Floor cooling project model for a residential building in the city of Vienna using ground water (free cooling) and refrigeration system (Chiller).

A Master's Thesis submitted for the degree of “Master of Science”

supervised by
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Vienna, 13.05.2021
Affidavit

I, SARMAD ABDULRAHEEM, BSC OF ENGINEERING, hereby declare

1. that I am the sole author of the present Master’s Thesis, “FLOOR COOLING PROJECT MODEL FOR A RESIDENTIAL BUILDING IN THE CITY OF VIENNA USING GROUND WATER (FREE COOLING) AND REFRIGERATION SYSTEM (CHILLER).”, 66 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and

2. that I have not prior to this date submitted the topic of this Master’s Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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_______________________
Signature
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Abstract

The cooling energy consumption takes up around 30–50% of the total consumption of data centers due to the inefficient cooling system and the necessity for it. Free cooling is an effective solution for reducing the power consumption of cooling systems. (H. Zhang, et al., July 2014 pp. 171-182)*

Free cooling is defined as the means to store groundwater coolness or cool air, to supply indoor cooling during the day, which means to use passive cooling solutions. Notable progress has been made in this direction. However, many passive solutions are limited to new projects and sometimes this feature is insufficient to meet the needs of cooling loads.

The research for this master thesis was conducted on such an example – a residential building in Vienna using groundwater (free cooling) with a refrigeration system (chiller) to cool the building by using floor cooling and fan coils distributor. The cooling requirement for this residential building is at 275 kWc, the free cooling capacity 59 kWc and the total capacity of chiller system is at 216 kWc.

The free cooling was fairly ineffective due to the increased groundwater temperature in the last couple of years and the chiller (without free cooling with groundwater) with a maximum cooling capacity of 216 kWc, cannot meet the cooling requirements for floor cooling and fan coils with a total of 275 kWc cover, if the well cooling fails due to the high groundwater temperature.

In this thesis, the free cooling with the design of the chiller system is explained in detail, followed by reasons for the defects and failure of free cooling. Furthermore, alternative variants are proposed for the model cooling system to improve the performance work of the chiller system. Finally, the investment cost and NPV of the model chiller system for a 20-year span is presented.
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1. Introduction

Energy consumption is an important issue in residential buildings for cooling and heating demand. Heating buildings consumes more energy than electricity or transportation, and the heating/cooling demand accounts for around half of global final energy consumption. “Of this, nearly 50% is consumed in industrial processes, while another 46% is used in residential and commercial buildings”. (IEA, 2020)

“The demand for heating and cooling is set to keep growing. Cooling demand has already tripled globally since 1990”. (C. Delmastro, June 2020)

To preserve energy, it is necessary to pursue 2 objectives. Firstly, to reduce the energy demand and secondly, to meet the existing demand with maximum efficiency.

The use of renewable energy could offer ways to achieve the objectives mentioned above. Building cooling with the groundwater source (free cooling) is one type of renewable energy that restores its power periodically. Not only is it a green concept, since no carbon is burnt for the purpose of cooling, but it also ensures the preservation of good indoor air quality in the building.

“The energy convenience of such an option depends on the annual energy needs, population density, and efficiency of heat production”. (M. Imai, 2015 pp. 18-26).

The groundwater thermal environment facilitates lower temperatures for cooling in the summer season and higher temperatures for heating in the winter season. In addition, the temperature fluctuates less, especially in comparison to the ambient air temperature change in extreme weather conditions.

The effect of a significant imbalance of fluid loop temperature (increase/decrease) between the heat rejection from the groundwater and heat extraction from the groundwater source on a yearly basis, can be moderated by adding the heat exchanger size. Furthermore, the groundwater source cooling/heating systems are economically more advantageous than the conventional heating system.

Moreover, to optimize the operation of groundwater source systems, it is necessary to develop a system using both groundwater and air sources, in accordance with temperature conditions and building loads. Furthermore, groundwater usage should
be dealt with carefully to prevent ground subsidence and maintain system performance for a long period.

This thesis examines residential project mistakes in the calculations of the design of the cooling system and in calculating the temperature for both free cooling and the outside temperature during summer season. The planner of the project in question assumed the temperature of groundwater at around 11.5°C and a cooling load of 18 to 20 W/m². However, the temperature of the groundwater is, according to the authorities, higher than the predicted one and the chiller designed only delivers a maximum of 216 kWc, intended for a theoretical maximum outside temperature of 32°C. In addition, in the recent years, the outside temperatures significantly and frequently exceed the theoretical temperature in summer season because of global warming. Finally, the focus of this thesis is on the inefficiency of underfloor cooling, which is generally only suitable for low cooling loads, with low-temperature groundwater as a justification for this failure.

2. Refrigerants

To address and resolve protection and environmental concerns, refrigerants need to have low toxicity, low flammability, and lengthy atmospheric life. Recently, refrigerants have come under scrutiny because of the environmental issues attributed to their use by scientific, environmental, and regulatory groups. Some refrigerants—particularly chlorofluorocarbons (CFCs)—are devastating for the stratospheric ozone. The relative cap potential of a refrigerant wrecking stratospheric ozone is referred to as its ozone depletion potential (ODP). CFCs were closed in accordance with the 1987 Montreal Protocol. The production of CFCs in certain international locations ceased in 1995, and their maximum (not unusual) place replacement, halogenated chlorofluorocarbons (HCFCs), are due for phase-out in the twenty-first century. Replacements for HCFC R-123 and HCFC R-22, which are typically used inside the industry, are being updated at the present time. Realistically, however, HCFCs could be manufactured around the middle of the twenty-first century and, without a doubt, at the lifetimes of machines presently being manufactured.
Overview of the Global Warming Potential and Greenhouse Gases

The potential global warming and climatic extrude connected to the emission of the greenhouse gases in the environment present one of the biggest environmental challenges of our time. The anthropogenic motives of this forthcoming weather deterioration could be attributed to the use of energy and the combustion of fossil number one assets of power and the associated emission of CO₂.

The global warming potential of a certain gas refers to the entire contribution to global warming, because of the emission of one unit of that fuel line, relative to one unit of the reference gas (i.e., carbon dioxide), that is assigned a price of 1. To calculate the GWP, the mass of gas is multiplied by its GWP price to get CO₂ equal emissions. For example, if a gas has a GWP of 100, it equals the CO₂ emission of two hundred heaps.

The global warming potential (GWP) is a technique for evaluating the weather consequences of emission, heat tapping cap potential at unique fees, greenhouse gases, and unique lifetime, using CO₂ as a benchmark for measuring the warmth trapping cap potential of each of the opposite gases.

The European Fluorinated gases (F-gas) regulation has limited the permissible leakage rates of HFC systems in 2007 and stipulates regular leakage tests for this purpose. In 2014, there was a revision or a significant tightening of the F-gas regulation, prohibiting HFC refrigerants with a GWP> 2500 in new systems from 01/01/2020. From 01/01/2022, this prohibition also applies to coolants with a GWP>
1500, provided they are used in commercial refrigeration systems with an output of 40 kW or more.

“*The greenhouse gases (GHG) that trap heat in the atmosphere are called greenhouse gases*” (EPA, 2009). “They let sunlight pass through the atmosphere, but they prevent the heat that the sunlight brings from leaving the atmosphere” (GARRITY, 2020).

In order to achieve the set climate protection goals, further tightening or revisions of the F-gas regulation are to be expected. According to current knowledge, in the long term, only Refrigerants with a GWP <150 (e.g., R290) can be viewed as future-proof.
There are the 4 main greenhouse gases:

1. **Carbon dioxide (CO₂):** Carbon dioxide enters the ecosystem via burning fossil fuels (coal, natural gas, and oil), solid waste, trees, and different organic materials, and as a consequence of positive chemical reactions (e.g., manufacture of cement). Carbon dioxide is eliminated from the ecosystem (or "sequestered") through plant absorption as part of the organic carbon cycle.

2. **Methane (CH₄):** Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills.

