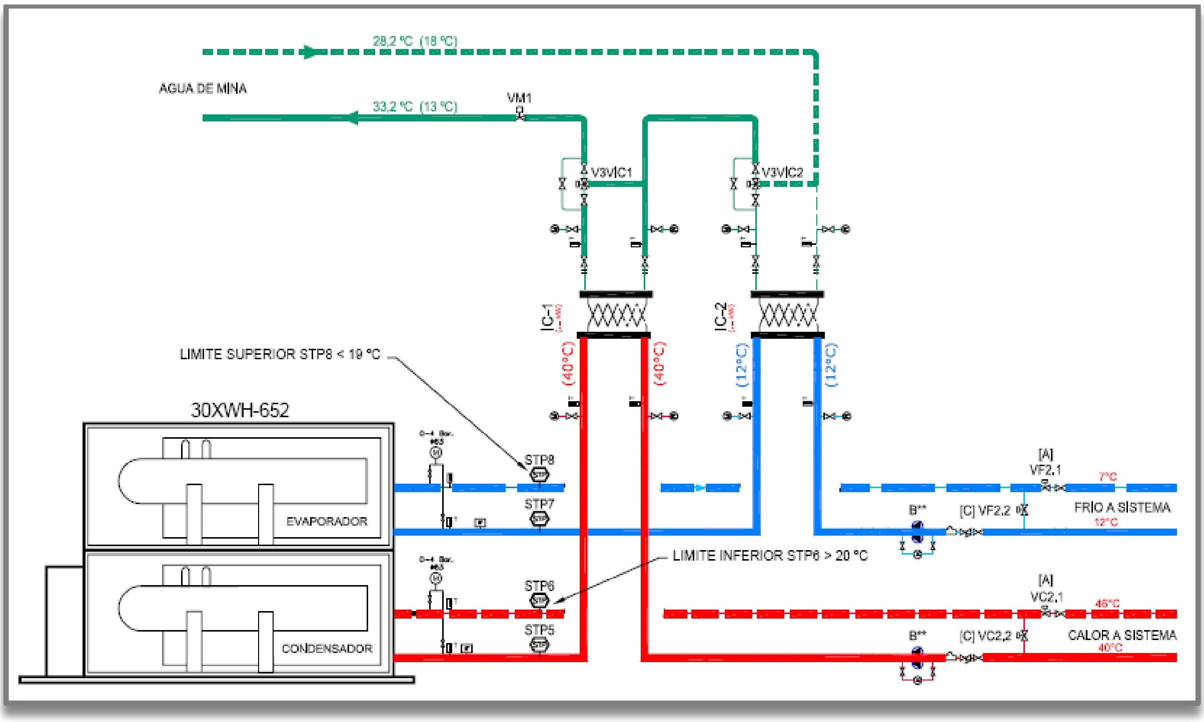


Figure 6.13. Heat pump GF2 in heating / cooling mode. In this diagram, cooling dominates heating and the condenser heat exchanger sheds heat to mine water.

In Figure 6.13, the (green) mine water-coupled heat transfer circuit is only used (i.e. thermally coupled to the heat pump) to receive or supply excess heat when the cooling strongly dominates over the heating, or vice versa.

The average effective COP [(heating + cooling delivered)/electricity consumed] of the Hospital system was reported as being 7.6 to 7.9 in the years 2015-2016 (Peña Fernandez 2017).

Figure 6.14. Barredo mine water pipeline, showing split between flows, Barredo shaft-top building. Photo by © David Banks

Figure 6.15. Shell-and-tube heat exchangers between mine water and secondary circuit (with circulation pumps) to hospital, Barredo shaft-top building. Photo by © David Banks

Figure 6.16. Shell-and-tube heat exchangers between mine water and secondary circuit to hospital, Barredo shaft-top building. Photo by © David Banks

Figure 6.17. Shell-and-tube heat exchangers (right) and circulation pumps on secondary circuit to hospital, Barredo shaft-top building. Photo by © David Banks

6.4 FAEN system

The FAEN system employs a shell and tube heat exchanger, a secondary heat transfer circuit and a single ecoGEO-HP 25-100kW heat pump of nominal 100 kW capacity. This can simply be used in either cooling or heating mode, using fan coil units, as shown in the diagrams below:

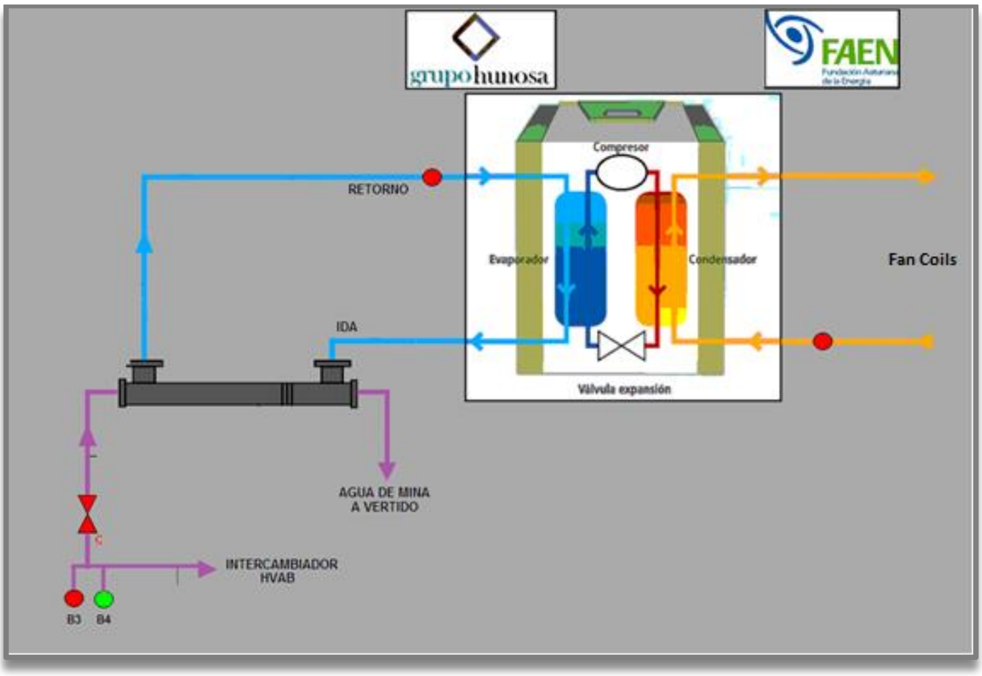


Figure 6.18. FAEN thermal system in heating mode. *Intercambiador HVAB* = hospital heat exchanger, *Agua de mina a vertido* = mine water to discharge