3. **Nitrous oxide (N₂O):** Nitrous oxide is emitted during agricultural and industrial activities, combustion of fossil fuels and solid waste, as well as during treatment of wastewater.
4. **Fluorinated gases**: Fluorinated gases: Hydrofluorocarbons HCFC, perfluorocarbons PFCs, sulfur hexafluoride SF6, and nitrogen trifluoride are synthetic, effective greenhouse gases that are emitted from loads of commercial processes. Fluorinated gases F-fuel is on occasion used as substitutes for stratospheric ozone-depleting substances (e.g., chlorofluorocarbons, hydrochlorofluorocarbons). These gases are usually emitted in smaller quantities, however, due to the fact they’re amazing greenhouse gases, they’re on occasion called High Global Warming Potential gases (High GWP gases)” (EPA, 2009)³

3. Cooling methods

For a better understanding of the possible uses of cooling systems, a general overview of the types of these systems is necessary. There are two types of cooling methods, namely active and passive cooling system. The two types will be briefly elaborated on in the following section.

3.1. Active cooling

Active cooling system is generally used when a high and individually adjustable cooling capacity is required. The functional principle of the heat pump is the absorption of heat from outside and the transfer of the heat to the building is reversed. The building, therefore, functions like a fridge. The heat pump must be equipped with a reversible or reversible cooling circuit. The original evaporator becomes the condenser, and the

![Figure 3: Greenhouse Gas Emission (EPA, 2009)³](image)
condenser becomes the evaporator. When the temperatures are higher, the heat pump absorbs excess room heat and cools it down using the compressor. If an additional heat exchanger is installed, the resulting waste heat can be used efficiently, for example, to heat drinking or service water.

3.2. Passive cooling

Passive cooling system refers to the technology or strategies which might be used to chill the constructing interior with or without minimum electricity usage. In addition, the heat pump is not used, rather, the cooling machine is in operation, which lowers electricity costs. Thus, only the circulation pumps in the source and heating circuit works.

Buildings may be cooled passively at the same time as the usage of numerous natural warmth sinks, like ambient air, higher atmosphere, below surface soil, etc. Passive cooling is not quite as effective as active cooling. On the other hand, it is advantageous because of the lower investment costs and more energy-efficient operation, that is almost free of climate-damaging CO₂ emissions.

The traditional cooling system consumes a large quantity of energy due to three main reasons:

   Traditional vapor compression system needs to work all year-round, even at night or in winter when the temperature is low.

2. Large energy consumption in the piping system. A lot of energy is used by pumps and fans to transport cold water or air. Meanwhile, long-distance transportation results in a loss of cold source.

3. Mixing of cold and hot air streams. Entrainment of the hot air into the cold aisles is widely seen due to the lack of airflow control devices”. (H. Zhang, et al., July 2014 pp. 171-182) (J. Rambo, 2006 pp. 923-945)
The efficiency of the cooling system for the second and third aspect presented above, can be improved by using control methods proposed by scholars, that include utilizing frequency conversion fans, ceiling coolers, optimizing the structure of perforated tiles, the relative position of racks, and the mode of supply and return air. Moreover, the solution for the primary aspect is the use of free cooling technology.

Furthermore, passive cooling techniques are classified according to the natural source from where the cooling energy is derived. The classification of the passive cooling techniques is presented and explained in the figure below.

![Classification of passive cooling techniques for building applications. (Givoni, 1994)](image)

Passive cooling benefits from the fact that the temperature in the ground is around 10 to 14°C all year round at a depth of 15 meters. In Summer, the ground creates one cold storage and one heat source in Winter. The heat supply in Summer can increase the temperature of the ground. This reduces the cooling effect, but it does in turn make, the subsequent heating with the heat pump more effective in Winter. In addition, a combination of active and passive cooling is also possible: For example, it is advisable to first use energy-saving passive cooling when there is less cooling demand and when it is larger switch heat to active cooling.
3.2.1 Evaporative cooling

“Evaporative cooling is the technology for the cooling of air by the evaporation of water. When water evaporates, it absorbs heat from the surrounding air and consequently, the air is cooled. After water evaporates, it enters the air as water vapor and transmits the heat absorbed during evaporation back to the air in the form of latent heat. Therefore, the air is humidified, and the total heat, or enthalpy, of the air, hardly changes. The humidified and cooled air is used in the building for cooling purposes and the process is known as direct evaporative cooling which is most suitable in dry and hot climates. In indirect evaporative cooling of the air, adding moisture to the air is avoided by separating water and air, which makes it more attractive in humid climates.” (Y.M. Xuan, et al., 2012 pp. 3535-3546), (A. Waqas, 2013 pp. 607-625), (R. Velraj, 2012), (R. R. Kolhekar, 2020)

3.2.2 Soil cooling

Hot ambient air can be cooled down by installing a heat exchanger that is buried 2–3 meters below the earth surface, which causes air circulation (S. Guevara, 2011). The earth’s surface holds a stable temperature at a depth of approximately 2–3 m, which is below the average ambient temperature. “Soil cooling implemented in desert climate may reduce the peak indoor temperature by 3 °C during hottest Summer months”. (A. Waqas, 2013 pp. 607-625)

3.2.3 Ventilation cooling

Ventilation techniques can be used to improve the enjoyment conditions of buildings. One of these techniques is to provide the physiological cooling effect for the building occupants by introducing sparkling cool ambient air in the construction at better air velocity. “The physiological cooling effect is provided by opening the windows, or doors, through cross ventilation, or by electric fans” (A. Waqas, 2013 pp. 607-625) to let the ambient air in, thus providing a higher indoor airspeed and having tenants feel
the decrease in temperature. Physiological cooling is normally used when the ambient temperature is lower than the indoor temperature.

4. Free cooling

Free cooling is an effective way to decrease the energy consumption of compressor-based cooling, which is commonly known as the economizer cycle. It captures and preserves the cold air in the heat source at night, and it absorbs heat during the day when building temperatures are high.

In free cooling, a storage medium is used to accumulate the cold air when ambient temperature is lower than room temperature, and the stored cold air is extracted from the storage medium whenever it is needed, by using an electric fan. The storage medium for free cooling is normally in the form of sensible and latent energy type.

“When the outdoor temperature is sufficiently below the data center temperature, the heat will naturally flow to the outside without the need for the “temperature boost” provided by the compressor and the vapor-compression refrigeration system, so its function is unnecessary. Therefore, under favorable conditions, the compressor can be bypassed, which can save energy significantly” (H. Zhang, et al., 2014 pp. 171-182). When the compressor is bypassed, economizers are used to exploit natural cold sources. Two categories of economizers are currently in use, i.e., the waterside economizer and airside economizer.

The main difference between free cooling and nocturnal ventilative cooling is that in nocturnal ventilative cooling, the building structure (like walls) acts as “the storage medium while in free cooling technique, a separate thermal storage unit is used for the storage of the cold” (A. Waqas, 2013 pp. 607-625) and a mechanical device, such as a fan, is used to store and extract the cold from the storage unit. The vantage point of free cooling over nocturnal ventilative one, is that the accumulated cold can be extracted whenever it is needed by circulating ambient or room air through the storage unit.
There are three categories of free cooling system, and they will be elaborated on in the following sections.

**4.1 Airside free cooling**

“Airside free cooling systems make use of outside air for cooling” (H. Zhang, et al., July 2014 pp. 171-182)\(^d\). In this system, sensors are used for monitoring outside and inside air conditions and temperatures. When the outdoor temperature is fitting, the airside economizers draw the air from outside directly inside or utilize the outside air cooler indirectly with air-to-air heat exchangers. Airside free cooling is a technology with wide application prospect.

![Schematic diagram of direct airside free cooling](J Niemann, 2011 p. 132)

**4.2. Heat pipe free cooling**

Heat pipe heat exchanger (including thermosyphon) has superior temperature control features and the ability to transfer heat at small temperature differences without external energy, which is suitable for utilizing natural coldness sources.
4.3. Waterside (groundwater) free cooling

Free cooling involves natural groundwater basins allowing for the free cooling process to be introduced without compromising the internal environment. The groundwater has a constant temperature generally related to the site annual temperature and transfers the cold from the groundwater loop to the user through a heat exchanger.