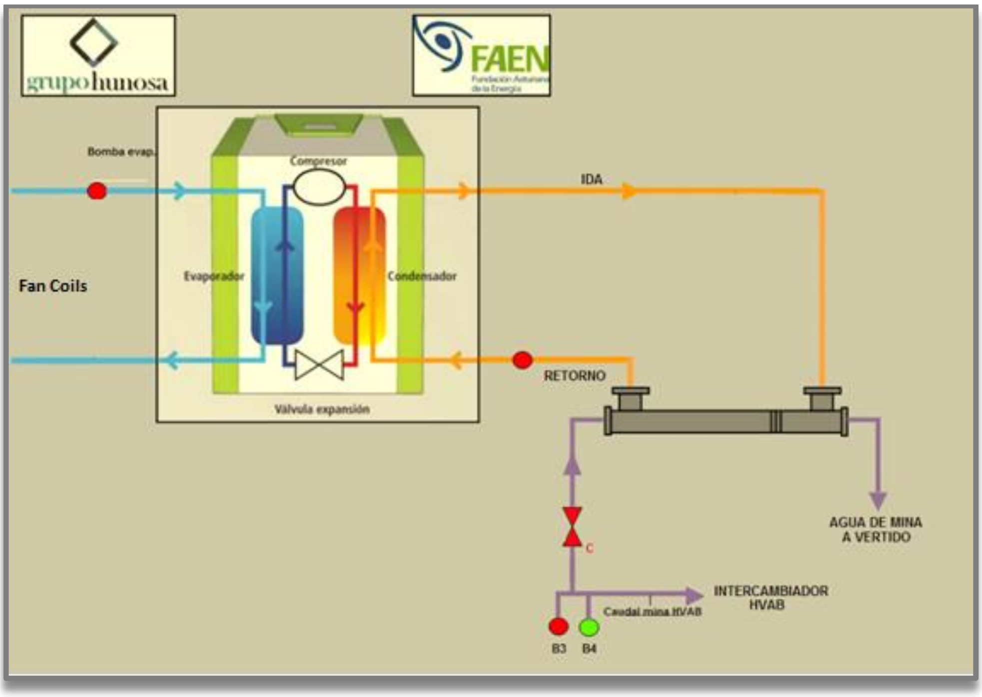


Figure 6.19. FAEN thermal system in cooling mode.

The mine water flow taken from the main minewater circuit can be varied in response to heating / cooling demand by a variable control valve (*C* in figure 6.18).

7. Case Study 2: Springhill

This chapter considers the municipality of Springhill, Nova Scotia, Canada. Instead of a centralised mine water heating and cooling system, various commercial, industrial and public buildings all operate their own geothermal abstraction / injection well doublets based on the interconnected coal mine workings beneath the town. This section considers two of these systems, managed in the public domain, based on information kindly provided by Mr Brian Herteis, the Capital Projects Engineer for the Municipality of Cumberland, based at Springhill, supplemented by notes made by Dr Neil Burnside (University of Glasgow) during a field visit to Springhill during 2016.

The background is also described in full by papers by Jessop (1995), Jessop et al. (1995), Arkay (2000), Michel (2007), Michel (2009), Tweedie (2014) and MacAskill (2015).

7.1 Springhill, Nova Scotia: background

Springhill is a relatively small town in Nova Scotia (population c. 2500), which had an important coal mining industry between 1872 and 1958. Seven westerly-dipping Late Carboniferous coal seams are identified (in order of increasing depth – somewhat confusingly - seams 3, 1, 2, 4, 5, 7 and 6, with outcrops progressively from west to east), with workings reaching depths of c. 1350 m to the west of the town. Below the main town and industrial estate, however, the workings are typically much shallower. Workings are a combination of longwall and room-and-pillar. According to prevailing knowledge in 1995, the flooded coal mines below Springhill were judged to contain around 4,000,000 m^3 of water (Jessop, 1995), although this figure has subsequently been revised upwards to over 5,500,000 m^3 in seam 2 alone (Tweedie, 2014).

The average annual air temperature is around 6°C (Michel, 2009), and typical shallow ground water temperatures are 7-8°C (Tweedie, 2014), while a geothermal gradient of 14 to 17°C per km is estimated (Jessop, 1995). As temperatures of up to 20°C are observed in mine water near the surface, some form of convective overturn in the workings, as well as natural forced convection, has been postulated by Jessop (1995). Temperatures of around 18°C were indicated during initial pumping tests (e.g. at Ropak – Jessop, 1995; MacAskill 2015), although in subsequent installations, somewhat lower groundwater supply temperatures have been found typical (14-15°C).

A mining museum south of the town (45.6339°N 64.0739°W), at the former Syndicate Mine, abstracts water to control mine water levels (in 1995, around 1000 m^3/d to keep levels at some 50 m bgl, or c. +100 m asl – Jessop, 1995). In the town area, the mine water depths are typically 14 - 33 m below ground level (MacAskill, 2015).

MacAskill (2015) reports relatively low dissolved oxygen contents in the mine water, with electrical conductivity in the range 1153 – 2137 µS/cm and pH 6.6 to 7.4. Total iron concentrations are typically in the range 1.2 to 5.7 mg/L. Michel (2009) describes calcium sulphate/bicarbonate type waters, often with significant H_2S concentrations. Michel (2009) also describes the inadvertent introduction of oxygen causing iron clogging problems in one well system (Surette Battery).