There are no standards and recommendations for water quality for operating a groundwater cooling system. Water is pumped through waterside via a piping system (loop), while the chiller running in cooling mode rejects heat to the loop. In addition, to save energy, the heat may be removed from one zone and added to another.
Heat Pumps vs. Air Conditioners

“When looking for an HVAC system to cool your home, either a heat pump or air conditioner will do the job. Both systems use compressed refrigerants to collect heat from inside your home as air passes over the coil in the air handler and transfer it outside. Heat pumps and air conditioners essentially move heat from inside your home to an outdoor location. The heat pumps and air conditioners are essentially the same when operating in cooling mode, with no significant difference in operation, efficiency, or energy costs. While essentially identical in cooling mode, the heating mode is a completely different story. Air conditioners do not provide heating, but heat pumps do. “A heat pump can heat and cool, but an air conditioner cannot, which is the primary difference between the two HVAC systems” (Energy, 2012). An air conditioner is typically paired with a furnace to provide heat during the cold months. “Together, an air conditioner and furnace are a complete heating and cooling system” (Viñolo, 2020).

In addition, a heat pump can heat a home, when outside temperatures drop below freezing. Typical heat pump systems have an auxiliary electric heater added to the indoor unit to add supplemental heat when outdoor temperatures drop. The energy-efficient heat pump systems provide heating using only electricity. In these conditions, they can be less costly to operate compared to systems that use more expensive heating fuel sources such as natural gas, oil, or propane. If temperatures drop below freezing, the heat pump requires more energy to maintain comfort inside,
reducing efficiency and increasing the electricity required. *We can solve this problem by creating a Hybrid Heat system.*

*In cooling mode, both heat pumps and air conditioners come in models with high SEER ratings, providing energy-efficient cooling during the warm summer months, the higher the SEER, the more efficient the unit. In heating mode, heat pump efficiency is expressed in COP. The higher the COP, the higher the efficiency. In areas with moderate temperatures, a heat pump is a better option for efficient heating than air conditioners*. (Carrier, 2021)

5. **Types of Air Conditioning system**

In ventilation systems, where the outdoor air that is drawn in is only heated, air conditioning systems fulfil four thermodynamic functions, namely heating, cooling, humidifying, and dehumidifying. They keep the temperature, the humidity, and the purity of the air at specified values all year round. If one of the functions is missing, it is a partial air conditioning system. Depending on the mode of operation and installation location, air conditioning systems can be installed in:

1. Central systems
2. Decentralized systems
3. Types of ventilation function in:
   a) Air-only systems
   b) Air-water systems
   c) Air-refrigerant systems
   d) Water-only systems

Furthermore, there are two types of cycle chillers:

1. Chillers with electric compressors
2. Chillers with thermal compressors (absorption chillers)
5.1. Central air conditioning

Central air conditioning system carries out all the necessary air conditioning in a central supply air device and in a central exhaust air device. Air ducts are distributed from the control center to the individual rooms, which is often the case with hotels or large modern public buildings. Moreover, if a larger cooling capacity is required (from approx. 50 kW), central systems with cold water generators, which use R407C and R410A as refrigerants, are utilized. Turbo chillers are also used when the cooling capacity is 250 kilowatts or higher, and have R134a as a refrigerant.

5.2. Decentralized air conditioning

Decentralized air conditioning systems carry out the air treatment, conveying, filtering, and controlling temperature directly in the room. Examples of decentralized air conditioning units are split systems, door air curtains, façade fans, and fan coil units. Furthermore, decentralized air conditioning systems, although similar in structure, cannot be equated with room’s air conditioning units.
5.3 Types of ventilation function

5.3.1. Air-only systems

In air-only systems, the air is processed exclusively with the fresh air supplied. This process takes place in central devices that are built into a ventilation center, and depends on the air-only systems, especially in larger rooms such as halls, theatres, or meeting places. Depending on the type of volume flow, a distinction is made between single-channel systems with variable (VVS) and constant (KVS) volume flow. Two-channel systems can also be found in the building stock.

Figure 9: Fan coil unit (left) and door air curtain device (right) (Sabiatech)

Figure 10: Air-only system, single-channel system Source: VDI Lexicon
In single-channel KVS systems, a central device feeds the conditioned air to one or more rooms via the air duct, keeping the volume flow at a constant. Moreover, same state supply air flows into all rooms. The individual regulation of the heat demand is only possible with additional radiators. Furthermore, typical applications of a single-channel KSV system are buildings with individual rooms such as theatres, cinemas, assembly rooms, or halls. In contrast, in single-channel systems with variable supply air (VAV systems), the supply air temperature for the individual rooms is constant. The different heating and cooling loads of the individual zones are compensated by a volume flow controller which changes the supply air. Additionally, VAV systems are used in offices or laboratories.

5.3.2. Air-water systems

The air conditioning of an air-water system does not only take place in the air conditioning center. Rather, the basic preparation of the outside air, and where it takes place, depends on the outside temperature (primary air). An additional water system (two, three, or four-pipe system) supplies the local heat exchangers with hot/cold water. Moreover, induction devices and fan coil systems (fan convectors) are mainly used.

Induction systems

The central air conditioning unit prepares the so-called primary air. It corresponds to the minimum outside air rate and is constant over the entire year. The primary air flows to the individual induction devices in the rooms. From the rooms, it flows out of nozzles into the room at high speed, tearing them in the processed secondary air with induction. Compared to air-only systems, the air volume flow is reduced to 25 to 30% much faster. Moreover, induction systems are mainly used as high-speed systems (high-pressure induction systems). Induction devices are available for installation in parapets, floors, and ceilings.
Fan coil systems (fan convectors): Fan convectors are functionally comparable to induction devices; the difference is in the drive. Instead of nozzles, the air is blown into the room by a radial fan. Convectors are for the Ceiling and parapet set up available. Typical air intake /Air outlet temperatures are 23 °C / 15 °C.

5.3.3. Air-refrigerant systems

The decentralized air-refrigerant system is a combination of a KVS and a split system, and consists of an inner part (evaporator) which extracts the heat from the room, and an outer part (Condenser) which releases heat into the environment. Because of the use of a split system, the air can only be cooled and dehumidified in one room or
heated in heat pump mode, whereas the outside air is supplied by a KVS system. The HFC blends R407C and R410A are predominantly used.

**VRF systems**: VRF (Variable Refrigerant Flow) multi-split systems are further developed split systems. They are the air conditioning system that takes up the least amount of space. With them, an external unit supplies several split units with air outlets in many rooms.

The most common are air/air refrigeration systems with electric heat pumps, but there are also systems with an integrated gas heat pump. They are installed as two- and three-wire systems. With an external unit, all rooms can only be cooled or only heated. The three-line systems have an additional refrigerant line and switchover unit, where an outdoor unit can be used to variably heat or cool different rooms. An internal "heat shift" is possible. In addition, a part of the connected decentralized indoor units can be used for heating, and another part can simultaneously be used for cooling. The external unit links the energy flows, which enables high efficiency of air conditioning.
For security reasons, the use of hydrocarbons in multi-split or VRF systems, in which a connection between refrigerant-carrying components and rooms where people are staying (apartments, offices), apart from the larger filling quantities. VRF systems are also available with refrigerant carbon dioxide (R744), that, however, have significantly lower COPs than the HFC standard variants.

5.3.4. Water-only systems

Water-only systems, additionally referred to as silent cooling systems, no longer have an air change function. These include cooling ceilings, sails, and convectors as well as concrete core activation. Separate ventilation devices may be used to cover a hygienic exchange of air.