Today, the town has a much more diversified and relatively large industrial and commercial base. The main alternative sources of heating are oil and wood, against which mine water-sourced heat can compete efficiently in terms of marginal costs.

The Springhill systems are amongst the earliest mine water-based thermal energy systems in the world, with the earliest studies being conducted in around 1984-85. By the mid-1990s, around eight geothermal systems were established, with users including (Jessop, 1995; MacAskill, 2015):

- Ropak Can-Am Ltd. (plastic manufacturing) - 45.6456°N 64.0681°W – Nos. 2 and 3 seams. From 1988. Now Bway Plastics.
- MBB Ltd. (boilermaker)
- Surette Battery Ltd. (lead battery manufacturer) - 45.6535°N 64.0644°W, Nos. 1 and 2 seams. From 1989.
- Pizza Delight Ltd. restaurant, Nos. 6 and 7 seams. From 1990
- Town loop for district heating, currently used only by GOVRC. From 1992
- Parkview Professional Centre, two wells, from 1993

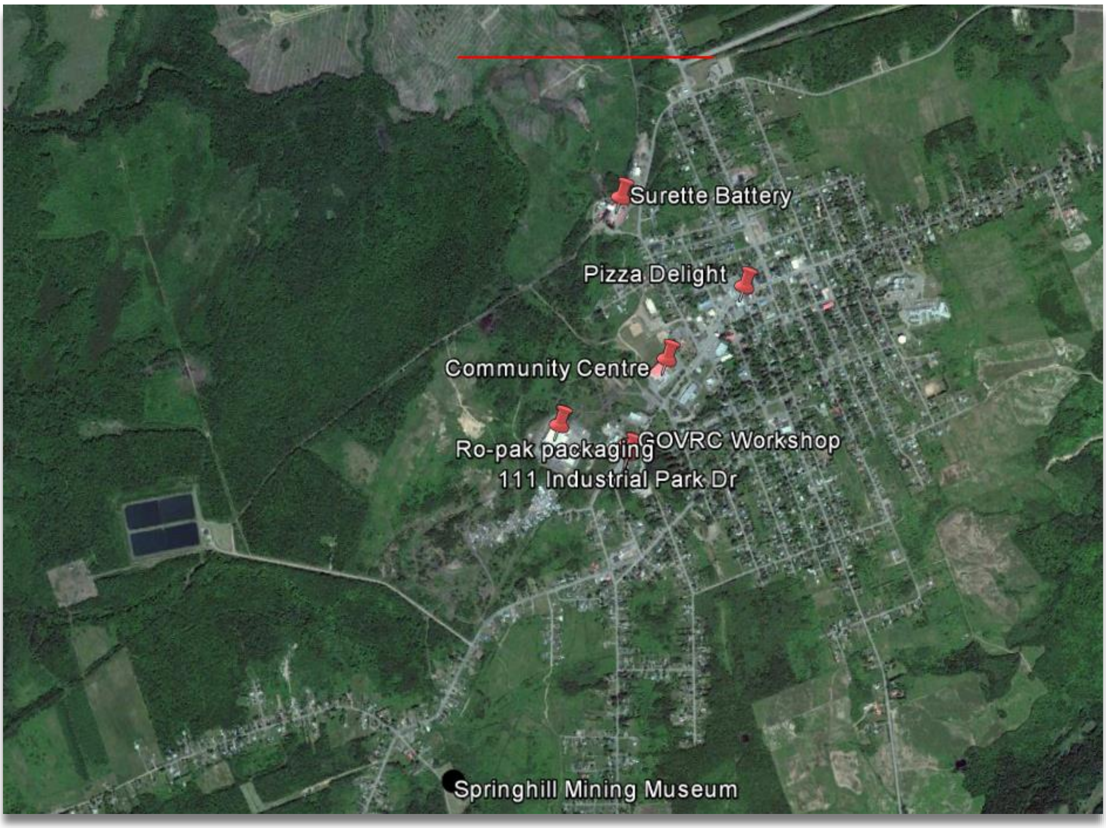


Figure 7.1. Google Earth image of Springhill, Nova Scotia, showing location of mining museum and geothermal users. The red bar at the top is 1 km for scale.

Most schemes have supply and return of water in different, though hydraulically interconnected, seams (MacAskill, 2015). Well yields of 10-15 L/s in the mine workings have been typical (Michel, 2009).

The systems typically reject more heat in summer than they extract in winter (i.e. mostly cooling-dominated – Jessop, 1995; Michel, 2009). In some supply wells (Town District Heating Loop, Surette Batteries, Community Centre), there is evidence that groundwater supply temperatures are creeping slowly upwards (MacAskill, 2015).

7.2 GOVRC mine water doublet

The enterprise GOVRC utilises a doublet comprising an abstraction and recharge well (Figure 7.2), serving two heat pumps. The system is based on the doublet constructed in 1992 for the proposed town district heating loop. The pumped mine water stream is split into two streams:

1. The first stream passes through a water-to-air heat pump, providing hot air to a greenhouse

2. The second stream passes through a heat pump that can be operated in heating or cooling mode, providing space heating / cooling (as hot / cool air) to the GOVRC workshop buildings.