Surface cooling systems: cooling ceilings and cooling sails dissipate high cooling loads. They offer a great deal of design freedom and more comfort because of low drafts and flow noises. Unlike conventional ventilation, only small temperature differences arise, which increases the thermal comfort in a room. Surface cooling systems work as follows: for cooling purposes, cool water (usually 16 ° C) flows through a pipe network and cools the room air. The cooling ceiling should be combined with a dehumidification system for an optimal indoor climate. Moreover, cooling ceilings are connected to the heating or cooling water systems for media supply.
Depending on where they are used, surface cooling systems are divided into ceiling, wall, and floor cooling systems. Closed ceiling cooling surfaces can perform from 80 to 100 W/m². Systems in the form of metal panels and coffered ceilings with pressed pipe coils and thermal insulation are used. The open ceiling cooling surfaces (100 to 130 W/m²) include cooling plates and cooling sails, where parts of the ceiling surface are suspended for cooling sails. For plastered cooling ceilings, capillary tube mats are inserted into the ceiling plaster and plastered over. In addition, a form used is specially developed sandwich panels with foamed-in Capillary tube mats. They combine the cooling ceiling with a PCM latent heat storage system and work by means of radiation and convection. Each room and each zone can be air-conditioned separately via a temperature controller and have a dew point monitor to prevent condensation.

**Component activation:** “Thermal component activation or concrete core activation describes cooling systems (also heating systems) that use the building mass for temperature control. During component activation, meander-shaped pipe systems, mostly made of plastic, laid in concrete floors. The cooling medium is water” (Glück, 1999). During the day, heat loads are stored in the concrete, and at night, the concrete releases its heat back into the cooling water. Thermal component activation is suitable for the cooling mode with heat pumps.

Apart from the systems already elaborated on, there are additional ones, which are discussed in the following part. These are mobile room air conditioners, which, if not installed in a fixed location because of their compact design, they have smaller refrigerant fill quantities and less tendency to leak. However, this type of devices cools rooms. They are far less effective than split air conditioning units, as the heat extracted from the room is transported outside using a hose, by means of an air stream. This leads to negative pressure, creating warm air flows into the room coming from the outside. If the exhaust air hose is not routed through a hole in the wall, but through an open window, the cooling effect is very low. The room temperature is then only a few degrees lower than the outside temperature.
6. Types of the refrigeration system (Direct use of solar thermal heat, absorption)

Unfortunately, the majority of the population is unaware of the fact that heating buildings consume extra energy than that used for electricity or transportation, thus growing “the use of solar thermal energy is not only important but timely as our demand for energy continues to steadily grow” (SHC, 2020).

Solar thermal energy is suitable for both heating and cooling. “Key applications for solar technologies are those that require low-temperature heat, such as domestic hot water heating, space heating, pool heating, drying processes, and certain industrial processes” (M. Treberspurg, 2011). Solar applications also can meet cooling needs, where the supply (sunny summer days) and the demand (desire for a cool indoor environment) are well-matched” (SHC, 2020).

6.1. Solar heating & cooling

Solar heating utilizes daylight to warm up water or air in buildings. “There are two types of solar heating, passive and active. A building roof with flat-plate collectors that capture solar energy to heat air or water. Passive heating relies on architectural design to heat buildings” (Encyclopaedia, 2018). “The Summer sun, which heats up offices, also delivers the energy to cool them. The thermal use of solar energy offers itself” (G. Med El-Amine, 2013). “Days that have the greatest need for cooling are also the very same days that offer the maximum possible solar energy gain” (TechDev, 2021).

“The demand for air conditioning in offices, hotels, laboratories or public buildings such as museums is considerable” (G. Med El-Amine, 2013). This is not only the case in Southern, but also in Middle Europe.

“Under adequate conditions, solar and solar cooling systems can be reasonable alternatives to conventional air conditioning systems. Such systems have advantages over those that use problematic coolants (CFCs), not to mention the incidental CO₂ emissions that are taking on increasingly critical values” (V.K. Sharma, et al., 2010).
6.2. Solar Air conditioning

“Should buildings be cooled with the help of solar energy, then water-assisted air conditioning systems or ventilation systems can be powered with heat that is made available by solar collectors” (S.S. Verma, 2015). The sun can, at least seasonally, at middle to higher latitudes, provide a substantial part of the energy needed for air conditioning. Moreover, a combination of water-assisted structures and airflow structures is also a possibility. “The basic principle behind (solar) thermal driven cooling is the thermo-chemical process of sorption: a liquid or gaseous substance is either attached to a solid, porous material (adsorption) or is taken in by a liquid or solid material (absorption)” (Hug, 2009).

“The sorbent (i.e., silica gel, a substance with a large inner surface area) is provided with heat (i.e., from a solar heater) and is dehumidified. After this “drying”, or desorption, the process can be repeated in the opposite direction. When providing water vapor or steam, it is stored in the porous storage medium (adsorption) and simultaneously heat is released. Processes are differentiated between closed refrigerant circulation systems (for producing cold water) and open systems according to the way in which the process is carried out: that is, whether or not the refrigerant comes into contact with the atmosphere. The latter is used for dehumidification and evaporative cooling. Both processes can further be classified according to either liquid or solid sorbents” (Hug, 2009).
7. Types of Refrigeration Cycles

There are various kinds of refrigeration cycles, however, the two most relevant ones i.e., the adsorption refrigeration and vapor refrigeration machines, are discussed in the sections below.

7.1. Adsorption refrigeration machines

“Closed absorption refrigeration machines with liquid sorbent (water-lithium bromide) are most often operated in combination with heat and power generation (cogeneration) (i.e. with block unit heating power plants, district heating), but can also be assisted by vacuum tube solar collectors (These systems work with lower hot water temperatures from approx. 60 - 80 °C)” (Hug, 2009), which is easier for solar heat generation flat plate collectors and is, thus, beneficial. The refrigerating machine is composed of two adsorbers, an evaporator and a condenser. The refrigeration process does not take place continuously. Moreover, the refrigerant is enclosed in a solid material and must, therefore, be cycled between adsorption and desorption. The circuit can be changed by switching of the heating and cooling.

“An adsorber chamber takes up the water vapor, which is transformed into the gas phase under low pressure and low temperatures (about 9°C) within the evaporator. Granulated silicate gel, well known as an environmentally friendly drying agent, then accumulates it (adsorbs the water vapor). In the other sorption chamber the water vapor is set free again (the chamber is regenerated or "charged") by the hot water from the solar collector (about 85°C). The pressure increases and at the temperature of the surroundings (30°C) the water vapor can be transformed once again into a fluid within a cooling tower (condensed)” (Hug, 2009). Through a butterfly valve the water is led back into the evaporator and the cycle begins anew.
2. Vapor refrigeration machine

Refrigerating machines such as heat pumps are based on a thermodynamic cycle. A simple refrigeration machine consists of four components, namely, a compressor, a condenser, an expansion valve, and an evaporator. They are connected in a circuit which is filled up with a fluid called refrigerant. In the case of a refrigeration machine - in contrast to the heat pump - the heat $Q$ (add) supplied to the refrigeration machine is viewed as a benefit, because the evaporator acts as a heat exchanger in which heat
is transferred from the heat source to the refrigerant. This causes the refrigerant to evaporate, because the heat supplied to the refrigeration machine is extracted from the room and cooled. After evaporation, the refrigerant is drawn into the compressor for compression, which causes an increase in pressure and temperature of the refrigerant, thus making it possible for the refrigerant to reject heat back to the secondary circuit in the condenser at a higher temperature. The heat $Q$ (reject) dissipated from the refrigeration machine can, except in domestic water systems, usually no longer be used and must be re-cooled (air or water). The heat transfer from the refrigerant to the condenser, causes the refrigerant to cool down and condense, after which it enters the expansion valve. Then, the refrigerant expands in expansion valve, which causes a reduction in pressure and temperature. When the refrigerant enters the evaporator again, the decrease in temperature allows the refrigerant to extract heat from the heat source again, completing the cycle.

![Diagram of a single-stage electric chiller](ARANER, 2021)

**Overview of Hybrid cooling systems and groundwater source**

Ground source cool/heat systems (GSHP,) additionally called geothermal heat pump (GHP) systems, are an energy-efficient alternative for heating and cooling of residential, commercial, and institutional applications. The moderate and constant earth temperatures used by the GSHP system as a heat sink/source are more...
advantageous than the outdoor air used by air-source heat pump systems. Furthermore, the system usually consists of a ground loop heat exchanger (GLHE), through which water or an antifreeze solution circulates, and one or more water-source heat pumps. The advantages of using a GSHP system are higher energy efficiency in comparison to conventional systems, lower CO₂ emissions, and lower maintenance costs. Although the system is beneficial, GSHP system market penetration has been limited because of its high initial costs.

Water loop heat pump systems (WLHP) are heating and cooling structures that can be used in residential and institutional applications to provide space heating and cooling for multiple zones. Typically, a heat pump is placed in each building zone to meet its heating and cooling demands, and the water is pumped through each heat pump via a piping system (loop). Moreover, heat pumps running in heating mode remove heat from the loop, while heat pumps running in cooling mode reject heat to the loop. The water is maintained at desired temperatures with the assistance of a heat rejecter, e.g., cooling tower or fluid cooler, and a heat source, such as a heat exchanger. When the system is running with some heat pumps for heating and others for cooling, heat that may be removed from one zone can be added to another, thus saving energy. Figure 20 shows a typical WLHP system with a water-to-water heat exchanger. The experts put much emphasis on energy conservation and lower initial cost, which is why WLHP systems have become increasingly popular.
Types of Cooling Towers

“Cooling towers come in a variety of shapes and configurations. A “direct” tower is one in which the fluid being cooled is in direct contact with the air. This is also known as an “open” tower. An “indirect” tower is one in which the fluid being cooled is contained within a heat exchanger or coil and the evaporating water cascades over the outside of the tubes. This is also known as a closed-circuit fluid cooler.

The tower airflow can be driven by a fan (mechanical draft) or can be induced by a high-pressure water spray. The mechanical draft units can blow the air through the tower (forced draft) or can pull the air through the tower (induced draft). The water invariably flows vertically from the top down, but the air can be moved horizontally through the water (crossflow) or can be drawn vertically upward against the flow (counterflow)” (K. Peterson, 2018).

The most common types of cooling towers encountered in the HVAC chilled water plant are:

- Spray towers
- Forced draft cooling towers

Figure 20: Schematic of a WLHP system with water-to-water (Z. Tu, et al., 2020)
• Induced draft cooling towers

When designing energy-efficient central chilled water plants, it is critical to select the right condenser water system. The efficiency of the chillers is affected, not only by the operation of the cooling towers and associated pumps, but also by the temperature and quality of the condenser water.

Piping Heat Recovery Options

Heat rejected from chillers may be utilized in several ways, inclusive preheating domestic hot water and heating buildings, with the usage of double-package bundle heat recovery chillers. In the case of preheating domestic hot water, the condenser water is routed via a double-wall warmness exchanger that is either an indispensable part of a storage tank or is remotely positioned with a stream pump to the storage tank.

8. Modelling of groundwater refrigerant system (Chiller) (The Case Study: The Smart Energy Building)

The groundwater systems (Free cooling) need a complementary framework, interpretation of interaction, feedback, and adaptable and dynamic control interpretations. These are the key elements for an optimal and sustainable use of the subsurface. Using free cooling and low-temperature floor, with a temperature change of a few Kelvin between two wells, is sufficient to efficiently cool. The buildings can be efficiently cooled in the Summer using groundwater from the cold well. Overall, a groundwater system requires less primary energy use for heating and cooling of buildings. If the cooling is carried out by the well, it is called free cooling. The heated groundwater is then returned to the groundwater source via two injection wells. The paper examines the cooling case in summer. The supply cold takes place, on the one hand with groundwater via a suction well with a planned discharge capacity of 66 m3/h (18.33 litres/s), and on the other hand, if the cooling capacity of the groundwater during summertime is not sufficient, it is possible to use a cooling machine (chiller) to achieve the cooling demand.
The cooling coil temperatures for floor cooling of rooms, and fan coils for flow and return are designed for 16°C/22°C. Therefore, the groundwater is prioritised since it is available free of charge. In addition, a separating heat exchanger must be connected between the groundwater circuit and the cooling circuit to avoid contamination of the internal circuit.
The heat dissipation of the refrigeration machine by condenser takes place on the roof of a building, using an air/water heat exchanger and a heat exchanger connected in series with a groundwater source. The heat exchanger (evaporator and condenser) is tested and stamped for a maximum operating pressure $P$ of 3200 kPa on the refrigerant side and 1000 kPa on the waterside. “This cooler with groundwater is bypassed with 100% free cooling” (N. Lal. Shrestha, et al.). In designing energy-efficient central chilled water plants, it is extremely important to select the proper condenser system. Moreover, the efficiency of the chillers is affected not only by the operation of the cooling towers and associated pumps, but also by the temperature and the quality of the condenser.

Figure 24: Separation heat exchanger (Dwyer, February 2017)
9. Thermal Comfort Basics

Thermal comfort depends on certain influencing factors, e.g., a room climate that is conducive to health exists when the heat of the human body is balanced (heat emission = heat generation). Thus, the body’s own heat production depends on the degree of workload (level of activity). The factors that are decisive for heat emission
are air temperature, room enclosing surface temperature, air speed, air humidity, and clothing. In general, people respond to this rapidly, adapt to thermal stimuli (adaptation) and adjust to the thermal environmental conditions in the long term (acclimatization). However, based to the multitude of factors mentioned above, it becomes clear that comfort is perceived differently from one individual to the next and that there cannot be an optimal room climate. Therefore, it can only be spoken of a comfort zone in which some people are satisfied with the indoor climate. Are several influencing factors such as air temperature and humidity considered simultaneously with their specific comfort zones, comfort fields result?

Recommendations for the relative humidity are between 35% and 65% with indoor air temperatures between 18°C and 23°C.

10. Cooling with dehumidification

Humidification and dehumidification are vital processes in air conditioning and refrigeration for controlling the air moisture supplied to space. The dehumidification process in which the air is cooled sensibly, and at the same time from which moisture is removed, is called cooling. The cooling and dehumidification process is obtained
when the air at the given dry bulb (DB) and dew point (DP) temperature is cooled below the dew point temperature.

“When the air comes in touch with the cooling coil this is maintained on the temperature beneath its dew point temperature, its DB temperature begins reducing. The process of cooling continues and at some point, it reaches the value of the dew point temperature of the air. At this point, the water vapor within the air starts getting converted into the dew particles due to which the dew is formed on the surface of the cooling and the moisture content of the air reduces thereby reducing its humidity level” (Engineering, 2009). Thus, at the same time as the air is being cooled underneath its dew point temperature, there is cooling in addition to dehumidification of air.

![Figure 27: cooling and dehumidification (Withouse, 2018)](image)

The temperature of the cooling medium must be observed when cooling. If the temperature of the cooling medium is too high, such as the case with groundwater or bank filtrates as shown in figure 28, at point 3 the dry bulb temperature is 32°C and it reduces to 25°C (saturation curve). It continues cooling down to point 4, reaching the necessary degree of dehumidification. However, it is still too high to be able to achieve the comfort zone. This process is called cooling and dehumidification. The result between points 4 and 5 is not satisfactory, it is too humid, and the room climate is called. This type of cooling is called passive cooling or free cooling.
However, the cooling medium temperature can be cooled down to approx. 10 °C (see point 6) by means of cooling machines, with a subsequent warming up (point 7) to move the system into the comfort zone. This type of cooling is called active cooling.