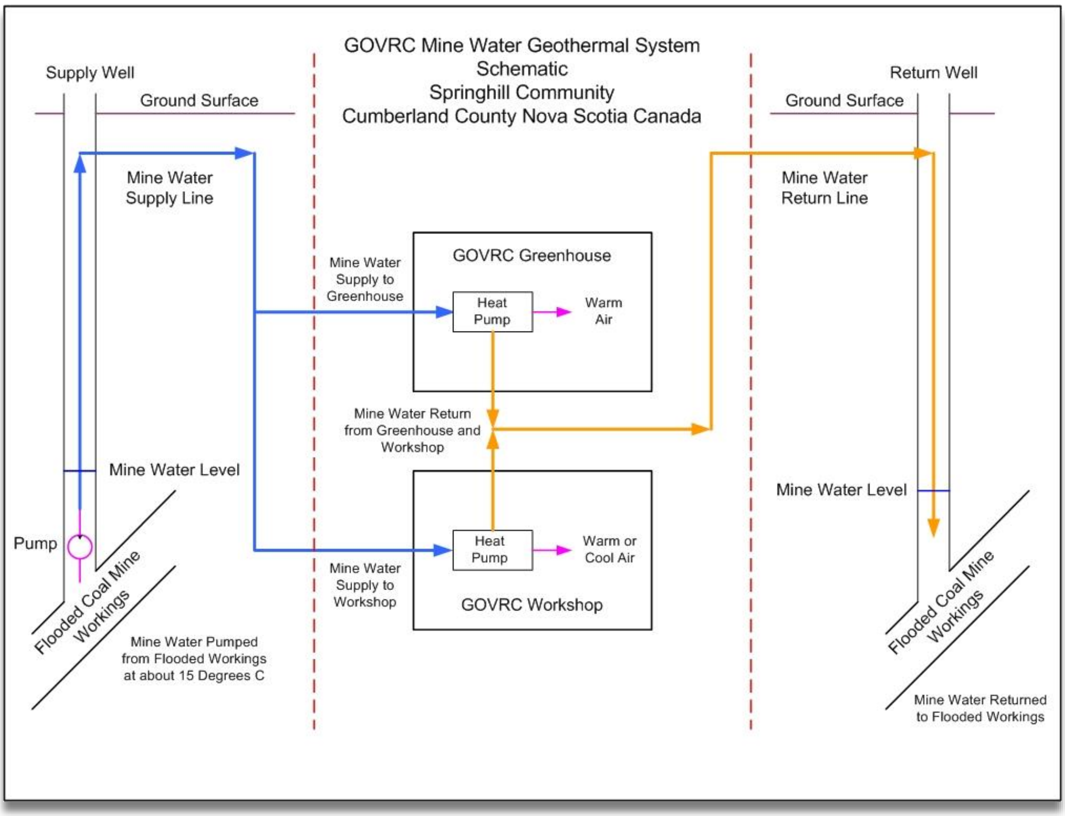


Figure 7.2. GOVRC mine water geothermal system schematic (provided by Brian Herteis)

7.3 Springhill Community Centre mine water doublet

According to its website (http://www.cumberlandcounty.ns.ca/facilities-parks.html), the Springhill Community Centre offers a 1580 m² arena with a NHL (national (ice) hockey league) -sized ice surface with a seating capacity of 812, five dressing rooms, a room for officials, lobby, storage facilities, canteen with kitchen, coatroom, meeting/boardroom, walking track, 290 m² common room, and a teen centre. The new arena was constructed following the catastrophic collapse of the former centre in 2001. The Springhill Community Centre scheme was commissioned in 2004.

The pumped mine water (at 198 gallons per minute = 12.5 L/s) passes through a prophylactic plate heat exchanger (MacAskill, 2015) to a secondary heat transfer fluid circuit. This circuit serves four individual heat pumps:

- Two heat pumps operate in heating mode, providing domestic hot water, and heating of the arena's spectator seating area.
- One heat pump provides either space heating or space cooling in the Community Centre
- The other heat pump provides ice-making facilities for the ice rink.

Thus, the secondary heat transfer circuit couples heating and cooling requirements, with the surplus thermal energy being transferred to or from the mine water (Figure 7.3).

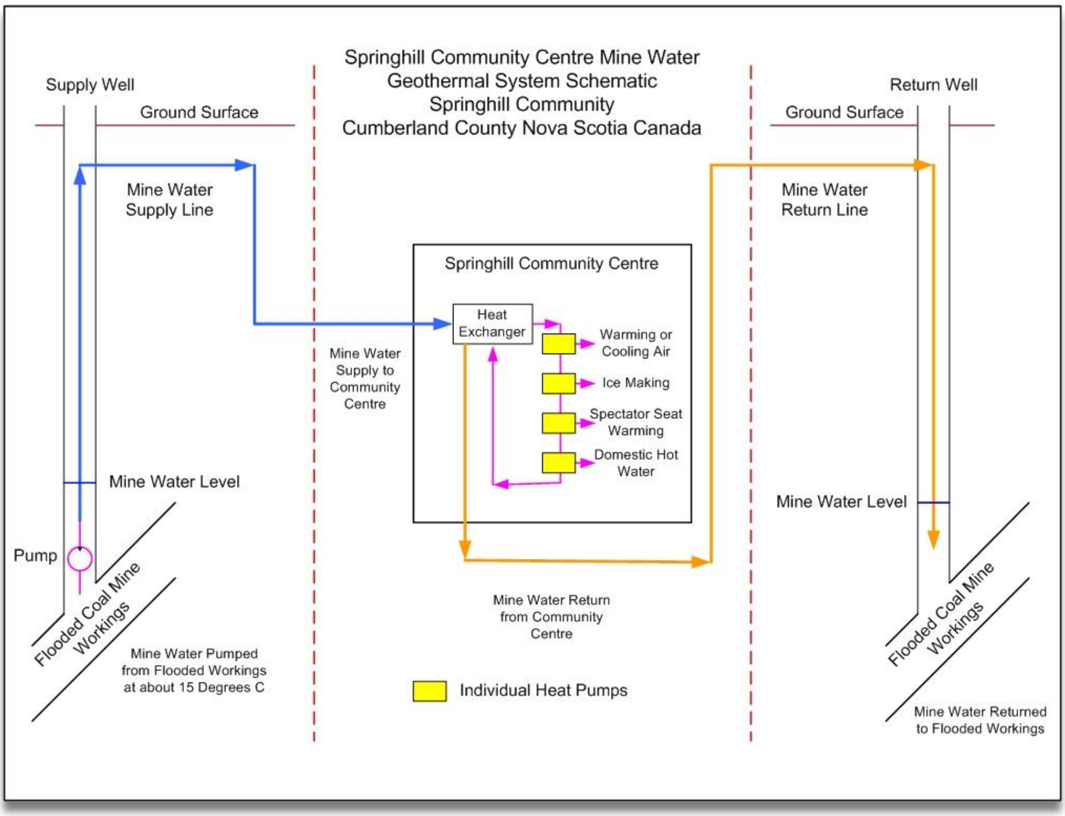


Figure 7.3. Springhill Community Centre mine water geothermal system schematic (provided by Brian Herteis)