11. Floor cooling

Surface cooling (underfloor cooling) is a type of heat exchange between people and large cooling surfaces mainly through radiation, whose goal is to create pleasant room climate even in hot temperatures. In contrast to air conditioning, it cools the surface quietly and without air turbulence. However, it is only sufficient for low cooling loads. The cooling load calculation is closely related to the heating load calculation, but presents some different approaches. In summer, for example, at 35°C in the shade, the indoor space is usually not cooled down to 20°C. The desired temperature is usually somewhere between 25-26°C. Independence of the rooms to be cooled then in turn result in the heat flows on the walls and windows to the outside, whereby the temperature differences are much smaller than in winter. To cool down a room, a limit (namely the dew point) must be observed.
This dew point must not fall below the acceptable temperature, otherwise, the resulting condensate would need to be drained off. Moreover, the smaller the difference between the coolant and the room temperature, the greater the cooling energy must be supplied this area. This cooling surface must then be large and spread over the entire floor to avoid the inevitably small temperature difference and to achieve a cooling effect in the room. Regarding the dew point, it should be noted that with a room air temperature of 25°C and relative humidity of 60%, the dew point temperature is 16.8 °C. With the increase of humidity, the dew point also increases (see t-x diagram for moist air). If the cooled floor was to fall below the dew point temperature, the result would be a wet floor that would create the basis for dust mites and mold growth, both in- and outdoors.

The desired cooling performance can only be achieved if both the surface temperature and the design flow temperature are above the dew point temperature of the ambient air. To avoid condensation on the system components, a dew point-controller to manage the flow temperature must be provided.
12. The refrigeration system (Chiller Case Study)

The Carrier 30 RW chiller unit is chosen to conduct this study and the calculation of the cooling load is carried out according to appropriate standards such as VDI 2078, ÖNORM H 6040, ÖNORM EN 15243, and others. The 30 RW units have been specially designed to optimize systems operation using dry coolers as a heat rejection system. Because of the use of the variable-speed condenser water pump integrated into the 30 RW and the complexity of traditional systems, a three-way valve has been eliminated. The 30 RW unit is designed to be installed undercover at outside temperatures between +5°C and +40°C. Therefore, they no longer encompass anti-freeze protection as standard, based on a maximum outside temperature of 35°C. Moreover, practice in recent years has shown that the maximum outside temperatures are often exceeded and that temperatures between 35-40°C occur frequently in summer because of global warming. Since the air/water heat exchanger of the chillers are installed on the roof in a freely exposed position, where temperatures exceed 40°C by far on hot days, they are also unprotected from solar radiation. A typical picture in practice is the under-dimensioning of the dry cooler, which either leads to a reduction in the performance of the refrigeration machine or to a load shedding. As the operating range of the Carrier 30 RW chiller shows, the design point according to the system diagram is just outside the operating range at a design temperature of 35°C.
5.2 - Operating range 30RW

- Evaporator - water outlet temperature: 16 °C
- Condenser – water outlet temperature: 50 °C

A Carrier type 30 RW 210 refrigeration machine with a nominal cooling capacity of 216 kWc is installed.

“Standard EUROVENT conditions: evaporator entering/leaving water temperature = 12°C/ 7°C, condenser entering/leaving water temperature = 30°C/35°C”.

(Carrier, 2003)

The refrigeration cycle

To visualize the changes of the refrigerant it is useful to use a PH- chart. In Figure 31, the cycle of Chiller Carrier 30RW210 is presented in the PH-chart.
“When operating the unit at full load for a while, use a saturated condensing temperature between 45 and 50°C. Under these conditions, the apparent subcooling which is equal to the saturated condensing temperature (1 - on the saturated dew point curve) minus the liquid refrigerant temperature (3) ahead of the expansion device must be between 12 and 14°C. This corresponds to an actual subcooling temperature of between 6 and 8 K at the condenser outlet, depending on the unit type” (Carrier, 2003).b

Actual subcooling is equal to the saturated liquid temperature (2 - on the saturated bubble point curve) minus the liquid refrigerant temperature (3) ahead of the expansion device. The pressure tap supplied on the liquid piping is used to charge the refrigerant and to calculate the pressure of the liquid refrigerant.

Legend
1 Saturated condensing temperature at the dew point
2 Saturated liquid temperature at the bubble point
3 Liquid refrigerant temperature
4 Saturation curve at the dew point
5 Saturation curve at the bubble point
6 Isotherms
7 Apparent subcooling (1 - 3)
8 Real subcooling (2 - 3)
   L, V, L + V Liquid + vapor
13. Components of the refrigeration cycle

13.1. The evaporator

“Two types of evaporators are used in water chillers- the flooded shell and tube and the direct expansion evaporators, both types are shell and tube, heat exchangers. While water is the most common fluid-cooled in the evaporator, other fluids are also used. These include a variety of antifreeze solutions, the most common of which are mixtures of ethylene glycol or propylene glycol and water. The use of antifreeze solutions significantly affects the performance of the evaporator but may be needed for low-temperature applications” (Roy, 2015). The fluid creates exclusive heat transfer traits inside the tubes and has exclusive pressure drop characteristics. The overall performance of the machine is typically derated, as the usage of fluids apart from water. In the first part, the refrigerant is within the two-phase region and in the latter part, the refrigerant becomes completely vaporized by super-heating. In an ideal case, the pressure remains constant over the evaporator, but in reality there is a pressure drop on the part of the evaporator. Moreover, the primary reason why the refrigerant is super-heated is to make sure that the refrigerant is completely vaporized when it enters the compressor to prevent small amounts of liquid particles from entering the compressor, and possibly causing damage. The capacity of the evaporator is called the cooling capacity since it removes heat from the heat source and thus cools the heat source.
The value of enthalpy and pressure can be extracted from Figure 32: PH diagram:

\[
\begin{align*}
\text{Evaporation} & \quad \text{Compression} \\
\text{Verdampfer} & \quad \text{Verdichter}
\end{align*}
\]

The cooling capacity \((Q_c)\) can be calculated by multiplying the mass flow rate by the difference in enthalpy over the evaporator.

\[
Q_{\text{evap.}} = (h_1 - h_4) \quad \ldots \ldots (1)
\]

\((Q_{\text{evap.}})\) – the cooling capacity \([\text{kW}]\)

\((\Delta h)\) – the change in enthalpy \([\text{KJ/Kg}]\)

13.2. The compressor

There are four basic types of compressors used in packaged water chillers:

1. Reciprocating
2. Rotary
3. Centrifugal
4. Scroll
The type of compressor chosen for this unit is the hermetic scroll compressor. Thus, the only refrigerant permitted for these compressors is R-407C. The reciprocating and scroll compressors are widely used in tonnage ranges chillers, where the compressor design is usually a hermetic compressor. Scroll compressors have largely taken over this market. Capacity modulation is achieved through the staging of multiple compressors that are grouped (piped in parallel) in several circuits, which creates fewer redundancies in case of a compressor fail. In addition, as positive displacement machines, they retain near full cooling capacity, and are, therefore, highly suitable for air-cooled applications, and to be used as heat recovery machines. “Control is achieved by stepping unloaders and cycling compressors on/off, which creates a choppy part-load performance curve” (energydesign, 2009)d. Scroll chillers tend to be low first-cost machines. Inside the compressor, the refrigerant vapor is compressed from the evaporation pressure to condensation pressure. “Scroll compressors are unidirectional, and refrigerant compression is only ensured when the phase order is followed” (Carrier, 2017)d. The power input to the refrigerant is calculated with the enthalpy change over the compressor.

\[ w_{comp.} = (h2 - h1) \] ..........(2)

\( w_{comp} \) – the work done to drive the compressor [kJ/kg]
\( (\Delta h) \) – the change in enthalpy [KJ/Kg]

13.3. The condenser

“There are a number of different kinds of condensers manufactured for the packaged water chiller. These include water-cooled, air-cooled, and evaporative-cooled condensers” (Roy, 2015)b.

Inside the condenser, the refrigerant condenses when the heat rejects during the heat transfer. Consequently, the enthalpy of the refrigerant decreases. In most heat pump applications, the refrigerant is being subcooled. The heating reject (Qcond) of the chiller can be calculated using the formula presented below:

\[ Q_{cond} = m * (h3 - h2) \] ..........(3)
(Qcond) – the heat rejected by the condenser [kJ/kg]
(Δh) – the change in enthalpy [KJ/Kg]

13.4. The expansion valve

The purpose of the expansion valve is to reduce the pressure and temperature of the refrigerant to achieve the liquid and gaseous state of the refrigerant when it enters the evaporator.

14. Performance indicators for cooling machine system

“At peak design conditions the efficiency of water chillers is rated by coefficient of performance COP or Energy Efficiency Ratio EER” (energydesign, 2009). Energy Efficiency Ratio (EER) is the ratio between the amount of power being provided by the system (output cooling energy) and the power being consumed by the compressor (electrical input energy).

\[
EER = \frac{Q_c}{W} \quad (4)
\]

(Qc) – output cooling energy over a season
(W) – input electrical energy during the same season

Moreover, the EER is calculated by using power instead of energy, meaning that it only provides an indicator for the instantaneous performance at a given moment in time. When evaluating a cooling system, it is also useful to calculate the Seasonal Energy Efficiency Ratio over a period of time, for example, a year. After performing the calculations for the vapor compression cycle, the EER is calculated at 3.21. The seasonal energy efficiency ratio is calculated using the following formula:

\[
SEER = \frac{1.12 - \sqrt{1.2544 - 0.08 \times EER}}{0.04} \quad (5)
\]
The ESEER (European Seasonal Energy Efficiency Ratio) is used to describe the energy efficiency of a refrigeration machine over one year period, which is calculated as the ratio of the accumulated useful energy (cooling) divided by the amount of accumulated consumed energy (electricity) over a certain period of time, usually on a yearly basis.

“The ESEER is calculated by combining full and part load operating Energy Efficiency Ratios (EER), for different seasonal air or water temperatures, and including for appropriate weighting factors” (JSTOR, 2011).

These values are shown in the following table:

<table>
<thead>
<tr>
<th>Partial load ratio</th>
<th>Air temperature (°C)</th>
<th>Water temperature (°C)</th>
<th>Weighting coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>35</td>
<td>30</td>
<td>3%</td>
</tr>
<tr>
<td>75</td>
<td>30</td>
<td>26</td>
<td>33%</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>22</td>
<td>41%</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>18</td>
<td>23%</td>
</tr>
</tbody>
</table>

The formula for ESEER can then be presented as follows, where a, b, c & d are the load profile weighting factors relevant to the proposed application:

\[
\text{ESEER} = a(EER@100\% \text{ load} \times 0.03) + b(EER@75\% \text{ load} \times 0.33) + c(EER@50\% \text{ load} \times 0.41) + d(EER@25\% \text{ load} \times 0.23) \quad \ldots \ldots (6)
\]

(Y. SAHEB, 2005)

15. Simulation of different variants on cooling systems

All variants were calculated based on a selected maximum cooling capacity of 275 kWc to enable a comparison of the variants. After system design, 4 variants of simulation of the cooling system were analysed and are presented in the following section.
1. **Variant**: represents the design variant according to the system scheme. A groundwater temperature of 11.5°C and one result in cooling temperatures on the secondary side (floor pipes) of 16 °C/22°C. The design point of the central, speed-controlled circulation pump is 18.33 kg/s. The groundwater requirement of approx. 14.06 kg/s (210 kWc free cooling and the rest of 65 kWc using a refrigeration machine including water cooling) would be below the consensus water volume of 18.33 kg/s (66 m3/h). The cold for free cooling could be 100% covered by groundwater according to the scheme. Moreover, a separating heat exchanger is amply designed for this process with 310 kW. No deficiencies were found in the design.

2. **Variant**: the groundwater temperature is raised to 15.5°C, and the flow temperature of the underfloor cooling rises to 20°C. In principle, the water in the pipes can only be circulated without achieving the necessary cooling capacity, which are considerably below the 20-25 W/m² according to the design. It can be seen here that the chiller cannot cover the entire refrigeration requirement of 275 kWc. However, the groundwater could be used for the condenser cooling of the chiller, that would prevent the air cooler from being overloaded at high outside temperatures. The water re-cooling would be the only useful function in the use of groundwater. If necessary, it should be checked whether the condenser pressure of the refrigeration machine can be reduced further by lowering the return to the cooler below 40°C and thus reducing the power requirement. Moreover, 45 °C saturation temperatures appear to be quite high when using groundwater.

3. **Variant**: the refrigeration machine works at full load with 216 kWc and with the heat dissipation through the water cooler with 15.5 / 19.5°C groundwater extraction and groundwater infiltration temperature. This operational case would only be approved for 4 weeks according to the notification. The simulation with the approved infiltration temperature was carried out. Unfortunately, the water/water cooler alone does not provide cooling, because the consensus water quantity is exceeded.

4. **Variant**: the refrigeration machine works at full load with 216 kWc and with the heat dissipation through the air cooler. It can be seen that at an outside temperature of 32°C, the limit of the cooler has been reached. Hence, a mixed cooling of water re-cooling and air cooling is necessary at higher outside temperatures.
16. Presentation of results

In a model of this study, the dew point is monitored and for each floor circle and room, a humidity sensor is installed. The cooling requirement of the property is 275 kWc, based on the design outside temperature of 35°C. However, since the chiller could only deliver a maximum of 216 kWc, the rest of the cooling capacity comes from free cooling. Furthermore, the groundwater temperature for cooling was assumed at 11.5°C, at which temperature, a floor pipe temperature of 16°C could be achieved and free cooling would be effective. The evaluation of the original system of groundwater design and dimensions shows there is a difference between design data and actual operating data for the well/groundwater cooling.

The groundwater temperatures are up to approx. 16.6°C. According to the authorities (Team Hydrography MA 45/ Vienna the temperature of groundwater is measured in the closest measuring point between 2016 and mid-2019), the temperature of the groundwater body, which is located about 1.7 km northwest of the requested property, is measured between 14.3°C in winter and 16.6°C in summer.

According to Municipal Department 58 / Water Law Vienna decision, the maximum groundwater withdrawal quantities are 18.5 l/s or 1,600 m³ per day or 250,000 m³/a for the operation of the water/water cooling pump. Due to the high groundwater temperature and the degree of the temperature of the heat exchanger and other temperature losses between the extraction point and floor distributor, the water temperature in the floor pipes flow is at 20-22°C. At such a high temperature, the floor cooling, where the cold transmission happens through radiation, is no longer effective and does not correspond to the agreed quality.

It was found using the design of the cooling system that the design point according to the scheme of the system is directly outside the operating range at a design temperature of 35°C. Since the chiller could only deliver a maximum of 216 kWc, if it fails in well cooling due to the high groundwater temperature, the chiller does not cover the missing capacity. Therefore, refrigeration machine is neither suitable to take over the additional, nor to cover the total cooling demand.
17. Calculation

In addition to planned operating costs, there is an added electricity demand and the increase in maintenance costs due to higher operating hours, as the chiller machine must also take over the free cooling portion. The higher electricity demand, due to the increased operation of the refrigeration machine, was calculated in a simulation calculation (difference in internal electrical demand between Variant 1 and Variant 3) and amounts to approximately 67 kWe - 20 kWe = 47 kWe. Given 800 full load hours for cooling, calculated over a technical service life of the system of 20 years and a mixed electricity price of 20 cents / kWh, additional costs of (67 kWe-20 kWe) x 800 h /a x 20 a x 0.2 EUR / kWhe are at EUR 150,400 without interest. Because of the increased use of the refrigeration machine, a rise in maintenance costs can also be assumed. The maintenance of refrigeration and air conditioning components is necessary to assure the functionality and safety of the systems, making maintenance an essential part of the operation. Furthermore, the maintenance costs of a refrigeration machine are around 2% of the investment costs per year. Assuming costs of EUR 450/kWc x 210 kWc= 94,500 EUR, maintenance costs of EUR 1,890 per year are calculated. Due to the otherwise lower operating hours, only 1/3 of the costs would be incurred per year. Thus, estimated over 20 years it results in 1,890 EUR / a x 2/3 x 20a = 25200 EUR additional costs for maintenance of the refrigeration machine without interest. The total additional costs from the title of operating costs and maintenance costs without interest thus amount to EUR 150,400 + EUR 25,200 = EUR 175,600 EUR.