According to Michel (2009), the pumping and reinjection wells at the Community Centre are c. 30 m apart and also less than c. 100 m from the Ropak wells. Typically, groundwater temperatures in the supply well rise during the period January to Autumn and then decrease from Autumn to January. It is believed that this may represent feedback of hot or cool water in the ground during episodes of cooling or heating respectively. Superimposed on this fluctuation there has been a steady rise in mine water temperature year-on-year, from around 15.5°C in 2004-05 to 22°C in 2006-07. This may represent upwelling of deep groundwater, or conceivably, net dumping up heat to the mine system.

8. Case Study 3: Heerlen

The town of Heerlen lies in the south-eastern part of the Netherlands, close to the border with Germany, near Aachen. The town is underlain by extensive coal mine workings at several levels. The initial development of the flooded workings for heating and cooling provision focussed on the suburb of Heerlerheide. It now encompasses provision of both heating and cooling via District Heating and District Cooling networks. The project is described by Minewater Project (2008), Ferket et al. (2011), Verhoeven et al. (2014)

8.1 Background

The three main interconnected coal mines below Heerlen were known as Oranje Nassau I, III, and IV, which were closed between 1965-74, allowing the mine voids to become flooded. In 2003, planning for the use of the mines as a geothermal resource commenced. The Mijnwater website (www.mijnwater.com) subdivides the development of the network into three phases, termed Mijnwater 1.0, 2.0, 3.0.

8.2 Mijnwater 1.0 (2008 – 2013)

In 2005, five wells were drilled to different depths in the workings as warm and cool abstraction and recharge wells:

- Two warm abstraction wells (HH1 and HH2) were drilled in the northern part of Heerlen to c. 700 m depth, with water temperatures of c. 28 °C
- Two cool abstraction wells (HLN1 and HLN2) were drilled in the southern part to c. 250 m depth, with water temperatures of c. 16 °C.
- A fifth intermediately located well (HLN3), was drilled to 350 m for return of thermally spent water from the cool and warm wells, typically at between 18°C and 24°C.

The interconnectivity and potential flow pathways between these wells were investigated by Ferket et al. (2011). 8 km of three-main (cool flow from HLN1 and HLN2, warm flow from HH1 and HH2 and combined return to HLN3) pipeline was laid to distribute minewater to two initial end users:

- In 2008, the Heerlerheide Centre (HHC) Gen Coel thermal system was commissioned to serve 30,000 m² of indoor space, including homes, shopping and community areas and offices
- This was closely followed by the Statistics Netherlands (CBS) system (22,000 m² office space).

The minewater was distributed to the end user buildings. Heat pumps at the system end-user were utilised to either:

- Extract heat from the warm minewater main to provide low-temperature heating

- Reject heat to the cold minewater main to provide high temperature cooling (with a facility for free cooling)