The Feed-In Tarif is 0.035 (€/KWh) (Schröder, 2009), Full Load Hours of chiller 800 (h/year), Discount rate 5 (%/year), Electricity price 0.077 (€/kWhe) (Energie, 2021), and the investment horizon for the investment project has calculated 20 years.
Table 3: Financial Parameters

Financial Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling capacity</td>
<td>210 KWc</td>
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<tr>
<td>Discount rate (r)</td>
<td>5 %/year</td>
</tr>
<tr>
<td>Investment cost</td>
<td>94,500 €</td>
</tr>
<tr>
<td>Feed-In Tariff (FIT)</td>
<td>0.035 €</td>
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<tr>
<td>electricity price</td>
<td>0.077 €/kWhe</td>
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<tr>
<td>FLH</td>
<td>800 h/year</td>
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<tr>
<td>Real escalation costs of O&amp;M</td>
<td>2 %/year</td>
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<tr>
<td>Investment Horizon (T)</td>
<td>20 year</td>
</tr>
<tr>
<td>Seasonal Energy Efficiency Ratio</td>
<td>3.03</td>
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<tr>
<td>Annual cooling energy output</td>
<td>168,000 KWh/year</td>
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<tr>
<td>Operation &amp; maintenance (O&amp;M)</td>
<td>1,890 €/year</td>
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<tr>
<td>Investment/ Replacement t=10</td>
<td>11,340 €</td>
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<tr>
<td>Capital Recovery Factor (CRF)</td>
<td>0.08</td>
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The annual cost operate unite 800 h/year x 47 KWe x 0.077 = 2,895 €/year.
The annual cooling sale 210 KWc x 800 h/year x 3.03 x 0.035 = 17,816 €/year.

Table 4: Financial calculation of project

<table>
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<tr>
<th>Year</th>
<th>Discounted CF</th>
<th>Nominal CF</th>
<th>Replacement</th>
<th>Operation costs of unit</th>
<th>O&amp;M Escalation cost €/yr</th>
<th>Cooling sale</th>
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</table>
The net present value of (NPV) 56,220 € is calculated.

The capital recovery of factor CRF = \[ \frac{r(1+r)^T}{(1+r)^T-1} \] ..........(7) \[ \to 0.08 \]

Thus, the cost annuity is \( a = \text{NPV} \times \frac{r(1+r)^T}{(1+r)^T-1} \) ..........(8) \[ \to 4508.83 € \]

**Sensitivity of the Annuity to Variation of O&M Costs**

With the increase of percent range, the overall costs of the operation rise, which results in the increase of generation costs, resulting in a rise that is above Feed-In Tariff, making it a bad investment.

<table>
<thead>
<tr>
<th>Var.</th>
<th>O&amp;M</th>
<th>Annuity</th>
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<td>1701</td>
<td>3009</td>
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<td>-9%</td>
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<tr>
<td>-8%</td>
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<td>-7%</td>
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<tr>
<td>-6%</td>
<td>1777</td>
<td>3609</td>
</tr>
<tr>
<td>-5%</td>
<td>1796</td>
<td>3759</td>
</tr>
<tr>
<td>-4%</td>
<td>1814</td>
<td>3909</td>
</tr>
<tr>
<td>-3%</td>
<td>1833</td>
<td>4059</td>
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<tr>
<td>-2%</td>
<td>1852</td>
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<tr>
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<tr>
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<td>4509</td>
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<tr>
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<tr>
<td>10%</td>
<td>2079</td>
<td>6009</td>
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</table>
18. Conclusion

Floor cooling is generally only suitable for low cooling loads. At 11.5°C the groundwater temperature could have been expected at 18 to 20 W/m² of cooling load. According to the planner, these loads were appropriate, however, at temperatures above 16°C, the cooling capacity of groundwater decreases considerably. Therefore, at high temperatures the groundwater is almost ineffective for floor cooling, and in this case could only be seen as relieving the air cooling from the water cooler. This reduces the air cooler's own electrical consumption by approx. 12 kWh per MWh, hence, less heat dissipates in the air cooler. It should be checked during a test run whether the condenser inlet temperature can be reduced below 40°C. This would reduce the condensing pressure of the refrigerant and, as a result, the power requirement of the compressor would also decrease.

It should be noted that when using cooling by water cooling floors where the cooling water is too low, then the floor gets slippery because the humidity of the air starts condensing. The condensation occurs when the warm, moist air from the room meets the colder surface of the heat exchanger (evaporator). Moreover, the air temperature unexpectedly drops when it gets in touch with the less warm floor, reducing the quantity of moisture it can normally hold. This results in moisture formation of condensation.
In case of failure of the well cooling and in accordance with the data presented above, the refrigeration machine (without free cooling with groundwater) with a maximum cooling capacity of 216 kWc cannot take over the additional cooling load of, in total 275 kWc, to cover the total cooling requirements of the property, floor cooling and fan coils. Thus, the system would have to be dimensioned 30% larger. In mathematical terms, the groundwater cooling would take approximately 2/3 of the cooling requirements, and the rest should be accounted for by the cooling machine. Hence, groundwater cooling would be more economical than the operation of a refrigeration machine.

It can be concluded that using ceiling cooling by means of free cooling for buildings is better and more effective than cooling by floor cooling, as it dissipates high cooling loads. Ceiling cooling offers great design freedom and more comfort, as they have no flow noises compared to conventional ventilation, which increases the thermal comfort in a room.
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**Internet Sources:**


Abbreviations

€ Euro
°C Celsius
a Year
CFCs Chlorofluorocarbons
CH4 Methane
CO2 Carbon Dioxide
COP Coefficient of Performance
CRF Capital Recovery Factor
db Dry bulb
DP Dew point
E Electricity
ESEER European Seasonal Energy Efficiency Ratio
F-gas Fluorinated gases
FIT Feed In Tarif
FLH Full Load Hour
GHG Greenhouse Gases
GHP Geothermal Heat Pump
GLHE Ground Loop Heat Exchanger
GSHP Ground Source Heat Pump
GWP Global Warming Potential
h Hour
HCFC Hydrofluorocarbons
HCFCs Halogenated Chlorofluorocarbons
HFC Hydrofluorocarbon
HVAC Heat Ventilation Air Conditioning
K Kelvin
KJ/Kg Kilo Joule per Kilogram
KVS Constant Volume System
kWc Cooling Capacity
kWe Kilo Watt Electricity
KWh Kilo Watt hour
L Liquid
MWh Megawatt hour
N2O Nitrous Oxide
NPV Net Present Value
O&M Operation & Maintenance
ODP Ozone Depletion Potential
P Pressure
PFCs Perfluorocarbons
PH Pressure and enthalpy
Q_{evap} Heat absorbed by the evaporator
Qab Heat reject
Qc Cooling capacity
Qcond Heat reject by condenser
Qh Heating Capacity
Qzu Heat Add
<table>
<thead>
<tr>
<th>RW</th>
<th>Type of Carrier chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Entropy</td>
</tr>
<tr>
<td>SEER</td>
<td>Seasonal Energy Efficiency Ratio</td>
</tr>
<tr>
<td>SF6</td>
<td>Sulfur Hexafluoride</td>
</tr>
<tr>
<td>V</td>
<td>Vapour</td>
</tr>
<tr>
<td>VRF</td>
<td>Variable Refrigerant Flow</td>
</tr>
<tr>
<td>VVS</td>
<td>Variable Volume Flow</td>
</tr>
<tr>
<td>w comp</td>
<td>Work done to drive the compressor</td>
</tr>
<tr>
<td>WLHP</td>
<td>Water loop heat pump systems</td>
</tr>
<tr>
<td>Δh</td>
<td>Change in enthalpy</td>
</tr>
<tr>
<td>EER</td>
<td>Energy efficiency ratio</td>
</tr>
</tbody>
</table>
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