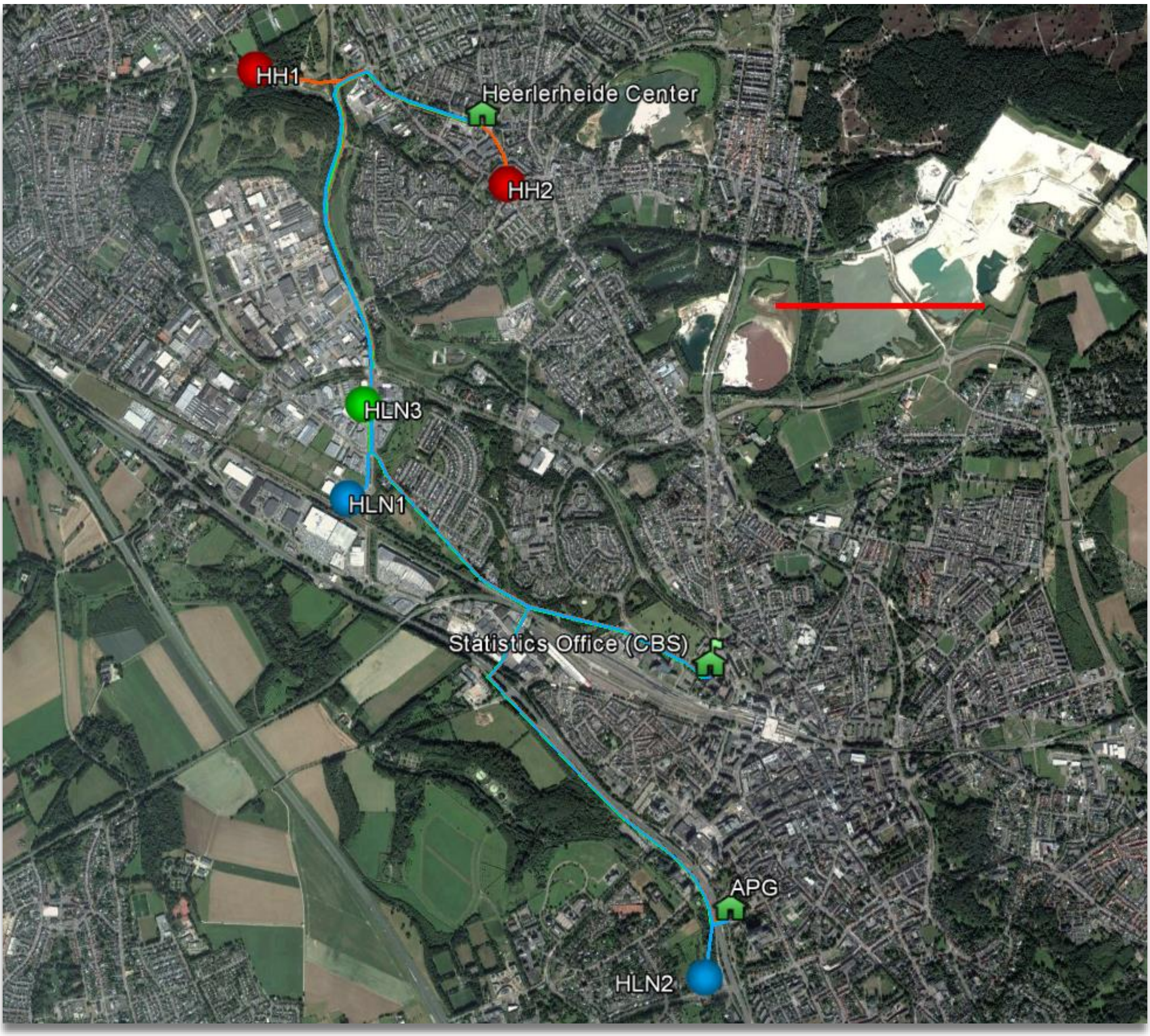


Figure 8.1. Schematic of Heerlen mine water scheme phase 1.0. Warm wells and flow pipeline in red, cold wells and flow pipeline in blue, return well and combined return pipe in green. The red bar is a 1 km scale. Based on a schematic from the www.mijnwater.com website.

[See Mijnwater website: http://www.mijnwater.com/minewater-then/?lang=en; http://www.mijnwater.com/minewater-now/mijnwater-1-0/?lang=en].

8.3 Mijnwater 2.0 (2013 to date)

Modelling studies suggested that, in some scenarios, the continued reinjection of intermediate temperature water to HLN3 might, at some point in the future, lead to increases in temperature at HLN1 and decreases at the warm wells. In around 2013, the Heerlen mine water scheme was reconceptualised:

- Expanded to include the so-called Arcus-APG cluster towards the south of the previous system

- Altered to maximise the quantity of passive energy transfer taking place
- Refocussed to emphasise Aquifer Thermal Energy storage, i.e. using the mine system as a store of warm water (around the warm wells) and cool water (around the cool wells)

In this concept, HH2 was re-engineered to allow reinjection of warm water (i.e. surplus heat), while HLN2 was re-engineered to allow reinjection of cool water, i.e. surplus "coolth" (http://www.mijnwater.com/minewater-now/minewater-2-0/?lang=en). The aim is to reinject water to HH2 at as close to the temperature of HH1 as possible, and to reinject cool water at HLN2 as close to the temperature of HLN1 as possible. HLN3 is maintained as a standby for intermittent use.

The system can incorporate allow heat or coolth supplied by other thermal sources in addition to the mine system.

The (primary) mine water spine delivers warm or cool mine water to the usage clusters, where heat stations use passive heat exchange or heat pumps to supply (secondary) cluster-level district heating networks (DHN) or district cooling networks (DCN). At each individual property, building (tertiary) heating or cooling systems exchange heat via heat exchangers with the DHN or DCN.

The objective of this approach is:

- To allow buildings to supply or dump heat from their own building (tertiary) circuits, via heat exchangers to the secondary (heat transfer fluid) cluster networks, in order to obtain as good a heat balance within the cluster as possible. In other words, surplus heat from one building can supply a heat demand at another building within the cluster. The objective is for buildings to reject heat at as close to 28°C as possible and to reject "coolth" at close to 16°C.
- If a cluster has a heat imbalance, the surplus heat or coolth can be transferred (via the primary mine water spine) to another cluster on the network.

The first "cluster of buildings" to be developed as part of Mijnwater 2.0 was the so-called ARCUS (University) – APG cluster on the southern end of the system (Figure 8.2).

The system is controlled by demand (Figures 8.3 and 8.4):

- Changing demand is reflected in a change in temperature in the building (tertiary) heating and cooling circuits;
- Control systems register changing temperatures to alter flow rates in the secondary (water-based heat transfer fluid) cluster circuits;
- This in turn results in changes in pressures and flow rates in the primary mine water "spine".

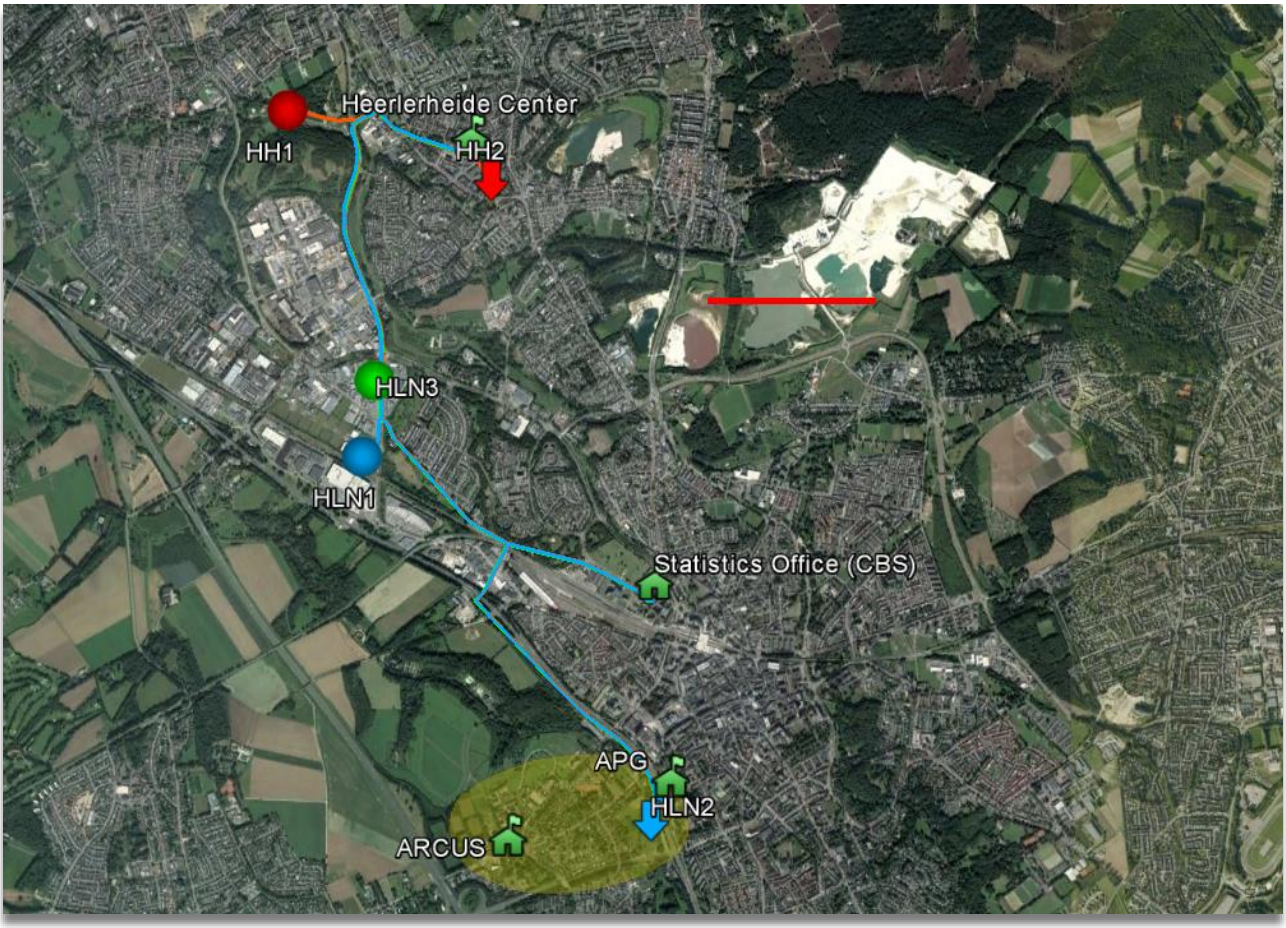


Figure 8.2. Mijnwater 2.0 as of 2013, showing HH2 as a warm reinjection well, and HLN2 as a cool reinjection well, with the yellow ellipse showing the district cluster around ARCUS and APG.

8.4 Mijnwater 3.0 (the future)

In the future years, it is intended to expand the Mijnwater 2.0 concept to include a further three district heating / cooling clusters along the mine water "spine" (http://www.mijnwater.com/minewater-now/mijnwater-3-0/?lang=en) and:

- to increase the degree of automation and responsiveness to demand
- increase thermal energy storage within clusters
- convert all four wells HH1, HH2, HLN1, HLN2 to become bidirectional
- to incorporate other primary decentralised heat and cooling sources onto the network.

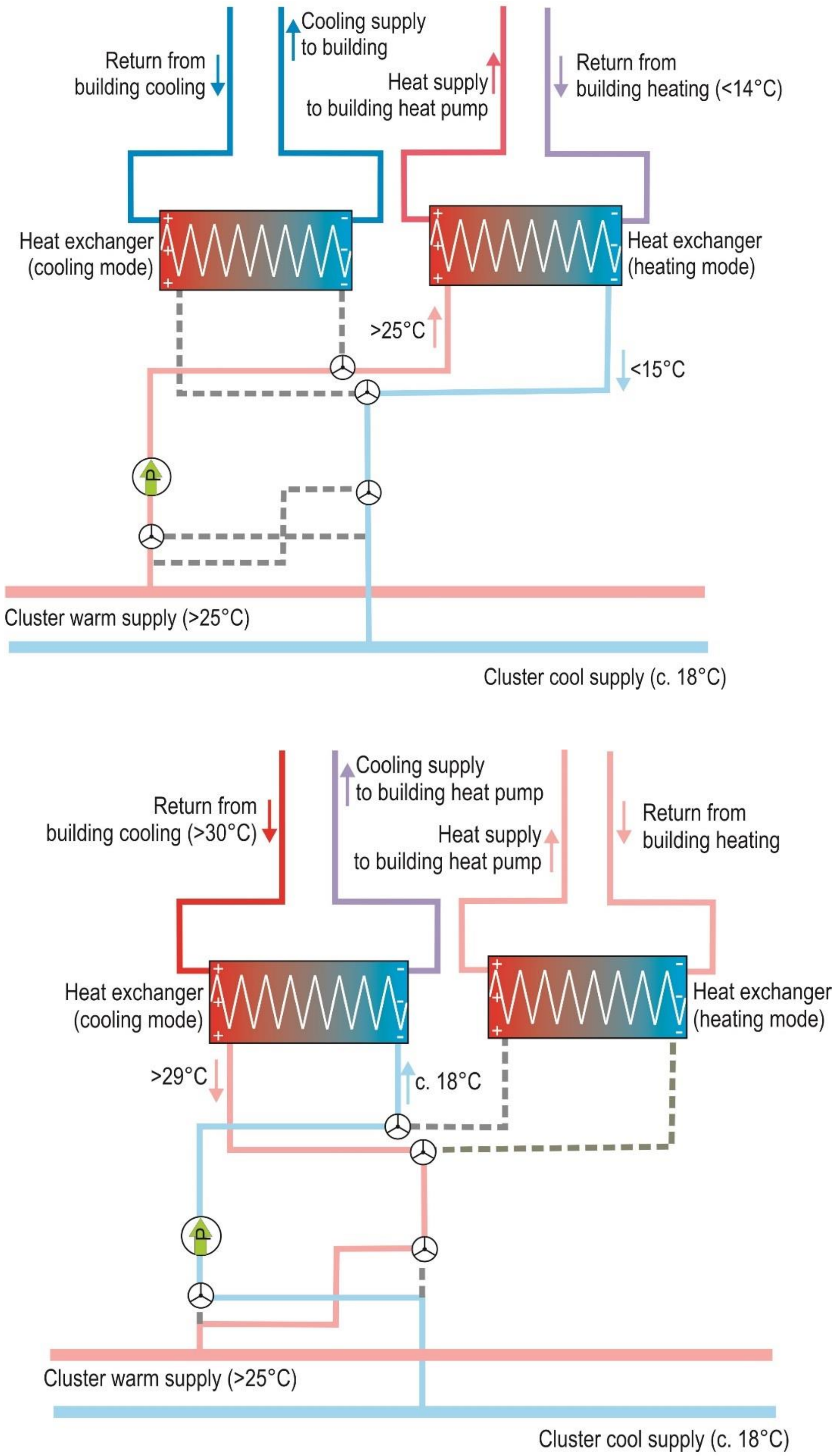


Figure 8.3. Schematic of heat transfer at Heerlen from secondary (cluster) to tertiary (consumer building heat pump) levels, in (top) heating and (bottom) cooling modes, using double heat exchangers. Grey dashed lines indicate temporarily not in use.

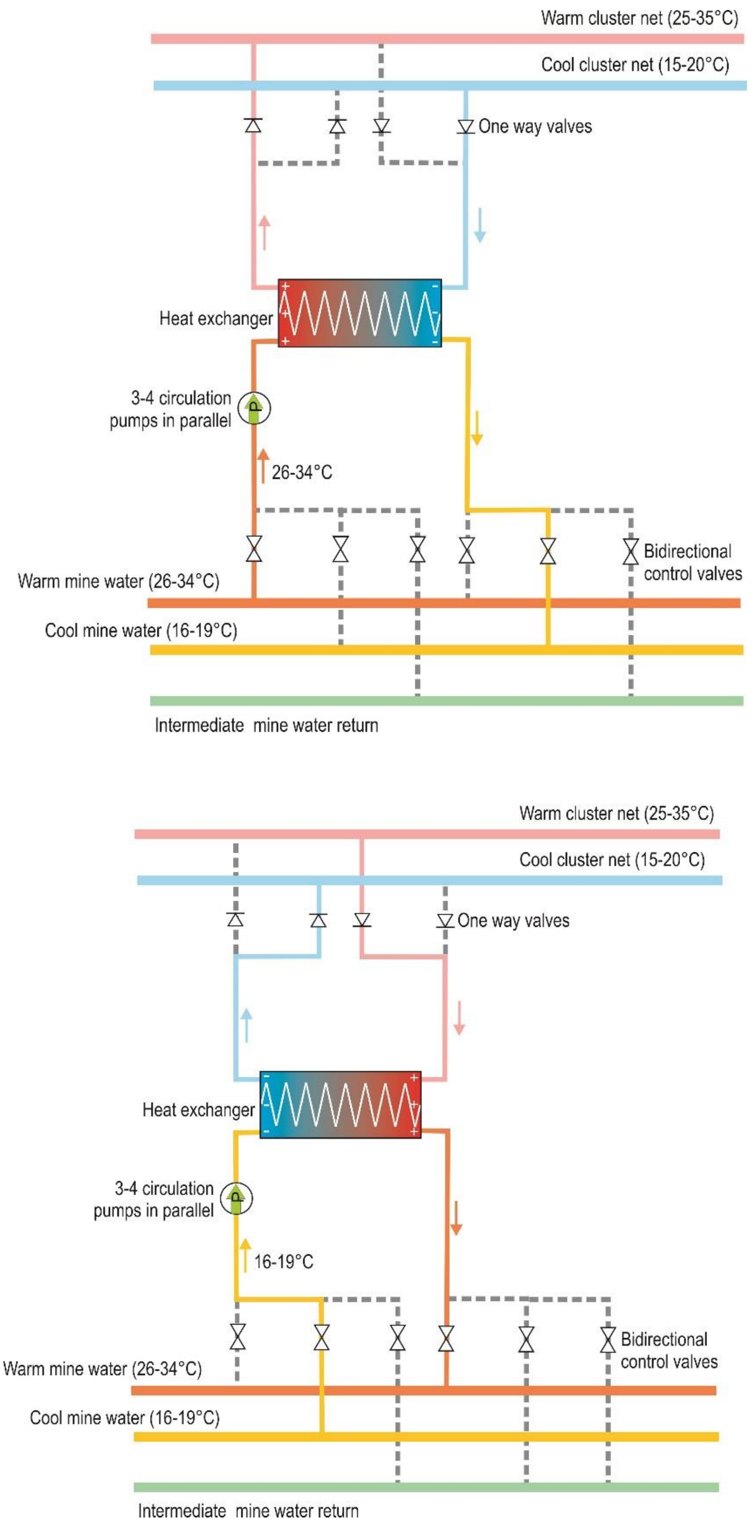


Figure 8.4. Schematic of heat transfer at Heerlen from secondary (cluster) to primary (mine water) levels, in (top) heating and (bottom) cooling modes. Grey dashed lines indicate temporarily not in use. Note, that no circulation pumps are employed on the cluster side at this primary heat transfer stage. From Figure 8.3, it will be seen that when cooling demand dominates, pressures will drop in the cooling main due to pumping through secondary heat exchangers (Fig. 8.3), thus automatically inducing flow from the warm main to the cool main via the one-way valves and the primary heat exchanger (and *vice versa* when heating demand dominates). Return water on the primary side can be directed to the warm or cool minewater mains, if temperatures are suitable, or to the intermediate return main, if they are not.

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Integration of Cooling into Mine Water Heat Pump Systems

Task 3.3, Work Package 3 of the European Research Fund for Coal and Steel LoCAL Project

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